PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA

68

STUDY WEEK

ON:

REMOTE SENSING AND ITS IMPACT ON DEVELOPING COUNTRIES

June 16-21, 1986

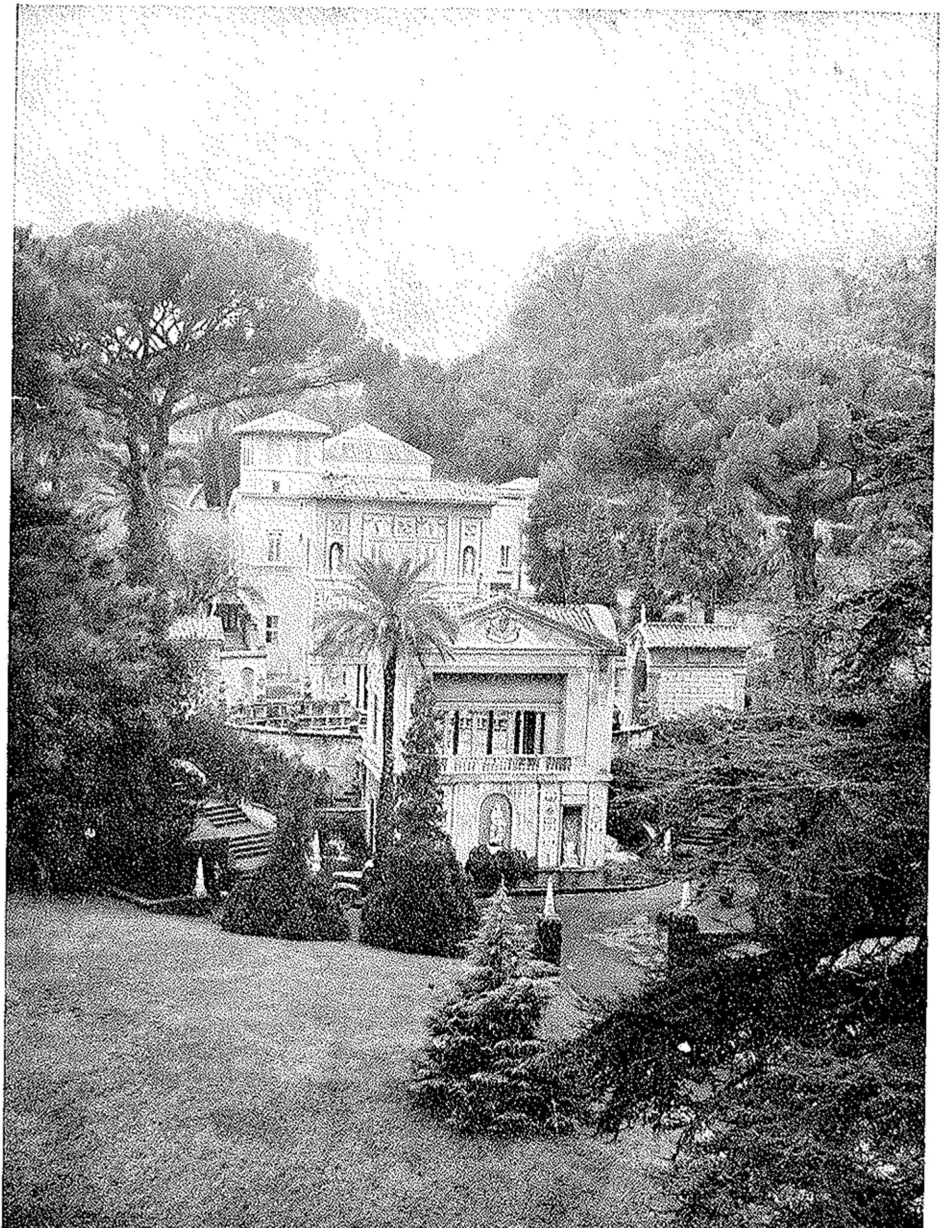
EDITED BY

CARLOS CHAGAS and VITTORIO CANUTO

PONTIFICIA ACADEMIA SCIENTIARVM

EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA

MCMLXXXVII



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FOREWORD

In the VII book of Plato's Republic, *there takes place a dialogue between Socrates and Glauco that is refreshing in its simplicity and yet captivating in its foreknowledge. The teacher and student agree that the study of astronomy should be pursued not only because it "purifies" man's intelligence, obfuscated by daily burdens, but also because it helps mankind with the knowledge it brings to military strategists, agriculture and the prediction of the seasons.*

The latter activities are what we call today Remote Sensing, RS, a new discipline complementary to astronomy: rather than looking at the skies from the earth, one looks at the earth from the sky. RS has provided the first synoptic view of the earth. However, the large areas it surveys are not just patches of the earth's surface, they are in most cases the home of millions of people sometimes affected by natural phenomena against which they often feel powerless. To quote a specific example, in the 1970 floods in the Bay of Bengal, half a million people lost their lives; the economic damages were in the hundreds of millions of dollars. Desertification, famine, locust invasion are other well known examples of potential natural disasters.

It is a generally accepted fact that a judicious use of RS may greatly alleviate these global problems. The RS technologies are an offspring of space technologies. The latter, as we all know, belong to very few nations, while most of the countries affected by the problems mentioned above lack the RS means to alleviate their problems. This is just one of the difficulties; there are many others. For example, RS data may yield information that is very sensitive for sensed states because its dissemination might expose their economic and strategic status. In this respect, it has frequently been feared by developing countries that RS data may be "misused". Stated differently, a nation might be at a great disadvantage if it did not have access to data to which it has a right. Under easily foreseeable circumstances, this may become an act of sovereignty violation.

Through RS it is possible to detect undiscovered resources and in this way increase a nation's productivity. While this is very desirable, it has also given rise to at least two types of problems. The first was clearly spelled out by Pope John Paul II in the following terms: "The resources of science make it possible to feed the whole human family, with the remedying of past and present mistakes and shortcomings. Nevertheless, one cannot help noting that there is still a lack of firm determination in political circles to make proper use of the technological means. We know that progress must not be the exclusive privilege of the favoured few. We should not forget the words of Pope Paul VI, who said that 'development is the new name of peace' ".

The second potential problem is that nations with technological capabilities to operate in outer space are in a position to collect resource data which may actually be under the territorial jurisdiction of other countries. Problems of international law immediately arise. It is my opinion that it would be necessary to first establish whether a state has the right to gather information without the observed nation's consent. Then, the question arises as to its right to divulge the information without permission to do so from the sensed nation. RS activities are carried out in/from outer space, where states cannot claim property rights, and yet data on natural resources are for use on earth, where sovereignty exists.

In order to foster stronger links among those who possess RS technology and those who do not have it but need it, as well as to stress once more the fundamental concept that earth resources are a patrimony of mankind and not a property of few privileged countries blessed by technological advances, the Pontifical Academy of Sciences organized a Study Week on: "Remote Sensing and its Impact on Developing Countries", which was held in the Vatican on June 16-21, 1986. The work carried out by the experts called upon by the Pontifical Academy of Sciences, was conducted in a spirit of collaboration, amity and sincere desire to help illuminate these new problems as well as to suggest possible solutions. The conclusions and recommendations published here have recently become an official UN document.

It is my desire and privilege to thank all the participants for their efforts to make the Study Week a success. I wish particularly to thank Professor Vittorio Canuto. Without his devoted help and collaboration, the Study Week and the present Proceedings would not have been possible. At the same time, it is my pleasure to thank the National Science Foundation, Washington, D.C., and in particular Dr. H.M. Uznanski, for the *financial help provided to the American participants. Professor U. Colombo of ENEA, Rome, and TELESPAZIO, Società per le Telecomunicazioni Spaziali, of the IRI-STET group, provided generous financial support to defray some of the expenses incurred by the Study Week. My sincere thanks go also to the Banca Nazionale del Lavoro for its generous contribution towards the realization of the present publication. The Pontifical Academy of Sciences is most grateful for all this generous help.*

Every Study Week has the support of the small but diligent group of co-workers who help me here in Rome. It is a pleasure to thank Father Enrico di Rovasenda, Ing. R. Dardozzi, Madame Michelle Porcelli, Mrs. Gilda Massa and Silvio Devoto for what they bring to my task.

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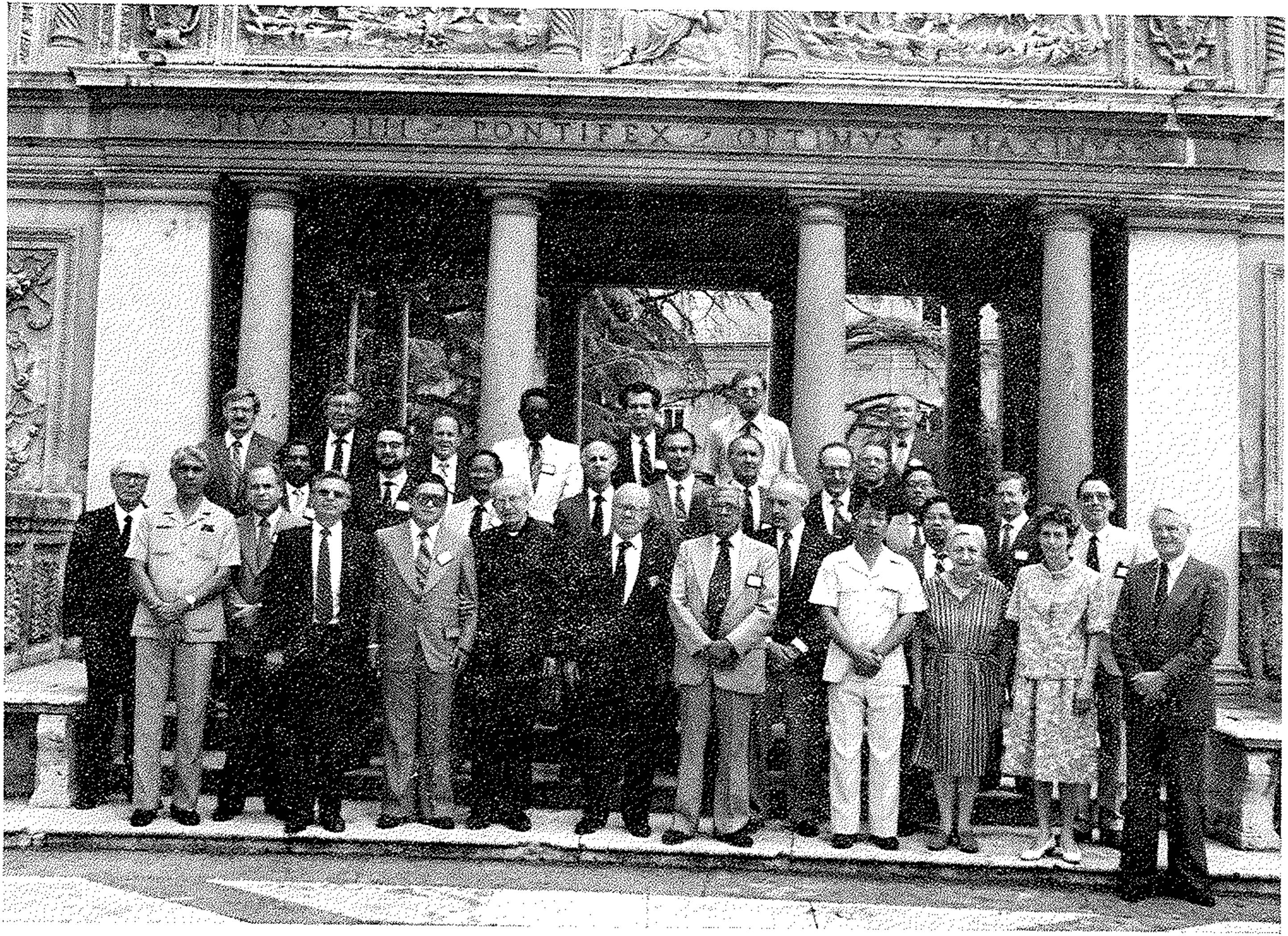

Participants in the Study Week.

AUDIENCE OF THE HOLY FATHER

On June 20, 1986, His Holiness John Paul II granted an Audience in the Sala del Concistoro of the Apostolic Palace in the Vatican to the participants in the Study Week on "Remote Sensing and Its Impact on Developing Countries".

Led by the President of the Pontifical Academy of Sciences, His Excellency Professor Carlos Chagas, and accompanied by the then Director of the Chancellery, Rev. Father Enrico di Rovasenda, and by the Co-Director, Ing. Don Renato Dardozzi, the group was introduced in the Apostolic Palace and paternally received by His Holiness, who at the end of the Audience personally greeted each participant.

President Chagas delivered the following address:

Holy Father,

Permit me to present to You the homage of admiration and respect of the members of the Study Week on Remote Sensing and its Impact on Developing Countries. With us are also members of the Academy and our staff. Thirty-five specialists coming from sixteen nations, from Sri Lanka or Bangladesh, Philippines, Thailand, from the lands of Africa and Asia to those of Latin and North America, and from Western Europe to the Urals, are here to hear Your advice and judgment on this very important scientific and technological topic, which should be increasingly employed for the benefit of the people of all the world, and particularly of the developing nations. The question of its use by these countries, however, is not very simple. In order that this technology be utilized for the true advantage of the people rather than becoming an instrument for the deployment of technological colonialism, one has to reach a minimum critical level of scientific and technological expertise. Otherwise, powerful industrialized countries may dominate or compromise the future of the poor countries.

A precise knowledge of the resources of a country is of paramount importance for its development, and Remote Sensing is by far the most relevant instrument to achieve that goal. The national inventory must be made under objective conditions and not, as has been seen many times, unreal ones. As You have said so many times, Holiness, science and technology should be used only for the benefit of men and women. Hopefully, Remote Sensing is one of the more powerful techniques one can use to serve humankind.

The technological advances the Academy has been discussing this week have not only the advantage of showing what a country has as natural resources, thus establishing a complete list of its potential capabilities. Remote Sensing can also show how human greed is destroying nature, ore deposits, renewable resources, etc., thus disrupting the equilibrium which must necessarily exist between man and his environment. This equilibrium is absolutely necessary for the future of humankind, but the so-called productive classes, so much attracted by consumerism, are unaware of this truth. However, let us proclaim that the ecological challenge is one of the most serious defiances the world is facing.

In bringing the importance of Remote Sensing to the attention of Your Holiness, the Pontifical Academy of Sciences is sure that, through Your appeal, all the nations of the world will pay more attention to the possibilities offered by this splendid technology as a tool to help poor societies to overcome the obstacles brought to its general use by political unawareness.

Holiness, Your appeal for the use of "Remote Sensing" for the benefit of developing nations will be heard throughout the world. By helping the promotion of the welfare of the poorer countries, the appeal will certainly be a new step in the March for Peace, of which You are the most heard and unequivocal herald. The experience of Your Academy, Holiness, is that Your words resound all over the world. You are the voice that eliminates the hurdles on the road of social progress. Thus it is with profound gratitude that we will hear Your authoritative voice express Your thoughts and wishes in relation to the use of Remote Sensing for the benefit of developing countries.

Your interest in our work, as well as Your blessing, will be a continuous stimulus to all those who, in the field of Remote Sensing, labour for the benefit of humankind.

The Holy Father answered with the following discourse:

Mr President,
Ladies and Gentlemen,

It is a pleasure to receive today those taking part in the Study Week organized by the Pontifical Academy of Sciences, on the subject of "Remote Sensing and Its Impact on Developing Countries".

An ever deeper knowledge of the earth, and in particular of its poorest zones, is the purpose for which the Pontifical Academy and its distinguished President have brought you together in order to study this theme.

1. *The new technique of remote sensing makes it possible to survey anything from a few square metres to huge expanses of the earth's surface. Certain areas, the home of hundreds of thousands of people, are being affected by the* terrible phenomenon of desertification, *with consequent famine and disease. The causes of this phenomenon vary from unsuitable methods of farming to climatic factors such as cyclones and other atmospheric disturbances.*

Surveys carried out with the aid of satellites *linked with a network of ground tracking stations can provide a detailed and exact picture of crops, including their increase or deterioration, and can offer the chance of using* technical means of combating the encroaching desert, *which imperils the livelihood of a high percentage of the world's population.*

With the help of remote sensing, it is possible to give useful advice for many schemes. These latter include the *improvement of soil condition, forecasting and increasing the development of crop harvesting both in quantity and quality, the introduction of new crops, the prevention of the destruction of forested areas needed for ecological balance, and the taking of measures to meet possible atmospheric conditions, both harmful and beneficial.*

By means of remote sensing it is likewise possible to detect the presence of concealed sources of energy, both renewable and non-renewable, as also the presence of food resources on the seabed and in rivers and lakes, together with the mineral wealth lying in the subsoil.

2. *Your meeting has highlighted the possibility of aiding all peoples, with the help of advanced technological methods, to attain a* more just form of worldwide coexistence, so that the earth's resources, which are the patrimony of all, may be fairly distributed and shared. *This is in accordance with the will of the Creator who made man and woman in his own likeness and said to them, "...have dominion over the fish of the sea and over the birds of the air and over every living thing that moves upon the earth... I have given you every plant yielding seed which is upon the face of all the earth, and every tree with seed in its fruit; you shall have them for wood" (Gen 1:28-29).*

The resources of science make it possible to feed the whole human family, with the remedying of past and present mistakes and shortcomings. Nevertheless, one cannot help noting that there is still a lack of firm determination in political circles to make proper use of the technological means which you have been examining during these days of study and of service to human welfare. We know that progress must not be the exclusive privilege of the favoured few. *We* *should not forget the words of Pope Paul VI, who said that development is the new name of peace.*

3. *It is a source of satisfaction that the conclusions of your previous Study Week, held in October of the year before last, on the subject of "The Impact of Space Exploration on Mankind", have been adopted by the United Nations Organization and sent to all member States. This is indeed a sign of profound respect for the relevance and importance of the work being done by the Pontifical Academy.*

It is my hope that by means of joint agreements and commitments all Governments will promote the peaceful uses of space resources, for the sake of the unification of the human family in justice and peace. *I take this occasion to express once more my conviction that national and international economic powers should serve all peoples and every individual, but with special preference for those whose lives are particularly threatened and who need assistance for securing their very survival and the means of living in a manner consonant with human dignity.*

May the Lord of heaven and earth look kindly upon you and grant to you and your families the abundance of His blessings.

SCIENTIFIC PAPERS

REMOTE SENSING: TECHNICAL ASPECTS

REMOTE SENSING: PAST, PRESENT AND FUTURE

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ABSTRACT

With the aid of 28 figures and 16 tables, this unabridged version of my paper seeks to provide an integrated, comprehensive overview of past, present and probable future developments in remote sensing. Consistent with the theme of this Study Week, special emphasis is given to the potential impact of remote sensing on developing countries. The presumption is made that the primary use of remote sensing in those countries, as elsewhere, would be in the inventory, monitoring and management of natural resources. This would include such *renewable* natural resources as timber, forage, water, and agricultural crops. It also would include such *non-renewable* natural resources as minerals and fossil fuels. It is, of course, recognized that some such uses already are being made of remote sensing in the developing countries.

In keeping with instructions given by the convenors of this Study Week, my paper seeks to elucidate, in "A-to-Z" fashion, the basic concepts, principles and considerations that constitute the foundation for modern remote sensing technology.

A primary objective of my paper, again in keeping with the instructions given, is to provide a framework within which other papers that are to be presented during this Study Week will fit as they collectively consider, in detail, the most relevant aspects of remote sensing. The major components of this framework, as encountered in one section or another of my paper, as appropriate, are (1) a tabular summary of the information requirements of resource managers; (2) an elucidation of the basic remote sensing-related principles and considerations; (3) a tabular summary of the components that comprise the "Multi-" concept, as it applies to the remote

sensing of natural resources; (4) a defining of the attributes of simply structured versus complexly structured areas in relation to the remote sensing of natural resources; (5) a diagrammatic summary of steps entailed in the remote sensing-aided management of an area's natural resources; and (6) a current tabulation of the applications that already have been cost-effectively made of modern remote sensing technology.

The paper concludes with a discussion of factors governing the acceptance and use of modern remote sensing technology, again with special emphasis on developing countries. In so doing, it raises questions about certain remote sensing-related considerations that are often overlooked, namely the *humanistic* ones. (For example, to what extent should a developing country's *non-renewable* natural resources be preserved as the birthright of future generations instead of being exploited to the fullest now, with the aid of remote sensing-derived information?) This is done in recognition of the fact that the Pontifical Academy of Sciences, by sponsoring and participating in this Study Week, provides us with a uniquely favorable opportunity for the airing of such humanistic considerations.

By its very "framework-establishing" nature, this paper may encroach severely on material that is to be ably covered by other participants during this Study Week. Apology is hereby made to them for any such undue encroachment. Furthermore, assurance is hereby given of my willingness — even my eagerness — to have major sections of this "unabridged" version of my paper deleted from the published proceedings of this Study Week.*

I. Introduction

My invitation to speak at this conference was accompanied by several guidelines. Specifically, (1) I am to "set the tone" by presenting an opening paper that will be consistent with the theme for this entire Study Week, namely "Remote Sensing and its Impact on Developing Countries"; (2) in doing so I am first to provide a few terminology definitions, as necessary to ensure that those participants who have only minimal ex-

(*) Editor's note: As the Study Week progressed it became apparent that Dr. Colwell's thorough overview paper needed to be retained in its entirety in order to fulfill its stage-setting role. Therefore it is printed here without deletions.

perience in remote sensing are quickly made conversant with certain terms that will be used throughout this Study Week; (3) then I am to describe (rather fully, I am told) the basic principles and considerations that are involved in modern day remote sensing; and (4) finally, building on this base, and consistent with the title which, at the outset, the convenors of this conference assigned to my paper, I am to provide the proper historical perspective by successively discussing the major past, present, and future developments in remote sensing. Of course my guideline-givers reminded me that, (5) as a courtesy to the many eminent speakers who are to follow me, I should achieve the above objectives in a way that will avoid encroaching unduly on those particular phases of remote sensing about which they, collectively, have been invited to speak. Both the content and the organization of the material appearing in the remainder of my paper will be found to reflect these guidelines.

A guideline that I soon realized I also would need was one specifying how long my paper should be if I was to fulfill the previously listed guidelines adequately. At one extreme I might offer little more than the enthusiastic but nebulous assertion that "remote sensing is great — so let's get on with it, especially in the developing countries". In that case I would merely fortify such an assertion by recounting a few of my own personal experiences with remote sensing during the past four decades, especially in developing countries throughout the world. And at the other extreme I might offer an amplification of the 2700-page *Manual of Remote Sensing* (American Society of Photogrammetry, 1983) as it was prepared by more than 200 internationally known experts, each contributing information on one aspect or another of remote sensing. So why might that extremely voluminous prize-winning tome need amplification? Because the most common criticism of it that has been directed at me, as the one who served as its "Editor-in-Chief" during the three years required to prepare it, is that certain important information is omitted in it.

Upon asking my guideline-givers how long my paper should be, the answer that I received (somewhat paraphrased here) was as follows: "Since yours is to be an *overview* paper, it should attempt to survey the entire field of remote sensing, doing so in such a way as to provide a framework for the Study Week's discussions. Therefore it should be reasonably complete, comprehensive and, above all, integrative. Be sure that your paper is long enough to satisfy those requirements". On hearing this, I indicated that such a paper might be 100 pages or more in length. In response I was encouraged to prepare such a paper, despite its formidable length, for eventual publication in the Proceedings of this Study Week. I was reminded, however, that I would need to reduce the *oral* presentation of my paper to the allotted 30 to 40 minutes — which, indeed, I shall do.

It should be emphasized that this Study Week concerns itself almost entirely with only one application of remote sensing, i.e., the use of aerial photography, space photography and related data with respect to the surface of the earth as aids to the inventory, monitoring and management of natural resources, especially in developing countries. Other applications range all the way from sensing the signals from transmitter-equipped people who are in distress at sea or in remote land areas to attempting to sense signals emanating from intelligent life in outer space. The first of these applications seeks to answer the friendly questions: "Is there anybody *down* there? If so, what are they doing and what might they do?" The second, known as SETI (Search for Extraterrestial Intelligence) seeks to answer the friendly questions: "Is there anybody *out* there? If so, what are they doing, and what might they do?" These and other aspects of remote sensing that have little or no direct bearing on natural resource surveys have been omitted from this paper.

II. Terminology

It has been aptly observed that an excellent indication of the newness and growth rate of any particular science or discipline can be found in the degree of preoccupation among its participants with the *terminology* that should be applied to it. By that standard the science known as "remote sensing" must, indeed, be very new and very rapidly growing.

Despite the foregoing we certainly cannot claim that remote sensing, in the broadest sense of that term, constitutes a truly *new* field of human activity. Even those who have little or no familiarity with the term "remote sensing" can correctly infer that, broadly defined, it pertains merely to "sensing at a distance", as opposed to "contact sensing". For example, the sensations perceived by a person through seeing an object from afar constitute remote sensing, while those perceived through touching and feeling it constitute contact sensing. In this broad sense of the term, therefore, remote sensing is an activity that man has been engaged in from time immemorial.

As previously indicated, a much more limited use of the term "remote sensing" has come to be accepted, however, by those who work with photography and/or photo-like images and who consider themselves to be modern remote sensing scientists. This more limited use stems from developments that began about 30 years ago, all of which centered around improvements that were being made then in the taking of aerial photographs and the extraction of information from them.

How then did the term "remote sensing", as it will be used throughout this Study Week, come into being? In the late 1950's it became apparent to many scientists that the term "photo" was being stretched much too far in view of the fact that "photography" literally means "to write with (visible) light". By then it had become possible to obtain photo-like images from aircraft, not only in the visible, near-infrared and near-ultraviolet parts of the electromagnetic spectrum, but also in the thermal infrared and microwave regions. Four of these regions are, of course, outside the visible range of humans. Given the photo-like images, however, the trained photo interpreter soon learned to extract information that was far in excess of the information he might have extracted from conventional aerial photography alone. Furthermore, in many instances it was not even necessary to produce photo-like images because, through the use of techniques and equipment that presently will be described, it became possible to obtain digital values of the terrain's "scene brightness" as sensed by an airborne line scanner, picture element-by-picture element. Then, suitably programmed, a computer could perform a digital analysis that would identify each kind of feature largely on the basis of its unique, digitally-expressed "brightness signature". The term "remote sensing" was coined to encompass this greatly expanded activity of data acquisition and analysis, whether the data had been acquired within, or outside of, the visible part of the electromagnetic spectrum.

In keeping with these developments it is helpful to present here a brief tabular comparison of the *old* with the *new* terminology, as in Table 1. It should be emphasized that, far from being obsolete, each of the old terms appearing in that table often is the proper one to use even today, but only in the limited context indicated by its definition. It is only because our capability for acquiring and analyzing remote sensing data has been greatly *broadened* in the last two or three decades that the corresponding new, but more inclusive term frequently must be used.

There are many additional remote sensing-related terms, together with acronyms, that comprise the rather formidable lexicon of a modern day remote sensing scientist. By and large, any such terms used in the remainder of this paper will be defined, either directly or by inference, where first used.

TABLE 1 - *Comparison of Old Versus New Remote Sensing-Related Terms.*

Old Term	Corresponding New, More Comprehensive Term
(1) *Aerial photo reconnaissance*: the acquisition of photos from an aircraft, whether for military purposes (hence the term « reconnaissance ») or for civilian purposes.	(1) *Remote Sensing*: the acquisition of photos and/or related basic data from an aircraft and/or spacecraft, together with the analysis of such data.
(2) *Aerial Photography*: the product obtained through use of a camera mounted in an aircraft.	(2) *Remote sensing imagery*: the product obtained through use of cameras, optical-mechanical scanners or other image-forming sensors mounted in either an aircraft or spacecraft.
(3) *Photographic interpretation*: the process by which humans examine photographic images for the purpose of identifying objects and judging their significance.	(3) *Image analysis*: the process by which humans and/or machines examine photographic images and/or digital data for the purpose of identifying objects and judging their significance.
(4) *Photo interpreter*: the human who engages in conventional forms of photographic interpretation.	(4) *Image analyst*: the human who engages either in conventional forms of photographic interpretation or in programming and interacting with machines during the computer-aided analysis of remote sensing data.

III. Basic Principles and Considerations

It is anticipated that, throughout this Study Week, a large number of basic remote sensing-related principles and considerations will need to be understood and dealt with. Accordingly, in keeping with the stage-setting role that has been assigned to me, and the request that I provide some kind of framework on which to hang the various items that will be discussed during this Study Week, I will attempt systematically to explain in this section the particular basic principles and considerations that are most likely to enter into our deliberations.

Most of the items that will be covered in the "A-to-Z" listing contained in this section have guided not only past developments in remote sensing but also those presently occurring and others likely to occur in the future. Hence, by describing here these basic principles and considerations we also will be setting the stage for the three sections of my paper that follow, dealing, respectively, with past, present and probable future developments.

A. *Rationale for the Remote Sensing of Natural Resources from Aerospace* (1).

For almost all remote sensing, including that of primary concern to us during this Study Week, the surface of the earth is the "target" or area of interest. Since the face of the earth looks to the sky, it follows that the sky is the most favorable vantage point from which to look at the face of the earth. This is a major reason why balloonists speak ecstatically of their "bird's eye view" in contrast with the "worm's eye view" of the on-the-ground observer. It also is why astronauts have repeatedly exclaimed "What a ride!" as they have commanded what has been termed the "God's eye view" of the earth.

As a corollary to this concept, and especially within the context of this Study Week, the most important reason for our viewing the earth from above is simply this: by such means we can better inventory, monitor, and manage the earth's natural resources, i.e., its timber, forage, agricultural crops, soils, water, minerals, fossil fuels, domesticated animals, fish, wildlife and also (while somewhat overlapping this listing) its oceanographic, atmospheric, recreational, aesthetic, cultural, urban/suburban, and environmental resources. The better we perform the inventory and monitoring tasks with respect to these resources, the better we will be able to comprehend what man has done and is doing to them and, even more importantly, the better we will be able to determine what needs to be done if these resources are to be managed wisely in the future.

Since shortly after the dawning of the space age nearly three decades ago, man has been given the opportunity for the first time to view the surface of the earth almost in its entirety. Since then, some important information about the earth's natural resources has been obtained merely through direct visual observations by astronauts as they looked down from an altitude of 100 miles or more and watched the terrain go by at the amazing rate of five miles per second. But of greater significance by far are the records of the earth's surface that have been obtained by cameras

(1) "Aerospace" (as the term will be used throughout this Study Week) is the generic term applied to the earth's atmosphere together with the "outer space" region just beyond it.

and other remote sensing devices, mounted in either manned or unmanned earth-orbiting satellites. It is not surprising that these highly detailed and permanent records, when variously enhanced and subjected to painstaking examination by teams of expertly trained and well equipped earth scientists, have yielded far more information about the earth's natural resources than could possibly have been obtained merely from the fleeting glimpse of them that is afforded to an earth-orbiting astronaut. Often such space-acquired remote sensing data can be made more informative if, through an appropriate process of sampling and subsampling, it is supplemented by still more detailed information about small, representative parts of the area as acquired from aerial photography and/or through direct on-the-ground observation. But as some of the photographs to be presented during this Study Week will clearly show, the old Chinese axiom that "a picture is worth ten thousand words" certainly is true when the picture is in the form of a remotely sensed image of the earth, and the words (which could not be supplied except through a careful study of the picture) pertain to the amount, distribution, and condition of the earth's natural resources.

By way of summarizing this section, then, we can express in a simple, five-part statement the rationale that governs most of our efforts to remotely sense the earth's natural resources from aerospace:

(1) Whether viewed on a local, regional, national, or global basis, the supply of most of these resources is rapidly dwindling and/or the quality of them is rapidly deteriorating.

(2) This process is occurring most dramatically at the very time when the demand for such resources is rapidly increasing [2]. (See Figure 1).

(3) The combination of these factors creates a compelling need for the wisest possible management of the earth's resources.

(4) An important step leading to such management is that of obtaining accurate resource inventories at suitably frequent intervals, so that the resource manager (i.e., the farmer, forester, range manager, etc.) will know at all times both the quantity and condition of each kind of resource that

(2) There is a multiplication factor with respect to this increased demand: not only is the world's population rapidly increasing, but so is the *per capita* demand for its natural resources, in both developed and developing countries, occasioned by man's insatiable desire for an ever higher standard of living.

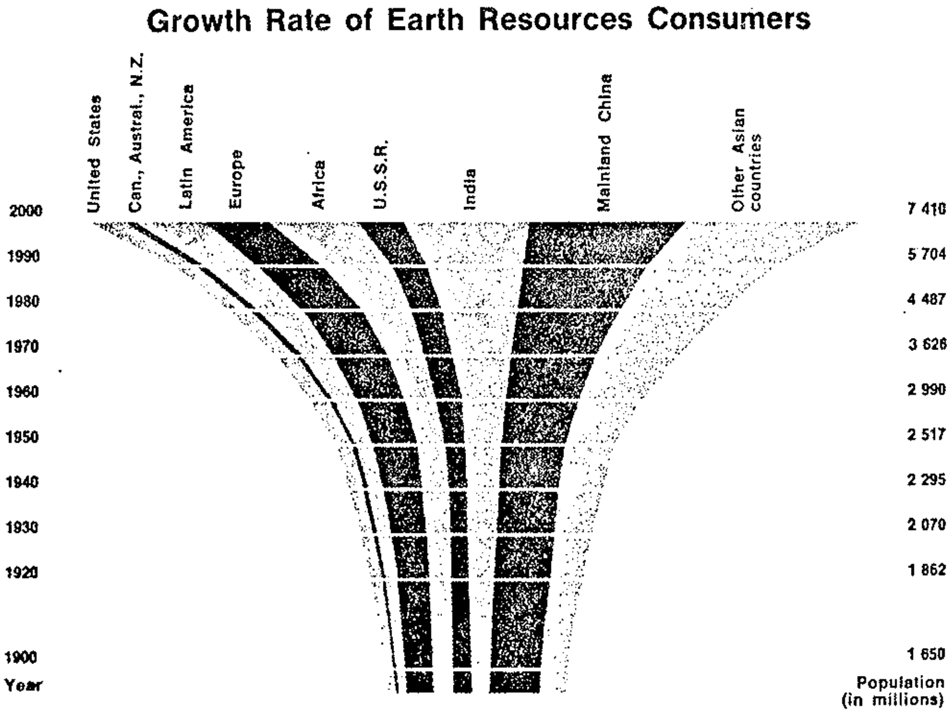


FIG. 1. During the 20th century the greatest increase in earth resource consumers has been and will continue to be among those living in developing countries. Increase in the *per capita* demand for such resources also is expected to be greatest in the same countries during the remainder of this century. (Photo courtesy of NASA).

is present in each part of the area for which he has management responsibility.

(5) As will be illustrated and otherwise documented in this Study Week, the required inventories almost invariably are best made through the analysis of data acquired by cameras and related remote sensing devices as they look at the earth's surface from aircraft and spacecraft.

Remote sensing from aircraft and spacecraft often provides the most suitable means for rapidly collecting data about the natural resources of an area, especially when the alternative is to make laborious on-the-ground surveys. There are several reasons why this is so. The task of inventorying an area's natural resources is, first of all, one of delineating boundaries between one resource characteristic and another. When confined to the earth, man often has great difficulty both in recognizing and in delineating these boundaries. This difficulty is attributable mainly to the limited visibility of terrain features that is afforded to him, especially in areas where the topography is heaviliy dissected or densely vegetated. In contrast, a "continuous plotting" of these resource boundaries often can be performed on vertical photos taken from aircraft or spacecraft.

A second reason for using aircraft or spacecraft results from the sheer vastness and inaccessibility of the area in which natural resource surveys often must be made. It is only from aircraft or spacecraft that the broad synoptic view, so essential for the quick and economical delineations of natural resource features in such an area, can be obtained. The fact that a vast portion of the total area that is to be inventoried can be photographed at a single point in time and space and under relatively uniform lighting conditions constitutes an additional advantage.

The ability of an aircraft or spacecraft to travel quickly from one camera station to another constitutes still another advantage when the objective is to acquire detailed information about a large region in a short period of time and with a minimum of discomfort to personnel performing the inventory.

There are strong proponents for the use of aircraft rather than spacecraft when making natural resource surveys. Conversely, there are proponents for the use of spacecraft rather than aircraft when making such surveys. Several of the examples that will be presented during this Study Week provide strong support for a third view, viz., that such surveys might best be made by means of a "multistage" sampling technique that employs spacecraft, aircraft, and ground observations. Each of these data-collecting components, in turn, provides a progressively closer look at a progressively smaller area and, in so doing, provides progressively more information. Then, through a process known as "data expansion", each part of this detailed information is applied to the progressively larger area or "stratum", of which it is a sample.

B. *The Three Steps Involved in Wisely Managing the Earth's Natural Resources.*

Because emphasis throughout this Study Week is to be placed on remote sensing as a potential aid to resource management, we need to recognize from the outset that there are three distinct steps leading to wise resource management. These are: (1) inventory, (2) analysis, and

(3) implementation. Briefly stated, it is in the *inventory* step that a determination is made of "how much" of "what" is "where" in relation to the resources that are to be managed; it is in the *analysis* step that decisions are made regarding how the resources should be managed (based on an examination of the inventory information just mentioned, in relation to the known cost-effectiveness of certain resource management practices); and it is in the *implementation* step that these management decisions are executed. It will be apparent from the example given in the next section of this paper — which presumes that agricultural fields are the area of interest — that remote sensing, and the products obtained from it, can be used to great advantage in each of these three steps.

C. *Uses of Remote Sensing in Each of the Three Steps* — An Agricultural Example.

I. In the *Inventory Step*: Obtain more timely and accurate information as to:

(a) the type of crop growing in each field,
(b) the condition or overall vigor of each crop,
(c) the causal agent or organism, wherever a loss of vigor is detected,
(d) the probable yield (3) in each field, per unit area,
(e) the area for each field, crop type, and condition class, and
(f) the probable production, (4) crop type-by-crop type, for the entire agricultural area of interest.

II. In the *Analysis Step*: Through the use of aerospace photography and other remote sensing-derived products obtain a "picture" of the situation that exists in each portion of the agricultural area, the better to visualize it; then decide "what" to do "where" and "when" (e.g., where and when to irrigate, cultivate, or apply insecticides, fungicides or herbicides).

III. In the *Implementation Step*: Through the use of suitably annotated aerospace photography and other pictorial displays, determine the best route of approach to each area that is to be treated, and verify, upon arriving there, that the proper location has, indeed, been reached

(3) Yield is the amount produced per unit area.
(4) Production is the total amount produced, i.e., it is the product of yield x area.

and that conditions there are, indeed, as they had been deduced through remote sensing; then implement the management measures there.

Note: Once a given cycle of the Inventory/Analysis/Implementation activities has been completed, remote sensing is again very useful for "monitoring" the area in terms of both the results thus far achieved and the additional measures that may need to be implemented.

D. *Application Areas for the Remote Sensing of Natural Resources.*

Table 2 lists the kinds of information sought (and hopefully obtainable through remote sensing data-analysis) by workers in various disciplines that entail the inventory, monitoring and management of the earth's natural resources. It will be noted there that, under each discipline, both the *basic* and *applied* kinds of information sought by these workers are listed. In the long run, both kinds of information can be of great value to the resource manager. *Basic research* by definition seeks to understand the fundamentals on which a particular science rests; the types of data derived from basic research are therefore called "*basic data*" and, when analyzed, lead to the types of *basic information* listed in Table 2. On the other hand, *applied research* seeks to solve the specific problems in an applied or practical manner. The types of data derived from applied research (and subsequently from operational systems and procedures based on such research) are therefore termed "*applied data*" and, when analyzed, lead to the types of *applied information* listed in Table 2.

For example, I have indicated in Table 2 that foresters, range managers, and agriculturalists wish to acquire basic information on "the amount and distribution of the earth's biomass", on "the amount and nature of energy exchange phenomena" which involve vegetation, and on the functioning of the ecosystems of which they are a part. University scientists in the disciplines of forestry, range management, and agriculture are, indeed, justifiably interested in such basic information, and in its long-term significance. This basic information may even be of some small interest to the forester, range manager, or farmer in his capacity as a citizen of the world. However, he finds little in this kind of information that tells him how better to grow timber, livestock, or agricultural crops on a parcel of land for which he has management responsibility, or even whether, during the period in question, there is likely to be an overproduction or an underproduction of the type of forest, range, or agricultural product *ers in Various Disciplines.*

I. Foresters, Range Managers, and Agriculturalists

A. *Basic*

1. Amount and distribution of the "biomass"
2. Nature, extent, and function of important "ecosystems"
3. Amount and nature of energy exchange phenomena

B. *Applied*

1. The species composition of vegetation in each area studied
2. Vigor of the vegetation
3. Where vegetation lacks vigor, the causal agent
4. Probable yield per unit area and total yield in each vegetation type and vigor class
5. Information similar to the above on dynamics of livestock, wildlife and fish populations
6. Changes resulting from past practices

II. Geologists

A. *Basic*

1. Worldwide distribution of geomorphic features
2. Energy exchanges associated with earthquakes and volcanic eruptions
3. The nature of geomorphic and mineralization processes

B. *Applied*

1. Location of certain or probable mineral deposits
2. Location of certain or probable petroleum deposits
3. Location of areas in which mineral, and petroleum and ground water deposits of economic importance probably are lacking

III. Oceanographers

A. *Basic*

1. Diurnal and seasonal variations in sea surface temperatures and subsurface temperatures
2. Vertical and horizontal movements of ocean currents and individual waves
3. Global, regional and subregional shoreline locations, characteristics and the changes in these characteristics with time
4. Diurnal and seasonal movements of fish, algae and other marine organisms

B. *Applied*

1. The exact location, at a given time, of ships, icebergs, tsunamis, storms, schools of fish and concentrations of kelp
2. The location of ocean beaches suitable for recreational development
3. The rate of spread of water-pollutants and the kind and severity of damage caused by them
4. Health/vigor of fish and mammal populations
5. The formation of ocean storms and their movement to land areas.

IV. Meteorologists

A. *Basic*

1. Diurnal and seasonal variations in cloud cover, wind velocity and air temperature and humidity in relation to topography and geographic locality
2. Accurate statistical data on the points of origin of storms, the paths followed by them, their intensities, and their periods of duration

B. *Applied*

1. Early warning that a specific storm is developing
2. Accurate tracking of the storm's course
3. Accurate periodic data on air temperatures, humidity, and wind velocity
4. Accurate quantitative data on the response of the atmosphere to weather-modification efforts
5. Selection and assessment of precipitation and growing conditions in remote areas

V. Hydrologists

A. *Basic*

1. Quantitative data on factors involved in the hydrologic cycle (vegetation, snow cover, evaporation, transpiration, and energy balance)
2. Quantitative data on factors governing climate (weather patterns, diurnal and seasonal cycles in weather-related phenomena)

B. *Applied*

1. The location of developable aquifers and target areas for ground water exploration
2. The location of suitable sites for impounding water
3. The location of suitable routes for water transport
4. The moisture content of soil and vegetation
5. Systems of enhancing ground water recharge

VI. Geographers

A. *Basic*

1. Global, regional, subregional, and local land use patterns
2. The nature and extent of changes in vegetation, animal populations, weather, and human settlement throughout the world

B. *Applied*

1. The exact location, at any given time, of facilities for transportation and communication
2. The interplay of climate, topography, vegetation, animal life and human inhabitants in specific areas
3. The levels of economic activity and the purchasing habits of inhabitants in specific areas
4. Geographic distribution and dynamics of socio-economic and political factors influencing the production and use of earth resources
5. Land cover and characteristics related to land-use potential

which he is in the business of producing. Instead, he needs information of the applied type as to the vigor, for example, of the vegetation in each part of the forest, rangeland, or farm area which he is attempting to manage. Furthermore, in those places where the vegetation is suffering from a vigor loss, he needs to know the identity of the causal organism or agent so that he can take the necessary remedial action. All of the above considerations are reflected in Table 2 under the heading "Foresters, Range Managers, and Agriculturists".

The remaining portions of Table 2 give similar distinctions between the basic and applied information needs of other potential users of modern remote sensing technology as applied to the earth's land resources, including geologists, hydrologists, geographers, oceanographers and meteorologists.

E. *Considerations with Respect to the Electromagnetic Property that is Being Sensed.*

Within the context of our deliberations throughout this Study Week, in modern day remote sensing the property that is being sensed, of course, is energy emanating from the various earth-resource features. In most instances it is electromagnetic energy that is being sensed, i.e., energy that is traveling at the velocity of approximately 186,000 miles per second in a harmonic wavelike motion. Within a single beam or bundle of such energy traveling toward the sensor from a feature on the ground, some of the wavelengths are as short as a millionth of a micron, while others are as long as several billion microns (Figure 2). In between these extremes is an entire "spectrum" of wavelengths emanating toward the sensor from each earth resource feature. As will presently be seen, remote sensing commonly is done simultaneously in each of several parts of this electromagnetic spectrum. In any given instance involving the remote sensing of energy *reflected from* a feature being sensed, the specific characteristics of the energy reaching the sensor will depend upon (1) the nature of the illuminant (e.g., the sun, a radar beam, or a laser beam) and (2) the atomic, molecular, and macro-molecular composition of the matter comprising the earth-resource feature. Item (2) also is of importance in instances involving the remote sensing of energy *emitted by* a feature being sensed (e.g., thermal energy).

Sometimes the information desired about earth-resource features is best obtained by sensing in one wavelength band of the electromagnetic spectrum, while in other instances the information desired requires sensing

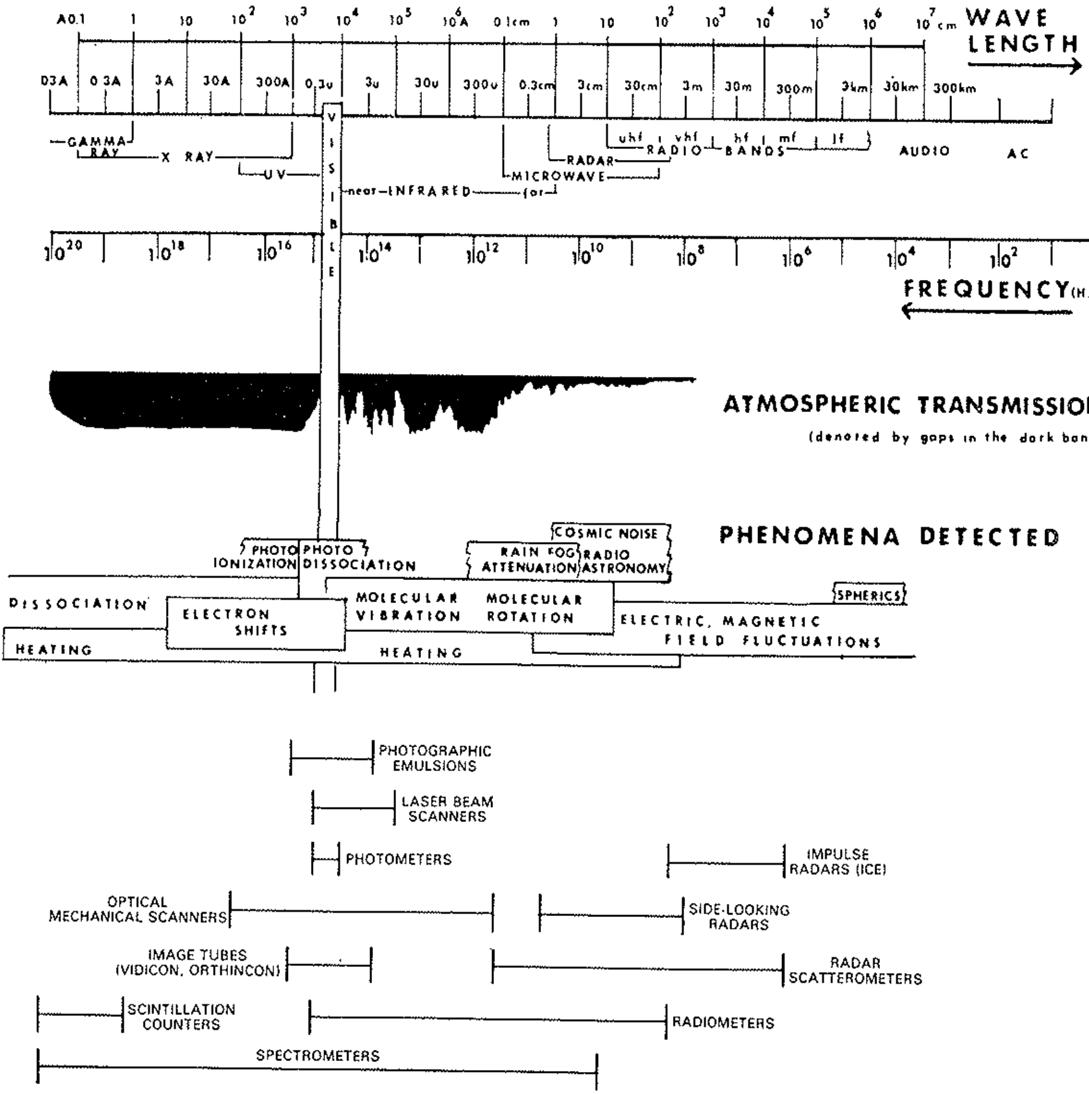


FIG. 2. The electromagnetic spectrum, atmospheric windows, and the spectral operating range of sensors. Modified by Short (1972) from R. Colwell (1961) (upper diagram) and from Remote Sensing of Environment, J. Lintz and D.S. Simonett (Editors) (1976).

in a different part of the spectrum. It follows that more complete information about the total resource complex of an area is best obtained by simultaneously sensing in two or more wavelength bands — a process that is variously known as "multiband sensing", "multispectral sensing", and "multiband spectral reconnaissance" (Colwell, 1961). In order to appreciate the value of this process, we first need to answer the following question: Why should we expect to be able to inventory earth resources better through multiband sensing than through sensing in only one wavelength band? The answer to that question, and the rationale behind it, can be expressed as follows: Our ability to inventory earth resource features through multiband sensing rests on the fact that every type of feature encountered on the surface of the earth tends to reflect and emit radiant energy in distinctive amounts at certain specific wavelengths. Consequently, when remote sensing is done simultaneously in each of several properly selected wavelength bands, each type of feature theoretically becomes identifiable by virtue of its multiband "tone signature" or "spectral response pattern". Obviously, if only one band is used, the complete tone signature is not decipherable; consequently, the data analyst experiences numerous uncertainties regarding the identities of features, and the accuracy of the entire natural resource survey is degraded.

In most parts of the electromagnetic spectrum for which we have a remote sensing capability, the information is recorded either directly in photo-like form or else in a form which can readily be reconstituted into a photo-like image. Consequently, as we address ourselves to certain basic considerations in this stage-setting paper, the principles listed in the next section of this paper are worthy of emphasis.

F. *General Principles Employed in Acquiring Remote Sensing Data.*

Most of the principles that are considered in this section are best comprehended through a concurrent study of Figure 2.

1. In order for a remote sensing system to operate effectively within any specified wavelength range of the electromagnetic spectrum there must be:

a. an energy source which will provide photons having the proper energies and hence the proper range of wavelengths,

b. a collection of matter (i.e., a target) which will interact with photons in this range,

c. an energy detector which is sensitive to photons that are being radiated from the matter in this range,

d. a propagating medium (or else a void) between detector and target, which will transmit photons in this range, and

e. an energy filter which will screen out unwanted photons to which the detector is sensitive, while transmitting the wanted ones.

2. The radiant power peak of the sun is at a wavelength of about 0.5 microns. It is an excellent energy source when we wish to accomplish remote reconnaissance of the earth by use of reflected energy in the V. (i.e., the visible part of the spectrum) as when using a panchromatic film (0.40 to 0.75 microns), or reflected energy in the near infrared (0.75 to 1.2 microns), as when using an infrared-sensitive film. Atmospheric haze effects usually preclude remote reconnaissance of the earth's surface in the UV (less than about 0.4 microns).

3. The radiant power peak of the earth is at a wavelength of about 9.6 microns. This radiant energy is an excellent source when we wish to accomplish remote reconnaissance of the earth by use of emitted energy in the thermal IR, as when using a "heat-mapping" sensor in the 8 to 14 micron range.

4. There are practical methods of artificially obtaining electromagnetic radiation of almost any desired wavelength for use, as needed in some remote sensing systems (see Figure 2). Specifically:

a. X-radiation can be obtained from high-voltage cathodes,

b. Radar and microwave radiation, from specialized tubes and resonating cavity sources,

c. radio-frequency radiation, from oscillating dipole sources, and

d. radiation for most of the other parts of the spectrum, from masers, filaments and gas lamps.

5. The atmosphere is a turbid medium, full of particles of various sizes that interact with radiant energy. For atmospheric "haze" particles that have dimensions roughly of the order of the radiation's wavelength (e.g., smoke), laws developed by the physicist, Mie, apply; hence the term "Mie scattering". For particles that have much smaller dimensions (e.g., molecular gases, such as water vapor) laws developed by the physicist, Rayleigh, apply. In fact Rayleigh's law, as applied to such particles, states that the amount of scattering is inversely proportional to the fourth power

of the wavelength of the radiant energy. Finally, particles that have much larger dimensions than the radiant energy's wavelengths give rise to non-selective (wavelength-independent) scattering.

6. The atmosphere exhibits distinct molecular absorption bands at various points in the electromagnetic spectrum caused by the presence of such molecules as N_2 O_2 O_3, H_2O, CO, and CO_2. The location and intensity of each of these bands are predictable from a knowledge of the matter and energy relationships for each type of molecule present in the atmosphere.

7. In the photographic process, latent image formation in the silver halide crystal takes place in the following distinct steps:

a. The crystal absorbs a photon, which raises the energy state of an electron in the crystal.

b. This electron passes from the crystal to a silver sulfide "speck" associated with the crystal.

c. The electron on the "speck" attracts, and unites with, a silver cation, thus forming an atom of metallic silver.

8. The three-step process of latent image formation is repeated as each additional photon is absorbed, thus causing the "speck" to grow. During film development, reducing agents provide many additional electrons to each silver halide crystal that is associated with an activated "speck", thus reducing all the silver halide in the crystal to opaque metallic silver. According to Tarkington (1959), when compared to the number of photons required to *produce the latent image*, the number that would be required to *complete the reduction process* would be a billion-fold greater if the proper reducing agents had not been "discovered".

9. In attempting to select the combination of filter and sensor which will "optimize" the image quality obtainable by remote reconnaissance, we must recognize that there may be significant variability in:

a. the intensity and spectral composition of the illuminant,

b. the reflectivity and emissivity of the target,

c. the sensitivity of the film or other sensor,

d. the transmissivity of the filter, and

e. the transmissivity of the atmosphere, water or other medium intervening between target and sensor.

10. Because of this spectral variability, statistical analyses of spectral data are far better than mere visual inspection of such data for determining which parts of the electromagnetic spectrum will provide the most favorable tone signatures for various objects and conditions. This spectral variability results largely from variability in the molecular and macromolecular composition of the features being sensed.

G. *Some Highly Relevant Basic Laws of Physics.*

In addition to the considerations just mentioned in "F", some basic laws of physics strongly support the use of "tone" or "scene brightness" as the attribute on which to base feature-identification through the use of modern remote sensing technology. Specifically:

(1) All matter, including the materials of which various kinds of natural resources are composed, is made up of a collection of particles held together by finite forces.

(2) These particles are the fundamental building units of atoms and molecules, dominated (in bulk) by the electron clouds surrounding atomic nuclei.

(3) The electrons, for any specific kind of matter, have definite frequencies of vibration, rotation, precession, etc., on both atomic and molecular scales. Hence the electron structures of the atoms or molecules of which a given kind of matter is composed are different from those of the atoms or molecules comprising some other kind of matter.

(4) The high frequency and minute energies that are associated with the individual electrons are roughly the same as those associated with the individual photons in electromagnetic waves of the ultraviolet, violet, visible, and infrared parts of the electromagnetic spectrum.

(5) When a photon of any specific energy strikes the boundary of solid matter, the energy can either be absorbed, emitted, scattered, or reflected. (In remote sensing the sun is usually the photon source).

(6) *Absorption, emission, scattering and reflection of electromagnetic energy by any particular kind of matter are selective with regard to wavelength, and are specific for that particular kind of matter, depending primarily upon its atomic and molecular structure.*

(7) It is *reflected* energy, primarily, that is sensed when the camera, line scanner, or other remote sensing device operates in the ultraviolet,

visible, and/or near infrared parts of the spectrum. It is *emitted* energy that is sensed in the thermal infrared region. (In the microwave region it is either reflected energy that is sensed, as with radar sensors, or emitted energy, as with passive microwave sensors).

(8) In view of the foregoing facts, we can in principle identify the material constituting *any* target (such as a particular natural resource feature) by means of a series of simultaneously acquired *multiband* photographs or digital records that are sufficiently detailed to show its unique spectral reflectance and/or emission properties.

H. *Considerations Involved in Applying These Laws and Principles to the Remote Sensing of Vegetation Resources.*

In the developing countries, as elsewhere, vegetation resources are of primary and direct interest to foresters, range managers, wildlife managers, and agriculturalists. Vegetation resources also are of interest to water resource managers (e.g., in relation to estimating the amount of evapotranspiration), and to soil scientists and geologists (e.g., in relation to the controlling of soil erosion and to the use of "plant indicators" in the identification and mapping of certain soil types and mineral deposits). It is because there is such a great breadth of interest in vegetation by resource managers that this section makes specific use of the vegetation component of the landscape to illustrate some of the principles covered in earlier sections.

As previously indicated, the amount of energy that is reflected wavelength-by-wavelength from a feature is governed not only by the intensity and spectral composition of the illuminant, but also by the chemical nature and physical structure of the feature itself. This important fact is appropriately illustrated here by using vegetation as an example. Since reflectance is the property being sensed, the illustration is simplified by our confining this discussion to those wavelengths of electromagnetic energy within which reflectance is largely confined and to which photographic emulsions are commonly sensitized. This combination of factors limits the present discussion to the visible (wavelengths 0.4 to 0.7 microns) and near infrared (wavelengths 0.7 to 0.9 microns) parts of the spectrum. Overall, therefore, we are concerned in this illustration with the spectral reflectance *throughout* the 0.4 to 0.9 micron spectral range.

Although a typical plant is comprised of several major components (viz., its roots, stems, leaves, flowers, and fruits), it is primarily the mass of foliage formed by its *leaves* that looks to the sky and therefore governs the plant's spectral response when it is sensed from an aircraft or spacecraft. Hence the initial question to be answered is: What are the chemical and physical characteristics of a *leaf* that govern its spectral response, especially in the 0.4 to 0.9 micron region of the electromagnetic spectrum, within which most modern day remote sensing is being performed?

As we seek to answer this question, it is not a gross oversimplification for us to assert that, as applied to a healthy green leaf, the primary *chemical* component governing its reflectance in the 0.4 to 0.9 micron spectral region is the chlorophyll molecule, while the primary *physical* component is the structure of the middle of the leaf, i.e., the "mesophyll".

Figure 3 shows the physical structure of a typical healthy green leaf. Figure 4 shows the typical reflectance spectrum of such a leaf (curve "a"). The major points to be emphasized in connection with these two figures are as follows:

1. The leaf's chlorophyll molecules, which tend to be concentrated somewhat in the upper sunlit part of the leaf, have the following properties:

a. they *absorb* large amounts of energy in the blue (0.4 to 0.5 microns) and red (0.6 to 0.7 microns) spectral regions and *reflect* green wavelengths (0.5 to 0.6 microns).

b. they *transmit* large amounts of energy in the near infrared (0.7 to 0.9 microns) region.

2. The leaf's spongy mesophyll (so called because it is a sponge-like tissue comprising the "middle of the leaf") has the following spectral properties:

a. *It is potentially able to reflect* large amounts of energy in the blue, green, and red spectral regions. This is evidenced by the glistening white appearance that the mesophyll exhibits when a leaf is carefully torn open so that this tissue is directly exposed to light. Ordinarily, the mesophyll is not given an opportunity to do so, however, because healthy green leaves tend to have their chlorophyll concentrated in the top layer of cells — a layer that overlies the spongy mesophyll. Hence, for reasons explained in 1a and 1b, above, only small amounts of blue, green, and red light reach the spongy mesophyll. As a result, this part of the leaf is somewhat inert with respect to reflectance in these parts of the spectrum (see Figure 3).

b. *It actually does reflect* very large amounts of energy in the near

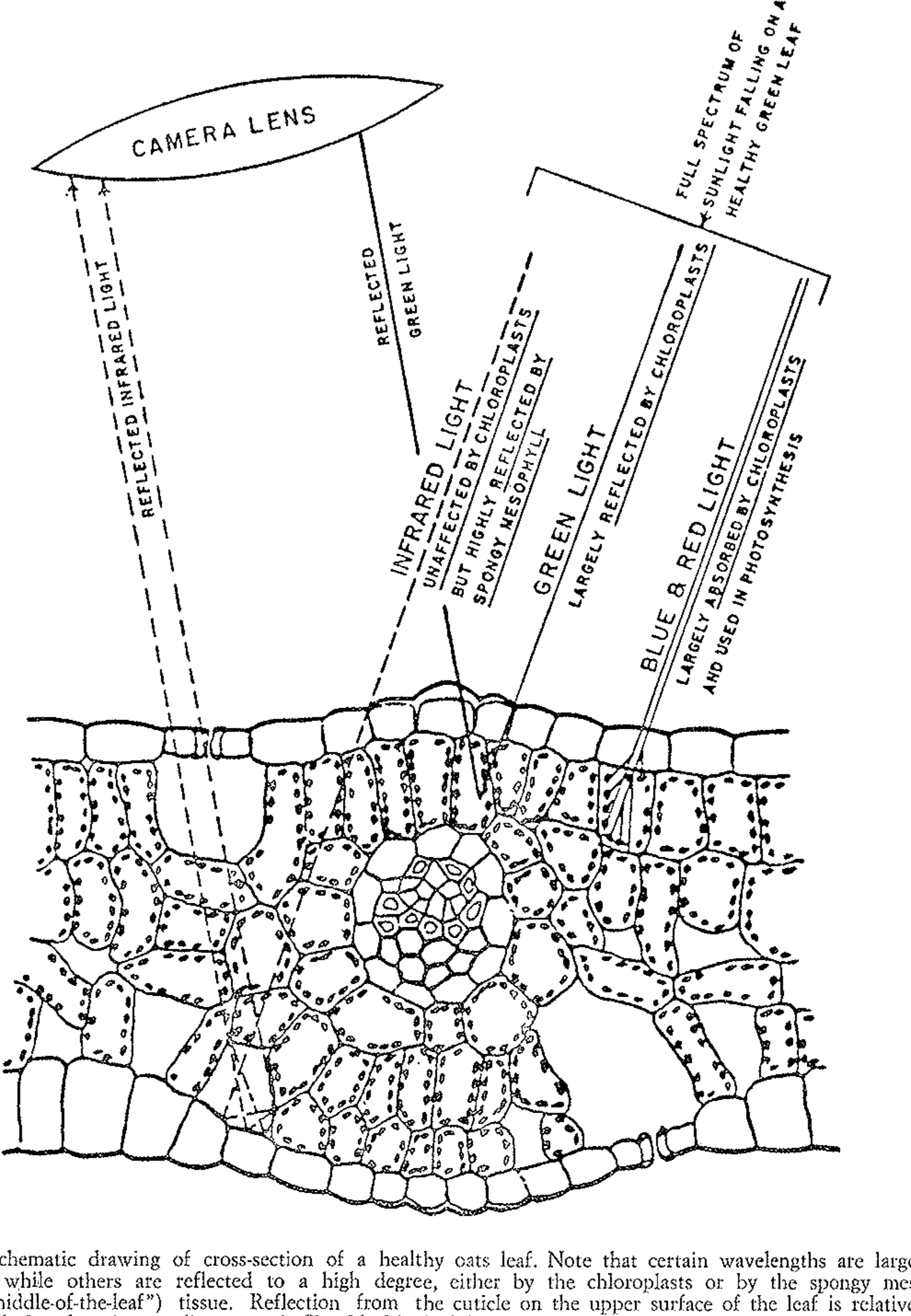


Fig. 3. Schematic drawing of cross-section of a healthy oats leaf. Note that certain wavelengths are larg absorbed while others are reflected to a high degree, either by the chloroplasts or by the spongy mes phyll ("middle-of-the-leaf") tissue. Reflection from the cuticle on the upper surface of the leaf is relativ minor and therefore is not diagrammed. Should this leaf become diseased, its spongy mesophyll (which turgid and highly reflective of infrared light, as diagrammed in curve "a" of Figure 4) would either colla from lack of an adequate water supply to it or be plugged by hyphae of the fungus. Many other damagi agents, by restricting a supply of water to the spongy mesophyll, also may cause it to collapse, with consequent loss of infrared reflectance from it, long before decay of the chloroplasts will cause a chan in visible light reflectance. Such a condition is typified by curve "b" of Figure 4. Hence the loss of vig becomes detectable much sooner on infrared photography, as a result of dark-toned vegetation providi "pre-visual" symptoms, than on panchromatic photography (from Colwell, 1956).

infrared (0.7 to 0.9 microns) wavelength region. As explained in 1b, above, chlorophyll is nearly transparent to energy in the near infrared part of the spectrum. Hence, as these wavelengths coming from the sun strike the plant, they are free to penetrate to the middle of the leaf, essentially unimpeded and, upon being reflected, are free to pass back through the upper part of the leaf toward the overhead sensor (see Figure 3).

A combination of the factors mentioned in "a" and "b" above largely accounts for the shape of curve (a) wavelength-by-wavelength in Figure 4. In addition, a detailed study of Figures 3 and 4, together with the captions beneath them, serves to explain why a loss of vigor in plants usually can be detected significantly sooner through remote sensing of near-infrared wavelengths (in the 0.7 to 0.9 micron region) than of visible wavelengths. (Compare curve (b) with curve (c) in Figure 4). Hence, the term "pre-visual symptoms" is applied to early detection of vigor loss in plants on near-infrared photography or digital records. Early detection, in turn, often permits early treatment of the malady by the farmer, forester or range manager, thereby greatly reducing loss.

I. *Considerations Involved in Applying These Laws and Principles to Multiband Remote Sensing.*

As alluded to elsewhere in this paper, there are three major means by which photo-like images currently are being acquired from aerospace for use by ground-based image analysts as they seek to inventory and monitor the earth's natural resources:

1. by means of a conventional camera, operated by a member of a flight crew and returned with him to earth, complete with its exposed photographic film, which is then processed in the conventional manner to produce photographic prints and/or transparencies;

2. by means of an "electro-optical scanning device" (such as the Landsat Multispectral Scanner or Thematic Mapper) which observes, for each small picture element or "pixel" of the terrain that is being scanned, the "scene brightness" in certain wavelengths of the electromagnetic spectrum to which that particular sensor has been designed to respond. By the time this scanning device has observed and recorded scene brightness for the last pixel in a given scan line, the vehicle (e.g., the aircraft

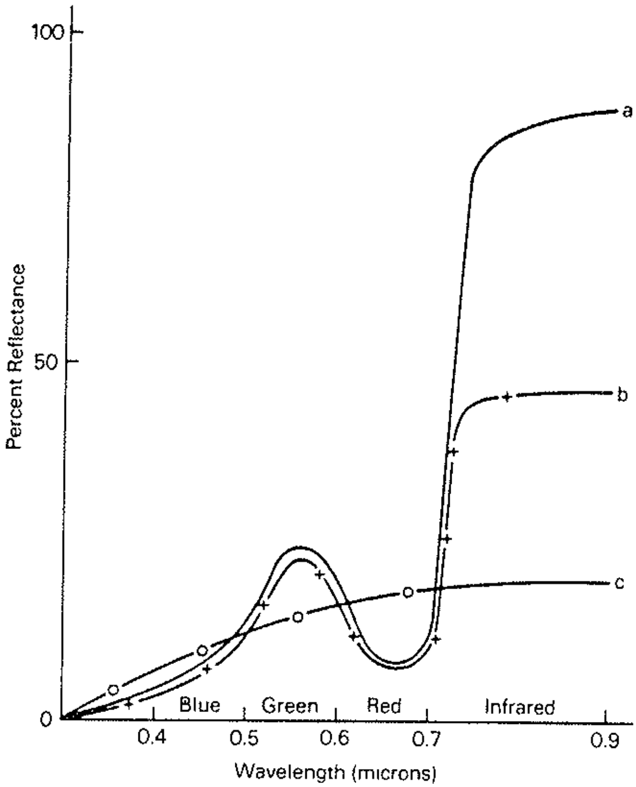


FIG. 4. Typical reflectance spectra for a leaf at each of three states of vigor. Curve "a" = a healthy green leaf; curve "b" = a leaf that is just beginning to suffer from a loss of vigor due, for example, to its having been invaded by some harmful insect or pathogen; and curve "c" = a leaf suffering from a more advanced stage of vigor loss. The significance of curve "b" in relation to the early detection of vigor loss on infrared photography (thereby permitting early remedial measures to be taken) is discussed in the text.

or Landsat spacecraft) has advanced to a point from which scanning of the next line of terrain should and does begin.

3. by means of a "linear array" (such as on the French satellite, SPOT) which observes an entire line at a time. Usually, when the scanning device or linear array is employed in an earth-orbiting spacecraft, each observation of scene brightness is converted by the space-borne sensor system into a digital value; these digital values are then transmitted, pixel-by-pixel, from the spacecraft to a receiving station on earth, where the signals are recorded and stored on magnetic tape. Later, as

the taped record is played back, pixel-by-pixel and line-by-line, a corresponding amount of electrical current is made to actuate a small light bulb known as a "photo diode". This very small spot of light glows brightly or dimly during the playback process, as it responds to each digital value in turn, while traveling across a piece of previously unexposed photographic film. In this way it correspondingly exposes the film, pixel-by-pixel and scan line-by-scan line. Subsequent processing of the film produces a seemingly continuous photo-like black-and-white image for that portion of the earth's surface that has been observed by the sensor system. If a photo-like *color* image is desired, as is usually the case, this can be obtained by optically or electronically color-coding and combining the black-and-white images that have been obtained, as described above, from two or more spectral bands. The equipment and techniques used in producing this color coded image are described in a later section.

In addition to the direct visual analysis of these space-acquired photographs, an ever-increasing amount of success is being achieved through computer-aided analysis of the "scene brightness" digits, themselves. Such analysis exploits the fact that, just as the *multiband photographic record* tends to provide a unique *tone signature* for each category of earth resource that is to be identified from the space photo, so the corresponding *multiband digital record* tends to provide a unique *digital signature* which, by proper computer programming, can likewise lead to identification of the feature.

J. *Considerations with Respect to Broad Band Versus Narrow Band Remote Sensing.*

Almost all remote sensing of natural resources that has been done from aircraft and spacecraft up to the present time has employed relatively *broad wavelength bands* of electromagnetic energy. For many practical purposes these broad-band reconnaissance systems not only are adequate, in relation to the information that is to be derived through remote sensing; they actually are optimum. Specifically:

1. They provide good tone, color and/or digital separations among such broad categories as vegetation, bare soil, bare rock, and open bodies of water.

2. Because each band that is exposed in the remote sensing process is so broad, it contains a relatively large amount of energy. Consequently, a remote sensing camera, line-scanner or similar device that has only moderate sensitivity, does not require an unacceptably long "dwell time" in order to collect enough energy to sense most features of interest. (The longer the "dwell time" the greater the image blur due to forward motion of the aircraft and/or vibrations during the exposure period).

There are many desired identifications, however, that can only be made by means of very narrow band remote sensing that will be indicative of the atomic and molecular composition of the features that are to be identified. Because of this fact, the capability recently has been developed for accomplishing remote sensing simultaneously in each of a very large number of narrow wavelength bands. Each band may be only a fraction of a millimicron wide and each sensing element may be more than a thousand times as sensitive as the various sensors listed in the preceding paragraph. For example:

1. The U.S. federal government recently has developed an Airborne Imaging Spectrometer (AIS) with such a capability, and

2. Dr. Thomas Haase of the Haase Institute has developed a "Narrow Band Ratio-Imaging Spectrometer".

For a great many identifications that require sufficiently narrow-band remote sensing to indicate the atomic and molecular composition of features, these recently-developed devices offer a capability that heretofore was unattainable. An additional advantage of the Haase "ratio-imaging spectrometer" lies in the fact that its output consists of highly meaningful *ratios* of signal returns from two bands, thereby reducing the recording and/or transmission data-load while at the same time accentuating spectral differences between two features that otherwise would be undifferentiable.

K. *Considerations Involved in Transmitting Space-Acquired Remote Sensing Data.*

There are several means by which space-acquired remote sensing data can be made available to those on the ground who seek to use such data for the inventory and monitoring of natural resources.

If the space-acquired data have been obtained by an astronaut through the exposing of photographic film in a camera, the exposed film usually is returned to earth with the astronaut. At one time (e.g., in the U.S. Gemini, Apollo and Skylab missions) this was accomplished through a hazardous maneuver known as "re-entry and splashdown" which, in turn, was followed by a helicopter pickup of the astronaut and his space-acquired photographic data as he bobbed about in the ocean waves. More recently, however, this return to earth has been accomplished in the U.S. by the use of a runway for making a more graceful and dignified landing of the Shuttle vehicle and its payload, once the mission has been completed.

In some *military* reconnaissance missions, the photographic film is exposed in an *unmanned* spacecraft. In such instances, the exposed film is returned to earth in increments by periodically issuing command signals from the ground each causing the vehicle, while still in orbit, to jettison one of a series of "buckets" containing some of the recently exposed film. Each bucket, after reentering the earth's atmosphere, automatically deploys a parachute that slows the rate of descent of the bucket so that it can be "air snatched" by a manned aircraft that is skillfully piloted while towing its bucket-catching "basket".

If the space-acquired data has been recorded, not as exposed film but as digital data indicative of scene brightness (as discussed in the "Present Status" section of this paper), the digital data is telemetered to a receiving antenna on the ground. Sometimes this is done directly and almost immediately upon acquisition, but, if there is not a "line-of-sight" positioning of the vehicle at that time with respect to a ground-based receiving station, the digital data may be temporarily stored by means of an on-board tape recorder, later to undergo a "data dump" on command, once the vehicle and receiving station are intervisible. Alternatively, a Tracking and Data Relay Satellite (TDRS) which, because it is in geosynchronous orbit at about 23,000 miles above the earth, has a tremendous field of intervisibility with respect to the reconnaissance satellite, serves as the relay station via which the signals are transmitted to the ground. Eventually, the digital data can be processed to produce a photo-like image, or else the desired resource inventory may be produced directly, through use of a computer program that is based on the digital "signature" for each type of resource feature. Both methods are described in later sections of this paper.

L. *Discrimination Versus Identification in the Analysis of Remote Sensing Data.*

In order to appreciate both the usefulness and the limitations that are associated with the employment of aerospace remote sensing for the inventory and monitoring of natural resources, two terms must be employed: *discrimination* and *identification*. As applied to the mapping of resources within an area that has been remotely sensed, the term discrimination pertains to the act of determining where differences exist in one component or another of the total resource complex. Usually discrimination also includes the drawing of "stratification" boundaries between one condition and the others that surround it, even though it usually is not possible to determine, merely from an examination of the remote sensing imagery or related data, the exact identity of features on either side of the stratification boundary. On the other hand, "identification" pertains to the act of determining what the specific attributes of the resource complex actually are within a given portion of the area (e.g., within the confines of a given stratification boundary).

On space photographs the spatial resolution is such that, when combined with the spectral or color differences exhibited on such photographs, one usually can discriminate differences sufficiently well to draw remarkably accurate and highly useful stratification boundaries. Once these boundaries have been drawn, however, it usually is necessary to acquire, within each category of area that has been outlined by the discrimination process, limited amounts of aerial photography for sample areas. These are areas which, from a study of the space-acquired imagery, have been selected as being representative of a given category. In keeping with the concept of "multistage sampling", still more detailed observations with respect to the circumscribed resource category than can be obtained from the aerospace photography alone must commonly be made by means of direct on-the-ground inspection. The making of such observations on the ground is a costly and time-consuming process. Fortunately, however, these observations need to be made only within *subsample* areas that are selected, from a study of the aerial photographs, as being representative of the *sample* areas to which they apply, respectively. Thus it is apparent that the accurate drawing of stratification boundaries (even though they may merely provide discrimination rather than identification) is a key to the beneficial use of multistage sampling.

M. *The Eight Image Attributes Used by Humans in the Analysis of Remote Sensing Data.*

1. *Shape*: The term shape relates to the general form, configuration or outline of an individual object. It is perhaps the most important single

factor which we use in recognizing the objects about us. It is also of great importance in recognizing objects from their photographic images. Inasmuch as vertical photographs are the most common type used in photo interpretation, the three-dimensional shape or form of an object as seen stereoscopically from overhead is often a critical factor in its photo identification.

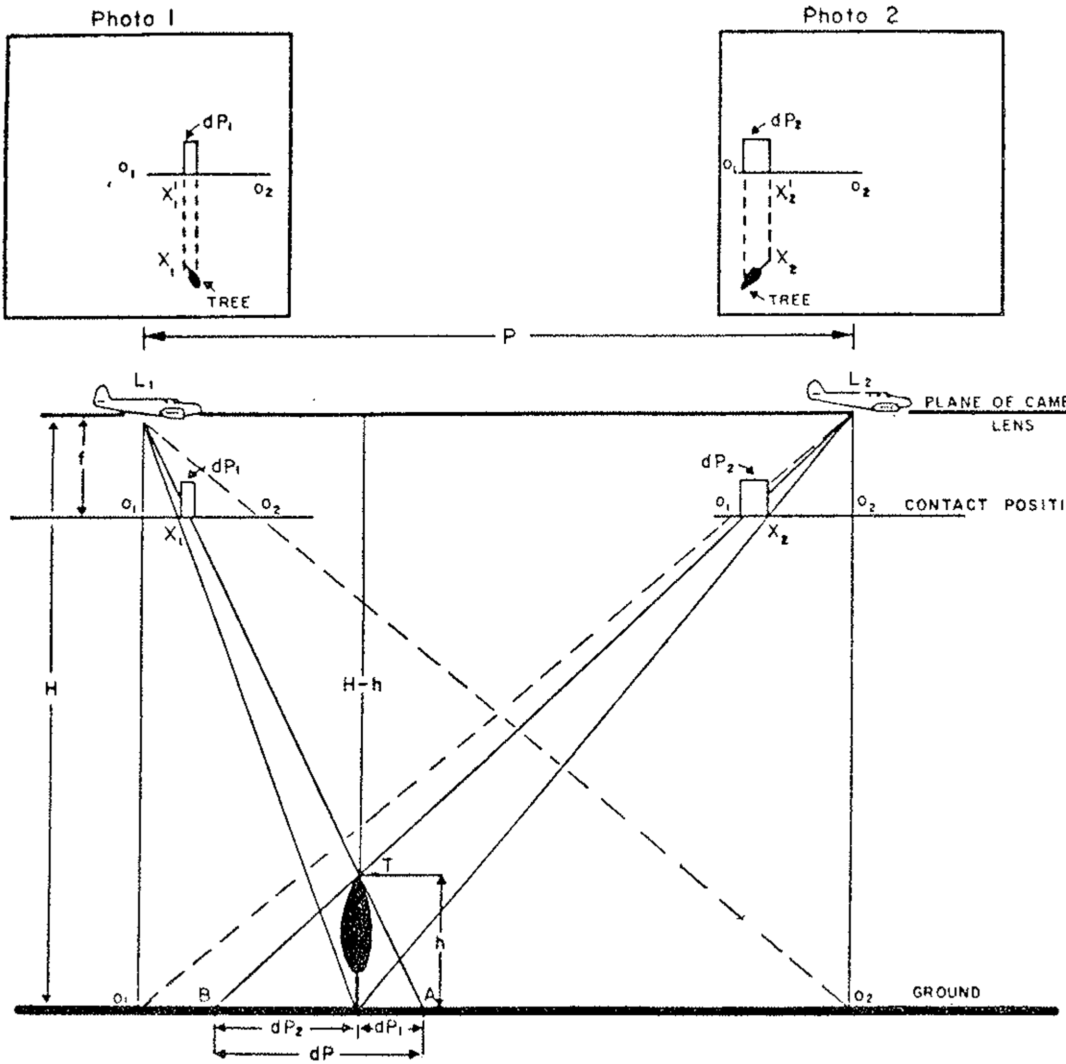
2. *Size*: The surface or volume dimensions of an object are also important clues to its identity. Since the photographic interpreter usually must identify objects from images which will vary in size from one scale of photography to the next, he will do well, knowing the scale of the photography, to make frequent calculations as to the actual sizes of the objects represented. The equation used by a photo interpreter or photogrammetrist in measuring the height of a feature from a stereoscopic pair of vertical photographs is derived in Figure 5.

3. *Pattern*: Pattern refers to the spatial arrangements of objects ([5]). The repetition of certain spatial relationships is characteristic of many agricultural objects and can give the knowledgeable photo interpreter valuable assistance in recognizing them. Examples include the planting pattern typically used for certain kinds of trees in an orchard, or of grapevines in a vineyard, or the "contour pattern" sometimes followed on rolling topography or in the layout of rice fields. Pattern also is of importance for the interpretation of certain wildland features.

4. *Shadow*: The fact that an intervening object prevents the sun's direct rays from striking certain areas imaged on the photograph usually makes shadows of importance to the photo interpreter in two respects, one of which constitutes an advantage and the other a disadvantage: (a) the shape or outline of a shadow is indicative of the profile view of the object which casts the shadow, and thereby facilitates recognition of the shape of the object, and (b) objects within the shadow reflect so little light back to the camera as to be virtually indiscernible on the photograph.

5. *Tone*: This attribute of a photographic image indicates the amount of light (or other energy) that was being reflected back to the camera at

([5]) In recent years the jargonists of remote sensing, disregarding this time honored use of the term "pattern", have unfortunately introduced the term "pattern recognition" which pertains to an entirely different attribute, namely, the "spectral signature" or "spectral response pattern" of a feature.



h = ht. of tree

H = ht. of camera lens above base of tree

P = Absolute parallax of base of tree
(photo equivalent = $o_1\ o_2 = o_1\ X_1' + o_2\ X_2'$)

dP = Parallax difference of top of tree referred to base plane
(photo equivalent = $dP_1 - dP_2$)

From similar triangles: (BTA and $L_1 L_2 T$) $\frac{h}{H-h} = \frac{dP}{P}$

Transposing: $h = \frac{H\ dP}{P + dP}$

FIG. 5. Derivation of the parallax equation by means of which the height, h, of a feature can be determine photogrammetrically if the altitude of the photography, H, and the length, P, of the stereo base (bot readily determinable) are known. The parallax, dp, is the shift in the apparent position of one feature, suc as the top of the tree in this diagram, with respect to another feature, such as the base of the tree, cause by a shift in the point of observation (i.e., by a shift from the perspective provided at camera station 1 on the left, to camera station 2, on the right). The value, h, that is determined in this instance is th height of the tree (American Society of Photogrammetry, 1960).

the time of photography (by the feature being imaged) within that part of the spectrum (a) to which the photographic film being used was sensitive and (b) for which the photographic filter being used was transparent (i.e., it permitted the light to pass). As already emphasized, it is this attribute, tone, (sometimes known as "scene brightness") that modern remote sensing technology senses, converts into digits, and uses as the primary aid to object identification. In multiband form it usually is converted to "color signatures".

6. *Texture*: As applied to a photographic image, texture may be defined as the frequency of tone change within the image. Texture is produced by an aggregate of unit features too small to be clearly discerned individually on the photograph. It is a product of their individual tone, size, shape, pattern, and shadow attributes. As the photographic scale progressively diminishes, the texture of a given object becomes progressively finer and eventually disappears. This does not mean that small-scale photos have no texture; it simply means that the size of the object required to influence texture increases as the photographic scale decreases. Thus, on very large-scale photography of a fruit orchard, leaves of the trees contribute to texture of the branches, which are individually discernible. On intermediate-scale photography, branches on the trees contribute to texture of the tree crown; and on still smaller-scale photography, tree crowns contribute to the texture of the orchard. On space photos, entire orchards may be imaged at such a small scale as to contribute to the texture by means of which agricultural areas that are devoted primarily to orchards can be discriminated from all other agricultural areas.

7. *Site*: The topographic location of an agricultural crop may be a helpful clue to its identity. Thus, among the "small grains" or cereal crops as grown in the United States, rice-growing areas are typically on relatively flat land (to facilitate the construction of levees that will permit the water level to be controlled, field-by-field); in contrast, however, other small grains, such as wheat, oats and barley, commonly occupy rolling topography if they are to be grown strictly through "dryland" agricultural methods. No such limitation of rice-growing to flat land areas is found, however, in many of the developing countries. In many instances the site occupied by a certain kind of wildland vegetation by a certain kind of man-made structure or even a certain kind of mineral deposit is a valuable clue to its identity.

8. *Association*: The location of an agricultural field in relation to other features may be a very helpful clue to the type of crop to which the field is, or will be dedicated. For example, the presence of silos, particular kinds of farm implements, etc., or (in the case of some perishable vegetable crops) proximity to urban areas of high population, may all be useful clues to crop type. Other examples of the use of association as an aid in the identification of features will be found in Figure 6, from an early article by Colwell (1946) that is still frequently referred to.

N. *The One Attribute Used by Machines in the Analysis of Remote Sensing Data.*

As previously indicated, the attribute almost invariably used by machines for the computer-aided analysis of remotely sensed data is "tone" or "scene brightness". The rationale for using this particular attribute is as follows:

1. Modern remote sensing technology makes extensive and intensive use of digits (a) in recording remote sensing data picture-element-by-picture-element (i.e., "pixel-by-pixel") at the time of acquisition; (b) in telemetering the data from aerospace to ground as necessary, for example, from unmanned satellites; (c) in storing the data on computer-compatible tapes; and (d) in making identifications of agricultural crops, and other features, through computer analysis. Unless digits can be fed to the computer, then, in the words of the robot, "it does not compute".

2. Of the previously-listed photo image characteristics, the one that is most accurately and meaningfully expressed in digital form is *tone*, or "*scene brigthness*".

3. The line-scanner, linear array, or other remote sensing device that senses scene brightness and converts it to digits quite commonly is superior to the human. Specifically, the human eye can only differentiate *consistently* among about 10 shades of gray. On the other hand, a remote sensing device of the line-scanner or linear array type usually is constructed so as to *consistently* differentiate among (and record) a total of 256 shades of gray.

4. A line scanner or linear array of the "multispectral" type can simultaneously record scene brightness in many spectral bands, thereby permitting multiband "tone signatures" to be computer programmed and/or color coded to greatly increase identification accuracy.

KEY FOR THE IDENTIFICATION OF VEGETATION TYPES IN THE TROPICAL PACIFIC AREA

A	Plants with palm-frond leaves.	See B
A	Plants without palm-frond leaves.	See D
B	Trees up to 100 ft. in ht.; scattered rather than in pure stands; normally confined to well drained sites.	Coconut
B	Trees less than 30 ft. in ht.; in nearly pure stands; normally confined to swampy sites.	See C
C	Leaves light in tone; rarely in distinct rosettes; all plants in clumps of uniform height (about 10 ft.); without distinct flower stalks. Usually grow in compact stands along stream banks near coast with roots submerged in brackish water.	Nipa
C	Leaves dark in tone; in distinct rosettes; plants in same clump usually of variable height (10-30 ft). Conspicuous white flower stalk frequently protrudes above center of rosette. Usually grows in rather open stands in areas subject to periodic flooding by fresh water.	Sago
D	Plants growing in swampy or poorly drained soil; subject to frequent flooding.	See E
D	Plants growing in well drained sites; rarely or never subject to flooding.	See G
E	Grass of uniformly grey tone and with "velvety" texture resembling sugar cane; usually confined to stream banks.	Wild Cane
E	Trees of variable tone and texture.	See F
F	Trees usually dark in tone, with uniform height of 20 to 40 feet; confined to muddy coastal fringes and stream banks inland to the limits of brackish water.	Mangrove
F	Trees of mottled tone and variable heights up to 150 feet; often bounded on the seaward side by mangrove and on the landward side by rainforest.	Swamp Forest
G	Grass of uniformly grey tone and very fine texture.	See H
G	Plants of mottled tone and coarse texture.	See I
H	Grass from 4 to 12 feet high; on moist level sites.	Tall Grass
H	Grass from 1 to 4 feet high, on well drained rolling to steep terrain.	Short Grass
I	Bushes and trees (20 feet or less in height) densely entangled by vines; ordinarily confined to areas that have been cleared of jungle in recent years by man, fire, landslides, etc., and left to revert back to the jungle climax vegetation. Usually bounded by jungle hardwoods on at least one side.	Secondary Growth
I	Trees 50 feet or more in height.	See J
J	Trees resembling pine with narrow, pointed crown and long slender stem extending nearly to top of tree. These features frequently discernible from shadow cast on light-toned sandy beach to which tree is usually confined; crowns of trees have a light grey tone in aerial photos.	Casuarina
J	Trees with broad, rounded crown and branching stem.	See K
K	Trees widely spaced, with grass-covered ground readily apparent between them; confined to dry areas.	Savanna
K	Trees densely spaced, with bushes and vines, instead of grass, constituting the understory; confined to humid areas.	See L
L	Trees normally confined in tropics to elevations of 4,000 to 11,000 feet. Light in tone because of light reflected from dense growth of moss and lichen on branches and ground. Tallest trees usually less than 100 feet high.	Moss Forest
L	Trees ranging from sea level to an elevation of about 6,000 feet. Mottled in tone, being composed of many species of trees which almost invariably grow in mixed stands. Tallest trees 150 feet high or more.	See M
M	Dense undergrowth beneath trees; crown canopy of trees usually of variable height with frequent small openings where direct sunlight can strike ground. Common on steep slopes, along stream banks and at edge of clearings.	Rain Forest with Undergrowth
M	Very little undergrowth beneath trees; largest trees form almost continuous crown canopy which permits little or no direct sunlight to strike the forest floor.	Rain Forest

FIG. 6. Dichotomous photo interpretation key for the identification of vegetation types and associated terrain conditions of the Tropical Pacific Area (from Colwell, 1946).

O. *Based on these Attributes, a Commonly Used Categorization of Natural Resources.*

As a first cut, virtually every portion of the landscape that is imaged by remote sensing from aerospace can be readily recognized by either a human or a machine as belonging to one of three major types: wildland, agricultural or urban/suburban.

By coincidence, the next categorization used in each type ordinarily distinguishes *six* categories which, collectively, are both necessary and sufficient for classifying the entire landscape. Specifically:

— In a *Wildland* area the six categories are: Trees, Shrubs, Grass, Rock, Bare Soil, and Open Water.

— In an *Agricultural* area the six categories are: Orchards, Vine and Bush Crops, Row Crops, Continuous Cover Crops, Irrigated Pasture Crops, and Fallow Ground; and

— In an *Urban/Suburban* area the six categories are: Residential, Commercial, Industrial, Transportation, Open Improved, and Open Unimproved.

Once a resource feature has been placed in the appropriate category based on the above listing, the specific identity of the feature, hopefully, is determined by using a locally applicable photo interpretation key [6] to all of the specific kinds of features that are likely to be encountered locally within that category.

P. *Possible Interactions Between Humans and Machines During the Analysis of Remote Sensing Data.*

To a major extent these interactions depend on whether the machine is being asked initially to make an "unsupervised" or "supervised" classification, as explained below. In either event, however, the classification is based on digital values that constitute the unique "tone signatures" or

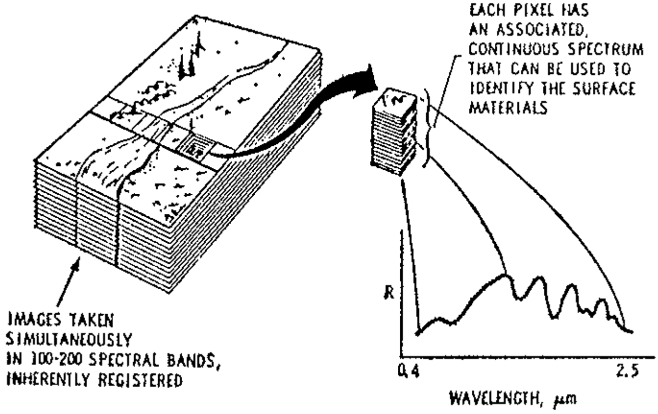
(6) A photo interpretation key is reference material designed to facilitate the rapid, accurate identification of a feature from a study of its photographic image. Usually such a key is composed of two parts: (1) illustrative photographs for each kind of feature and (2) word descriptions that set forth, in some systematic fashion, (such as "dichotomous key" of Figure 6) the photo recognition characteristics by means of which the feature in question can be differentiated from all other kinds of features with which it might otherwise be confused.

spectral response patterns of the resource feature, pixel-by-pixel. It is to be emphasized that the spectral responses of features ordinarily cannot be obtained without ambiguity when only one wavelength band of remote sensing data is being used. This problem is usually overcome if multiband sensing is done in properly selected bands. Most tone signatures are based on broad band remote sensing as will later be discussed in connection with Figure 22. It has recently become possible to perform very effective narrow band sensing, however, as exemplified by Figure 7 and the discussion associated with that figure.

As described by Short, 1982, the nature of the interaction between humans and machines during the computer-assisted analysis of remote sensing data depends in large measure upon whether the classification that is being developed is supervised or unsupervised.

In an *unsupervised* classification, identities of the categories that are to be specified as classes within a scene are not generally known *a priori*, because appropriate ground truth is lacking or surface features within that scene are not well defined. The computer is asked to group (cluster) pixel data into different spectral classes distinguishable according to some statistically determined separability criterion. For Landsat data, these clusters are usually distributed in four-dimensional spectral/space bands. Hopefully, any individual unknown point (pixel) will occur somewhere in one of the spaces that have been thus defined. The point is tested by the same separability criterion to determine whether it falls within a cluster and therefore belongs to the (still unknown) class defined by that cluster. If so, it is assigned to that class. If not, it is assigned to another class, as determined by some decision rule (e.g., Nearest Neighbor). Thus, every data point will be identified with one of the separable classes, even if that point actually represents an unrecognized cover type. Natural class names must then be given to these spectral classes by associating the latter with characteristic groups of surface features through referral to subsequent field observations, aerial photos or, if suitable, spectral signature banks.

In a *supervised* classification, identities of the cover types of interest are already known, for small areas (training sites) within a larger scene. These identities have been established from field work, aerial photos, maps, personal experience, etc. The first step is to locate within the data set those areas of high spectral homogeneity likely to correspond to the dominant cover types within each training site. Appropriate multivariate statistical parameters (means, standard deviations, covariance, cor-



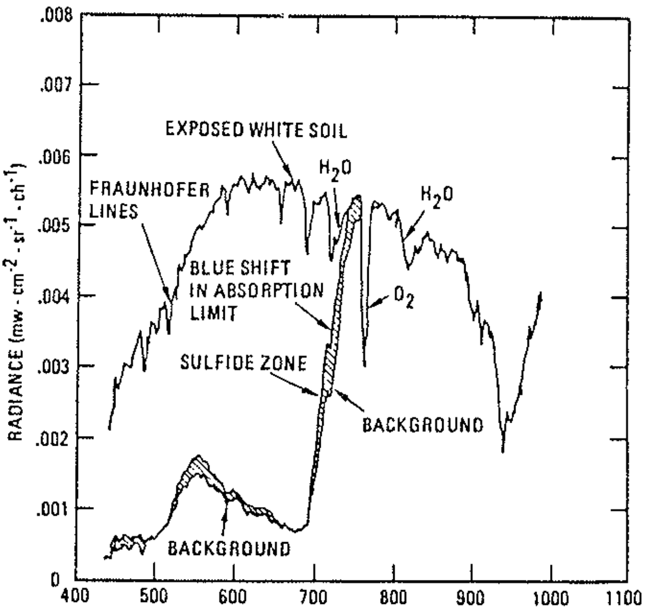


Fig. 7. *Top*: Figure from Vane (1985) dealing with narrow band remote sensing spectrometry, i.e., the simultaneous acquisition of images in many narrow contiguous spectral bands throughout the visible and near-infrared portions of the electromagnetic spectrum. *Bottom*: The upper curve in this diagram shows the many reflectance peaks and troughs that are available for diagnostic use if *narrow-band* remote sensing is performed in the visible and near-infrared regions. If broad-band remote sensing is used, however, these peaks and troughs are smoothed out to such an extent that they lose most of their diagnostic value. This figure deals primarily with the effects of various kinds of geochemical stress on photosynthesizing plants and, therefore, with the possibilities for geobotanical exploration by means of narrow-band remote sensing. (From Short, 1982).

relation matrices, etc.) are then calculated for each site and stored in the computer memory. Correct identification of every unknown point outside the training sites becomes merely a matter of matching its multispectral properties to the known class having the closest similar properties, as tested by appropriate multivariate statistics.

For both the unsupervised and supervised classification methods, the generalized procedures can be presented in the form of "flow diagrams" as shown in Figure 8. For both methods, it is customary to view the classification at any intermediate stage as a printout using alphanumeric characters or a TV display using theme colors for the classes being set up.

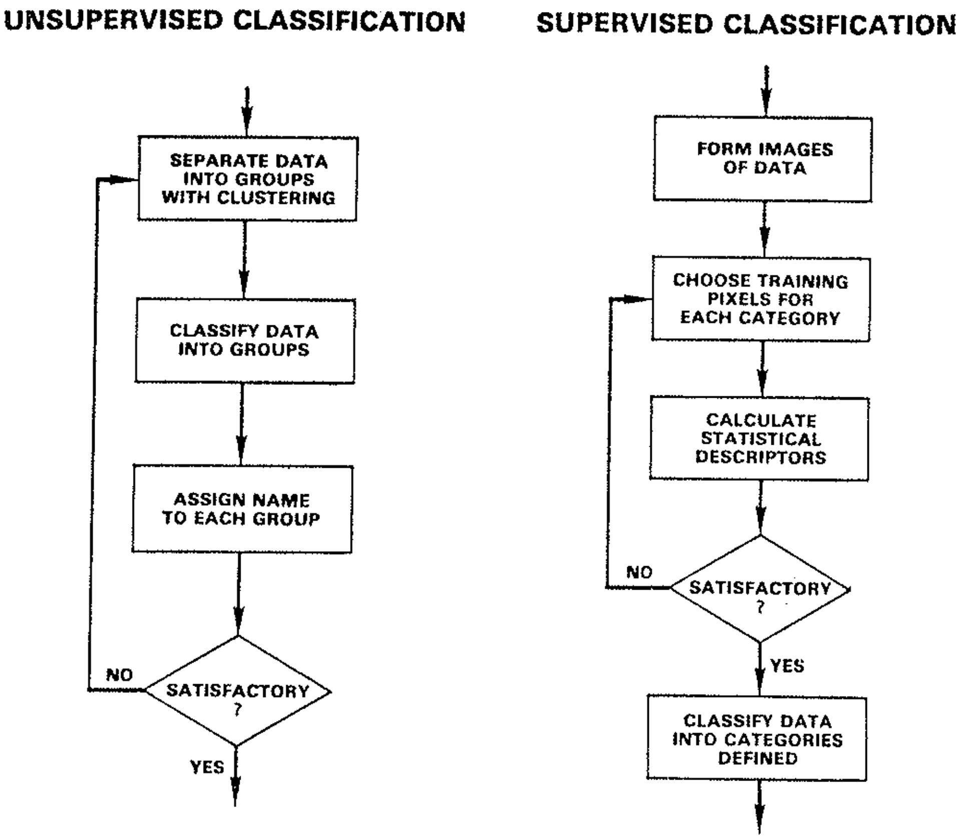


FIG. 8. As discussed in the text, there are two generalized procedures (unsupervised and supervised) that can be employed in developing a program for the computer-classification of natural resources. These procedures are shown above in the form of flow diagrams. (From Short, 1982).

A certain fraction of unknown points (pixels) will have been misclassified, especially for classes with overlapping variances; this results in lower accuracies. Each version is checked against available ground truth to pick out these misclassified areas. Changes in the number of classes selected are made until misclassified points are reduced to a practical minimum; this will also cause shifts in boundaries and changes in size of already classified areas of the scene.

If all relevant classes within a scene have been properly specified, and both scene and training sites are reasonably homogeneous, the accuracy of the supervised classification can be quite high — up to 98 percent for three to five vegetation or crop classes, for example, when multitemporal Landsat data are combined.

If a significantly lower classification accuracy results, the problem usually is one of pixel unhomogeneity from the perspective of inherent class variability. As implied in a preceding paragraph, a single class (such as a field crop) will normally show some natural variation in spectral response because of differences in individual plant sizes, shapes, spacing, and vigor, as well as differences in soil clump size, moisture, and the like. Measurement values of surface reflectance for a given class made from different individual sampling points will tend to cluster around an average (mean) but will, nevertheless, show a spread or range (usually estimated as its standard deviation). If the class is general enough, different field crops may show distinct differences evidenced as separable means and non-overlapping spreads as will later be shown in connection with Figures 23, 24 and 25. However, in many instances, a Landsat classification may fail to distinguish the various crops or other categories with acceptable accuracy but can, at least, lead to a distinction between all field crops (combined) and other, possibly similar, categories or classes.

Q. *The Concept of Signature Extension.*

This concept pertains to the possibility of using a single spectral signature for any given resource category, as derived in one geographic locality, in various other localities where the same resource category is found. As a specific example, the signature for wheat might be expected to be essentially the same throughout all parts of the globe where wheat is grown. If so, this should greatly increase the prospect of being able to make globally uniform, timely inventories of wheat, based on the uniform "look" that is provided globally by an earth-orbiting reconnaissance vehicle such as Landsat. Judging from the limited tests that have been conducted to date, this concept shows great promise despite its obvious limitations. Certainly the concept is highly germane to our considering during this Study Week the feasibility of using remote sensing for the benefit of the world's developing countries.

R. *Principles Involved in Constructing and Using a "Confusion Matrix".*

This concept is best conveyed by means of an example such as the one shown in Figure 9. In that instance five feature classes (e.g., five crop types) were to be interpreted. In the photo interpretation test, 500 spots were interpreted. They consisted of 100 examples of each of the five features, as previously selected by the one who designed the test, and in each instance "ground truth" for the test spot had been obtained by visiting it in the field. An examination of the test results shown here permits one to draw the following highly relevant conclusions: (1) Feature class A is rarely if ever confused with anything except feature class B, and vice versa; (2) Feature class C is identifiable with essentially perfect accuracy;

Photo Interpreter's Results by Feature Class	Ground Truth by Feature Class: A	B	C	D	E
A	90	7	0	0	0
B	10	91	0	0	0
C	0	0	100	0	0
D	0	1	0	80	7
E	0	1	0	20	93
Percent Correct	90	91	100	80	93
Percent Omission Error	10	9	0	20	7

FIG. 9. An example of a "confusion matrix" (also known as an "error matrix") used in (a) summarizing the results of a photo interpretation test and (b) determining what specific items of confusion (among the types that are to be identified) are the most important ones to minimize when future efforts are made to improve photo interpretation accuracy. For further explanation, see text.

(3) Feature class D is rarely if ever confused with anything except feature class E, and vice versa; and (4) there is an especially great need for substantially reducing the confusion between classes D and E (e.g., through the obtaining of photographs having better spatial, spectral, and/or temporal resolution).

S. *Principles Involved in Presenting Remote Sensing-Derived Information to the Resource Manager.*

To an ever-increasing extent the resource manager is charged with managing as intelligently as possible all components of the entire "resource complex" throughout the geographic area that falls under his purview. Furthermore, in so doing he must give proper consideration both to (a) the short-term and long-term revenue potentially derivable from each resource component and (b) the short-term and long-term measures that might best preserve or enhance the environment. If he is to approximate the achieving of this multifaceted goal he must have information about each resource type and its condition, area-by-area, and similarly specific information with respect to various environmental considerations.

It is obvious that the totality of this information, even when available, cannot be placed comprehensively on a single map. Instead, separate "thematic maps" are needed, each of which is designed for use in conjunction with the common "base map". The foregoing has led to increasingly greater use of the "multiple overlay" concept by resource managers in recent years. As indicated in Figure 10, each overlay deals with only one important attribute (e.g., terrain cover or the intervisibility of features). These overlays can be superimposed, individually or in various combinations as appropriate, with respect to a base map that emphasizes primarily the planimetric and/or topographic features of the area.

The comprehensibility of a map or overlay usually can be improved if each feature of importance is assigned an appropriate color. Thus, for example, various shades of green may be used for various vegetation types; various shades of yellow for various categories of resource management problems; and bright red for the delineation of areas having a high hazard of some kind or, at the other end of the color-coding spectrum, an area having unusually high potential for the conduct of mining operations or some other promising resource-related enterprise.

Some kinds of remote sensing-derived information are best presented to the resource manager by means of a series of thematic maps; other kinds

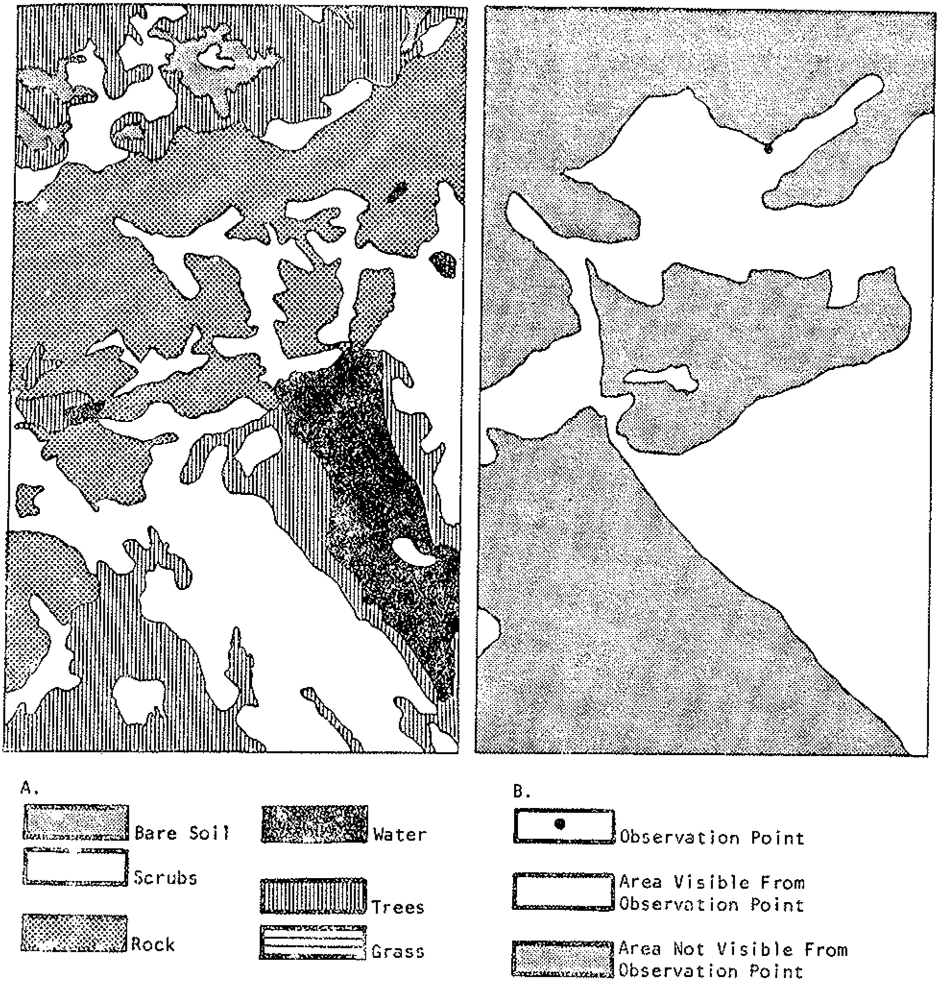


FIG. 10. These two maps of the same area (a portion of the area that is shown in Figure 20) illustrate the "multi-thematic" presentation of findings that often must be prepared, especially when the lines drawn on one attribute-map of the area bear little relation to the lines drawn on a map that portrays a different attribute. On the *left* is a *vegetation/other land status* map based on photo identifications made through use of a dichotomous key. On the *right* is an *intervisibility* map based on an interpretation of the same photos to determine whether the observation point marked with a dot permits aesthetically appealing features to be seen (lakes, waterfalls, healthy timber stands, etc.) and prevents aesthetically unappealing features from being seen (denuded and eroding slopes, garbage and trash dumps, unhealthy timber stands — because of recent attack by insects, diseases, forest fires, etc.). From Colwell, 1975.

by means of topographic maps, three-dimensional models, or annotated photo mosaics. It follows that he can best comprehend the total situation with respect to the resource complex of the area if he not only has all such products but has them in compatible formats with respect to scales, legends, color codes, and the total geographic area encompassed by each.

T. *Principles and Considerations Involved in Area Determination.*

The following mechanisms, each based on somewhat different principles, are among those most commonly used by remote-sensing scientists for determining areas.

1. *The old fashioned "Cut-and-Weigh" method.*

a. On a sheet of paper having uniform thickness (and associated weight per unit area of the paepr) produce a map, such as an agricultural map that shows crop types, field-by-field, for the entire area of interest, and to a specific scale.

b. Equate the weight of the map paper to the land area of any given feature (e.g., an agricultural field) that appears on the map as follows: from a sample piece of this kind of paper cut out, and weigh on a balance or scales, a portion of it which, at the map scale, corresponds to a unit area (e.g., a square that corresponds to 1 acre, or 10 acres or 100 acres).

c. To determine the acreage total for all fields of any given category, cut out all such fields and weigh the resulting pile of paper, as a unit; then apply the relation derived in "b" above.

2. *Tracing the perimeter of areas with a cursor.*

a. Place the completed map (e.g., of agricultural fields) on the copper-wire-gridded platform of an area digitizer/computer.

b. Through use of the cursor that accompanies this device, trace out the perimeter, as seen on the map, of each field or group of fields for which an acreage determination is desired, taking care to read the digital dial of the device at both the start and the finish of this operation.

c. Using a separate calculation of the relation between land area acreage, at the map scale, and the difference between the initial and final digital dial readings, calculate land areas for each entity traced out by the cursor in "b" above.

3. *Pixel-Counting during computer analysis.*

a. By means of a line scanner (e.g., multispectral scanner) remotely sense the entire area of interest, recording the digital response, pixel-by-pixel.

b. Determine the land area that is covered by a single pixel.

c. Establish the digital signature (i.e., the range of multiband scene brightness values) for each category (e.g., crop type) for which acreage is to be determined.

d. As the digital tape is processed in accordance with digital signatures, program it to keep a running total of the number of pixels encountered for each signature, and

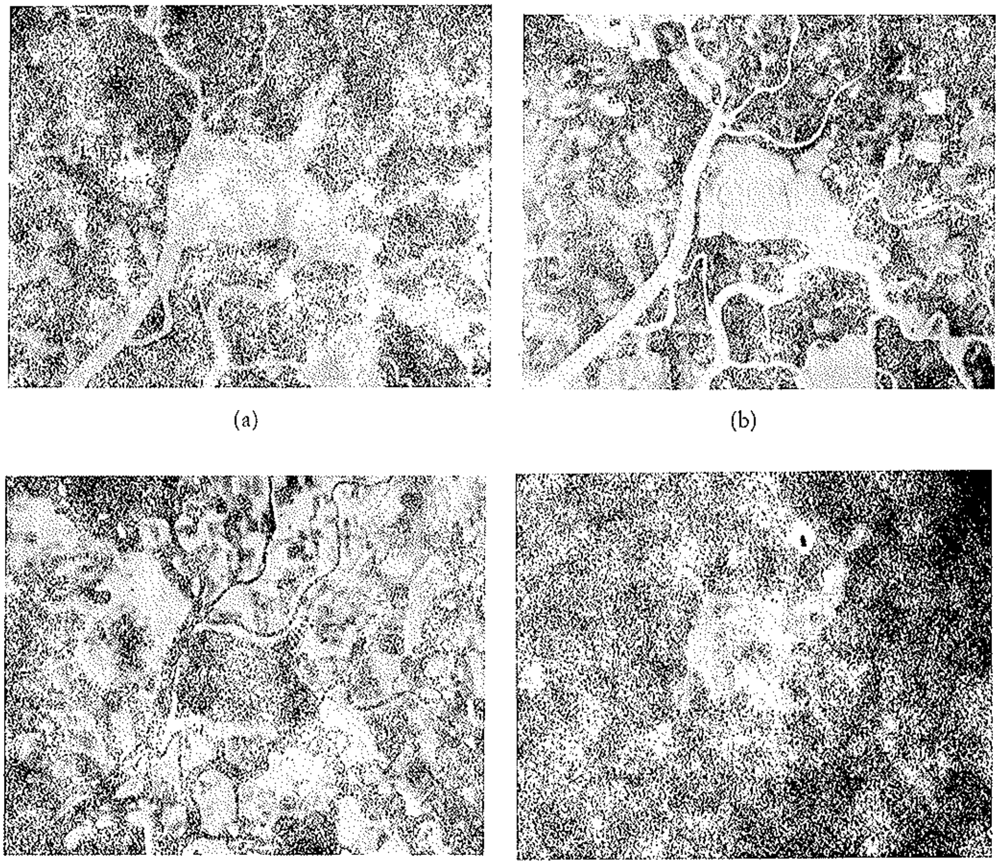
e. knowing the land area per pixel, calculate the total land area for each category.

U. *Principles and Considerations Involved in "Change Detection".*

It is axiomatic that "renewable" natural resources (timber, forage, water, etc.) are constantly undergoing change. The same is likely to be true, even for "non-renewable" resources (minerals, fossil fuels, etc.) when man is actively exploiting them. Not only is it desirable to have an initial inventory in all such cases but a periodic re-inventory so that both the beneficial and potentially beneficial changes can be detected through a process known as "monitoring". This commonly is done through the making of a pixel-by-pixel comparative analysis of sequentially-acquired remote sensing data. One effective means of accomplishing this is through the use of sequentially-acquired Landsat data as illustrated in Figure 11A. A change detection image with respect to vegetation cover for the entire northern hemisphere, as prepared from NOAA satellite data by J.E. Colwell and D.R. Hicks (1985) is shown in Figure 11B.

V. *Cost Versus Accuracy Considerations.*

A major factor in gaining the resource manager's acceptance of modern remote sensing-based capabilities is to be found by presenting to him reliable "accuracy versus cost" curves with which he can compare



(a) (b)

(c) (d)

FIG. 11A. Change detection as accomplished by the comparison of two dates of Landsat MSS imagery. These four Landsat photos pertain to an agricultural area from which flood waters from a levee break along the river were in the process of receding rapidly. All four photos were obtained from Band 7 (a near-infrared band) because it provides a favorable tone contrast between water and vegetation. (a) Negative rendition of the image acquired on July 26. (b) The same area as imaged by the Landsat MSS 36 days later. (c) A positive rendition made from the negative image that appears at (b). This rendition was made so that it could be superimposed as a positive transparency over the negative transparency made from the top left illustration, thereby facilitating "change detection". (d) The composite image formed by this superimposing of the two images over a light table. Note that the light toned areas in (d) are the ones from which flood waters have receded during the interim period. All other areas tend to appear uniformly dark gray because they have undergone little change; hence the darker they appear on one of the two transparencies, the lighter they appear on the other, and vice versa. Multidate monitoring such as this permits one to determine how long a given area was flooded. Such information improves the accuracy of certain predictions such as (1) crop yield and (2) the amount of tree mortality that is likely to occur in the orchards when flood waters have prevented adequate aeration of the tree roots for a known length of time (from Colwell, 1975).

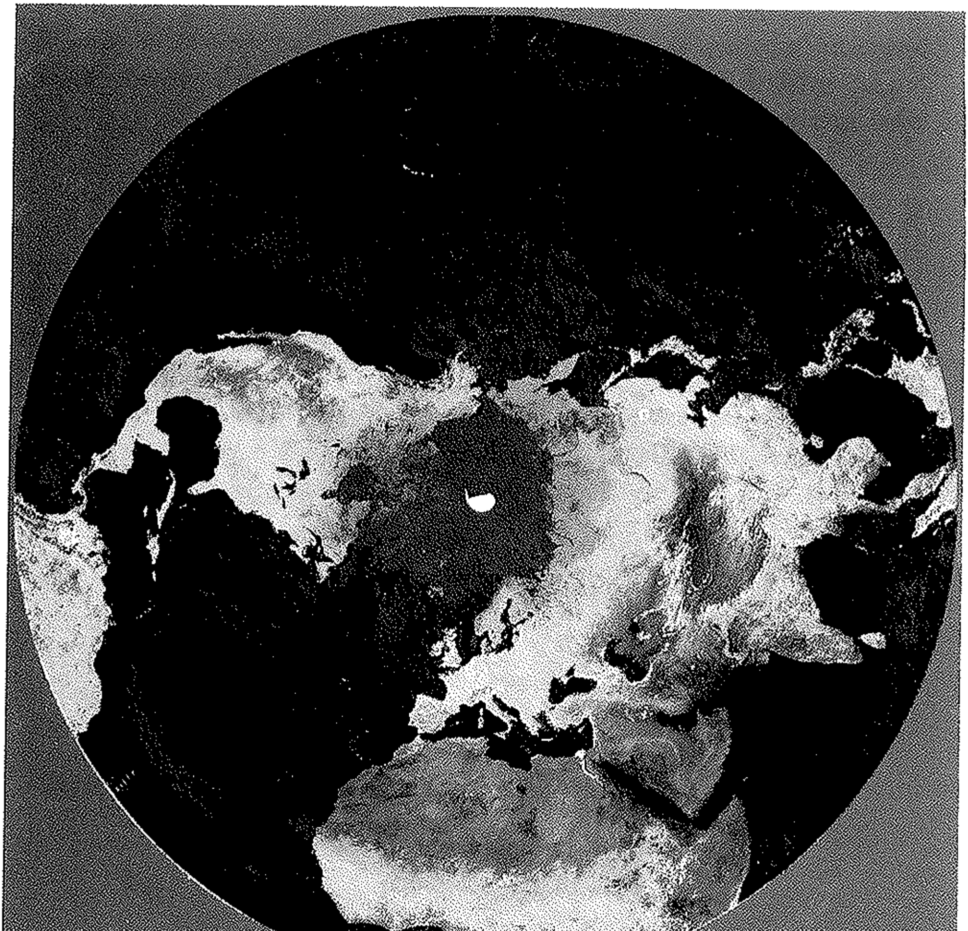


FIG. 11B. A "change detection" image of the northern hemisphere, made from NOAA/AVHRR data acquired in May and August, 1983. The following color code was used: May Vegetation Index = Red; August Vegetation Index = Green; Channel I for May = Blue. Image prepared by J.E. Colwell, Environmental Research Institute of Michigan, and described in article by J.E. Colwell and D.R. Hicks (1985).

the "old" technology that he presently is using for the inventory and monitoring of earth resources with a technology that is based on modern remote sensing capabilities. By comparing such curves he can readily see possibilities, as indicated in Figure 12, for achieving (1) higher inventory accuracy at a given cost; (2) the same accuracy as at present, but at reduced cost; or (3) some combination which will provide somewhat greater accuracy at somewhat lower cost.

W. *Time Delay Considerations.*

Unless the resource manager has *timely* access to remote sensing-derived information about the resources that he seeks to manage, all of the concepts and efforts that are embodied in the remote sensing of his resources may lead to little if any benefit. This is a matter of such importance in relation to the theme of this Study Week that it is dealt with at length under item "B" of a later section of my paper — the section that deals with the future outlook for remote sensing.

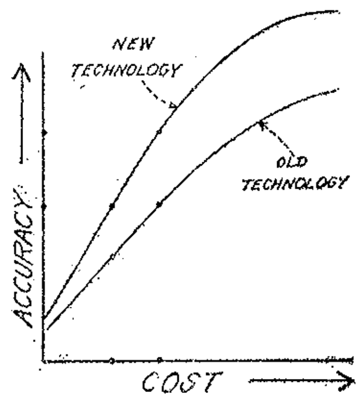


FIG. 12. A major factor in gaining the resource manager's acceptance of modern remote sensing-based capabilities is to be found by presenting to him reliable "accuracy/cost" curves with which he can compare the "old" technology with the new. By comparing such curves he can readily see possibilities for achieving (1) higher inventory accuracy at a given cost; (2) the same accuracy as at present, but at reduced cost; or (3) some combination which will provide somewhat greater accuracy at somewhat less cost. There are many other important factors that can govern his acceptance of modern remote technology, however, as summarized in a later section.

X. *Cost Versus Production Considerations.*

Superficially the curves shown in Figure 13 look so similar to those in Figure 12 as to prompt the question of whether any new concept is involved under this final heading under the "Basic Principles and Considerations" section of my paper. Indeed there is a difference, however, as indicated by the captions beneath the two figures.

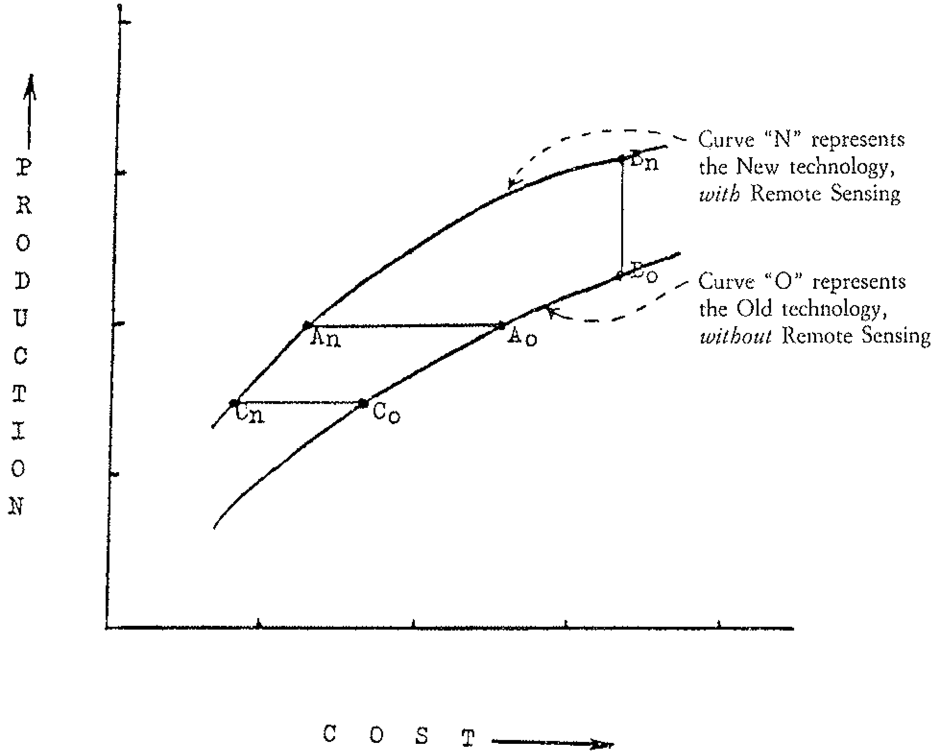


FIG. 13. Superficially, these "Production/Cost" curves closely resemble the "Accuracy/Cost" curves of Figure 12. They deal with an entirely different concept, however. Specifically, these curves suggest that there are three different ways in which more cost-effective management of an agricultural area might be achieved through the use of modern remote sensing technology: (1) achieving the same production as before, but at significantly less cost (compare A_o with A_n); (2) achieving a great increase in production with little or no increase in cost (compare B_o with B_n); and (3) achieving only a moderate decrease in production with a great decrease in cost (compare C_o with C_n). Often alternative "3" provides greatest profitability.

Y. *Framework Within Which to Place These and Other Principles and Considerations.*

Now that we have described many (but certainly not all) of the principles and considerations that will be of importance throughout our Study Week, we should seek to provide a framework within which to place them. Table 3 provides such a framework in that virtually all of them (including several that will be described in the remaining sections of this paper) can be placed in a sequentially oriented framework. Organizationally, this framework serves to properly place each of a very large number of principles and considerations, especially when they are stated in the form of remote sensing-related "concepts" as in Table 3.

Z. *Rationale for Including Here an Account of Certain Past, Present and Probable Future Developments in Remote Sensing.*

Because the convenors of this Study Week specified, in selecting the title of my paper, that I should provide an adequate historical perspective somewhere within it, we might do well to ask ourselves why it is important to dwell, at least to some extent, on the past, present and probable future developments in this fast-growing field known as remote sensing. Fortunately there are some brief but highly germane quotations that will adequately answer this question inferentially.

As for why we should survey the *past*, we have Santillana's assertion that "Those who ignore the past are doomed to repeat it". As for why we should concern ourselves with the *future*, we have the equally philosophical and oft-quoted assertion, "because we will spend the rest of our lives there". And with respect to the *present* (as a bridge between the past and the future) we have Abraham Lincoln's assertion (even though it was made 125 years ago, and in a much different context), "If we better knew where we are, and whither we are trending, we would better know what to do and how to do it".

Perhaps it is the last of these three quotations that says it all as we seek this week to survey the field of remote sensing and ultimately to consider its potential impact (for better or worse) on developing countries. It is only through such thoughtful consideration that we will be able to determine, by the end of this Study Week, whether the idea of using remote sensing extensively in developing countries is a viable one.

TABLE 3 - *Concepts That Govern the Usefulness of Remote Sensing for the Inventory and Monitoring of Natural Resources.*

The concepts are logically considered under five major headings, as listed below:

1. *Defining the Resource Manager's Information Requirements*

   A. The Concept of Surrogates
   B. The Concept of Trade-Offs
   C. The "Half-Life-of-Usefulness" Concept

2. *Selecting the Remote Sensing Data Acquisition Components*

   A. The Synoptic View Concept
   B. The "Multi" Concept
   C. The "Sensitivity Analysis" Concept
   D. The "Cost vs. Accuracy" Concept
   E. The Critical Mass Concept
   F. The Data Compression Concept
   G. The Ancillary Data Concept
   H. The Vertical Integration Concept

3. *Analyzing the Remotely Sensed Data*

   A. The Human Factors Concept
   B. The Machine Factors Concept
   C. The Concept of Binary Choice
   D. The Convergence of Evidence Concept
   E. The Multidisciplinary Conference Concept
   F. The Confusion Matrix Concept
   G. The Complexity of Structure Concept
   H. The Concept of Change Detection

4. *Presenting the Remote Sensing-Derived Information*

   A. The Multiple Overlay Concept
   B. The Color Coding Concept
   C. The Concept of Synthetic Stereo
   D. The Concept of Multiple Use of Information

5. *Gaining Acceptance of the Technology*

   A. The Concept of Appreciation vs. Adoption
   B. The Concept of Requirements for Adoption
   C. The Concept of Progression Toward Adoption
   D. The Concept of Deterrents to Adoption
   E. The Maintenance of Momentum Concept
   F. The Procedural Manual Concept
   G. The Technical Assistance Concept

The foregoing, then, constitutes the rationale for preparing the next three sections of my paper dealing, respectively, with past, present and probable future developments in the fast-growing field of remote sensing.

IV. Past Developments in Remote Sensing

Since the technology of modern remote sensing probably would not have been developed without the prior development of photography itself, this part of my paper will begin with a description of events which led to the discovery and development of the basic science of photography. As the account proceeds, the development of *aerial* photography, including color and infrared photography, will be traced. This historical account will then continue with a documentation of some of the events that occurred during World War II and shortly thereafter, setting the stage for a concluding section that deals with remote sensing progress during the past 30 years, or so (i.e., since the dawning of the Space Age).

Perhaps the best accounts from which to draw historical material on photography are those found in the Manual of Photographic Interpretation and the Manual of Remote Sensing, both of which were prepared and published under auspices of the American Society of Photogrammetry (1960; 1983). The following historical account is based partly on these references. However, a unique emphasis is given here — one which seeks to relate these events specifically to the development of modern remote sensing technology and its use in the world's developing countries.

A. *Observations of Our Progenitor, the Cave Man.*

The first human to engage in remote sensing (in the broadest usage of the term) was, reportedly, the cave man. We can visualize him now, as he picked up his club, strode from his cave and a few moments later crouched high in a tree or stood atop a ridge. There he strained his eyes, his ears, and his nostrils in an effort to "sense" the presence of an animal that might either constitute a supply of fresh meat for him or be seeking at that very moment to convert him into a supply of fresh meat for itself. In either event, remote sensing has been a pretty serious business, ever since.

B. *Observations by Ancient Philosophers.*

Several ancient philosophers, including Aristotle, understood the principle of the camera obscura. The camera obscura exploits the fact that light passing through a small aperture in a dark box or chamber can be made to form pictures. The manuscripts of Leonardo da Vinci (1452-1519) contain the first clear description of the process of projecting images through a small opening onto a wall in a darkened room. In 1646 the Jesuit Atanins Kircher (1601-1680) described how landscape drawing can be accomplished through the camera obscura.

C. *The First Practical Photography.*

The co-inventors of the first practical means of photography were Joseph Nicephore Niepce (1765-1833) and Louis Jacques Mandes Daguerre (1787-1851). In about 1840 Arago, Director of the Paris Observatory, referred to the Daguerrotype process before members of the Chamber of Deputies, and advocated the use of photography for topographic purposes.

E. *The Talbotype Process for Making Prints from Negatives.*

In 1841 it was discovered by William Henry Fox Talbot (1800-1877) that an image formed on paper coated with silver iodide though barely visible, could be developed or strengthened with gallic acid and silver nitrate. First called "Calotype" and later "Talbotype", the pictures made in this way did not have the brilliancy and sharpness of daguerrotypes, but they did make it possible to produce any number of positive copies from the negative.

F. *The Early Development of Image Enhancement Techniques.*

In 1851, Scott Archer prepared a suspension of silver chloride in nitrocellulose and coated it on glass. It had the advantage over Talbot's process that it was more sensitive and produced better definition than was possible on paper negatives although it required immediate processing.

The silver halide emulsion is naturally sensitive only to blue light (and to some shorter, non-photographic wavelengths), but in 1873 Herman Vogel discovered that the emulsion could be sensitized to record longer wavelengths by introducing certain dyes to it. As a result, in the ensuing decades new dyes were found and ortho, panchromatic and infrared plates and films were developed.

In 1889 a film base of nitrocellulose, which retained the clarity of glass plates, eliminated their fragility, and reduced their bulk and weight, was developed by George Eastman. This promptly led to the use of roll film, as a replacement for glass plates, in the taking of aerial photographs.

G. *Developments in Optics*

Joseph Fraunhofer (1787-1826) and Louis Pierre Guinand (1748-1824) were the first to produce large pieces of optical glass without striae. Frederick Voigtlander produced fast lenses in 1841 that were used for portraits as well as landscapes.

H. *First Attempts in the Development of Aerial Photography.*

In 1858 the photographer Gaspard Felix Tournachon (later known as "Nadar") ascended in a captive balloon to an altitude of several hundred meters and took the first known aerial photograph, covering the village of Petit Bicetre, France. In this photograph the houses could be clearly seen. Colonel Aime Laussedat followed, later in the same year, with an experiment involving a glass-plate camera supported by several kites. Much later, the use of kites as aerial camera platforms was substantially furthered by an English meteorologist, E.D. Archibald, in 1882.

In 1860 Samuel A. King and J.W. Black took aerial photos of Boston, Massachusetts, U.S.A., from a captive balloon at a height of about 400 meters. These reportedly are the earliest aerial photos still on record.

In 1889 Russian experimenters connected seven unmanned kites, mounted a camera on each, and sent the assembly aloft to obtain "panoramic" photography which proved to be useful both for cartographic purposes and for the interpretation of features in remotely situated areas.

The use of birds as aerial camera platforms was engaged in successfully when Julius Neubronner designed and patented, in 1903, a breast-mounted aerial camera for carrier pigeons. It weighed only 70 grams and took negatives that were 38 mm square. Through the use of a built-in timing mechanism, exposures were automatically made at 30-second intervals.

In about 1900, a captain in the Austrian Army, Theodore Scheimpflug, attached an eight-lens camera to the basket of a balloon. By grouping seven oblique lenses around one vertical one he obtained coverage of the entire area visible from the aerial camera station.

J. *Development of a Navigable Platform.*

Before aerial photography could become an integral part of the technique of the earth sciences, a navigable platform for the aerial camera had to be provided. The balloon, pigeon, and kite platforms were not navigable in the strict sense of the word, although many excellent photographs were taken from them. The development of dirigible balloons offered an opportunity for taking photographs from planned positions not possible with captive or free balloons. The piloted aircraft can carry a camera to any part of the earth, as long as the airways are politically unobstructed. Without the piloted aircraft, there would have been little advancement of aerial photography.

Wilbur Wright is credited with having obtained the first photographs from an airplane when, on April 24, 1909, he took motion pictures over Centocelle, Italy. Shortly after this, German aviation students, training in English flying schools, began to use cameras on advanced training flights.

The first photography known to be used for *mapping* from an airplane was described by Captain Tardivo in 1913 in a paper presented at a meeting of the International Society of Photogrammetry held in Vienna.

K. *Developments During World War I.*

Aerial photography of a practical nature dates from the early days of World War I. The first aerial photographs of German-held territory made by the British were taken by Lieutenant Laws of the Royal Air Force (RAF). The importance of aerial photographic reconnaissance was recognized by both sides during World War I. Vigorous efforts were made in France, Britain, and Germany to provide the military with photographic equipment and to develop proper methods of photography, processing, and photo interpretation.

L. *Developments Between World Wars I and II.*

During the 1920's, and largely because of developments during World War I, there were throughout the world many advocates of the use of aerial photos for various *civil* purposes. For example, there were foresters in the United States, Canada, Germany, India, and Burma who saw clearly the multifaceted uses of aerial photos in forestry as an aid to the construction of planimetric and topographic maps, in the appraisal of timber and other forest resources, and in planning the location of logging roads, sawmills, landings, and camps. To the Canadian and German foresters goes much of the credit for the development during that period of the basic concepts upon which many of the present day forestry uses of aerial photographs are founded.

Despite considerable photogrammetric experimentation in the 1920's and the publication of many enthusiastic articles which pointed out the indisputable advantages of using aerial photographs in many different ways, there remained a problem of "technology acceptance". More will be said in a later section about this continuing remote sensing-related problem. Suffice it to say here, in more general terms, that this one problem often results in a very long delay between the time when new technology has been demonstrated to be of great value and the time when those who could use it to great advantage actually adopt it to the point of using it operationally in the appropriate ways.

For the reason indicated above, it was not until the middle of the 1930's that the extensive use of aerial photographs came about. Then it seemed as though all the seeds of enthusiasm which had been planted by visionary aerial photogrammetrists and photo interpreters in seemingly barren soil during the previous 10 to 15 years sprouted at once.

It was also in the 1930's that the first practical black-and-white *infrared* photographic film was developed. As far back as 1873 Vogel had made the discovery that by treating photographic materials with certain dyes one could make them respond to wavelengths of light to which they were not naturally sensitive. Also the first *practical* infrared dye, Kryptocyanine, was "discovered" in 1919 at the Bureau of Chemistry in Washington. Further progress was made with the development of Neocyanine by Eastman Kodak in 1925. By 1935 infrared photography was possible out to 1.35 microns.

In the 1930's the U.S. Army Air Corps and the National Geographic Society were the two main U.S. boosters for the development and use of infrared films. During their jointly sponsored stratosphere balloon flight that was made over parts of the U.S. in 1935, an altitude of 72,395 feet was attained and the infrared photographs obtained on that flight were very successful. By March, 1937, the first infrared aerial film was made commercially available to the general public by the Eastman Kodak Company, Rochester, New York, and the use of such film steadily increased thereafter. Bradford Washburn obtained some excellent infrared photographs of Alaska in 1938.

Color photography also was developed primarily in the post-World War I period. In 1924 Mannes and Godowsky patented their first work on a multiple-layer color film which eventually led to the development of Kodachrome. There has been emphasis on three-color systems ever since the first three-layer color film came on the market in 1935. The question soon arose, however, of whether to make color film that could be developed to a negative or to a positive. It was decided that "reversal positive film" would be preferable. One such film that proved to be especially suitable for the obtaining of *aerial* photography, was designated as Kodacolor Aero Reversal Film; it was the forerunner of present day Ektachrome film.

M. *Developments During World War II.*

Just as World War I had provided great impetus to the development and use (eventually the civil or peacetime use) of aerial photography, the same also was true with respect to World War II. One example entailed the development of a new kind of color film, primarily for use in the detection of military camouflage but later used very extensively, even up to the present time and in only slightly modified form, for the detection of vigor losses in plants. For both such uses the basic principle to be exploited is the same: When vegetation is damaged, whether it be by the cutting off of tree branches to obscure military vehicles or by the invasion of certain plant-loving insects or fungi, there is a loss in near-infrared reflectance that tends to occur well before there is any detectable loss in visible light reflectance. (This highly significant phenomenon is discussed more fully in an earlier section in connection with Figures 3 and 4). Since more useful information is obtained by photographing in both the *visible* and *near-infrared* parts of the spectrum, it was first suggested in 1941 to combine infrared and panchromatic photographic emulsions with *color* processing. From the Kodak Research Laboratories in England, Spencer and Marriage reported on this possibility and shortly thereafter transferred their work to Rochester, New York, where they developed three different structures for a multilayer film which included an infrared layer. A form of "false color" processing was employed, as discussed in a later section of this paper. In the names of Jelly and Wilder a patent was filed on the basic structure of color infrared film in late October, 1942, and the patent was issued on July 9, 1946, by which time some use had been made of the film in the concluding phases of World War II.

In World War II the infrared false color film that was made available to the military for testing was known as "Aero Kodacolor Reversal Film, Camouflage Detection". A currently used infrared color film known as "Kodak Ektachrome Infrared Aerial Film, Type 8443" is basically a modification of the Type B structure recommended by the U.S. Army Air Force in 1942.

The origin of what the Russians call Spectrazonal film can be found in the description of a material having only two layers responding to peak sensitivities at wavelengths of about 680 and 740 nm, respectively ([7]).

Paralleling these World War II improvements in photographic films were other improvements leading to further increases in the quality of photographic images. Many of these improvements were in aerial photographic equipment and techniques. During World War II intensive military research succeeded in developing cameras with fast and nearly distortion-free lenses, fast and dependable shutters, mountings which absorb aircraft vibrations and stabilize the camera against changes in attitude of the aircraft, and film-drive mechanisms which partly compensate for image blur due to the forward motion of the aircraft.

Perhaps the most significant impact of World War II, however, on the historical development of what we now term "remote sensing" had to do with the people who were drawn into that field from a variety of civil pursuits and who, after the war, returned to civilian life. This aspect is more fully discussed below.

([7]) By recent international agreement among scientists, the term "nanometer" (abbreviated "nm") is expected eventually to replace the equivalent term "millimicron" when speaking of a unit of distance which is 10^{-9} meters, and the term "micrometer" (abbreviated "µm") is expected to eventually replace the term "micron" when speaking of a unit of distance which is 10^{-6} meters. Indicative of this hoped-for change, the present paper uses the old units of measure for the most part (because they still are the most familiar ones) but occasionally uses the new units as a token of the terminology that scientists will use in the future—unless they change their minds again.

N. *The Post-World War II Impact of Photo Interpretation Trainees.*

Shortly after the end of World War II a very significant development occurred in relation to the increased use of remote sensing throughout the globe. For example, in the United States at that time there were at least 1,000 photo interpretation officers (more than 600 from the Navy alone) released from active duty to return to civil pursuits. These were individuals who had been recruited during the war, commissioned as reserve officers and then trained and given a great deal of operational experience in various aspects of aerial photographic intelligence. Upon completion of the war the vast majority of them returned to civil life to work in the professions from which they had been recruited. Most of these professions dealt, in one way or another, with the earth's natural resources — professions such as geology, forestry, range management soil science, hydrology, and the agricultural and engineering sciences ([8]). Almost all of these individuals had the following combination of attributes: (a) they possessed a B.S. degree in one of the above listed disciplines; (b) they possessed good qualities of leadership, much of it having been developed during their service as military officers; (c) by virtue of their military training and experience in studying aerial photos to assess "trafficability conditions" (i.e., conditions governing the ease of movement of personnel and various kinds of mechanized equipment), they were well aware of both the uses and the limitations of aerial photos in assessing certain kinds of information that would be of interest also to the manager of natural resources (Colwell, 1946), including information with respect to terrain analysis, vegetation identification and soil mapping); (d) they were young, vigorous and eager to build on their military-acquired experience, if possible, as they returned to pick up the threads of their pre-war careers; and (e) they were well qualified, and usually well motivated, to teach others how to interpret aerial photographs.

The impact of these individuals on the development of remote sensing in the United States during the post-war era can scarcely be overemphasized. Reportedly other nations benefited in a similar manner as their military-reservists returned to civil life.

As listed below, there were at least four other important training-

([8]) Such professions also make extensive use of maps and other "plan view" representations of features, roughly analogous to the view portrayed in a vertical aerial photograph. In fact it was for this reason that most of the officers commissioned for photo intelligence work in World War II had been recruited from these professions.

related developments that occurred in a great many countries during the post-World War II era with respect to remote sensing. These were:

1. the rapid increase during the post-war era in university-level course offerings dealing with one aspect or another of photo interpretation and photogrammetry;

2. associated with the above item, the rapid increase in the number and quality of textbooks dealing with aerial photographic interpretation and photogrammetry;

3. the rapid increase in the number, quality, and types of equipment for use in photo interpretation and photogrammetric activities; and

4. the growing stature of photo interpretation in various professional societies, one example of which is discussed in the next section.

O. *Founding of an International Commission on Photo Interpretation*

An international development of particular significance in the growth of remote sensing was the formation in 1952 of a special Commission on Photo Interpretation (Commission VII) within the International Society for Photogrammetry (ISP). As the one who served as president of that commission for its first eight years, I can clearly recall that, during that period, the following assertion was frequently made by photogrammetrists: "Photo interpretation is not of sufficient stature to merit its own commission". (This is in sharp contrast with the subsequent renaming of that Society as the International Society for Photogrammetry and Remote Sensing mainly to acknowledge the importance of photo interpretation. Similarly, the American Society of Photogrammetry has changed its name to the American Society for Photogrammetry and Remote Sensing) (9).

Part of the steadily increasing interest in remote sensing that has occurred during the past three decades has resulted from the great increase that occurred during that time in both the total amount and the availability of photography and other types of remote sensing data. Many of the "Johnny-Come-Latelies" to the field of remote sensing find it hard to believe that, in the early 1950's, photo interpreters in the United States,

(9) The term "photogrammetry" literally means "photograph measurement" — usually the measurement of distances, directions and areas on photographs as when making maps from them. Originally photogrammetrists tended to refer derisively to "photo interpretation" as the mere identification of features, incidental to the map-making process.

and indeed throughout the globe, were continuing to work (as in previous decades) almost entirely with a single type of imagery. It was almost invariably black-and-white vertical aerial photography, that had been taken at some time during the preceding 10-year period, probably during cloud-free midsummer high sun-angle conditions, using panchromatic film and a "minus blue" filter, and employing a camera having approximately 8-1/4" as its focal length and a 9"×9" negative size, operated from an altitude of about 13,750 feet above the terrain to give a photographic scale of 1/20,000, or thereabouts. While the great potential benefits of acquiring and interpreting multiband, multidate, and multistage photography were recognized, it was totally unrealistic in most instances to consider that such kinds of photography could be made routinely available to the photo interpreter at any foreseeable future date.

At this point let us examine quite specifically the role of Commission VII in relation to the photo interpretation progress that is about to be discussed.

Until Commission VII (Photo Interpretation) of the ISP was founded, there was no organization which might logically serve as the international "clearing house" on photo interpretation matters. Prior to that time, therefore, there was needless duplication of effort both in the conduct of research and in the reporting of results and activities relative to the field of photo interpretation. In many instances, the problem was one of omission rather than duplication.

Each of the other commissions of the ISP, having been formed many years earlier, had solved such problems through (1) the appointment of reporters from each of the countries most active in that aspect of photogrammetry with which the commission was concerned; (2) the publication of pertinent articles, papers, and newsworthy information in *Photogrammetria*, the official publication of the ISP; (3) the organizing and presenting of international symposia once every four years as part of the quadrennial meeting of the ISP; and (4) the publication of a very complete and prestigious record of the proceedings of those quadrennial meetings of their commission. For each such commission it was common practice that the Commission's president and vice-president for any given four-year period be appointed from two of the countries that currently were most active in work of the type dealt with by the commission.

All of these highly desirable attributes have been emulated by Commission VII from the very time of its formation. It is in consequence that this part of my paper, dealing primarily with progress in photo interpretation in the past three decades, indirectly constitutes a tribute to the activities of Commission VII since its founding in 1952.

Historically speaking, this early, highly successful and still continuing development of international cooperation in photo interpretation (as achieved through Commission VII of ISP) is one of great potential relevance to our deliberations during this Study Week. Specifically, it sets the stage, and provides the mechanism, for an unusually important kind of international cooperation that will be needed to an ever-increasing extent if remote sensing is to have any substantial favorable impact on developing countries. I refer to the international cooperation that will be needed not merely in data *acquisition* techniques but in data *reduction* (i.e., information extraction) techniques. For the latter are the ones with which Commission VII continues to deal. And these are the techniques without which the potential benefits for developing countries — the benefits derivable through the marvels of modern remote sensing technology — will never be adequately realized.

P. *Improvements During the Past Three Decades in Sensor Platforms and Sensor Systems.*

Before photographs taken of the earth's surface from space became available, most remote sensing specialists underestimated the potential advantage that would be given by the overall "synoptic view" as recorded from an altitude of one hundred miles or more and covering a ground area per frame of photography that was at least a thousandfold greater than that to which they were accustomed. There also was a failure, prior to the dawning of the space age, to perceive the remarkable improvements that would be made in cameras and other sensor systems. For instance, the aerial photography of a quarter century ago rarely permitted more that 25 line-pairs per millimeter to be discerned (10). Since then, improvements in both the emulsions of photographic films and the optics of sensor systems have been sufficient to make quite commonplace a fourfold improvement in such resolution. Furthermore, serious discussions regarding the potential for obtaining fortyfold improvements frequently are heard.

There also have been some startling improvements in recent years

(10) The concept of "line pairs" is explained in a later section of this paper in connection with the resolution target appearing in Figure 16.

in various other kinds of sensor systems, including panoramic cameras, continuous strip cameras, optical mechanical scanners, and side-looking airborne radar systems. (Most of these will be discussed in the section of my paper that deals with the present status of remote sensing). Each of these systems, when used individually aboard a spacecraft, is able to provide certain kinds of information that cannot be obtained from any of the others. More importantly, when the remote sensing data that has been acquired by several of these sensor systems is placed in the hands of a competent image analyst, the "convergence of evidence" principle can be exploited in respects that heretofore were not feasible, thereby adding greatly to the amount and accuracy of information derivable from space-acquired remote sensing data.

Q. *Improvements During the Past Three Decades in Capabilities for the Analysis of Remote Sensing Data.*

The techniques and equipment used by *humans* in the analysis of remote sensing data were, for the first time, comprehensively described and illustrated in the *Manual of Photographic Interpretation* as mentioned previously (American Society of Photogrammetry, 1960). Since then, great advances have been made in developing capabilities for the analysis of remote sensing data by *machines*. As a result, there is today a valuable and extensive field of photo interpretation (or more broadly stated, of "computer-assisted analysis of remotely sensed data") that was virtually unknown three decades ago. For example, almost no mention of this capability appears in the *Manual of Photographic Interpretation*, whereas it constitutes a very major part of the material contained in a companion volume published roughly a quarter century later entitled *Manual of Remote Sensing* (American Society of Photogrammetry, 1983b).

Because of this modern day dual approach to the analysis of remote sensing data, some very important questions are currently being addressed relative to ways in which the human and machine should interface in order to bring about the most complete, accurate, and expeditious analysis of remote sensing data through a suitable combination of human and automated techniques. More information with respect to this important topic will be found in a later section of this paper that deals with a look to the future.

R. *Controversies of Three Decades Relative to the Usefulness of Photo Interpretation Keys.*

Evidence of the interest commanded by photo interpretation keys three decades ago is to be found merely from a survey of the literature for that period. For example, this matter was of such interest that in 1952, in the Report of the President of Commission VII (Photographic Interpretation) of the ISP, almost half of the entire report was devoted to discussing and illustrating such keys and to a parallel discussion of terminology problems and solutions associated with their use. Yet despite that seemingly disproportionate allocation of space to one topic, photo interpretation keys were again the primary topic at the 1955 annual meeting of the American Society of Photogrammetry in the course of which a panel presentation consisting of no less than nine papers was devoted to this subject. Although it is probable that the heyday for photo interpretation keys has passed, their usefulness both as training and reference manuals should not be dismissed, even to the present time.

One of the most definitive tests ever performed relative to the effectiveness of photo interpretation keys as training aids was conducted in the United States using 60 high school students as the test subjects and a dichotomous key contained in the book *Pacific Landforms and Vegetation* as the test material. Since most of the Tropical Pacific is considered to be a "developing" part of the world, details with respect to this particular test are deemed to be relevant here. Specifically, such details indicate the great potential usefulness of photo interpretation keys when inventories are to be made, through remote sensing, of a developing country's natural resources. The key tested dealt with wildland vegetation types such as Nipa Palm, Casuarina, Mangrove, and Moss Forest — types which no one in the test group had ever seen or perhaps even heard about. Within a six-hour day of instruction the students, starting from "ground zero", were first taught the principles of aerial photography and stereoscopy and given practice in the three-dimensional viewing of overlapping vertical aerial photographs through a stereoscope. They were then taught the principles and use of the previously mentioned dichotomous key that was to be tested. Finally, during the last hour each student was given a set of operational photos of a representative portion of the Tropical Pacific Area within which were to be found some of the most complex vegetation associations that might be encountered anywhere in the world. The students were asked with the aid of the key (1) to identify the type of vegetation, area-by-area, (2) to estimate "trafficability conditions", and

(3) to delineate on the photographs the best route of travel from point-to-point. Fully one-third of the students identified the many vegetation types with nearly 100 percent accuracy and selected point-to-point routes of travel that were known to be among the most favorable, based on "ground truth". The word descriptions, dichotomously arranged, and used in identifying the various vegetation types in the tests just described, appear in Figure 6.

Despite encouraging findings such as these, photo interpretation keys seem to be less used today than 30 years ago.

S. *Conclusions With Respect to This Account of Past Developments.*

Other factors of historical significance might well be included in this section, dealing as it does with the development of remote sensing technology. However, most of these additional factors blend into the present status of remote sensing and hence will be discussed in the section that immediately follows this one.

This section will have achieved two of its primary objectives if its account of the historical development of remote sensing serves to provide those who are attending this Study Week with (a) an adequate background against which to view the present and probable future developments of remote sensing, as they will be described in the next two sections of this paper; and (b) an adequate appreciation of the rich heritage that is enjoyed by modern day remote sensing scientists, thanks to the dedicated, brilliant and sometimes even inspirational labors of our predecessors in this field from many parts of the world.

In fact, for some of us such a historical account brings to mind the observation made by Aristotle more than two thousand years ago when he said,

> "The search for truth is in one way difficult and in another easy. For no one can master it fully nor escape it wholly. But each, through his efforts, contributes a bit to our understanding and from the knowledge thus assembled there arises a certain grandeur".

V. The Present Status of Remote Sensing

In this part of my paper a brief description will first be given of the present status of remote sensing with respect to some of the representative cameras, films, sensing systems, and platforms that currently are being used in the *acquisition* of remote sensing data from aerospace. This will include a discussion as to the present status of both the U.S. Landsat program and the French SPOT program. Then some representative kinds of equipment for the *analysis* of remote sensing data by humans and machines will be described, together with some of the classification schemes employed in the inventory of an area's natural resources. Because of the dynamic nature of modern remote sensing technology, it is probable that most of the sections described in this part of my paper are becoming obsolete, even while they are being written. Allowance for this factor will be reserved, however, for the section following this one, dealing with the future outlook for remote sensing.

A. *Aerospace Cameras.*

At present there are three major types of cameras used in remote sensing of the earth's surface from aircraft and/or spacecraft. These are (1) the conventional aerial camera, (2) the panoramic camera, and (3) the multiband camera. The essential nature of each of these cameras will now be described and illustrated.

1. *The Conventional Aerial Camera.* Most of the basic components of a modern camera are shown diagramatically in Figure 14. These consist of the magazine, drive mechanism, cone and lens as described below.

The magazine is essentially a light-tight box in which the photographic film is held. In most cases it is detachable from the rest of the aerial camera. The film, as received from the manufacturer, usually is in the form of a continuous roll, 9½ inches wide and 200 feet long, mounted on a supply spool. Approximately 250 exposures, each 9 inches square, can be taken on such a roll. Both the supply spool and the take-up spool fit snugly inside the magazine as illustrated in the diagram.

The drive mechanism is a series of cams, gears and shafts designed to drive the film from the supply spool to the take-up spool. The film, in passing from one spool to the other, is routed, via guide rollers so constructed as to meter the amount of film passing from the supply spool to the take-up spool between exposures, thereby assuring a correct and uniform spacing of exposures on the film roll. As a result of this recycling operation, an unexposed portion of film is properly positioned in front of the locating plate between exposures.

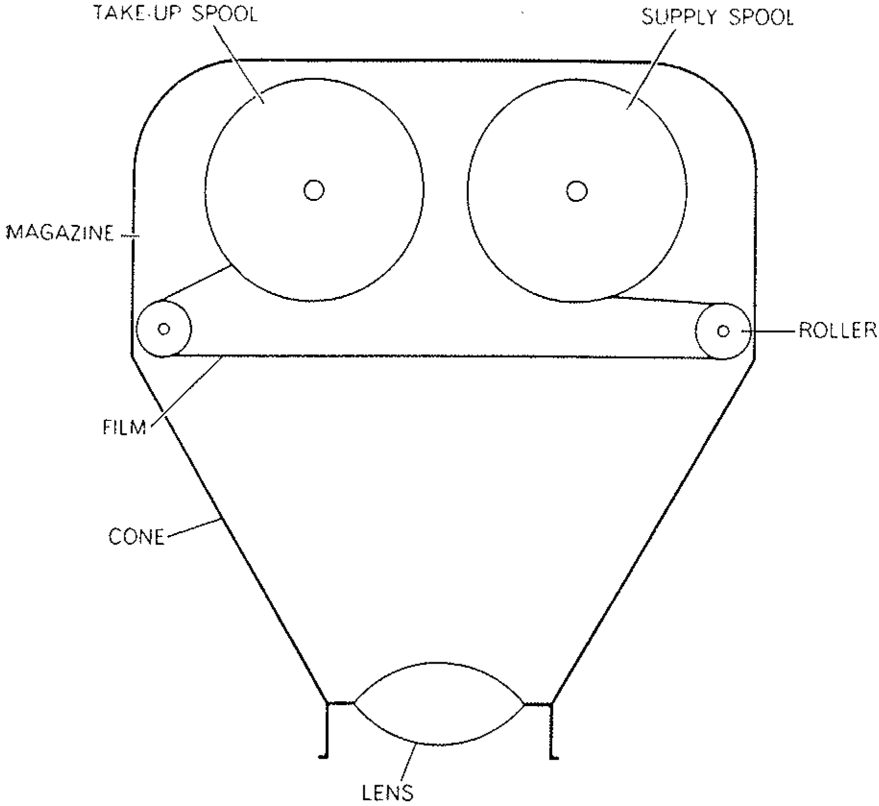


FIG. 14. The conventional aerial camera uses film in roll form and can make about 250 exposures per roll, each 9 inches square. The magazine holds the film, and the cone positions the lens with respect to the film at a distance governed by the focal length of the lens. By means of a vacuum cylinder, as each frame of photography is being taken the film being exposed is held flat against a locating plate to minimize distorsions and provide uniformly sharp images.

While an exposure is being made, suction is created behind the locating plate either by means of a conventional aircraft venturi tube or a magazine vacuum cylinder and piston apparatus which is built into the magazine. This suction is transmitted to the film through a network of small perforations and grooves in the locating plate, thereby holding the film in a flat plane against the plate at the instant of exposure. Distortion of the photographic image caused by a warped position of the film at the instant of exposure is thereby minimized.

The cone is a light-tight element which serves to position the camera lens at the proper distance from the exposable portion of the photographic film. The perpendicular distance from the film to the rear nodal point of the lens (of the camera) is known as the focal length. Several commonly used aerial cameras have interchangeable cones of different focal lengths for the same magazine. Most aerial photography currently being taken for the inventory of natural resources employs focal lengths of either 6, 8¼, or 12 inches.

The lens consists of several carefully ground and mounted glass elements which sharply focus on the photographic film the light rays reflected to the lens by illuminated objects on the ground. Aerial camera lenses ordinarily are of the fixed focus type, being focused at infinity and lacking a focusing adjustment. The altitude of the photographic aircraft or spacecraft above the ground usually is such that all objects on the ground will be in sharp focus when the lens is focused at infinity.

On most aerial cameras the shutter is located between the front and rear lens elements and accordingly is termed a "between-the-lens" shutter. In recycling the camera between exposures, the camera drive mechanism automatically re-cocks the shutter at the same time that it draws a new portion of unexposed film into position.

2. *The Panoramic Camera.* The principle on which the panoramic camera operates is indicated in Figure 15. With this camera it is possible to photograph a large area in a single exposure at very high resolution (i.e., with a high degree of image sharpness in every part of the photograph). The camera meets a need but creates some special problems. In order to get a sharp image when photographing large areas, one paradoxically needs a narrow angular field so as to minimize aberrations of the lens. Such a field is provided in the panoramic camera by a narrow slit in an opaque partition near the focal plane of the camera. The long dimension of this slit is parallel to the camera platform's line of flight. With such a slit, however, one will be able to photograph only a narrow swath of terrain unless the optical train of the camera is equipped to "pan" (move from side to side) as the aircraft advances. The optical train of the panoramic camera is designed to make such movements.

On the other hand, for the panoramic camera to maintain a uniformly clear focus as the optical train moves, the frame of film being exposed must be held in the form of an arc instead of being kept flat as in a conventional camera. With the film in an arc the photographic scale becomes progressively smaller as the distance of objects on the ground increases to the left and right of the flight path. In some applications

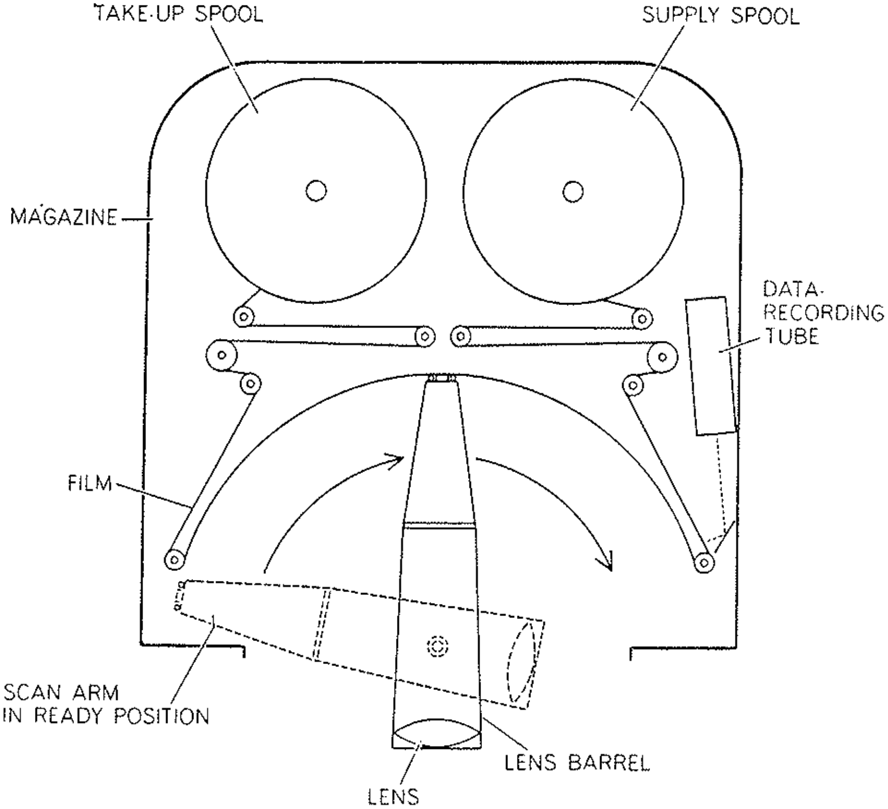


FIG. 15. The panoramic camera was developed to provide sharp aerial photographs at large scale and with wide swath width. Since the camera must have a long focal length it also must have a narrow angular field for maximum sharpness. As a result it requires a scanning mechanism that moves the lens barrel to left and right. At any instant during the course of a scan, only the light passing through a narrow slit falls on the film.

the scale problems outweigh the advantage of a panoramic field of view, so that it is preferable to use a conventional camera. There are many resource managers, however, who are beginning to make very effective use of the panoramic camera to obtain, with only a limited number of flight lines, ultra high resolution imagery of very wide swaths of terrain.

3. *The Multiband Camera.* Recent investigations have shown that far more information can be obtained about natural resources from a study of images taken simultaneously in each of several wavelength bands

than is obtainable from images taken in any one band. Realization of this fact has led to the previously mentioned concept known as "multi-band spectral reconnaissance" and to the development of various multiband cameras for the taking of simultaneous photographs in each of several bands. In a camera of this type, each film-filter combination employs its own "collecting optics". Such a camera permits exploitation of the concept of multiband spectral reconnaissance throughout the visible and very near infrared parts of the electromagnetic spectrum (roughly 400 to 900 milli-microns). With it one can take simultaneous exposures of exactly the same area, using several spectral zones. By proper choice of photographic film and filter, the limits of each spectral zone can be controlled.

For both conventional cameras and multiband cameras, film transport mechanisms have been significantly improved. Through employment of a principle known as "forward motion compensation", the film can be made to travel, even during the instant of exposure, at a rate commensurate with the rate of travel of images at the focal plane, caused by the camera's forward motion as the aircraft or spacecraft flies along. By this means, sharper images can be obtained since the image of any particular feature is in effect "frozen" to the same spot on the film during the entire time that the exposure is being made. Such a refinement is necessary to minimize "image blur" when taking aerial photos of the earth's surface from high speed aircraft at low altitudes.

Even when space photography is being taken at earth-orbital altitudes (e.g., 100 to 200 miles), failure to compensate for forward motion could limit the sharpness of the image. Consider, for example, a large earth orbital reconnaissance satellite of the future equipped with a camera of long focal length, say 120 inches, and a lens-filter system capable of resolving detail as small as 100 line pairs per millimiter on the photographic negative. If the satellite were placed in orbit at the conventional altitude of 150 miles, photos taken from it of the earth below theoretically should "resolve" (show individually) features less than 3 feet in diameter (see Figure 16). However, if the vehicle were traveling at a conventional earth-orbital speed (e.g., 18,000 miles per hour or 25,000 feet per second) and the camera were to be set at a conventional shutter speed (e.g., 1/100 of a second), a distance of 250 feet would be traversed during the "instant" that the camera shutter was clicking. Hence, without forward motion compensation, each small feature photographed would be recorded on the film as a streak which (in terms of the corresponding ground distance) would be roughly 250 feet long. This situation obviously would be

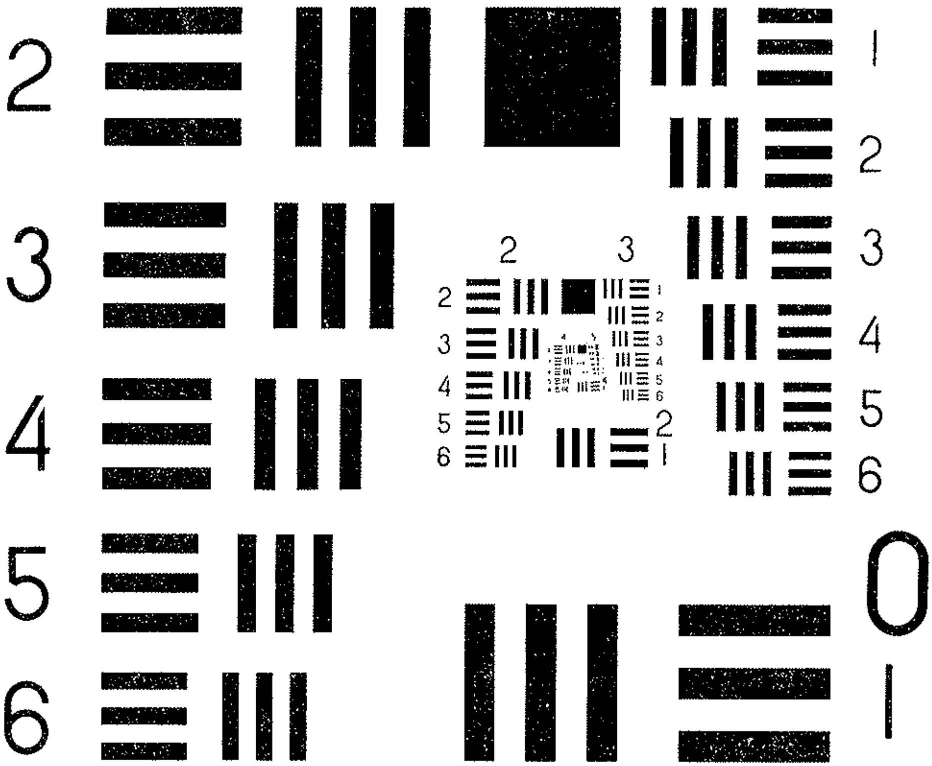


FIG. 16. A typical resolution target for use in determining the spatial resolution obtainable with any given photographic system. One measure of resolution is provided by determining, from photographs taken of a target such as this, the closest spacing of "line pairs" that can be resolved individually and expressing the result in "resolvable line-pairs per millimeter distance on the negative".

inconsistent with the objective of achieving 3-foot ground resolution. The remedy to such a problem is simply to impart a compensating amount of forward motion to the film during exposure. One device capable of accomplishing this important task consists of a light-sensitive scanner which measures the rate at which images of bright features on the landscape are traveling at the camera's focal plane, where the film is situated. The scanner in turn activates a servo-drive unit which can accelerate or decelerate the film's rate of transport to achieve the necessary forward motion compensation.

B. *Films for Recording Photographic Images.*

In all three of the devices described in the preceding section (viz., the conventional camera, the panoramic camera, and the multiband camera) images are formed on film that is placed directly in the focal plane of the "collecting optics" or lens system. Some rather delicate choices sometimes must be made in deciding exactly which of many black-and-white or color films will be used to record images when using such devices. It is primarily for this reason that an introductory paper such as mine would not be complete unless it gave a description of the various films which they can employ.

The first portion of this discussion deals with representative black-and-white panchromatic films currently being used to photograph areas in which the forest resources are to be inventoried. That discussion is followed by similar treatment of black-and-white infrared-sensitive films. Finally, there will be a discussion of various color films, some of which are sensitive only in the visible part of the spectrum while others are sensitive to the near-infrared part as well.

Several panchromatic, black-and-white aerial films that have been developed by Eastman Kodak are compared in Table 4. From this table it is apparent that photographic scientists continue to struggle with the

TABLE 4 - *Characteristics of Some Commonly-Used Panchromatic Aerial Films.*[a]

Name	Type	Resolution (line pairs/mm)[b]	Speed Relative to Type 3403	Granularity Values	Wratten No. 12 Filter Factor
High-definition aerial	3403	550	1	0.023	1.5
High-definition aerial	SO-243	440	1.2	0.016	1.6
Special fine-grain aerial	SO-190	180	3.7	—	1.5
Panatomic X aerial	3400	150	9.0	0.052	1.9
Plus X aerial	3401	100	33.0	0.088	1.7
Super XX aerial	5425	75	41.0	—	2.0

[a] Courtesy of Eastman Kodak Company.

[b] Average difference in target luminance 6.3 : 1.

inherent "trade-off" that exists between film speed and film definition as explained below.

On the one hand it is desirable, especially when taking aerial or space photography from unstable, fast-moving platforms, to use films of high speed. With such films one can obtain an adequate photographic exposure in a very short interval, thereby minimizing blur effects due to various kinds of image motion. But to achieve this high speed we must use a film that has large silver grains in the emulsion, so that only a few photons of energy will be needed to form the picture. These few photons, upon striking a given silver halide crystal, even if it is a large crystal, will produce sufficient "latent image nuclei" to raise the crystal's energy level above a critical point. Thereby, as explained in an earlier section, the crystal will become able to accept additional electrons when later placed in contact with a suitable developing agent. Consequently, during the film-developing process, the entire silver halide crystal can be reduced to opaque metallic silver and, because of its large size, can contribute substantially to the production of a negative of proper density.

On the other hand it is equally desirable when taking aerial or space photography (i.e., photography which is necessarily of small scale because of the great distance from camera to ground) to use films of high definition. With such films one can obtain very sharp edge gradients and perceive important photographic detail by viewing the image under suitably high magnification. To achieve this high definition, we must use a film that has very small silver grains in the emulsion, so that important details will not be blurred from view as indeed they are in a coarse-grained film. But the smaller the crystal size the larger the number of crystals required per unit area of emulsion. It is at this point that we must pay the price in terms of film speed, because as the crystal size decreases the number of photons required to activate the crystal does not decrease proportionately. Consequently, the finer the film grain, the larger the total number of photons required to produce a negative of suitably high density. In order that this large number of photons can be captured, the film must be given a longer exposure, i.e., the film is "slower". Because of this longer exposure, the resulting photograph is likely to suffer from blur effects caused by various kinds of image motion, such as vibration of the camera, forward motion, and changes in attitude of the camera-carrying vehicle.

The following conclusions are indicated by Table 4: (1) consistent with our discussion, there is an inverse correlation between film resolution and film speed, and (2) as evidenced by the filter factors for a traditionally used Wratten 12 ("minus blue") filter, the high definition films are slower (less sensitive to light — especially blue light). This fact partly accounts for their lower speeds, although a compensating factor is their extended red sensitivity.

As the term "panchromatic" implies, these films are about equally sensitive to all parts of the visible spectrum, although with some modification as indicated in the preceding paragraph. The human eye is "panchromatic" in the same sense. Consequently, the relative tones or brightness values of objects are essentially the same on panchromatic photography as those seen directly by the human eye. The resulting natural appearances of features may greatly facilitate their photo identification. Herein lies one of the primary advantages of black-and-white panchromatic photography as compared with black-and-white infrared photography for those wishing to interpret natural resource features on aerial photographs.

Infrared black-and-white aerial film is produced in the United States by only one company, Eastman Kodak. The spectral sensitivity of this film in terms of wavelengths of energy is from 0.36 to 0.90 microns. Consequently, to obtain pure infrared effects with it, the ultraviolet and visible wavelengths to which it is sensitive should be screened out by use of a Wratten 89B filter, or equivalent.

The resolution of Kodak Aerial Infrared Film (Type 8443) is only 55 line pairs per millimeter, but when aerial photographs must be taken on hazy days, or even on clear days but from very high altitudes, the superior haze penetration obtainable with this film may enable it to produce sharper images than could be otained with a nominally high-resolution panchromatic film.

As explained and diagrammed earlier in this paper, healthy broad-leaved vegetation has very high infrared reflectance and therefore photographs very light in tone on this film. When such vegetation becomes unhealthy (e.g., due to damage done by diseases, insects, drought, mineral deficiency or mineral toxicity), it is likely to undergo a loss in its ability to reflect infrared light, even before any other changes in its spectral behavior occur. Consequently, it is of more than passing interest to the natural resource manager that infrared photography may provide him with "previsual symptoms" of unhealthy conditions that are developing in the broadleaved vegetation within certain parts of a landscape that he seeks to evaluate. Conversely, if the broadleaved vegetation registers only in light tones on infrared photography, the resource manager can be reasonably sure that it is not suffering from *any* of these maladies.

Aerial color films are of three types: (1) natural color positive films, (2) natural color negative films, and (3) false color films. Each is potentially useful to the natural resource manager for specific purposes. However, the cost of obtaining such photography, when compared to that of black-and-white photography, is not always justified by the additional information it provides.

Natural color positive films are sensitized to three primary colors, blue, green, and red, and when exposed and processed produce transparencies which appear similar to the original scene when viewed by white light. Two such films that have been in common use are Kodak Ektachrome Aero (E-3 process) and Anscochrome D/200. The former has an ASA film speed of 160, and the latter of 200; both are capable of resolving approximately 100 line pairs per millimeter. Since the resource manager is accustomed to seeing and identifying objects, not only by their size, shape and association, but also by their color, such films give him one more important dimension for use in making his aerial photo identifications. For example, Heller *et al.* (1964) reported that the accuracies with which tree species could be identified were 17 percent higher on large scale color transparencies than on the same scale of panchromatic prints. According to Evans (1948) the human eye can separate over 100 times as many color combinations (based on hue, brightness and saturation) as gray scale values, although color films cannot discriminate as many colors as the human eye can see.

Natural color negative films have the dye coupler components incorporated in the emulsion layers at the time of manufacture. After the film has been developed and bleached, dye images remain that are not only negative to the tone gradations of the subject, but also complementary to colors of the scene photographed. From such negatives it is possible to make positive color prints and transparencies as well as black-and-white prints and transparencies, the latter of which are almost indistinguishable from those made using panchromatic negatives.

Cooper and Smith (1966) report that color prints made from a negative color film are somewhat lacking in color balance and have considerably poorer resolution than color transparencies. The color balance was found to be most deficient for blue and green objects, including vegetation. Until recently, aerial negative films were approximately three-fold slower than aerial positive films, a factor which sometimes further limited the resolution obtainable with them.

One recent development in color photography is the Kodak Aero-Neg system. The heart of this system is Kodak Ektachrome MS Aerographic Film (Estar Base), Type SO-151. Although this film is more commonly known as a reversal color film that can be processed to a positive transparency, it is now possible to process the film to a negative also. The aerial exposure index for this film when processed to a color negative is only 10, and this relatively slow speed may constitute the greatest limitation on its use from aircraft and spacecraft. However, it reportedly has higher resolution than other negative color films. The most thorough testing of this film to date has been done by various groups of Australian scientists, notably those of the Commonwealth Forestry and Timber Bureau. They find it has an unusually wide latitude of acceptable exposure and that, by proper filtering techniques at the time of printing, one can eliminate most of the adverse bluish cast and haze-related effects that usually plague high-altitude color photography.

False color films are those on which objects purposely are imaged with different colors from those they exhibit in nature. The purpose of the false color is to accentuate certain features and facilitate the making of certain distinctions, even at the expense of making features of lesser importance less interpretable. One such film is Kodak Infrared Aero (E-3 process) which also is referred to either as "Infrared Ektachrome" or as "Color Infrared" film. Since the film is normally exposed through a Wratten 12 filter, blue light does not contribute to formation of the image. The three dyes of this film respond to green, red and near-infrared wavelengths, respectively, with the net result that green objects (except vegetation which is also highly infrared reflective) appear blue; red objects appear green; and infrared-reflective objects (such as healthy vegetation) appear red.

Because of the unusual colors with which features are rendered on Infrared Ektachrome film, we would do well to describe the unique properties of this film. This is doubly important because image color is used to such an extent in identifying earth resource features on this type of photography. Consequently, unless the photo interpreter knows the spectral responses of the three-layer emulsion comprising that film, he is likely to make many erroneous interpretations of photography taken with it.

Infrared Ektachrome is known as a "subtractive reversal" color film. In such a film the dye response, when the film is processed, is inversely proportional to the exposures that were received by the respective emulsion layers. In devising Infrared Ektachrome film, the manufacturers had one major objective in mind — that of causing healthy vegetation to exhibit a strong photographic color contrast with respect to other features. More specifically, it was decided that a subtractive reversal photographic film should be devised on which healthy vegetation would appear bright red while everything else would appear in colors other than red. To accomplish this objective, it was necessary to exploit the fact that healthy vegetation exhibits very high infrared reflectance *and* relatively low reflectance of visible light. Thus, when the manufacturers were devising the three-layer emulsion of Infrared Ektachrome film, they linked a cyan dye to the infrar-sensitive layer of film, and they linked yellow and magenta dyes to the green- and red-sensitive layers, respectively. Although this film has undergone some modification since it was first produced during World War II as "Camouflage Detection Film", the foregoing is an accurate description of its present characteristics. Whatever blue-sensitivity exists in the three layers is rendered inconsequential through use of a "minus-blue" (Wratten 12 or 15) filter over the camera lens at the time of photography.

Consistent with the foregoing, and keeping in mind that the dye responses are inversely proportional to exposures received, the following responses occur in each area on Infrared Ektachrome film where healthy vegetation is imaged: (1) there is a great deal of yellow and magenta dye left in the film after processing, because the film was only weakly exposed to red and green wavelengths to which those dyes are linked; and (2) there is little cyan left in the film after processing because the film was strongly exposed by infrared wavelengths to which the dye is linked.

When the processed Infrared Ektachrome film, in transparency form, is viewed over a light table through which white light is shining (i.e., light which contains approximately equal amounts of blue, green and red), the following factors are operative in those parts of the transparency where healthy vegetation is imaged: (1) the concentration of yellow dye is so high that blue light is almost completely absorbed, (2) the concentration of cyan dye is so high that green light is almost completely absorbed, and (3) the concentration of magenta dye is so low that red light is completely transmitted. The net result of these factors is to cause the healthy vegetation to appear red. Since virtually no other features have this peculiar combination of spectral reflectances, there are no other features which appear red on the transparency.

Why then was the predecessor to this Infrared Color film (one known as "Camouflage Detection Film") used as early as World War II? Primarily it was used to differentiate green camouflage paint from green (but highly infrared-reflective) foliage. The two looked the same to the naked eye and on panchromatic or conventional color films, but conspicuously different on the Camouflage Detection Film — hence the name. Eastman Kodak Company (1963) reports that the new emulsion provides better resolution and is three times as fast as the old one. Because of its sensitivity to long wavelengths and the exclusion of short ones through use of a Wratten 12 filter, this film has the ability to penetrate haze exceptionally well.

A false color film containing only two dyes and known as "SN-2 spectrozonal film" is produced by Russian film makers. One layer of the emulsion responds to visible wavelengths of energy; the other to infrared wavelengths in the 0.7 to 0.9 micron region. During film development, color dyes are introduced into both layers to produce images in various colors.

Both of the above-mentioned false color films are of great potential interest to the resource manager. Some features of interest to him can be distinguished on photography taken in the visible part of the spectrum, but not on that taken in the infrared part; exactly the reverse is true for other features. These false color films combine in a single composite color image the possibility of distinguishing both types of features. The spectral responses of several color films being used in aerospace remote sensing are given in Table 5.

C. *The Color Video System.*

In an earlier section of this paper dealing with "Basic Considerations" the potential usefulness of color infrared (CIR) photography was discussed, particularly with reference to the early detection of loss of vigor in plants. Most of the *potential* advantage of this early-detection capability is lost at present because of time delays that are experienced in having the exposed CIR film specially processed and made available to the potential user of it. Additional difficulties have resulted up to the present time in keeping the film refrigerated, judging the proper film exposure to use in any given situation, and achieving a sufficiently uniform "color signature" to ensure that reliable photo interpretations of the CIR photography could be made.

All of these difficulties are reduced or eliminated through the recent

TABLE 5 - *Spectral Responses of Natural Color and Infrared-Sensitive Color Films.*

Type of film	Spectral region			
	Blue	Green	Red	Infrared
Normal color film (e.g. Ektachrome):				
Normal color film sensitivities	Blue	Green	Red	
Color of dye layers	Yellow	Magenta	Cyan	
Resulting color in photographs	Blue	Green	Red	
Infrared sensitive color film (e.g., Infrared Ektachrome):				
Sensitivities with Wratten 15 yellow filter	([a])	Green	Red	Infrared
Color of dye layers		Yellow	Magenta	Cyan
Resulting color in photographs		Blue	Green	Red

[a] All three layers of Infrared Ektachrome film are sensitive to blue light, but the Wratten 15 yellow filter prohibits blue light from striking, and thus sensitizing, any of the three layers.

development of a color infrared video system known as "Biovision", developed in the United States by Douglas Meisner of the University of Minnesota Remote Sensing Laboratory. The Biovision camera generates a standard video signal, compatible with off-the-shelf monitors, recorded on tape. Through the use of an optical beamsplitter for spectral separation, the system provides precise spectral bands that are similar in wavelength range, but more sharply defined than those employed in CIR photography. The blue, green and red phosphors of a closed-circuit color television screen are used to provide the color composite image that heretofore had been obtained only through use of the corresponding dyes in CIR film. Exposure can be adjusted interactively by the operator of the system during image acquisition, ensuring optimum results. The image, as displayed on the TV monitor, also permits the aircraft pilot to navigate accurately, thereby ensuring that the desired area is, indeed, the one that is being imaged during the overflight. In addition to the instantaneous visual display on the TV monitor, the multiband data can be recorded in digital form indicative of "scene brightness", thereby facilitating computer analysis of the data. Since the device is compact (108 × 188 × 298 mm), light weight (3.5 kg) and low in power consumption (12W [1A, 12v]) it is well suited to use in even a light aircraft.

It is probable that the above combination of advantages would make the system especially useful in developing countries. An additional advantage is the system's low operational cost. Biovision uses standard, reuseable tapes, costing approximately $10 (U.S.) for two hours of data.

D. *Other Kinds of Remote Sensing Devices.*

At present there are four major types of remote sensing devices (in addition to the aerospace cameras that have just been described) that are used in remote sensing from aerospace. These are (1) the optical mechanical scanner or "line scanner" (whose principles are employed in the Landsat MSS and TM sensor systems and especially in thermal infrared-sensing devices), (2) the linear array or "pushbroom" imager used in the SPOT Image System, (3) frame scanners, and (4) side-looking airborne radar devices (i.e., SLAR equipment).

1. *The optical mechanical scanner.* In an optical mechanical scanning system, the "collecting optics" is in the form of a mirror, or series of mirrors, rather than a lens. When multiband reconnaissance must include sensing in the *thermal* infrared region, the optical mechanical scanner can provide photo-like images, whereas cameras of the types previously described cannot.

There are two reasons why reflective optics rather than refractive optics are used in an optical mechanical scanner, both related to problems of sensing in the thermal infrared portion of the spectrum:

a. relatively few materials can instantaneously transmit energy in any part of the thermal infrared region, and even fewer over the very wide range of wavelengths for which thermal infrared scanning is desired; and

b. refracting lens systems as previously indicated are unable to sharply focus, in a single focal plane, all radiant energy from a wide spectral band (i.e., one that encompasses a very wide wavelength range, such as the thermal infrared).

Both difficulties are overcome through the use of first-surface mirrors as reflecting optics.

An additional problem prevents the obtaining of thermal infrared imagery with a camera of conventional design. This problem pertains to the recording of images in photo-like form. Thermal infrared sensitive materials can be produced that are similar to the light-sensitive silver halides of a photographic film. However, if such materials are made to respond at ambient (environmental) temperatures, how can they be kept from becoming fogged due to gradual exposure, even as they repose, ready for use, inside the thermal infrared camera? Even the interior of such a camera (the portion facing the film) is continuously emitting thermal energy. Therefore, just as the conventional camera must be a "light-tight box" if it is to prevent light-sensitive film from fogging, so a thermal camera would have to have a "heat-tight box" if it were to prevent heat-sensitive film from fogging. In fact, the box would have to be cooled to a temperature of nearly absolute zero. Even if the required temperature could be achieved for such a sizeable structure, the weight and volume requirements for the cooling equipment required to maintain the system at this low temperature would prohibit its use in most aircraft or spacecraft. Furthermore, at such low temperatures additional problems would be entailed because of brittleness of both the film and certain camera components.

The solution which modern science has devised for the problem just described is the optical mechanical scanner diagrammed in Figure 17. This device consists essentially of three parts: (1) the energy collector system, (2) the detecting mechanism, and (3) the recorder.

The design of the energy collector reflects the fact that no satisfactory means has yet been found (when working with thermal infrared wavelengths) for simultaneously imaging separate elements in a wide angular field, the way a conventional camera does. Instead, it is necessary to focus on one small element at a time, and the size of this small "instantaneous field of view" determines the pictorial resolution.

All of the photons collected by the scanner within its instantaneous field of view are focused on the detector, eventually to form a picture element or pixel. There they generate an electric charge. As best seen in the top and bottom-left versions of Figure 17, the greater the energy being emitted within the field of view, the greater the charge or signal that is generated. This signal is then used to modulate a visible-light source such as one "instantaneous element" of a cathode ray tube. The output signal is made to scan the cathode ray tube in the same pattern as the collecting optics scanned the scene beneath the aircraft. The mirror of the collecting optics rotates on the axis that is parallel to the flight line and thus scans a line that is lateral to the flight line. The mirror looks at only one small portion of the terrain at any given instant, and the beam collected illuminates only a corresponding small spot (i.e., picture element or pixel) on the cathode ray tube and, correspondingly, on the

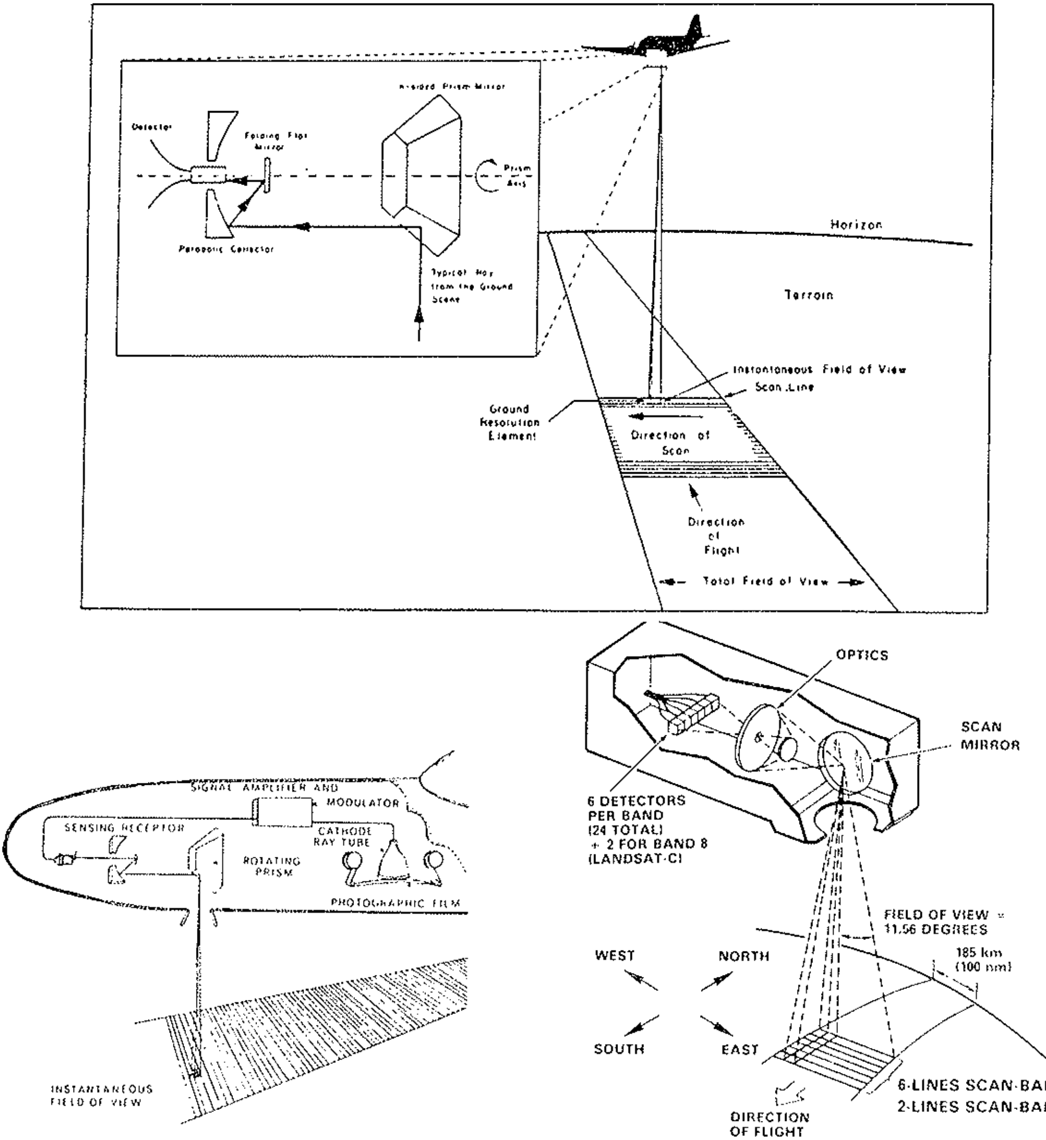


FIG. 17. Construction and mode of operation of an optical mechanical scanner, sometimes referred to as a "line scanner". The *bottom* left diagram has been included to indicate how the scanner can expose photographic film, line-by-line, while in flight. The *bottom right* diagram shows relevant details of one particular optical-mechanical scanner, viz., the Landsat multispectral scanner (MSS), as diagrammed by Short (1982).

photographic film placed in front of the tube (Figure 17), at the same instant. By the time one *swath* has been painted, pixel-by-pixel, on the film, two events have occurred: (1) the reconnaissance vehicle has advanced sufficiently so that the next of a series of companion mirrors, mounted in other positions on the same rotating shaft, begins to look at the next contiguous swath of terrain; and (2) each piece of film in the multiband installation has advanced sufficiently in its focal plane so that this next swath is painted on the film in proper juxtaposition to the first swath. The density of each portion of the exposed film is in direct proportion to the strength of the infrared signal coming from the corresponding terrain. Hence, as the aircraft advances, the film advances and a continuous photo-like image (thermogram) is formed.

2. *The Linear Array or "Pushbroom Imager"*. As shown in Figure 18, this sensor uses a wide-angle optics system in which all of any given line (i.e., a line encompassing the swath that is being covered) is imaged

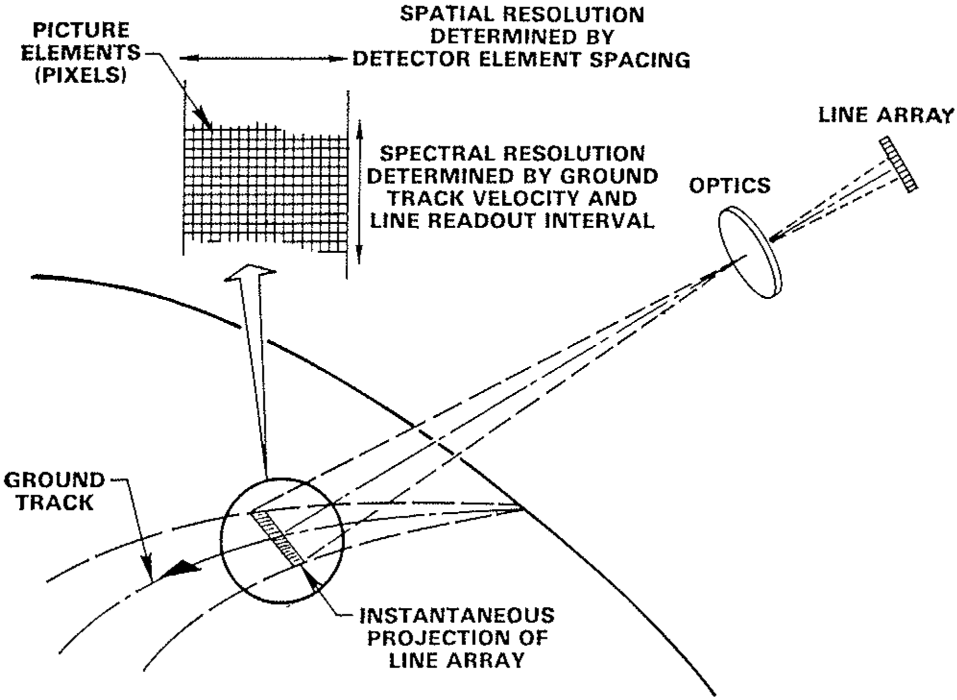


FIG. 18. Schematic diagram showing the general characteristics of a pushbroom imaging sensor (Short, 1982).

on a detector array *at one time*. In the simplest type of array, the signal from each detector is amplified separately and the individual output signals are usually sampled sequentially to provide a serial representation of the line of transmission from a remote location. As the platform moves along the track, successive lines are imaged by the array and sampled by the multiplexer for transmission. Since forward progress is made line-by-line, but not through pixel-by-pixel scanning in succession within the line, the linear array has been aptly termed a "pushbroom imager". More advanced arrays and processors permit the signals to be shifted out of parallel and processed sequentially.

The time that elapses between the imaging of two successive lines can be as long as the platform takes to move (parallel to the line of flight) the width of the swath that is being imaged. This dwell time is relatively long compared to that of the mechanical scanner that has just been described and represents the primary advantage of the pushbroom sensor in that a long dwell time leads to low noise in the signal. The other attractive feature of the pushbroom sensor is that no moving parts are required when it is operated from a moving platform.

The primary disadvantage is that a very large number of detectors is involved, which means that calibration is difficult and signal level correction represents a real data processing burden. The pushbroom technology is new and it can be expected that these disadvantages can be reduced in importance with future array development and sophisticated signal processing.

3. *The Frame Sensor*. The earliest frame sensors grew out of the television industry and provided the basis for the vidicons that were adapted for imaging the moon and Mars. In such sensors, photosensitive tubes with electron-beam scanning are located at the focus of wide-angle optics. Sensors mounted on moving platforms are equipped with shutters to prevent image blur and to control exposure time.

Photosensitive surfaces previously were restricted to the visible region of the spectrum, which meant that (1) small-sized optics could be used without encountering diffraction problems, and (2) exposure times could be sufficiently long to ensure the receiving of a good signal. The number of resolution elements remained at 500 to 1000 on a side until the development of the return beam vidicon (RBV), which is capable of sensing over 3000 elements on a side. The RBV has been used successfully as a high-resolution, multiband, earth-mapping device on Landsat.

Optics are designed to be compatible with an angular resolution of 33 microradians.

Two-dimensional arrays of detectors are improving to the point where they can be expected to supplant tubes. Just as the pushbroom simultaneously senses all of the pixels comprising an entire line, so the two-dimensional detector array would simultaneously sense all of the pixels in all of the lines comprising an entire frame of imagery. Two-dimensional arrays will offer a frame format with the advantages of extended spectral coverage, long life, and elimination of high voltage. Work is continuing to make arrays with detectors that are more nearly contiguous in both dimensions and to reduce the number of separate preamplifiers by shifting signals out of the entire array simultaneously for immediate multiplexing. The arrays, by providing "single point perspective" for an entire frame of imagery, have a potential for geometric accuracy which is superior to electron-beam devices. These sensors are best suited for imaging applications in single spectral bands with modest requirements on radiometric accuracy.

Table 6 lists the relative advantages of the three basic sensor systems that have just been discussed. It is based on a compilation by Short (1982).

4. *The Side-looking Airborne Radar Device* (*SLAR*). Because of its all-weather, day-and-night capability, and its ability even to penetrate the vegetation canopy and sense the terrain beneath, radar equipment is of great interest to those who seek to inventory natural resources by means of remote sensing. However, radar devices operate at much longer wavelengths than any of the equipment previously described. Consequently, difficulties arise in acquiring high resolution imagery with such devices because, as with any diffraction-limited system, the longer the wavelength the poorer the resolution.

Radar imagery can be acquired by either "brute force" or "synthetic aperture" means. When "brute force" means are applied, a transmitting antenna in the reconnaissance aircraft sends out a short pulse of microwave energy to one side of the aircraft and thus illuminates the roughly circular lobe on which points "A" and "B" have been annotated in Figure 19. This lobe corresponds to the instantaneous field of view in a "diffraction limited" radar system.

A receiving antenna mounted in the same aircraft collects energy reflected back from the illuminated terrain. The greater the distance from aircraft to target, the greater the time delay in return of the reflected signal. Through accurate measurement of the time delay, it is possible for this equipment to differentiate returns from various small concentric

TABLE 6 - *A Comparison of Three Optical-Mechanical Sensor Types.*

	Frame	Pushbroom (Linear Arrays)	Mechanical Scanner (Object Plane)
Optics Required	Wide angle, both dimensions	Wide angle, one dimension	On-axis
Sensitivity	Longest dwell-time	Next longest dwell-time	Most restricted dwell-time
Stereo Viewing	Good	Good	Adequate
Effect of Platform Instability	Least susceptible	Less susceptible	Most susceptible
Multispectral Use	Poor	Registration restricted by array* accuracy. Restricted space. Cooling load high.	Most suitable
IR Capability	Very limited *	Cooling load high	Cooling load modest
Radiometric Calibration	Very difficult	Difficult*	Least difficult
Geometric Accuracy	Poor for electron-beam devices. Detector arrays have good potential	Limited by array technology	Very high precision possible (1μ rad) (represents mature technology)
Number of Resolution Elements Covered in Scene	Limited by array size and optics *	Limited by array length and optics*	Unlimited

* Improvement is expected with technology advances.

"rings". Each ring represents the locus of all points (within the illuminated circle) that are roughly equidistant from the aircraft. Within any ring there is a spot, just opposite the aircraft, that moves along at the same speed as the aircraft. At any given time the distance from the aircraft to all *other* points on the ring is either increasing or decreasing. Consequently, through the Doppler effect the microwave energy reflected back to the aircraft from these other points is of a different frequency than that which had been transmitted to them by the radar pulse. The radar receiver is designed to accept the wavelengths (and associated frequencies) that correspond to those of the initial pulse, but to reject those that are significantly different.

Because of the two discriminating features just described, the only energy accepted by the radar receiver at any given instant is that which

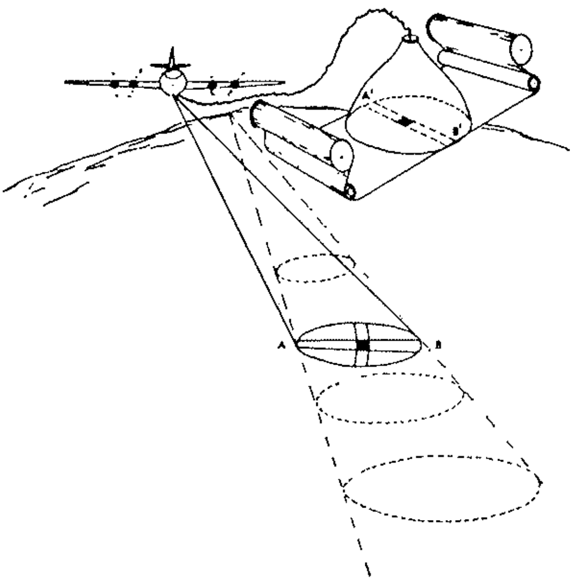


FIG. 19. Diagrammatic portrayal of Side Looking Airborne Radar (SLAR) imaging equipment. When a pulse or "chirp" emanates from the radar transmitter aboard the aircraft, it illuminates an area such as that encircled between "A" and "B". The arc shown here, midway between "A" and "B", constitutes a "resolution cell" roughly parallel to the line of flight, and is achieved by discriminating between the "time delays" as the reflected radar signals return to a radar receiving antenna aboard the aircraft. The narrow strip extending between "A" and "B", perpendicular to the aircraft's line of flight, constitutes a "resolution cell" within the arc. It is discriminated from cells fore and aft of it through use of the Doppler principle. The dark square marking the intersection of these two resolution cells is the "smallest resolvable detail" offered by the system.

satisfies two conditions: (1) it is in the narrow ring within which time delay is such that the energy is at that instant striking the receiving antenna, and (2) it is in that particular part of this ring which is directly opposite the aircraft (the area having zero relative velocity with respect to the aircraft and therefore exhibiting no Doppler frequency shift). The combination of these factors effectively provides a spatial resolution of the system that is adequate for the identification and mapping of most of the important earth resource features.

In order to record this accepted energy in photo-like form, two other radar components are used: a cathode ray tube and a roll of photographic film (Figure 19). The strength of the signal determines the brightness of a dot. The position of this spot on the cathode ray tube is changed synchronously with the antenna scan. Thus, for any given scan line, the signal that first returns is that from the inner edge of the illuminated area and is imaged at the bottom of the cathode ray tube. By the time the signal is returning from the farthest point illuminated, the spot on the tube has moved all the way from the bottom to the top of the corresponding narrow swath that is being imaged on the film. Photographic film which (as in the optical mechanical scanner) is in juxtaposition to the tube is exposed by this means, one line at a time. By the time the next pulse is transmitted, the film has advanced slightly and so has the aircraft. The density on each portion of the exposed film is in proportion to the brightness of the radar signal coming from the corresponding spot on the terrain. As the aircraft advances, the film advances and thus a continuous photo-like record of the terrain is produced (see Figure 19).

When a "synthetic aperture" type of radar is used, the signals returned from a large number of pulses are stored in some sort of computer memory, care being taken to retain phase as well as amplitude information. The signals in the memory are then processed in the same way that a much larger antenna would process them. For example, all the pulses transmitted during 1000 feet of flight may be combined to give a resolution cell of the same size as that theoretically achievable with an antenna 2000 feet long. Thus, although the real antenna might only be three to six feet long, the synthetic antenna is 2000 feet long. Since the resolving power of the system increases with the (effective) diameter of the antenna, this synthetic antenna (i.e., the "synthetic aperture" technique) can greatly improve the spatial resolution of the radar system. An example of the excellent radar image quality that was achieved by the Seasat SAR device appears in Figure 20.

Although the four devices which have just been described are the primary ones used for imaging the terrain, certain others are in the process of being developed. One of these is the passive microwave sensor (in contrast with radar which is an active microwave sensor), which relies on thermal differences emanating from the terrain itself. Because of the long wavelengths which it employs, it can produce a discernible image of a fire even through dense smoke and clouds.

E. *Kinds of Aerospace Vehicles Used as Remote Sensing Platforms.*

The following categories of vehicles are recognized: (1) fixed-wing aircraft, (2) rotary-wing aircraft, (3) lighter-than-air craft, (4) unmanned

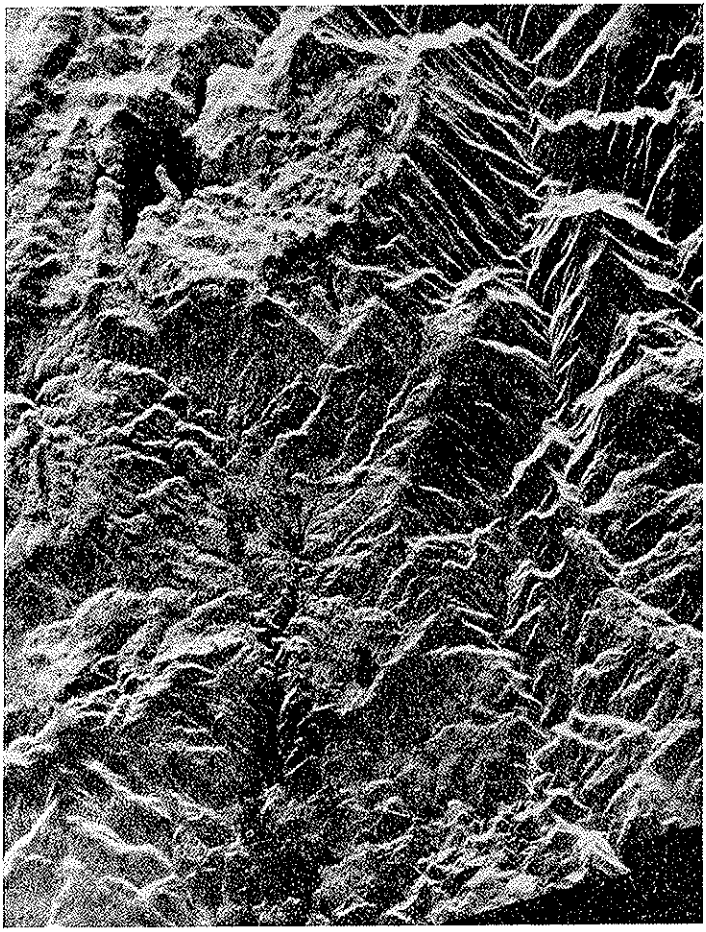


FIG. 20. Seasat SAR (Synthetic Aperture Radar) imagery of a wildland area, acquired from an altitude of 570 miles. It not only accentuates topographic features but also exhibits remarkably high spatial resolution for many features, including lakes and dark-toned marshy meadows. (Courtesy of NASA).

satellites which electronically transmit remote sensing data back to earth, (5) unmanned satellites equipped with film-recovery capsules that can be "air-snatched", and (6) manned satellites in which the exposed film and other remote sensing data can be returned to earth with the astronauts, (e.g., Gemini, Apollo, and Shuttle).

F. *Present Status of the U.S. Landsat Program.*

According to Short (1982) there is general agreement among earth resources specialists that Landsats are among the most sophisticated and productive satellites ever orbited. In order to appreciate the present status of the Landsat program, a brief historical review of that program and its precursor, the Gemini, Apollo and Skylab programs, is in order. The following review is based on material supplied by Short (1982) together with direct observations of the present writer as a NASA-funded investigator for remote sensing-related aspects of the Gemini, Apollo, Skylab and Landsat programs.

The NASA program of land remote sensing from space arose with the Gemini program, which obtained pictures of the earth with geological and agricultural significance. It was given an impetus by Project Apollo, the U.S. effort to land men on the moon. A crucial element of this effort involved the selection of landing sites on the moon, and for this purpose NASA undertook a precursor project called "Lunar Orbiter", in which five satellites orbited the moon (in 1966-67) and sent back thousands of pictures of the lunar surface. The instruments used in the Lunar Orbiter were first tested over terrestrial sites that simulated the lunar landscape, and the photographs thus obtained were compared with actual measurements on the ground (ground truth).

It soon became apparent that the photographs could be useful in studying geology and in mineral exploration on earth. The interest spread to other disciplines that could benefit from remote observation of the earth — i.e., agriculture, forestry, hydrology, cartography, coast and geodetic surveys, and urban planning. This interest led to the establishment of an earth resources survey program, sponsored by NASA and assisted by experimenters in universities and elsewhere. It also led eventually to the publication of three NASA Summary Volumes (National Aeronautics and Space Administration, 1971, 1973, 1976).

The first satellite devoted primarily to observing the land areas of the earth was named Earth Resources Technology Satellite-1 (ERTS-1). It was launched July 23, 1972, into a near-polar circular orbit of about 900 km altitude. Except for circumpolar latitudes of approximately 81° to 90° in both the northern and southern hemispheres, this orbit potentially gave complete coverage of the earth with a repeat cycle of 18 days. The satellite carried two observing instruments, one called the Return Beam Vidicon (RBV) and the other, the Multispectral Scanner (MSS). Both instruments were focused to observe a strip 115 miles wide as the satellite moved over the earth. The RBV was a set of three television cameras aligned to observe the same scene. The cameras carried different filters that determined the three spectral bands of the instrument — i.e., blue-green, yellow-red, and near-infrared bands. Thus, for each scene, the RBV produced three 185 × 185-km pictures (one in each band) with a ground resolution of 80 m.*

The central feature of the MSS was a mirror that oscillated in a plane perpendicular to the path of the satellite, thus continuously sweeping across the 185-km-wide ground track. At any given instant during the scanning process, the mirror focused the image (i.e., the "pixel") of a small segment of the earth on a set of photoelectric sensors with different spectral responses. For the first MSS, there were four bands, two in the visible region and two in the infrared.

After operating successfully for the first four weeks the RBV failed, but the MSS continued to operate for 5½ years (far beyond its expected lifetime), and it became the primary source of Landsat data. ERTS-1, later named Landsat-1, was the first of five Landsat satellites, of which the principal characteristics are given in Table 7, compiled by Short (1982).

Landsat 2, similar to Landsat 1, was launched January 22, 1975, and did not cease operation until February 1982. Changes were made in Landsat 3, which was launched March 5, 1978, and operated until March 1983. A fifth band in the thermal infrared was added to the MSS, but this band did not operate properly. The RBV was redesigned to use two identical cameras that were aligned to simultaneously view adjacent 84-km-square ground segments, thus increasing resolution by a factor of two above the previous MSS and RBV instruments.

For all Landsats, data were transmitted directly to a ground receiving station when the satellite was within range of one. When the satellite was not within range of a ground station, the instruments were turned on and the data recorded on magnetic tape, within the satellite, in accordance with commands that had been sent to the satellite by radio.

On the ground, the data were corrected for radiometric and geometric errors and then converted by an analog electro-optical system to photographic scenes 185 km square. This was a slow, time-consuming process, and it delayed the availability of data to ultimate users. NASA distributed Landsat data to its associated experimenters; a broader distribution was

(*) This expression of ground resolution (i.e., spatial resolution) is based on the concept portrayed in Figure 16.

TABLE 7 - *Characteristics of Data Acquired by Landsats 1 through 5.*

Landsat	Year	Sensor[1]	Approximate Resolution	Bands	Bits/Pixel[2]
1	1972	MSS	80 m	4	6
		RBV	80 m	3	
2	1975	MSS	80 m	4	6
		RBV	80 m	3	
3	1978	MSS	80 m	5[3]	6
		RBV	40 m	1	
4	1982	TM	30 m	7	8
		MSS	80 m	4	
5	1984	TM	30 m	7	8
		MSS	80 m	4	

[1] MSS = Multispectral Scanner; RBV = Return Beam Vidicon; TM = Thematic Mapper.
[2] Pixel = Picture Element.
[3] IR Band 5 did not work.

provided by the Department of the Interior's Geological Survey. USGS established an EROS (Earth Resources Observation System) data center in Sioux Falls, South Dakota, that made data available to all customers for the cost of reproduction.

During the first decade of operation (1972-1982), and prior to Landsat 4, the data had three principal limitations:

1. The spatial resolution was inadequate for some uses such as cartography, urban planning, and some agricultural studies. However, for other uses such as hydrology, coastal studies, and mineral exploration, the resolution was not of prime concern.

2. The choice of spectral bands was not optimum for some of the users because the choice had been a compromise among the needs of many users.

3. For most users, the time delay in availability of the data was a serious handicap. For example, in crop forecasting, especially during the growing season, prompt availability of data (within a few days) is critical. On the other hand, for geological studies, as in exploration for oil, timeliness is important only as a competitive element and has little relation to the utility of the data for analytical purposes.

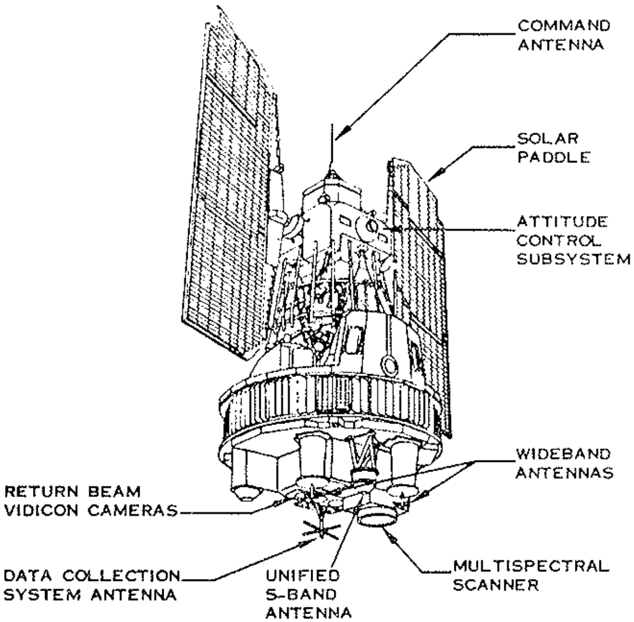


FIG. 21. The unmanned Landsat spacecraft digitally telemeters its remote sensing data (as acquired by a multispectral scanner, return beam vidicon, and/or more recently a thematic mapper) to a receiving station on the ground, where it can be stored on tape. Subsequent playback of the digital tape permits a photo-like image to be produced in each wavelength band that has been sensed, as explained in the text. The Landsat-1 spacecraft is approximately 10-feet tall and weighs one ton, including instruments. This schematic shows the control and sensor systems on Landsat-1. (NASA photos from Short, 1982).

For more than a decade the operation of Landsat, albeit in an experimental mode, created a new enterprise with at least a score of uses and hundreds of users in industry, in universities, and in federal, state, and local governments. NASA established educational facilities at several of its centers, principally at Goddard in Washington, Johnson in Houston, and MFT in Bay St. Louis, Mississippi, where potential users could come and be trained in the interpretation of Landsat data, using actual scenes, computers, and display equipment.

NASA attempted to interest federal agencies in the use of Landsat data as a way of improving the conduct of their normal functions. The U.S. Department of Agriculture (USDA) is responsible for crop forecasting both within the United States and worldwide. Starting in 1974, NASA, NOAA, and USDA undertook to use Landsat and other satellite data to predict the world wheat crop, especially the production of the Soviet Union, in a program called LACIE (Large Area Crop Inventory Experiment). Several years later, USDA, NASA, and NOAA combined in a long-term program called AgRISTARS (Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing) to extend the use of satellite data to other crops and to use it regularly in the United States. For example, the wheat, corn, and soybean production for seven states (Illinois, Iowa, Missouri, Kansas, Arkansas, Oklahoma, and Colorado) is forecast in this way.

Landsat 4 was launched July 16, 1982, and initiated a significant improvement in the quality of Landsat data. The RBV was abandoned and a new instrument, the Thematic Mapper (TM), commenced operation on an experimental basis. The TM was a considerably improved MSS. It had seven spectral bands (rather than the previous four). As in the MSS, the TM employed an oscillating mirror which (for TM) scans in both directions, making possible an improved resolution (30 m instead of 80 m) for six of the seven spectral bands (all except the thermal IR band, for which the resolution was 120 m). Landsat 4 carried a four-channel MSS to provide continuity of MSS data as a backup to the TM.

Although the superior quality of the TM data was recognized by many users, the data was not readily available because development of the ground processing system had not kept pace with the satellite-borne instrument. Landsat 4 was plagued with difficulties. Within months after launch, the X-band communications failed and limited the amount of TM data available. Then cables to two of the four solar panels separated, thus reducing power and limiting operations to one instrument at a time, either TM or MSS. The difficulties with Landsat 4 led to an early decision to expedite the launching of a replacement, Landsat 5.

Landsat 5 (containing the same instruments as Landsat 4 — MSS and TM) was launched March 1, 1984, and soon became the primary operational source of data. Since that time, it has experienced one transponder failure but it is presently operating at full capacity. The expected demise for Landsat 5 is December 1987, although it will be several months after this time when the back-log of processing has been completed. Landsat 5 is now the only U.S. earth resource satellite in operation.

Between 1979 and 1982 the responsibility for the operation of Landsat was gradually transferred to NOAA, in the Department of Commerce. At first NOAA was given responsibility only for the MSS operations, since the TM was considered experimental until 1984, when NOAA also assumed responsibility for the TM. Responsibility for Landsat data handling at the EROS data center in Sioux Falls, South Dakota, was also transferred, and NOAA was ordered to recover full operating costs through the sale of data, a result that was never achieved. NOAA increased the costs of MSS data by a factor of three, but sales fell off by the same factor, so that the revenue remained about the same. However, NOAA did actively prosecute the licensing of foreign stations and brought the total to ten: Argentina, Australia, Brazil, Canada, European Space Agency (2 stations), India, Japan, South Africa, and Thailand.

Commercialization of the U.S. Landsat program was formalized on September 27, 1985, with a contract authorized by the U.S. government. That contract was awarded to the Earth Observation Satellite Corporation (EOSAT), a joint venture/partnership formed by Hughes Aircraft Company and RCA corporation. In addition to the two principal partners, two other companies participate as major subcontractors: the Computer Science Corporation, a long-time provider of space program and Landsat operations software, and the Earth Satellite Corporation, a leader in making practical applications of satellite-acquired remote sensing data. Under the above-mentioned contract, (1) the U.S. government has provided EOSAT with a subsidy of $295 million for the construction and launch of two new satellites (Landsat 6 and 7), and (2) EOSAT operates the two Landsats presently in orbit (Landsats 4 and 5), manages the ground control equipment, and sells the pictures to customers. Further details are provided in a recent articles by Large (1986) and by Coyote Enterprises, Inc. (1986 a,b).

To succeed Landsat 5, original plans called for the timely launch of Landsats 6 and 7, each regarded as five-year life-on-orbit vehicles using proven components from the Advanced Thermal Infrared Observation System (known as TIROS-N) and the Defense Meteorological Satellite Program (DMSP). At present, however, EOSAT is developing a 20-year flexible platform, OMNISTAR, designed to be routinely and fully serviceable from the U.S. space shuttle. Since the OMNISTAR concept allows for on-orbit upgrades, EOSAT will be able to incorporate new sensor technology as it becomes available, with the economic benefits of a single space platform. Nominally, OMNISTAR will be available over a 20-year period as opposed to three or four satellites that would be required to support traditional land-remote sensing missions over the same time period if single-mission, single-use satellites were to be employed as originally planned.

In order to preclude a possible data-acquisition gap between the demise of Landsat 5 and the operation of Landsat 6 (scheduled for launch in December, 1988) EOSAT is planning to support the user community as follows: it will, if necessary, obtain data from alternate sources (such as SPOT Image, as described in the next section) and process and manage such data to the extent necessary. The use of OMNISTAR is not expected to change the Landsat launch schedule. Recent difficulties with NASA's shuttle program, however, may.

OMNISTAR will also allow EOSAT to offer an extended remote sensing capability, because its payload design will provide capacity for flying other sensors such as a wide-field-of-view moderate resolution scanner and an Ocean Color Scanner. These packages can be added to either the Landsat 6 Enhanced Thematic Mapper (ETM) with a 15-meter panchromatic band, or to the multiband thermal infrared channels that are planned as an option for Landsat 7. EOSAT is continuing to evaluate the possibility of a multispectral linear array design.

The Landsat/OMNISTAR program of the future is regarded as complementary to, rather than competitive with the SPOT Image system (described in the next section) although their products will, of course, compete with each other to some extent for available user money. Near the end of this decade, significant competition is also expected from the Japanese, the European Space Agency, and the Canadian Radarsat programs.

EOSAT's administrators are mindful of the "Open Skies" doctrine, which was originally espoused by the United Nations in the late 1960's. This policy outlines the rights under which a country can collect data over another country. It is designed to ensure the non-discriminatory aspects for the collection, availability and dissemination of satellite-acquired remote sensing data.

G. *Present Status of the French SPOT Image Program.*

SPOT (the acronym for Système Probatoire d'Observation de le Terre) is a project of the French government conducted through the Centre National d'Etudes Spatiales (CNES). SPOT 1, the first of a series of satellites under this project, was successfully launched from a French Guiana site on February 21, 1986.

According to Gilbert Weill, President of SPOT Image Corporation, "This launch marks the commercial beginning of the satellite remote sensing industry. While earth observation by satellite is not new, the attributes of SPOT make that technology available to commercial users on a worldwide basis for the first time". SPOT Image Corporation intends to enter into commercial agreements with primary customers quickly, in order to begin fulfilling requests for data promptly, now that the system has been pronounced operational.

Compared to Landsat (Table 7), SPOT reportedly offers three new features to the remote sensing user community: higher spatial-resolution data, stereoscopic viewing, and more rapid revisit time. As indicated in Table 8, SPOT data will provide 20-meter resolution in the multispectral mode and 10-meter resolution in the panchromatic mode. Studies that have been conducted on *simulated* SPOT imagery since 1980 have indicated that there is a great potential use for SPOT data in virtually all of the major areas that use remote sensing-derived information (see Table 2). A summary of the simulation studies that were made on test sites in the United States will be found in the August, 1985, issue of Photogrammetric Engineering and Remote Sensing.

Currently the SPOT Image Corporation is mounting a program known as SPOT PEPS (Preliminary Evaluation Program for SPOT). Unlike its predecessor, this evaluation program is based on actual rather than simulated SPOT data. It is providing certain remote sensing scientists with coverage of selected test sites in the United States, Europe and elsewhere for the purpose of determining the usefulness of SPOT-acquired imagery and digital data for the inventory, monitoring and management of natural resources throughout the globe.

Much earlier in this paper (Section III 0) it was stated that the three major types into which virtually every portion of the landscape can be divided are wildland, agricultural and urban/suburban; also that the next more refined categorization ordinarily distinguishes six categories in each of these three types. In terms of these 18 categories, SPOT was not found to be significantly more interpretable than Landsat TM imagery, (despite the higher spatial resolution of the former) in tests conducted by the present writer. This statement applies to his tests on both the *simulated* and the *actual* SPOT imagery. All of his tests were conducted on two NASA Test Sites in California: (1) the Bucks Lake Test Site in California's Sierra Nevada mountains, and (2) the Davis Test Site in California's Great Central Valley. Although SPOT had a greater stereoscopic capability and also a more frequent revisit capability than Landsat, these studies indicated that essentially the same amount of second stage sampling (with large scale aerial photos) and third stage sampling (with direct on-site inspection) was needed with SPOT as with the Landsat MSS system when the objective was to provide reasonably complete and accurate classification of the entire Landscape into these 18 categories.

H. *Sensor Systems that Facilitate making Macro Inventories.*

A macro inventory is one that covers a very large geographic area but usually with less accuracy and less detail than will be found in the resource inventories of smaller areas.

A recent article by J.E. Colwell and D.R. Hicks (1985) discusses some of the demonstrated and potential uses of satellite-acquired remote sensing data obtained through the use of devices that offer wide fields of view and a high frequency of coverage. Among these are the NOAA AVHRR (Advanced Very High Resolution Radiometer) and the Nimbus 7 CZCS (Coastal Zone Color Scanner). Pertinent characteristics of these sensor

TABLE 8 - *Principal Characteristics of the Spot Sensor System.*

Orbit	— Circular at 832 km — Inclination: 98.7 degrees — Descending node at 10 : 30 a.m. — Orbital cycle: 26 days
High Resolution Visible	— Two identical instruments — Pointing capability: + 27 degrees East or West of the Orbital plane — Ground swath: 60 km each at vertical incidence — Pixel size: • 10 m in panchromatic mode • 20 m in multispectral mode — Spectral channels: • panchromatic: .51 to .73 μm • multispectral: .50 to .59 μm .61 to .68 μm .79 to .89 μm
Image Transmission	— Two on-board recorders with 22 minute capacity each — Direct broadcast at 8 GHz (50 Mbits/sec)
Weight	— 1750 kg
Size	— 2 x 2 x 3.5 m plus solar panel (9 m)

TABLE 9 - *Principal Characteristics of the CZCS, AVHRR and MSS Sensor Systems.*

	CZCS[a] Nimbus 7	AVHRR[b] NOAA 6	NOAA 7	MSS[c] Landsat 1-3	Landsat 4, 5
No. of visible/near IR bands	5	2	2	4	4
Orbit altitude	955 km	850 km	850 km	920 km	705 km
Equator crossing	12:00	7:30	14:30	9:30	9:30
Nadir ground resolution	825 m	1100 m	1100 m	79 m	83 m
Swath width	1566 km	2250 km	2250 km	185 km	185 km
Field of view	± 39°	± 56°	± 56°	± 5.5°	± 7°
Effective repeat coverage	6 days	2 days	2 days	18 days	16 days

[a] Coastal Zone Color Scanner.
[b] Advanced Very High Resolution Radiometer.
[c] Multispectral Scanner.

systems appear in Table 9. A "change detection" composite image made from multidate AVHRR data appears in Figure 11B.

The authors discuss uses for such data for three types of applications: stratification, change detection, and area estimation. They conclude that such data have considerable promise as an aid in all three of these application areas and, indeed, in a wide variety of large area inventory/monitoring tasks (see Figure 11 B). They assert that NOAA satellite data have the following advantages compared to Landsat, especially for macro inventory: (1) large area coverage on an individual scene, (2) essentially simultaneous (unitemporal) coverage over large areas, (3) greater frequency of coverage, and (4) economy (lower cost per unit of area). The data may be used alone for some applications, such as broad stratification, but probably will be useful for other applications (e.g., area estimation) when used in conjunction with other data sources, such as Landsat.

I. *Equipment for the Image Analyst.*

Most of the information acquired by means of remote sensing is either in image form or in a form which can readily be reconstituted into a photo-like image (such as the data acquired by optical mechanical scanners or side-looking airborne radar devices). Consequently, most of the equipment needed for extracting information from remote sensing data is of a type that will facilitate image analysis in one way or another. Image analysts need equipment for three general purposes: viewing, measuring, and transferring or recording data. More than twenty devices for use in accomplishing these tasks are fully described and illustrated in the *Manual of Photographic Interpretation* (American Society of Photogrammetry, 1960), and these devices still represent "state-of-the-art" equipment, by and large.

When multiband photography is obtained, there is need for some form of equipment that will produce various "image enhancements". The objective in producing such enhancements usually is twofold: (1) to increase the total amount of information derivable from the "raw data" and (2) to facilitate the data extraction process. One common way of accomplishing this task is through the use of additive color techniques, as will presently be described.

If no image enhancement techniques are used, the photo interpreter is confronted with a laborious task. He first must observe the tone of any given feature on each photo of the multiband series separately; then he must attempt to identify the feature by comparing the "tone signature" he has just observed with a master set of tone signatures that have been compiled previously for this type of feature and for a host of other types of features as well. By this means he presumably will have identified the feature when he has found its closest match in this master set of tone signatures. (See Figure 22).

However, when additive color techniques are used, several multiband black-and-white images are presented to the viewer on a screen simultaneously and in common register. This can be done either optically or electronically.

When an optical method of image enhancement is used, an "optical combiner" is employed and each image in the multiband black-and-white series of photographs is projected through a different color filter and in common register with the other simultaneously projected images. If, for example, one of the images, in positive transparency form, is projected through a red filter, shades of gray on the original black-and-white photo appear as corresponding shades of red on the viewing screen. When these are combined with shades of green (for example) as projected from a second black-and-white photo, with shades of blue from a third black-and-white photo, etc., each type of feature which had a unique tone signature on

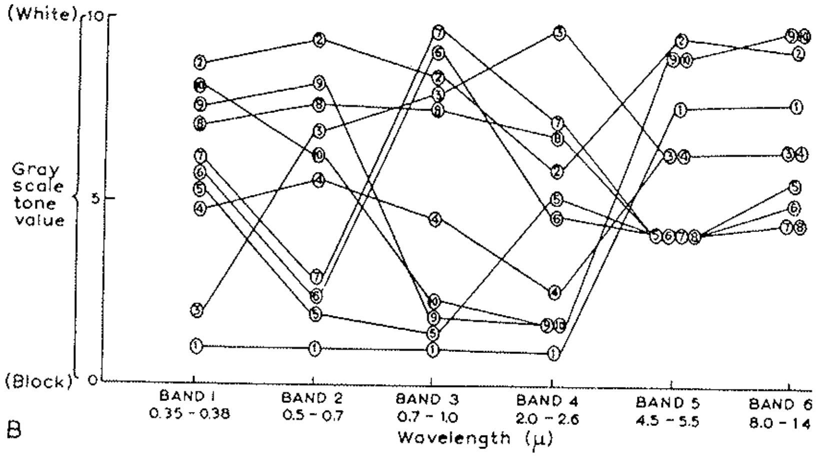


FIG. 22. An illustration of the use of tone values, as obtained simultaneously on multiband imagery from six spectral zones, for differentiating ten terrain types encountered in one particular geographic region, viz., Mud Lake Bog, Michigan, and its environs. The six-band "spectral signatures" for the ten vegetation/terrain types occurring in this wildland area: 1 = open water; 2 = bog mat; 3 = tule swamp; 4 = larch swamp; 5 = spruce, larch, birch swamp; 6 = birch, aspen swamp; 7 = hardwood swamp; 8 = tule/brush marsh; 9 = abandoned fields; and 10 = cultivated fields. Careful study of this diagram shows that these six bands are both necessary and sufficient to give each type a unique tone signature. A machine, through its capability to sense and then to analyze these "tone signatures" in digital form, is far superior to a human for making such wearisome analyses. (Imagery on which this diagram was based was provided to the author by the Environmental Research Institute of Michigan; diagram and analysis are from an article by Colwell, 1965).

the original set of black-and-white photos will exhibit a unique color in the composite image that appears on the viewing screen. It frequently is found that *one* filter-image combination improves the color contrast for detecting and identifying one kind of earth resource feature, but that some *other* combinations are preferable for detecting certain others.

One of the most modern devices used in the United States for achieving image enhancement electronically is the IBM 7350 image processor. It can accept, directly, the digitally-acquired remote sensing data. Frequently, however, the available remote sensing record is in the form of a series of multiband or multidate photographs. In such instances the photos are first scanned with a "DATACOPY" digitizing camera and the digits are recorded in hard disc form. Through use of an IBM Personal Computer/Visual Display system, the resulting digits are then presented to the previously mentioned image processor.

Another device commonly used for achieving image enhancements electronically is known as the IDIMS (Interactive Digital Image Manipulation System). It is a complete, self-contained image-processing system capable of extracting information from imagery of many different types, including multispectral data from Landsat. Its capabilities result from an effective combination of a minicomputer and a "floating point" array processor. This hardware configuration provides both the processing speed and memory capacity necessary to handle very large quantities of digital data.

Often there is a requirement to match a photographic image at one scale with a map at another scale. For such purposes the use of an optical device such as the Zoom Transfer Scope manufactured by Bausch and Lomb, Inc., will permit registration (superposition) of and comparisons between images and maps that differ in scale by factors of 14 or less. The ZTS can be equipped with a 35-mm or polaroid camera mounted along the viewing axis to allow the registered image pair to be photographed. At any scale, full image dimensions for the ZTS are equivalent to a Landsat scene whose outline is about 185 km (115 statute miles; 100 nautical miles) on a side.

J. *Remote Sensing-Based Resource Classification Schemes.*

Many applications dependent upon remotely sensed data require that the ground features of interest be located, identified, grouped into useful categories, and separated from extraneous objects within the scene. As previously indicated, this requires definition of discrete classes on the basis of their spectral signatures and/or characteristic shapes and textural relations. The general approach, with primary emphasis being given to tone signatures, forms the basis of *pattern recognition* — an automated intelligence technique originally developed by the military for determining attack targets or defense positions. It is based on principles and methods that have been readily extrapolated to civilian remote sensing and to such special applications as fingerprint identification and automated reading of zip codes. In fact a very rapidly growing capability, known as "artificial intelligence" because of its military origins, is being used perhaps even more in civil applications than in military ones. As now adapted to Landsat and other forms of remotely sensed data, the

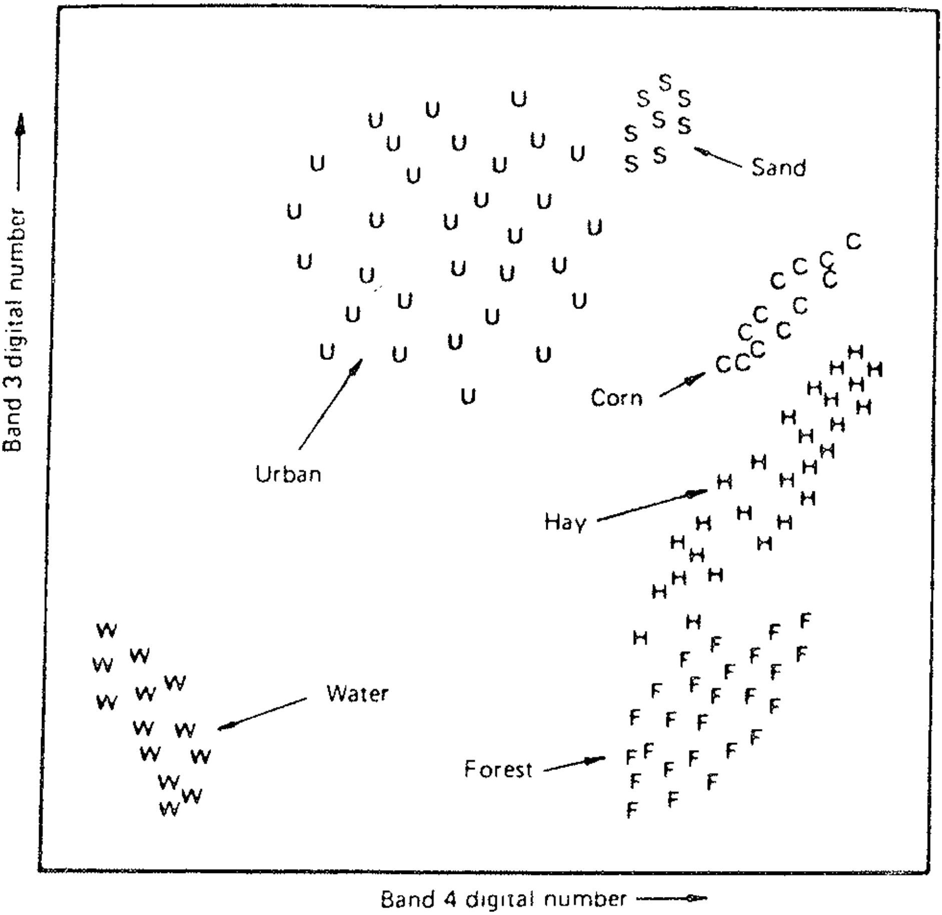


FIG. 23. Pixel-by-pixel observations of "scene brightness" in two bands, when converted to digital numbers, can permit identification of crops and other features by ratioing the digital returns from the two bands. As seen in this figure, ambiguities would result if only one band were to be used. Although there is some variation in the digital values for any given resource category, the ratioed values tend to be clustered, as shown in this example by Lillesand and Kieffer (1979).

recognition of land cover types whether through artificial intelligence means or otherwise is accomplished by *multispectral classification.*

The basis for classification of resource classes (e.g., cover types) is the correlation of different categories of interest with statistically separable groups of data as defined by their spectral properties in multidimensional space. (See Figures 23, 24 and 25).

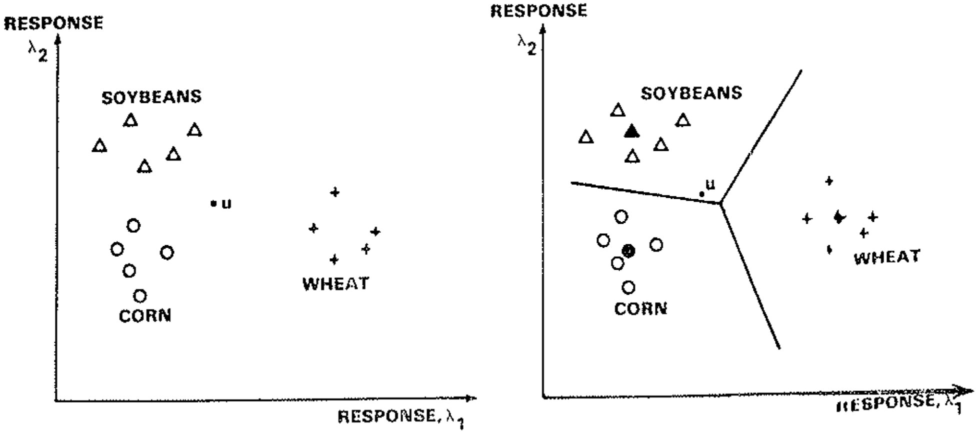


FIG. 24. An example of how the "nearest neighbor" concept can be applied in determining whether an unidentified field, "u", in an agricultural area consisting primarily of soybeans, corn and wheat, can be placed in the crop category to which it most probably belongs (from Short, 1982).

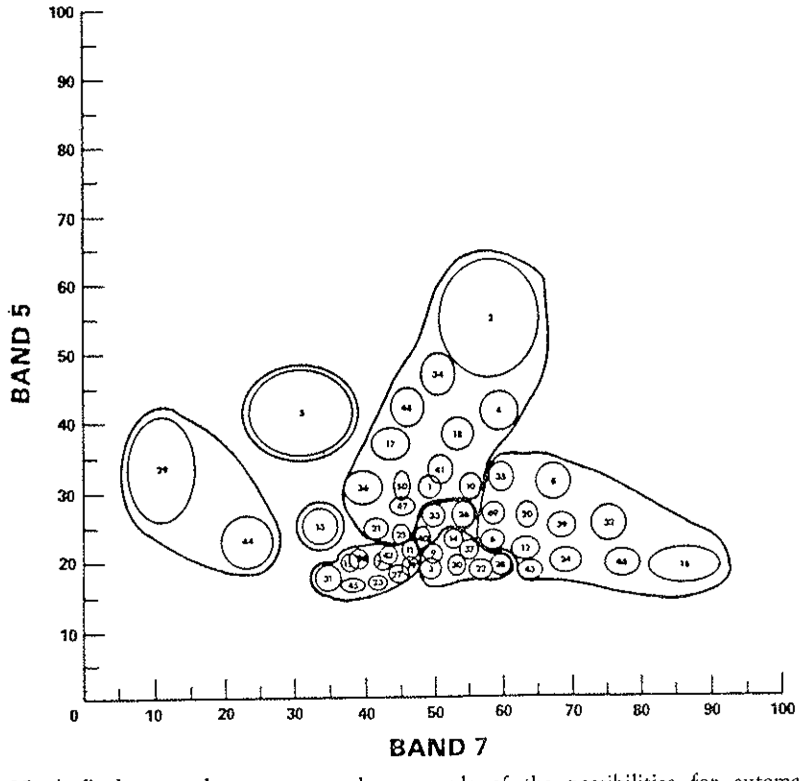


FIG. 25. A final, somewhat more complex example of the possibilities for automatically classifying features from their ratioed spectral responses in two bands. Shown here are clusters of 50 subclasses, representing nine land cover classes in an area in Virginia, as determined by a Landsat band 5/band 7 plot. From Short (1982).

L. *The Use of Computer Printout Techniques for Displaying the Derived Information.*

Whether digital data indicative of "scene brightness" is obtained by scanning the original scene or a photograph of it, a "shade print", solely in black-and-white, can be produced at the time of computer printout of the data. If, for exmaple, only four categories are to be identified and mapped, the following series of symbols may be used, since each successive symbol in the series uses more ink:

· = Category 1
C = Category 2
$ = Category 3, and
M = Category 4.

If, however, as many as 12 or 13 categories are to be recognized, color coding of the above symbols may be used by running the same sheet of computer printout paper through the printer a total of three times, but using a different ink color on each run. This extension of the "shade print" concept discussed above may be accomplished, for example as follows:

FIRST RUN: Print out, in *blue* ink, categories 1, 2, 3 and 4, using the above symbols.

SECOND RUN: Print out, in *green* ink, categories 5, 6, 7 and 8, also using the above symbols.

THIRD RUN: Print out, in *red* ink, categories 9, 10, 11, and 12, also using the above symbols.

Whether the final product is a black-and-white shade print or a color-coded shade print, some areas almost invariably will remain white (blank) on the printout sheet; such areas group together all remaining features and are commonly referred to as the "everything else" category (in this example, category 13).

VI. THE FUTURE OUTLOOK FOR REMOTE SENSING

The convenors of this Study Week requested that my paper include major attention to the future outlook for remote sensing, including its probable use in developing countries. For one to provide a reliable response to that request, especially with respect to a field that is as dynamic as remote sensing, requires that he have something more than mere 20/20 vision while gazing into a crystal ball. Realization that I lack such a capability does not deter me, however, from making some dogmatic predictions. Nor does it deter me from citing, perhaps ad nauseum, certain assignments that I have had in the past four decades and more, on the basis of which I make these predictions.

A. *There will be Very Substantial Progress Toward the Development of a Globally Uniform Information System, Based Primarily Upon Remote Sensing-Derived Data.*

We all are well aware that the rapid increase in both the world's population and the per capita demand for natural resources is occurring at the very time when the supply of many of these resources is rapidly dwindling and the quality of others is rapidly deteriorating. As previously indicated, this combination of factors creates an urgent need for the wisest possible management of such resources on a global basis. An important first step leading to such management is that of obtaining globally *uniform* inventories of resources. This step can best be taken if a globally uniform "look" at these resources can be obtained at suitably high resolution, as with an earth-orbiting remote sensing satellite, and at suitably frequent intervals. Herein lies a remarkably accurate description of the look that is provided by remote sensing devices that are on board the present sun-synchronous, near-circular-orbit Landsat and SPOT vehicles. Improvements in their remote sensing packages, as already scheduled for future generations of these vehicles, will make it all the more feasible to acquire globally uniform resource inventories through analysis of the remote sensing data acquired by them.

Some advocates of a globally uniform resources-information system have singled out *agriculture* as the field in which the greatest benefits might be derived. They look forward to the time when crop forecasting will have progressed sufficiently to permit a determination, to be made well in advance, that the northern hemisphere in some particular year is about to produce an over-abundance of barley, for example, but a serious dearth of wheat. Areas in the southern hemisphere that are capable of producing small grains are, of course, approximately six months out of phase with the grain-producing areas of the northern hemisphere. Hence the above information should be available at exactly the opportune time, so that grain growers in the southern hemisphere could be encouraged, in the instance cited above, to plant much more wheat and much less barley than they had intended, the better to balance out the global production, that year, of these two highly important crops. This is but one example of the potential improvement in the global management of natural resources likely to result in the near future from more uniform and more timely inventories of those resources.

B. *There will be a Very Appreciable Reduction in the Presently Intolerable Delay Between Data Acquisition by Remote Sensing Satellites and the Supply to Users of Needed Information Derivable from Such Data.*

Table 10 indicates the frequency with which various kinds of information about resources should be made available to users. In connection with that table it seems appropriate to introduce here, through analogy, the concept of "half-life" in relation to that frequency. Just as, in radiological research, the *usefulness* of an experimenter's radioactive isotope "decays" in conformity with that isotope's half-life, so the *usefulness* of a resource manager's remote sensing-derived information decays in conformity with a similar half-life concept. In the case of the resource manager, however, the half-life is based at least in part on how frequently a given type of information is needed by him. In this regard it is helpful to employ the term "half-life" in much the same way as it has been employed by radiologists and atomic physicists. The shorter the isotope's half-life, the more quickly a scientist must work with it once a supply has been issued to him. One half-life after he has acquired the material only half of the original amount is still useful; two half-lives after acquisition only one quarter of the original amount is useful, etc.

Whether by coincidence or otherwise, this half-life concept seems to apply remarkably well to nearly every item listed in Table 10. Specifically, if the desired frequency of acquisition of any given type of information, as listed in that table, is divided by two, a figure is obtained indicating the maximum time after data acquisition by which that particular item of information should have been extracted from the data and put to use. It is true that some value will accrue even if that item of information does not become known to the resource manager until somewhat later. But the rate at which the value of the information "decays" is in remarkably close conformity to the half-life concept.

TABLE 10 - *Examples Illustrating the* Frequency *with which Information About Vegetation and Related Land Use is Needed.*

For Agricultural Crops	For Timber Stands	For Rangelands	For Land Use Decisions
10-20 min: Observe the advancing waterline in croplands during disastrous floods. Observe the start of locust flights in agricultural areas.	*10-20 min:* Detect the start of forest fires during periods when there is a high "fire danger rating".	*10-20 min:* Detect the start of rangeland and brushfield fires during periods when there is a high "fire danger rating".	*10-20 min:* Not applicable.
10-20 h: Map perimeter of ongoing floods and locust flights. Monitor the Wheat Belt for outbreaks of Black Stem Rust due to spore showers.	*10-20 h:* Map perimeter of ongoing forest fires.	*10-20 h:* Map perimeter of ongoing rangeland and brushfield fires.	*10-20 h:* Not applicable.
10-20 days: Map progress of crops as an aid to crop identification using "crop calendars" and to estimating date to begin harvesting operations.	*10-20 days:* Detect start of insect outbreaks in timber stands.	*10-20 days:* Update information on "range readiness" for grazing, on wildland areas in critical periods, and also information on times of flowering and pollen production in relation to the bee industry and to hay fever problems.	*10-20 days:* Monitoring compliance with certain codes and construction rates in critical areas of land use change during peak construction periods.
10-20 mos: Facilitate annual inspection of crop rotation and of compliance with federal requirements for benefit payments.	*10-20 mos:* Facilitate annual inspection of firebreaks.	*10-20 mos:* Facilitate annual inspection of firebreaks, range production, and range conditions.	*10-20 mos:* Monitoring development and land use change in critical care areas for enforcement of codes and keeping valuations equitable and up to date.
10-20 yrs: Observe growth and mortality rates in orchards.	*10-20 yrs:* Observe growth and mortality rates in timber stands.	*10-20 yrs:* Observe signs of range improvement or deterioration, study the spread of noxious or poisonous weeds. Observe changes in "edge effect" of brushfields that affect suitability as wildlife habitat.	*10-20 yrs:* Reassess situation as necessary in order to fine-tune long-term land use plans and reevaluate policies. Provide improved data for prediction models and trend analysis. Revise or set long-term economic development goals.
20-100 yrs: Observe shifting cultivation patterns.	*20-100 yrs:* Observe plant succession trends in the forest.	*20-100 yrs:* Observe major plant succession trends on rangelands and brushfields	*20-100 yrs:* Document long-term changes in land use and monitor attainment of long-

While the analogy is by no means perfect, it serves to highlight the importance of minimizing the delay between the time when remote sensing data is acquired and when it has been "reduced" to information that can be used by the resource manager. This need is potentially as great in developing countries as elsewhere. Since no major technological "breakthroughs" will be needed to meet this need, it seems logical to predict that this requirement will be satisfied far better in the future than it *routinely* has been up to the present.

C. *Great Progress will be Made with Respect to the "Compression" of Remote Sensing Data.*

Judging from plans that are even now developing within NASA, ESA, and other major space agencies throughout the world, remote sensing from spacecraft in the future will entail higher spatial resolution, more spectral bands and more frequent coverage. The price to be paid for all of this is more "bits" of data to be telemetered from satellites to receiving stations on the ground — unless on-board computers will do much of the analysis that otherwise would be done on the ground. In that event, only the results of the analysis, rather than the initial remote sensing data, would need to be telemetered to the ground, and a much needed form of "data compression" would have been achieved.

The extent to which data compression of this type might conceivably be implemented is more clearly seen when, as previously discussed, we consider that the wise management of earth resources usually entails a three-step process: *inventory*, *analysis*, and *implementation*.

With respect to our maximizing data compression on-board a remote sensing satellite, we can foresee the possibility that one particular data-compression technique will evolve into a highly automatic operation. It is one in which an unmanned satellite orbiting the earth will carry multi-band sensing equipment together with an integrated set of computers. Thus equipped the satellite could, for any particular area, take *inventory* of the resources and produce an on-board printout that would amount to a resource map of the area. A second on-board computer could then use this inventory data in conjunction with preprogrammed factors (such as the ratio of costs to benefits that would be likely to result from each of several resource management practices) and could reach a decision for the optimum management of the resources in the area. This would complete the *analysis* phase. The decision, having been arrived at on board the satellite while it was still overhead, would be telemetered to the ground for whatever action seemed necessary in the *implementation* phase (Figure 26).

As a simple example, the satellite's sensors might spot a fire in a large forest. Its computer might then derive information on the location and extent of the fire and assess such factors as the type and value of the timber, the direction and speed of the wind and the means of access to the fire. On the basis of the assessment the computer would send to the ground a recommendation for combating the fire.

Capabilities of this kind need not be limited to emergencies. Many routine housekeeping chores now done manually by the resource manager could be made automatic by electronic command signals. Examples might include turning on an irrigation valve when remote sensing shows that a field is becoming too dry and turning off the valve when, a few orbits later, the satellite (or more likely a companion satellite) ascertains that the field has been sufficiently watered. In instances such as this, all

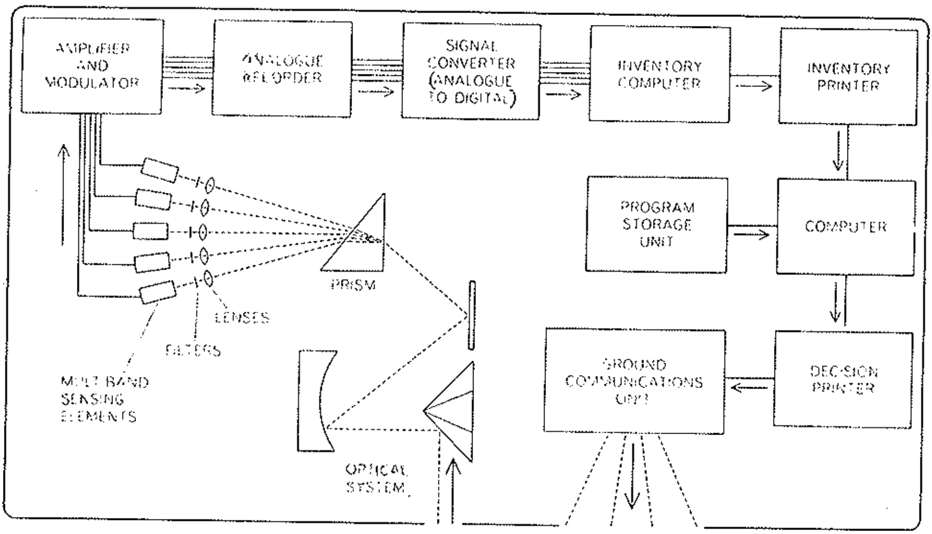


FIG. 26. A computerized satellite, containing the components shown here, could sense resources in several wavelengh bands simultaneously, automatically identify them, weigh them against previously programmed data on the cost effectiveness of various management possibilities, and send to the ground a decision on what should be done. In some instances, this highly automated system might even go one step farther by transmitting the proper command signals so that the resource management decision, itself, would automatically be implemented. An example is that of turning irrigation valves off and on, field-by-field, as required (from Colwell, 1968).

three of the previously described steps that are involved in resource management (inventory, analysis and implementation) would have been accomplished automatically via satellite.

A satellite of such capabilities may seem to be only a far distant prospect. After a few more years of developing the techniques for remote sensing, however, the prospect may well have become a reality, in which case data compression will have been developed to the ultimate.

D. *Great Progress will be Made in an Area Known as "Change Detection".*

A simple but effective means of using remote sensing imagery for detecting, portraying and mapping certain kinds of change already has been illustrated (Figure 11A). An example of the product obtained through use of a more complicated, but tremendously effective means is illustrated in Figure 11B.

Consistent with the previously mentioned "half-life" concept, the period over which the change that is of interest has occurred may range from a few seconds to many years — from the detection and analysis of various kinds of moving objects (animal herds, for example) to the detection and analysis of various kinds of plant succession. With respect to the latter it is instructive for us to reflect upon the amount that could be added to our present understanding of plant succession if only there were globally uniform data available, of the Landsat and "high-flight" types that had been acquired at suitable intervals during the past 100 years or so. Remote sensing scientists of the future are certain to look back at one highly significant benchmark period, viz., the early 1970's, when for the first time most of the globe was systematically covered by such remote sensing data. Much of the change detection and analysis of the rate and direction of change that will be made by future remote sensing scientists surely will hark back to that particular period.

E. *There will be a Very Significant Increase in the Amount of High-Resolution Remote Sensing Data — e.g., Data of the Type Now Being Acquired by Various Military Satellites — that will be Released and Made Available to Nonmilitary Users.*

A survey of even the unclassified literature (e.g., Smith, 1985; Tsang, 1985) leaves many clear inferences that military remote sensing satellites can provide the same resolution, in terms of "ground resolved distance" as we are accustomed to finding in the conventional 1/20,000 scale vertical aerial photographs with which most of us have worked so extensively in times past. Those who have not been privileged to work with space photography of such high resolution can scarcely envisage the extreme usefulness of it. Most of its increased usefulness results from the fact that a typical high resolution frame of space-acquired imagery covers more than 1000 times as much land area as the conventional 1/20,000 scale photo. The synoptic view of so large an area permits relationships of terrain features to be perceived that could scarcely have been appreciated from the piecing together in mosaic fashion of so many photos of the conventional type. Mismatches on them in both photographic tone and the geographic positions of conjugate images, greatly limit the usefulness of such mosaics.

F. *Space Photography will Largely Replace "Orthophotography", as Presently Produced, When the Need is for a Product that Provides Both the Plan View and a Large Amount of Photographic Detail.*

Many features that are of interest to resource managers are far better appreciated from a study of photographic images of those features than from a map which must rely on the use of conventional symbols. Up to the present time, however, it often has been necessary to eliminate the relief displacement that is inherent in vertical aerial photographs through a somewhat costly and time-consuming process known as "orthophotography". The intent here is not to disparage the ingenious methods that have been developed for producing ortophotographs but to predict that in the near future space photographs of high resolution and low relief displacement will largely replace orthophotographs.

G. *There will be a Significant Resurgence in Improving the Ability of Humans to Extract Information from Remote Sensing Data by Direct Visual Means.*

It has now been almost three decades since the writing of a book called "Manual of Photo Interpretation", under the auspices of the American Society of Photogrammetry. More than 100 experts in various aspects of photo interpretation significantly contributed to the writing of that 972-page book (1960). In so doing, they collectively provided an accurate record of what was then the "state of the art" with respect to the techniques and equipment used by humans in extracting information from remote sensing data by direct visual means. The most recent effort to provide a detailed, systematic update of material contained in that Manual is to be found in the Manual of Remote Sensing (American Society of Photogrammetry, 1983b). More than 220 experts contributed to the writing of that 2760-page, 2-volume tome. But unless my perception of developments in the field of remote sensing is grossly in error, there has been exceedingly little development during the past three decades in either the equipment or the techniques used by photo interpreters. (I base this dogmatic assertion, in part, on my having served as Editor-in-Chief for both of the Manuals). Nor has there been any significant increase in our understanding of what makes a good photo interpreter, and therefore of the factors that should be considered in the selection and training of such individuals. For example, we know essentially the same amount now as we did three decades ago with respect to the factors that govern the photo interpreter's visual mechanism, his mental acuity, his susceptibility to fatigue and the consequences of fatigue in relation to the reliability of the information which the photo interpreter is able to derive. Similarly, there has been virtually no further exploration during these three decades of the uses and limitations of the "conference system" or of "convergence of evidence" as applied to photo interpretation, nor of the use of such aids as photo interpretation keys, sound recorders, or enumerator's pencils. Temporarily, at least, these important aspects have been forgotten because of our preoccupation with the marvels of modern day remote sensing, including opportunities for computer analysis rather than human analysis of remote sensing data. Now that most of the cream appears to have been skimmed from this new technology (and now that there is greatly improved spatial resolution on "photos" constructed from space-acquired digital data), there almost certainly will be a renewed appreciation of the need to facilitate the extraction of information from remote sensing data by humans.

H. *There will be Increased Efforts to Define the Roles of Humans and Machines as They Function as a Team in the Derivation of Information from Remote Sensing Data.*

Remote sensing scientists are beginning to acquire a far greater appreciation than heretofore of both the uses and the limitations of machines in relation to the acquisition and analysis of remote sensing data. One encouraging sign is to be found in the fact that the machine analysis of remote sensing data is rarely referred to any more as "automatic data processing". Instead, use is made of the more aptly descriptive term "computer assisted analysis".

The following point (already expressed, but in a quite different context) is "key" to our appreciation of the uses and limitations of computers in the analysis of remote sensing data: If a computer is to provide meaningful assistance in the analysis of remote sensing data, usually the data must be in digital form. On the other hand a human, in making his analysis of remote sensing data relies not on digits but on such photo image attributes as size, shape, shadow, tone, texture, site, pattern, and association. Of all such attributes, *tone* stands out as the one which can be far more easily and meaningfully digitized than any of the others. Humans, therefore, still need to interpret the imagery in a way that will integrate the clues to a feature's identity that are provided by the eight attributes combined. Furthermore, there are instances in which the tone signatures are so simple and the objects to be identified are so few that the human will continue to be as good as, or even superior to the machine for making the identifications — even those based primarily on tone as the single image attribute. See, for example, the previously illustrated *broad band* tone signatures for dryland areas as compared with flooded areas, as derived from spectral data in Figure 11 A. It is probable, however, that in most future uses of *narrow band* signatures, digital ratioing will be employed and computer-assisted analysis will be greatly preferred to direct visual analysis by humans (Figure 11B).

I. *There will be a Better Realization that the Feasibility of Using Remote Sensing Techniques in Any Geographic Area Depends on Whether that Area is Simply or Complexly Structured.*

Table 11 is an attempt to set forth some of the characteristics of simply structured versus complexly structured areas in relation to the feasibility of making remote sensing-based inventories. Such characteristics apparently have been given little consideration by remote sensing scientists up to the present time. As a result there have been some seriously mistaken estimates made in the recent past as to the feasibility of using remote sensing techniques in various geographic areas.

The emphasis in Table 11 is placed primarily upon such renewable resources as agricultural crops, range vegetation, and forest vegetation; only limited treatment is given there to whether the geology, soils, and

TABLE 11 - *Characteristics of Simply Structured Versus Complexly Structured Areas in Relation to Natural Resources.*

SIMPLY STRUCTURED AREAS	COMPLEXLY STRUCTURED AREAS
1) *Agricultural Vegetation*	1) *Agricultural Vegetation*
a) Fields large, regularly shaped, usually homogeneous with respect to crop condition.	a) Fields small, irregularly shaped, frequently heterogeneous with respect to crop condition.
b) Few competing crops and cultural practices.	b) Many competing crops and cultural practices.
c) Little interspersion of cropland with non-cropland.	c) Much interspersion of cropland with non-cropland.
d) Fields of a given crop planted on about the same date and hence developing in essentially the same seasonal pattern.	d) Fields of a given crop planted on many different dates and hence developing with many different seasonal patterns.
2) *Range and Forest Vegetation*	2) *Range and Forest Vegetation*
a) Blocks of rangeland and forestland are large and relatively homogeneous.	a) Blocks of rangeland and forestland are small and relatively heterogeneous.
b) Elevation range is low to moderate and hence vegetation of a given type tends to develop with essentially the same seasonal pattern.	b) Elevational range is high to very high and hence vegetation of a given type tends to develop with many different seasonal patterns.
c) Few vegetation types present, all adapted to the same elevations and climatic range. Topography flat to gently rolling so that few vegetational differences are the result of differences in slope and aspect.	c) Many vegetation types present, each adapted to a particular elevation and climatic range. Topography steep so that many vegetational differences are the result of differences in slope and aspect.
d) Cultural practices with respect to range and timber resources are few and uniform.	d) Cultural practices with respect to range and timber resources are many and varied.
3) *Geology, Soils, and Hydrology*	3) *Geology, Soils, and Hydrology*
a) Geological, soil, and hydrologic formations are relatively large, simple, discrete, and homogeneous.	a) Geologic, soil, and hydrologic formations are relatively small, complex, intermingled, and heterogeneous.

hydrologic resources of an area make it a simply- or complexly-structured one. Consistent with the so-called "land systems" concept, however (as developed, for example, by Christiansen and Stewart for use in Australia), an area that is of complex geologic structure is very likely to be complex also in terms of its soil and hydrologic attributes and therefore in its associated vegetative attributes. While Christiansen and Stewart based their conclusions primarily on their study of one of the most arid parts of the world (central Australia) exactly the same conclusions apply in most other climes also. I base this generalization on extensive remote sensing work that I have done not only in Australia but also in such varied areas as (1) the Tropical Pacific, (2) Central America, (3) the Amazon Basin, and (4) the States of Alaska, California, Arizona and Louisiana.

The photo interpreter is likely to perceive, in reverse order, the attributes listed in Table 11. This is because in most areas, the vegetative attributes are most photogenic and hence are most easily perceived. Stating the matter in reverse order, therefore, it is highly probable that when the vegetation attributes of an area are found to be complex, the geology, soils and hydrologic attributes of that area are complex also. As a result, the feasibility of using remote sensing-based techniques for the inventory of such an area's entire "resource complex" is likely to be considerably more limited, and the requirement for acquiring ancillary "ground truth" data much greater, than if the area were more simply structured.

As I look to the future, I predict a growing realization by remote sensing specialists of the fact that there are fundamental differences, of the types suggested by Table 11, among various geographic areas. If so, when such scientists are attempting to make an extension of "remote sensing feasibility ratings" from any particular test area to other areas, they will take far more cognizance of these differences in the future than they have in the past. As a result there will be far fewer misjudgments (on either the overly optimistic or overly pessimistic side) as to the potential usefulness of remote sensing in any given geographic area.

J. *There will be a Greater Borrowing by Future Remote Sensing Specialists of Various Applicable Techniques and Procedures that Have Been Developed in Other Disciplines.*

In any discipline that is relatively new and fast-growing, there is likely to develop the belief that each problem encountered is an entirely new one, the likes of which have never been encountered by man or beast. Again, if my perception is correct, remote sensing is among the disciplines that have suffered from this belief — one that employs the "not-invented here" syndrome in rejecting worthy contributions from other disciplines. It is entirely probable that at this very moment many of the problems that remote sensing scientists are seeking to solve have already been solved, in only a slightly modified context, by workers in other disciplines.

To the extent that this is true, we should even now be testing the applicability to remote sensing image analysis of (1) various field-of-view search techniques used by astronomers or microscopists as they attempt systematically to search for information; (2) various counting or enumeration techniques used by doctors in determining the number of red and white corpuscles in a patient's blood sample; (3) various fatigue-reducing techniques used by industrial supervisors to ensure that their workers who are engaged in highly repetitive tasks will perform acceptably well throughout an eight-hour work day; and (4) various "convergence of evidence techniques" used by lawyers to maximize the prospect that a deduction made is the correct one.

Such a mass borrowing of information and techniques from other disciplines should not be regarded as a shameful practice, but as a highly intelligent one. For those remote sensing scientists who nevertheless might suffer pangs of conscience from engaging in this practice, adequate consolation should be found in the following thought: For each field or discipline from which remote sensing scientists might borrow information of the types indicated above (and for many other fields as well) repayment many times over is likely to be offered in the near future — the reciprocity in this case being in the form of remote sensing-derived information that could be used to great advantage in these and other fields or disciplines.

K. *Stereoscopic Effects will be Used to an Ever-Increasing Extent as an Aid to the Interpretation of Space Photography.*

The lack of relief displacement in a space photograph is a blessing when we wish to have a near-orthophotographic record of the landscape. Axiomatically, the lack of relief displacement is the very attribute that most limits the interpretability of a space photograph when the objective is to identify, from their three-dimensional configurations, certain important features that are of interest to the managers of natural resources. The remedy to this deficiency as applied to terrain features that are of sufficient size to be clearly resolvable on the space photograph is to be found in a form of "synthetic stereo" that can be produced for any area that already has been topographically mapped to a suitably small contour interval (Figure 27). In addition, important uses will be made of the *truly* stereoscopic view that is offered by SPOT imagery when nadir and off-nadir views are provided of the same terrain.

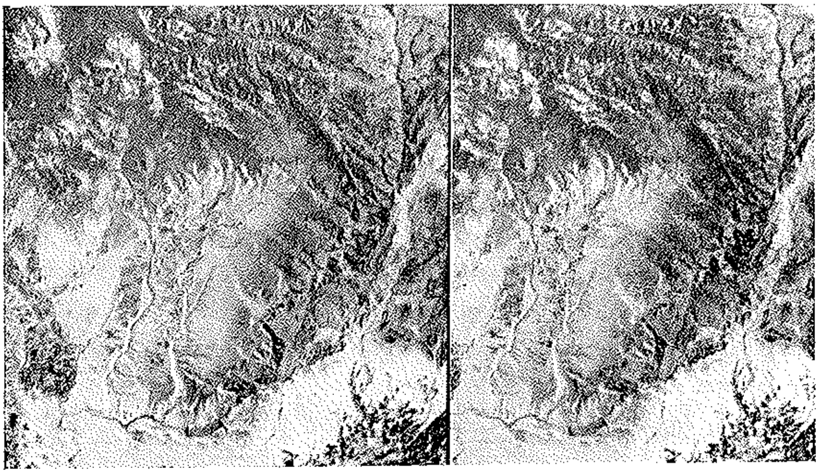


Fig. 27. "Synthetic stereo" has been introduced into the left photo of this Landsat stereogram so that the three-dimensional configuration of the terrain can be perceived visually by the image analyst. In order to implement this technique, a reliable topographic map must already be available for the area. From it the MSS Landsat data of this example were displaced left or right, pixel-by-pixel, by an amount equal to the elevation times 0.6 (the stereo base-to-height ratio). The product reveals a variety of lithologic, structural, and botanical phenomena not readily apparent without the use of this technique. (Prepared by Earth Satellite Corporation).

L. *Future Improvements in Sensor Capabilities and Resource Classification Schemes will Better Conform to the Requirements Imposed by Resource Policy Decisions and Management Objectives.*

In an earlier section of this paper some consideration was given as to the kinds of information, both basic and applied, that might be desired by those working in various resource-related disciplines. In the present section let us build on those considerations by acknowledging that either of two approaches might be used as we seek to relate remote sensing capabilities to user requirements. In the *first approach*, remote sensing capabilities would be considered at the outset and, in the light of these capabilities, an exhaustive list would be compiled showing all the kinds of information that might be attained through the full exercise of these capabilities. Then due consideration would be given to each item on the list in order to determine whether that item might conceivably satisfy some user's informational requirements.

In the *second* approach, a list of economically significant or otherwise important user requirements for information would be compiled. Once the list had been compiled, consideration would be given to the various remote sensing capabilities in an effort to determine which of these requirements might be met and by what remote sensing process.

If either of these two approaches were to be used, however, consideration would eventually need to be given to the best compromise between user requirements and remote sensing capabilities. For example, if under the second approach it were found that one of the desired items of information could not be directly obtained by means of remote sensing, the investigator should consider whether the requirement might be so modified as to make acceptable to the user some alternate kind of information which could, indeed, be derived through the remote sensing process. (This alternate information is sometimes referred to as "surrogate" or "proxy" information).

The foregoing suggests that, in many instances, a *third* approach is the best one to use — one that will be better discussed in a later section of this paper. It is the approach that is portrayed in the "flow chart" of Figure 28. That figure indicates that a determination of resource management *policies* should constitute the starting point for determining information needs and, from this, the classification schemes and sensor capabilities should fit into place as diagrammed.

M. *There Will Be Greater "Technology Acceptance" as Applied to the Use of Remote Sensing for the Evaluation of Earth Resources.*

With reference to the objectives of this Study Week, perhaps the greatest need is not one of developing a still better remote sensing capability. Instead, the greatest need seems to be that of getting resource managers, in both the developed and the developing countries, to exercise a higher degree of acceptance than they currently do with respect to the remote sensing technology that already is available to them. Therefore, in this section let us concentrate primarily on the problem of achieving a higher degree of acceptance and beneficial use of existing remote sensing technology on the part of natural resource managers.

In addressing this need, we first should differentiate clearly between the terms "appreciation" and "adoption" as applied to technology acceptance. The term "appreciation" simply means that we are cognizant of, and perhaps even impressed by, the technology. This is done largely in the *passive* sense, just as we may appreciate the stars at night and, in consequence, marvel at the orderliness and tremendous expanse of the

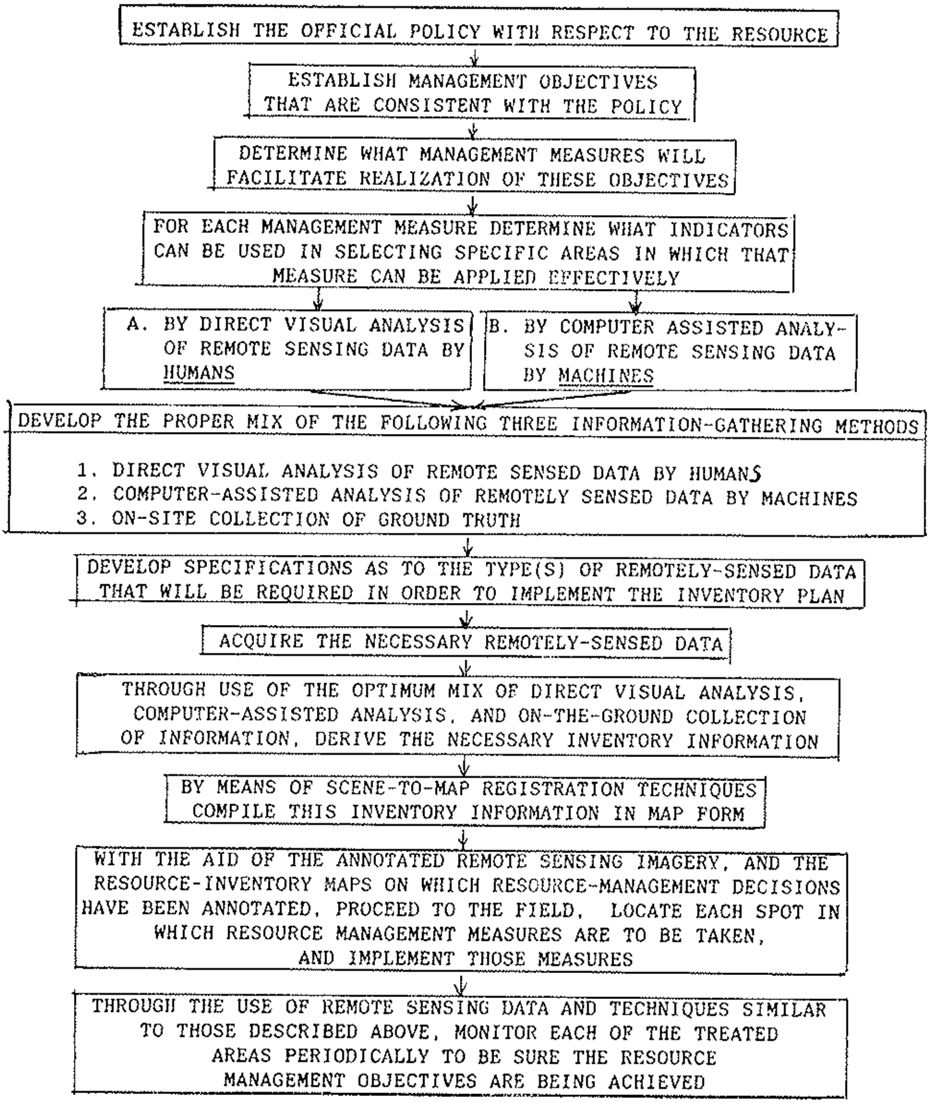


FIG. 28. The step-by-step procedure shown here usually is the best one to follow when seeking an orderly use of remote sensing technology for the inventory, monitoring and management of natural resources, as explained in the text.

celestial universe. The concept of "adoption", however, implies *action*. Thus, in any given organization, modern remote sensing technology has not been adopted until the following conditions exist: the top-level decision makers are sufficiently convinced of the potential usefulness of that technology for solving certain resource-related problems that (1) they *routinely* consider using it, as each resource inventory/monitoring/management problem arises; and (2) they forthrightly *direct* that it be used in each appropriate instance.

Perhaps the best description of what is entailed in technology acceptance (sometimes called "technology transfer") is that provided by Hoos and Sharp (1978) which, somewhat paraphrased, is as follows:

> "The transfer of a technology (such as remote sensing) can be considered as having been completed only when that technology, being readily available in the marketplace, becomes generally accepted practice by the user agency, and when the chief officer of that agency, upon routinely assessing all available technologies, decrees that the one in question is the one that shall be used in every instance where objective analysis indicates its potential superiority".

As implied by the above statement, remote sensing technology will not transfer itself. Instead, there is commonly a five-stage "adoptive process" by which this new technology is perceived, internalized and used: awareness, interest, evaluaton, trial, and adoption. Since this process may take years, there frequently are problems in maintaining the necessary momentum, especially when there commonly are disruptions in personnel and support along the way that can undermine both credibility and morale. And even after remote sensing technology has been adopted, it still may take years before this new technology will begin to bear significant amounts of fruit.

Since "adoption" is thus seen to go far beyond mere "appreciation", let us consider the requirements for adoption as applied to remote sensing. If modern remote sensing technology is to be adopted in any given instance, the decision maker needs to convince himself of the technology's (1) simplicity, (2) direct applicability, (3) continuing availability, and (4) economy. In many instances, the timeliness with which the desired information can be obtained through the use of the technology constitutes a fifth criterion in his deciding whether or not to adopt it.

The heart of our analysis in this section, however, must be found in our recognizing exactly what are the *deterrents* to adoption of modern remote sensing technology. While the specific deterrents may differ in nature and relative importance, depending upon the situation, it should be helpful to categorize the ones that already have been found to be important in one remote sensing-related situation or another. Thus far it has been found that the deterrents tend to fall in the following categories:

1. *Overselling*, resulting in the raising of user expectations to levels beyond what current capabilities can deliver;

2. *Overkilling*, as when the user is urged to use elaborate techniques of computer-assisted analysis even when the desired information could have been derived quite adequately through the use of simple, inexpensive, and more readily understood manual interpretation techniques;

3. *Undertraining*, most commonly exemplified when a novice who has just completed an "appreciation" course in remote sensing is required to plunge directly into the demanding tasks that are involved in making operational use of modern day remote sensing technology;

4. *Underinvolvement*, as when the user agency, plagued by a lack of qualified and/or motivated personnel, turns over the bulk of the work to consultants or others who lack familiarity with and/or concern regarding the user agency's resource problems, information needs, and perhaps even the resource itself;

5. *Spurious evaluation*, as when the user agency, forced by higher authority or others into a "rush to judgment" produces premature, incomplete, incestually validated, and usually overly optimistic appraisals;

6. *Misapplication*, resulting, in part, from the sheer glamour of the shiny new tool known as remote sensing, and perhaps best metaphorized by the saying, "give a small boy a hammer, and he soon discovers that everything needs to be pounded"; and

7. *Timidity*, (sometimes known as gutlessness), arising from the thought by the decision-maker of the great personal embarrassment that he might experience if the newly adopted remote sensing-based system proved to be unsatisfactory, after all.

Because this Study Week deals quite specifically with the potential use of remote sensing in developing countries, three other deterrents to its use that are likely to be found in such countries need to be added here.

8. *Inadequate infrastructure* (facilities, scientists, etc.) within the developing country for implementing any decision that might be made for the internal beneficial use of remote sensing.

9. *Inadequate understanding* by the country's leaders as to the potential benefits of remote sensing for development of their country's natural resources, and

10. *Inordinate distrust* of remote sensing, especially by the country's military establishment, on the grounds that a serious breach of the country's military security might result from the in-country use of modern, high resolution, remote sensing data. Recently this potential deterrent was emphasized by a senior remote sensing scientist, Dr. Charles Poulton, who has spent much of his professional career (e.g., as an FAO employee and AID consultant) trying to help developing countries make beneficial use of remote sensing. In addressing this problem, he states (Colwell and Poulton, 1985):

> "In some countries, highly generalized 1:2,000,000 scale resource maps and reports have been confiscated by military departments, shrouded in secrecy, and made totally unavailable to the responsible renewable resource agencies that stand to gain the most from use of such information... It is a real shocker for international agencies of the AID type, while working with their contractors, to embark on critically needed resource analysis/monitoring projects only to find that the local military establishment is throwing unanticipated and occasionally crippling road blocks in the way of project implementation. It is even worse to complete an information-gathering project and have the results buried under a vague cloak of presumed security".

The most substantial progress toward the adoption of modern remote sensing technology by a potential user of it appears, from experience to date in the United States, to be through the undertaking of demonstration-type projects that involve the potential users (i.e., the resource managers, themselves) throughout the entire process. Typical of the warnings that we have been given in this matter is the following excerpt from the previously mentioned report by Hoos and Sharp:

> "Most potential users of remote sensing technology are simply unmoved by paper-and-pencil evaluation games. They recognize that externally prepared benefit-cost ratios exclude many

of the considerations most important to them. They see impacts on their own decision processes, job security, and organizational behavior being overlooked and obscured behind voluminous but vacuous evaluative reports. The result for the technology developers is often an evaluative 'boomerang effect' in which users perform their own subjective assessments and conclude, for various reasons, that fruits from the technology are not worth their price".

Finally, we need to consider in this section the "Maintenance of Momentum" concept with particular emphasis on the acceptance of modern remote sensing technology. This need arises from the fact that too often a resource manager or his boss is given only a superficial exposure to the marvels of modern remote sensing technology through an "appreciation" type of course from which he graduates with great enthusiasm. Almost always there is no follow-up to ensure that his organization will begin to put this technology to practical use. Consequently, only a short time later he likely will have lost all of the momentum that has been instilled in him during the course. The key to solving this problem often is as follows: By prior arrangement, each attendant brings with him to the course a specific unsolved resource-inventory/management problem of importance to his organization. Also by prior communication with the instructional staff for the course, he brings with him (or the staff procures for him) the Landsat MSS or TM data tapes and/or aerial photography covering the problem area. During the concluding phases of the course, under supervision of the staff, he applies to his specific problem the data-enhancement and data-analysis techniques that have been dealt with earlier in the course. In this way he leaves the course having "solved" the problem. Almost invariably he can scarcely wait to field check his analyses, refine and correct them as necessary, and then implement the management measures that are dictated by such analyses. From this success, he can then progress to additional remote sensing-related problems. Thus, his momentum is maintained. If *procedural manuals* and *technical assistance* also are made available to the recent attendant of the course, these factors will aid him still further in maintaining his momentum, once he encounters difficult remote sensing-related projects while on the job.

VII. Summary

As requested, this opening paper of mine has sought to set the stage, and also the tone, for our pursuit during this Study Week of the theme, "Remote Sensing and Its Impact on Developing Countries". I have attempted to respond fully to the request made of me by the convenors of this conference that I do this in a "complete and integrative" way. I also have tried to do so in a manner that would minimize my encroaching on the subject matter of the many papers that are to be presented during this Study Week by other participants. I have realized from the outset that a considerable amount of encroachment would be unavoidable because of the sheer comprehensiveness provided, collectively, by topics on which the other participants have been invited to speak. Hopefully, there is a redeeming value to my paper that will ameliorate its sins, both of lengthiness and encroachment, namely, the value of providing an *integrated framework* for our deliberations this week.

Specifically, I have sought to clarify the terminology used by remote sensing scientists and practicioners, to elucidate many of the basic principles and considerations on which remote sensing is based, and to provide the requested historical perspective for remote sensing, including a look to the future.

As one important element of my summary I submit Figure 28. That figure seeks to present, in diagrammatic ("flow chart") form, the step-by-step process by which remote sensing usually is best accomplished and integrated with resource management policies and objectives.

From the technological standpoint, much of what has been described in this paper can be summarized under what has been called the "Multi" concept. In chapter 1 of the *Manual of Remote Sensing - First Edition* (1975), I gave a fully illustrated presentation of the concept. The reason for assigning the term "Multi" (at least tentatively) to the concept, is suggested in Table 12 of the present paper, wherein many of the elements of that topic are listed and inferentially defined. To summarize its relevance: (1) usually at least one of the 8 listed components can be used to advantage, but (2) if a remote sensing scientist were to insist on using all of these components on all remote sensing-related projects, he should very properly be discreditied on the grounds of being "Multi" happy. Perhaps it is in consideration of these two thoughts that we arrive, on balance, at the following conclusion: In the future it will indeed be possible, through intelligent and properly restrained use of the "Multi" concept, to increase significantly the amount of information derivable through the use of modern remote sensing techniques.

An additional component for the summary of my paper is proved by Table 13. That table seeks to list all of the major factors which

TABLE 12 - *Elements Encompassed by the "Multi" Concept as it is Applied to the Remote Sensing of Natural Resources.*

1. More information usually is obtainable from *multistation* photography than from that obtained from only one station.*
2. More information usually is obtainable from *multiband* photography than from that taken in only one wavelength band.
3. More information usually is obtainable from *multidate* photography than from that taken on only one date.
4. More information usually is obtainable from *multipolarization* photography than from that taken with only one polarization.
5. More information usually is obtainable from *multistage* photography than from that taken from only one stage or flight altitude.
6. More information usually is obtainable through the *multienhancement* of this photography than from only one enhancement.
7. More information usually is obtainable by the *multidisciplinary analysis* of this photography than if it is analyzed by experts from only one discipline.
8. The wealth of information usually derivable through intelligent use of these various means usually is better conveyed to the potential user of it through *multithematic maps*, i.e., through a series of maps, each dedicated to the portraying of one particular theme, rather than through only one map.

* The term "multistation photography" (not to be confused with "multistage photography") pertains primarily to successive overlapping photographs, taken along any given flight line as flown by a photographic aircraft or spacecraft. When two such photographs are studied stereoscopically, the photo interpreter is better able to perceive features than if a photo from only one of the two stations was available.

govern the potential usefulness of any given type of aerial or space photography to those who wish to inventory, develop, and manage an area's natural resources. The potential significance of such a table in relation to our discussion of the future of remote sensing is indicated by interest of completeness, several other components might be added to its accompanying explanatory notes.

Consistent with the note appearing at the top of that table, there can be, for each of the listed factors, an entire "spectrum" of conditions, ranging from very favorable to very unfavorable, in relation to the usefulness of remote sensing. However, in any given instance, the relevant factors probably can be assessed reasonably well, and even quantified, if only we will make the effort to do so. If so, the overall usefulness of remote sensing will be determined quantitatively by the aggregated effects of these various factors. In any specific instance, however, it probably will be necessary to assign a weight to each factor, in proportion to its estimated importance. Ideally, then, it will be this single aggregated value that will accurately indicate "remote sensing feasibility", the better to determine when it should be used and when not.

As emphasized by the note appearing at the bottom of Table 13, the statements appearing in the left column of that table are descriptive of highly *unfavorable* situations. Hence, to the extent that those descriptions apply in any given instance, there will be *minimum* benefit derived from the use of remote sensing techniques in relation to the inventory, development, and management of natural resources. In contrast, the statements appearing in the right column of that table are descriptive of highly *favorable* situations. Hence, to the extent that those descriptions apply in any given instance, there will be *maximum* benefit derived from the use of remote sensing techniques.

While the statements appearing in Table 13 could be improved and expanded upon, they should suffice, even in their present form, to make the desired point in relation to this section of my paper. Remote sensing scientists will, indeed, give far more attention to such considerations in the future than they have in the past, and with the following beneficial result: There will be far less overselling of remote sensing techniques for situations where they are not likely to be successful, and there will be far more extensive and intelligent use of remote sensing techniques in situations where they have the potential for being highly successful.

At the risk of overstating the matter, I will assert that, in the long run, it is the giving of proper consideration to statements and factors such as those listed in Table 13 that is at the very heart of remote sensing technology transfer and acceptance in the years to come. Axiomatically, it also is at the very heart of our attempts during this Study Week to assess the potential benefit of remote sensing, area-by-area, throughout the world's developing countries.

In attempting to set the stage for this Study Week, and mindful of the guidelines that were given me, I have sought in this opening paper to present, in framework form, the major remote sensing-related principles, concepts and considerations. Furthermore, I have attempted, while doing this, to provide the proper historical perspective. Such a perspective should cause each of this Study Week's participants to be appreciative of the rich heritage from which all workers in the field of remote sensing can gain great inspiration. But I would be remiss if, in concluding this

TABLE 15 - *Factors Which Govern the Potential Usefulness of Any Given Type of Aerospace Photography to Those Who Wish to Inventory, Develop and Manage Natural Resources.*

Note: For each of the factors listed in this table an entire "spectrum" of conditions is theoretically possible, ranging from very unfavorable to very favorable as regards its effect on the usefulness of the given type of photography in relation to the inventory, development, and management of natural resources. However, in any given instance, the applicable situation is likely to be well locatable and quantifiable. It follows that, in any given instance, the overall usefulness of this type of photography for the stated purpose will be determinable quantitatively by the aggregated effects of these various factors. Usually, however, a weight will need to be assigned to each factor, in proportion to its estimated importance; hence the aggregated value normally will reflect these individual weights.

1. Area to be analyzed is very *complexly structured* in terms of the criteria appearing in Table 11.	1. Area to be analyzed is very *simply structured* in terms of the criteria appearing in Table 11.
2. *Only photos having a GRD of, say, 10 feet* are available for use.	2. To the extent desired, *photos having a GRD of, say, 10 feet plus* any or all other forms of remote sensing can be used.
3. Clouds *usually* obscure the area that is to be analyzed.	3. Clouds *rarely* obscure the area that is to be analyzed.
4. Remote sensing can only be done on *one date* and at *one time of day.*	4. Remote sensing can be done on each of *many dates* and at *many times of day.*
5. There is *a very long delay* after the photos have been taken before they can be retrieved and placed in the hands of analysts.	5. There is only *a very short delay* after the photos (and other remote sensing data) have been obtained before they are retrieved and placed in the hands of the analysts.
6. Because of *rigid time constraints*, only a "*quick look*" *analysis* can be made.	6. For all practical purposes there are *no time constraints*; hence the making of a *complete data analysis* is feasible.
7. Only *one data analyst is available* and he is inexperienced, poorly trained, poorly funded, poorly equipped, little appreciated, and poorly motivated.	7. *An entire multidisciplinary team of analysts* is available and each of them is well-experienced, well trained, well funded, well appreciated, well supported by consultants (when they are needed), and well motivated.
8. The analysis required is limited to only *one natural resource* and consists of a *one-time inventory* of it in its static state.	8. The analysis required is one which will integrate all components of *the entire "resource complex"*, including renewable resources, and will make *repeated inventories* to monitor them in their dynamic state.
9. The resource classification scheme that is used is of *limited extensibility because* it is *locally specific.*	9. The resource classifciation scheme that is used has *great extensibiltiy* because it comprises one component of an overall scheme that is *globally uniform.*
10. The derived inventory data must be *tightly held* because of sensitivities that relate to the economic or military security of the area under study.	10. The derived inventory data can be made *freely available* to all interested parties without fear of economic or military sensitivities.
11. The *sole purpose* of obtaining the inventory data is to facilitate *resource preservation.*	11. The *multifaceted purpose* of obtaining the inventory data includes the facilitating of *resource development.*
12. *Few funds are available* with which to implement decisions derived from a study of the resource information that has been acquired; furthermore *the decisions, themselves, are suspect* because they were based on inadequate information as to the cost-effectiveness of each of several resource management alternatives.	12. *Very substantial funds are available*, and with them the necessary equipment, engineering knowledge, and local political stability, to ensure that both short-term and long-term benefits will derive from implementation of the resource management decisions; furthermore *the decisions themselves are sound* because they were based on reliable information as to the cost-effectiveness of each of several resource management alternatives.
Note: To the extent that the factors listed in the above column pertain, there will be *minimum* benefit derived from the use of this type of photography in relation to the inventory, development, and management of natural resources.	*Note:* To the extent that the factors listed in the above column pertain, there will be *maximum* benefit derived from the use of this type of photography in relation to the inventory, development, and management of natural resources.

paper, I took only a final, starry-eyed look at this field, around which most of my own professional activity happens to have been centered during the past five decades. Perhaps, as we set out this week to assess the potential usefulness of remote sensing for the developing countries, I should also attempt to summarize, in the cold light of reality, the *practical applications* of modern remote sensing that actually have been demonstrated to date in a cost-effective manner with respect to non-renewable and renewable natural resources (Table 14). Table 15 provides such a summary. That table uses several modifications of the framework that was employed much earlier in this paper as I sought in Table 2 to set forth the *kinds of information sought* through remote sensing by workers in various disciplines. For example, only a few of the "basic research" items listed in Table 2 are also listed in Table 15, since emphasis in the latter table is on practical applications. For each item listed in Table 15, specific practical applications could be cited here. But that

TABLE 14 - *The Value of Remote Sensing-Derived Information About* Non-Renewable *Versus* Renewable *Natural Resources.*

NON-RENEWABLE RESOURCES (e.g., Minerals and Fossil Fuels)	RENEWABLE RESOURCES (e.g., Agricultural Crops)
1. Short-term payoff is potentially very great because of prospects of discovering important resource deposits of great and almost immediate value to the developing country.	1. Short-term payoff is potentially less great because of the smaller immediate economic value to the developing country.
2. Because the resources are non-renewable, and in finite quantities, the long-term payoff steadily decreases and may become less than for renewable natural resources.	2. Because the resources are renewable, the long-term payoff steadily increases and may become greater than for non-renewable natural resources.
3. Desirability of fully exploiting the information through full resource development may be questionable because to do so may lead to early and permanent depletion of the resources. This, in turn, might diminish the birthright or inheritance of succeeding generations, both within the immediate area and throughout the world.	3. Desirability of fully exploiting the information through full resource development is rarely questionable because to do so may lead to steady increase of the resource. This, in turn, may increase the birthright or inheritance of succeeding generations, both within the immediate area and throughout the world.

TABLE 15 - *Summary of the Applications, by Category, That Already Have Been* Cost-Effectively *Made of Modern Remote Sensing Technology.*

Agriculture, Forestry and Range Resources	Land Use and Mapping	Geology	Water Resources	Oceanography and Marine Resources	Environment
Discrimination of vegetative types: Crop types Timber types Range vegetation	Classification of land uses	Recognition of rock types	Determination of water boundaries and surface water area and volume	Detection of living marine organisms	Monitoring surface mining and reclamation
Measurement of crop acreage by species	Cartographic mapping and map updating	Mapping of major geologic units	Mapping of floods and flood plains	Determination of turbidity patterns and circulation	Mapping and monitoring of water pollution
Measurement of timber acreage and volume by species	Categorization of land capability	Revising geologic maps	Determination of areal extent of snow and snow boundaries	Mapping shoreline changes	Detection of air pollution and its effects
Determination of range readiness and biomass	Separation of urban and rural categories	Delineation of unconsolidated rock and soils	Measurement of glacial features	Mapping of shoals and shallow areas	Determination of effects of natural disasters
Determination of vegetation vigor	Regional planning	Mapping igneous intrusions	Measurement of sediment and turbidity patterns	Mapping of ice for shipping safety	Monitoring environmental effects of man's activities (lake eutrophication, defoliation, etc.)
Determination of vegetation stress	Mapping of transportation networks	Mapping recent volcanic surface deposits	Determination of water depth	Study of eddies and waves	
Determination of soil conditions	Mapping of land-water boundaries	Mapping landforms	Delineation of irrigated fields		
Determination of soil associations		Search for surface guides to mineralization	Inventory of lakes and streams		
Assessment of grass and forest fire damage		Determination of regional structures			
		Mapping linears and fracture patterns			

table will have served its purpose if it simply provides a framework for much of our discussion this week on potential applications of remote sensing for the benefit of developing countries.

Despite the seeming comprehensiveness of Tables 10 through 15, and of the voluminous text preceding them, there is one highly important aspect, the *humanistic aspect*, that has been largely omitted. This aspect embraces the spiritual, ethical, cultural, social, and civic values, both positive and negative, that can accrue if modern remote sensing technology is used as an aid to the inventory, monitoring, and management of natural resources, especially in developing countries. That aspect can best be addressed not by me but by the convenors of this Study Week — the Pontifical Academy of Sciences — and indeed the Academy has done so at least broadly on various occasions. For example, the following excerpts (somewhat paraphrased) taken from the Academy's Bulletin No. 44, provide us with some highly germane general insights with respect to this omission in my paper (Pontifical Academy of Sciences, 1979):

> "We deplore the mental attitude that science and faith are opposed... Anyone who tries to fathom the secrets of reality is guided, though unaware, by the hand of God, who, keeping all things in existence, makes them what they are... Thus, the search for knowledge is through two fields of thought, the sacred and the profane, one theological and the other scientific. Truth is one, although it can be arrived at by different paths... Scientific culture, when it abandons its isolation and integrates itself with human culture, brings to the latter great benefits, i.e., values in the spiritual, ethical, cultural, social, and civic realms, for all of mankind".

What, then, do such lofty humanistic thoughts have to do with the potential impact of remote sensing in developing countries? Even among highly respected remote sensing scientists the answers given to that question might be expected to range from a derisive "almost nothing" to a tremulous "almost everything". My own answer would be more in keeping with the second of these views than the first, in that I believe there is a danger of our totally disregarding important values in the "spiritual, ethical, cultural, social, and civic realms" in our great enthusiasm for using remote sensing as an aid to cost-effectively developing (or exploiting for personal gain) an area's natural resources. But even those inclined to give a similar answer must know of complications that can arise as one simplistically seeks to translate humanistic concerns into remote sensing-based action with respect to the inventory, monitoring and management of a developing country's natural resources.

As one broad example of this complexity, we need to consider the dichotomy that is inherent because of the fact that some kinds of natural resources are non-renewable whereas others are renewable. Specifically:

1. As applied to the management of such *non-renewable* natural resources as minerals and fossil fuels, it is clear that our humanistic concerns might prompt us to advocate preserving most of the finite supply of them for use by future generations of mankind. Remote sensing may be very helpful for determining the location and extent of each resource. But it probably is only through humanistic considerations, leading to the preservation of a major portion of the known supply of these non-renewable natural resources, that future generations will inherit, as their legitimate birthright, a fair share of them.

2. As applied to the management of such *renewable* resources as water and timber, however, it probably is not so clear, but a decidedly different philosophy may be called for. Thus even our humanistic concerns might prompt us to advocate the extensive use — even approaching the maximum use — of them, *now*. In defense of this viewpoint, it needs to be pointed out that experience in almost every part of the world has demonstrated the validity of conclusions such as the following with respect to specific renewable natural resources:

a. If this year's supply of fresh water is not used before it returns to the ocean, its potential present benefit is lost forever. Therefore, if our present generation could benefit from more complete use of the water resource, even our humanistic concerns might prompt us to urge the more complete development of dams and reservoirs to temporarily impound the water (still preserving a few wild rivers and natural lakes in their God-given pristine condition); of canals, pipelines, and other aqueducts to distribute the water to those who presently need it; and of hydroelectric plants to generate power for the industrial and domestic use by the area's present population while at the same time *enhancing* the potential usefulness of the water resource for future generations.

b. Similarly, if the present supply of old growth timber is not used before it decays, tree-by-tree, and falls to the ground, its potential present benefit likewise is lost forever. Therefore, if our present generation could benefit from the careful harvesting of most of this old growth timber (still preserving a few stands in their God-given virgin condition) even our humanistic concerns might prompt us to urge the rapid harvesting of such timber, followed by the prompt seeding and/or planting of lands from which it was removed. This would increase the benefit of a nation's timber resource not only to its present population but also to its future generations as well. To realize the validity of this last point, we need to realize that, in keeping with any professional forester's concept of "sustained yield", the wise long-term management of timber resources usually calls for the annual harvest of timber to be approximately the same as the annual *net growth* of timber. The *net growth* is approximately zero in old-growth timber and approaches a maximum, on the very same land, once the old-growth timber has been replaced by a vigorously growing new forest stand.

Thus, in summary, it is my present view, but subject to modification if appropriate as this Study Week progresses, that there is very great potential benefit to a developing country, in both the short term and the long term and from both the economic and humanistic standpoints, that can be derived through intelligent use of modern remote sensing technology for the inventory, monitoring and management of that country's renewable and non-renewable natural resources.

VIII. Conclusion

It is probable that, throughout this paper, I have reflected my own enthusiastic attitude about remote sensing and its very promising potential, just as I have in most of the papers that I have presented on the subject in the past 45 years. In fact, throughout the years I have been accused of, or acclaimed for, "spreading the gospel of remote sensing" by those who either consider me guilty of "oversell" on the one hand, or by those who agree with me that far more beneficial use would be made of remote sensing throughout the world, and especially in the developing countries, if only there were a better realization of the great potential that it offers.

Today, in a mild response to my critics, I will ask: Where better to "spread the gospel" for the benefit of mankind than in an unpressured, unbiased Study Week such as this, blessed by the Pope and presented under auspices of the Pontifical Academy? I suspect that many of the speakers who will follow me share somewhat the same thought — a thought that has prompted me to search my Bible, especially the book of Romans and then to prepare one final, summarizing table (Table 16) for the consideration of this week's attendants. And if, in parallel fashion, there

TABLE 16 - *A Comparison of Two Messages to "The Romans".*

ITEM	MESSAGE No. 1	MESSAGE No. 2
1. When delivered?	1. In the *first* century A.D.	1. In the *twentieth* century A.D.
2. By whom?	2. The God-ordained apostle, Paul	2. This Vatican-convened group of remote sensing scientists
3. Where recorded?	3. In the epistle to the Romans	3. In the published proceedings of this Study Week
4. Proclamation made?	4. It offers the salvation of souls	4. It offers the conservation of natural resources
5. God-ordained action to be taken by mankind	5. Go into all the world and preach the good news (of what is offered through salvation).	5. Exercise dominion over all the world — and subdue it. (With the aid of remote sensing-derived information about natural resources).
6. Promised results	6. Renewal of the soul and assurance of eternal life for the believer	6. Renewal of certain natural resources and assurance of an eternal supply of them
7. Potential beneficiaries	7. All those who hear and heed the message including those in distant lands	7. All those who hear and heed the message including those in developing countries
8. Manifestation of the results	8. The satisfying of mankind's *spiritual* needs	8. The satisfying of mankind's *physical* (material) needs
9. Group best suited to further the message	9. Paul and his fellow apostles	9. The Pope and his Pontifical Academy of Sciences
10. Organizations best suited to "on site" implementation throughout the world	10. Local churches, through their congregations of believers and practicioners	10. Local remote sensing centers, through their staffs of scientists and practicioners

is a final quotation in the light of which the subject matter of my paper should be considered, it is the famous one made more than a century ago by Victor Hugo, the great French scientist and philosopher. I quote it here because it deals with *timing* as does much of my paper, in keeping with its title "Remote Sensing - Past, Present and Future". Victor Hugo said "There is nothing in this world as powerful as an idea whose time has come". His statement suggests that, even if the concept of using remote sensing extensively in developing countries is a powerful idea, we need to consider whether *now* is the time when that idea should be implemented. Hence, consistent with our attempting here to achieve the proper historical perspective, we can at least offer a pair of time-bracketing statements:

1. *A few years ago would have been too early* to implement such an idea because (as can be seen from our historical review) remote sensing technology had not yet been adequately developed, and

2. *A few years hence may be too late* to implement such an idea because (as can be seen from our having expressed the rationale for using remote sensing in developing countries) most of the irreparable damage to the natural resources of those countries, that might have been avoided through its use, already will have been done.

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AIRBORNE REMOTE SENSING TECHNOLOGY

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INTRODUCTION

The opportunity to review airborne remote sensing technologies in the context of this Pontifical Academy of Sciences meeting on "Remote Sensing and its Impact on Developing Countries" is a special treat for me. I have been fortunate in my career to have had numerous opportunities to work in developing countries in an attempt to help bridge the numerous gaps, including technical, political, economic and social, that must be overcome before the full opportunities inherent in airborne remote sensing can be realized by developing country institutions and their scientific and technical staff. My initial assessment of the Academy's overall program led me to conclude that I was being provided an occasion to present a "technology report" on airborne systems. Following discussions with various individuals involved in the planning of this meeting, and incorporating my own views on what are some of the more important issues involved in understanding the "impact of remote sensing on developing countries", I've chosen to limit my presentation to airborne technology *per se.* It is authoritatively discussed and reviewed in many readily available sources, some of which are included here. This, in turn, will allow me to introduce specific topics of discussion where airborne remote sensing, and remote sensing in general, does impact developing countries, and where I hope we spend most of our time and energy in discussions during this meeting.

I will present, therefore, an abbreviated technology report on airborne remote sensing in the first part of this paper, and move on to the "softer" realm of impacts of technology, which, I am personally convinced, are the more critical areas for debate and decision-making facing both the developing and the so-called developed world at this time.

Airborne Remote Sensing Developments

Airborne remote sensing was made possible by numerous inventions and the cumulative knowledge and insight of many well known scientists, and most assuredly, the work of many amateurs. Beginning with the nineteenth century, highlights of this period must include the successful collaborative work of Niepce and Daguerre which gave rise to the "daguerreotype" process, optical lens developments and improvements from many individuals but generally (initially) centered in Germany, and the insight, some would argue boldness, to carry early camera systems into the sky via "stable" platforms. Balloons were the first available airborne systems and Gaspard Felix Tournachon — Nadar — took the first aerial photograph from a balloon in 1858. Other aerial photography experiments with various platforms, from pigeons to kites, all contributed to the fascination as well as the functional aspects of early aerial remote sensing technology developments.

Airborne remote sensing, as a practical endeavor, was made possible through the invention of the airplane, since this allowed the pilot to direct the aircraft, and hence the onboard camera or other sensors, to specific locations in order to complete the mission. Wilbur Wright is a notable pioneer in the field by virtue of his work, both in designing and building airplanes, and by virtue of the fact that he took the first photographs via an airplane in 1909 over Centocelle, Italy. By World War I, aerial photography was a technology available to virtually all the combatants.

Wartime surveillance needs have historically played a key role in developing new technologies and/or improving existing systems. By the end of World War II a vast array of films, both black and white and color, and camera systems were available. Airborne radar systems had been developed, and even color infrared film was about to become available. One should also not overlook the developments related to mapping, photogrammetry, and photointerpretation that came along as well.

Public policy in the United States in the first third of the twentieth century, and elsewhere as well, also contributed to improvements in operational airborne remote sensing. The United States Department of

Agriculture initiated a comprehensive land use and crop survey program in the 1930's utilizing aerial photography, and the U.S. Geological Survey provided similar interest and support for mineral resource exploration activities. This latter field was also aided by private sector interests to discover and exploit fossil fuels, minerals and other valuable resources. Other public planning agencies and missions also contributed to a demand for information and products from airborne systems. This is especially notable in the fields of planimetric and topographic mapping, forest resource assessments, and highway planning.

In the past twenty-five years the widespread interest in understanding complex environmental systems has also fostered new airborne research and operational technologies. These include, for example, the multiband camera, the multispectral scanner, various active and passive microwave systems, and more recently, airborne video systems. An all digital airborne synthetic aperture radar (SAR) system is now being flown in a small, twin engine airplane, that only five years ago would have required an airplane at least two or three times as large.

At this point in time there is a rich and varied collection of proven platforms and sensors that have benefitted from and been perfected for a wide variety of applications. Depending upon one's requirements — and hopefully this will be a principal topic of discussion at this meeting — one can efficiently employ airborne systems ranging from something as straightforward as a hand-held 35 mm camera all the way up to a very sophisticated SAR system, so that airborne remote sensing technologies should clearly be appreciated as a family of well thought out, tested, and proven systems for literally countless requirements. This meeting will introduce and review many of the major earth science fields that can greatly benefit from these technologies, and yet I must now say, by way of introduction to the second part of my paper, that airborne remote sensing technology is not being used very effectively in developing countries, and I wish to examine some of the issues contributing to this situation.

Developing Country Impacts - Some Issues

If developing countries wish to capture the full benefits of airborne remote sensing — and here we might as well shift and simply say remote sensing — then current policies and attitudes must be evaluated and perhaps redefined into operationally (politically) acceptable terms so that both individuals and institutions are free to use contemporary technologies in the most advantageous ways.

Many developing countries are continually preoccupied with both internal and external threats to their territorial security, and to the intrinsic nature of their sovereignty and rights as nations. For governments involved in real threats to public order, the very nature of remote sensing, that is, information and the power which that information implies, is viewed skeptically even if tolerated at all. In fact, a full vision of the potential of remote sensing, whether airborne or from space, is potentially very intimidating to all but the most secure and stable institutions. While I do not wish to examine this particular issue in much further detail, I think it is vital for all those interested in using remote sensing to consider the specific dilemmas it presents to those who would use it.

The member states of the United Nations have been debating the central theme of open skies versus sovereign rights since the early 1970's, and as of this moment there is still no agreement on the terms and conditions under which space-based remote sensing can and should be employed. While the debate involves positions that are very difficult to properly define here, there is clearly a debate over whether a state has a right to collect data over another state from space without prior consent, and also whether the collected information can be freely distributed to third parties without the consent of the sensed state.

While the debate has been long and difficult, and some would claim foolish since there has been no consensus, the issues are nevertheless very important. Sovereign states do and should enjoy control over their territorial assets. Airborne remote sensing can be disciplined in a manner that suits individual state needs, since airspace and aircraft operations are readily controlled by state institutions. Very restrictive policies are in force in many nations, and these policies emanate from varied political structures. What is interesting to note, moreover, is that current space-based systems, Landsat and SPOT, are both generating data of a quality and detail (resolution) that exceed the allowable practice via airborne systems in many individual countries. While space-based remote sensing has not made current policies obsolete *per se*, it has or it will force many countries to reexamine their positions in light of the real change that these kinds of technological developments represent. And the use of space-based systems as a vantage point for data gathering will continue into the foreseeable future, putting additional pressure on existing policies which restrict airborne remote sensing operations.

It is also true that there are other situations which are clearly limiting the full use of airborne remote sensing in developing countries.

Cost is a real issue and, no matter how inexpensive remote sensing ever becomes, the decision to finance airborne remote sensing operations will always have to be justified in an environment of limited funds and with many other important demands on those funds. Having the necessary equipment and facilities goes hand in hand with the costs of conducting airborne remote sensing operations, and it can be argued that limited facilities and training have acted as a brake to full exploitation of airborne remote sensing systems in developing countries. In Latin America, for example, this author has confronted situations where a single agency, generally a military one, is the only authorized airborne data collection source available, and if one has a mission plan approved, the unusually high costs charged by these agencies (as a state authorized monopoly) clearly inhibit the full utilization of available technology.

There is another element of this issue that often goes unnoticed, and that is the phenomenon of "technology leap" that I have observed in the developing world. Many developing countries "discovered" contemporary remote sensing in the early 1970's following the successful deployment of Landsat 1. There was a rush by many foreign institutions to get involved with satellite-based systems and, in the process, the proven technological environment of airborne systems was simply overlooked and/or bypassed in a rush to develop new national remote sensing programs based upon Landsat. This has proven especially unfortunate since satellite-based systems were conceived as a logical and complementary element to existing technology (airborne). As such, satellites represented a natural extension of a whole series of technologies, and thus the decision to build space-based remote sensing programs, without the necessary and integral benefits of airborne systems, is conceptually and methodologically weak. To put it more succinctly, satellite-derived data has in many instances *increased* the need for airborne-derived data in order to realize the true benefits of space-based data. So my so-called "technology leap" does not imply a successful move, quite the contrary.

There are many other elements to the current debate on remote sensing systems and their implications when viewed from varied political or cultural settings, which could be introduced here.

I would state categorically that remote sensing at one point is an extremely democratic notion in concept and in practice, and yet a powerful intrusion on our personal and collective freedoms as well. Those who are attracted by its benefits, whether real or imagined, will have to face these dimensions of the technology sooner or later. Users in both the developed and developing world who are capturing measurable benefits from remote sensing are beginning to appreciate this dilemma to the technology and have accommodated it in light of their local circumstances. That is to say they have accepted the notion that information and its use is, and ought to be, a good, freely and openly used in our daily lives. This is not to say that sovereign nations do not have the right to enforce their own patterns on who, when, where and how it will be used, because they should. But it should be understood that remote sensing offers both opportunity and risks.

The recent events surrounding the unfortunate accident at Chernobyl offer a glimmer of the future that is before us. The daily television broadcasts of Thematic Mapper images perhaps added little to our information on the tragedy taking place on the ground, but the surveillance opportunity afforded us by virtue of Landsat's presence in space was a stark reminder of how this technology is changing the very way we have, up to now, been free to act.

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SATELLITE DATA COLLECTION SYSTEMS: ASPECTS AND PROBLEMS

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1. Introduction

This paper intends to describe the fundamental aspects and problems related to the reception, recording and archiving of data originated by space-borne remote sensing instruments.

The paper will consider, as case studies, both present remote sensing systems and those foreseen in the near future, i.e., the next 10-15 years.

After a brief introduction to satellite and instrument types, attention will be directed to the ground systems required for acquisition, recording and archiving. Some examples are provided, and the various options envisaged for acquisition stations and archives are analyzed.

An important and strictly related problem is briefly addressed here: the data distribution and dissemination problem which may severely impact on the availability and usefulness of data to users.

2. Data Collection from Remote Sensing Satellites: Aspects and problems

Satellites

Remote sensing satellites address a wide range of application fields, from meteorology to land use monitoring. They can nevertheless be classified in two basic type classes:

— geostationary
— low orbiting

The geostationary satellites are mainly dedicated to the observation of meteorological phenomena:

— winds

— sea surface temperatures

— cloud coverage, cloud top height, etc.

They are characterized by a global view of a large part of the earth's surface, and by a high frequency observation cycle (one image every half hour typically). A system of four geostationary satellites ensures full coverage of most of the globe except polar regions (Figure 1).

Low orbiting platforms observe the earth from altitudes varying from 300 km (e.g., space shuttle) to 1000 km (Nimbus type satellites). They usually serve a large variety of applications, both of a scientific or experimental nature and of an operational nature.

Consequently a large variety of sensors may be and actually are mounted on these platforms. While a geostationary satellite is in permanent visibility of a ground station, normally fully dedicated to the task of data acquisition and processing for that particular satellite, low orbiting satellites are visible from ground stations only in correspondence to specific areas of the globe (Figure 2). This paper will only briefly review the geostationary satellite problem and will concentrate on constraints imposed by low orbiting platforms and the related solutions.

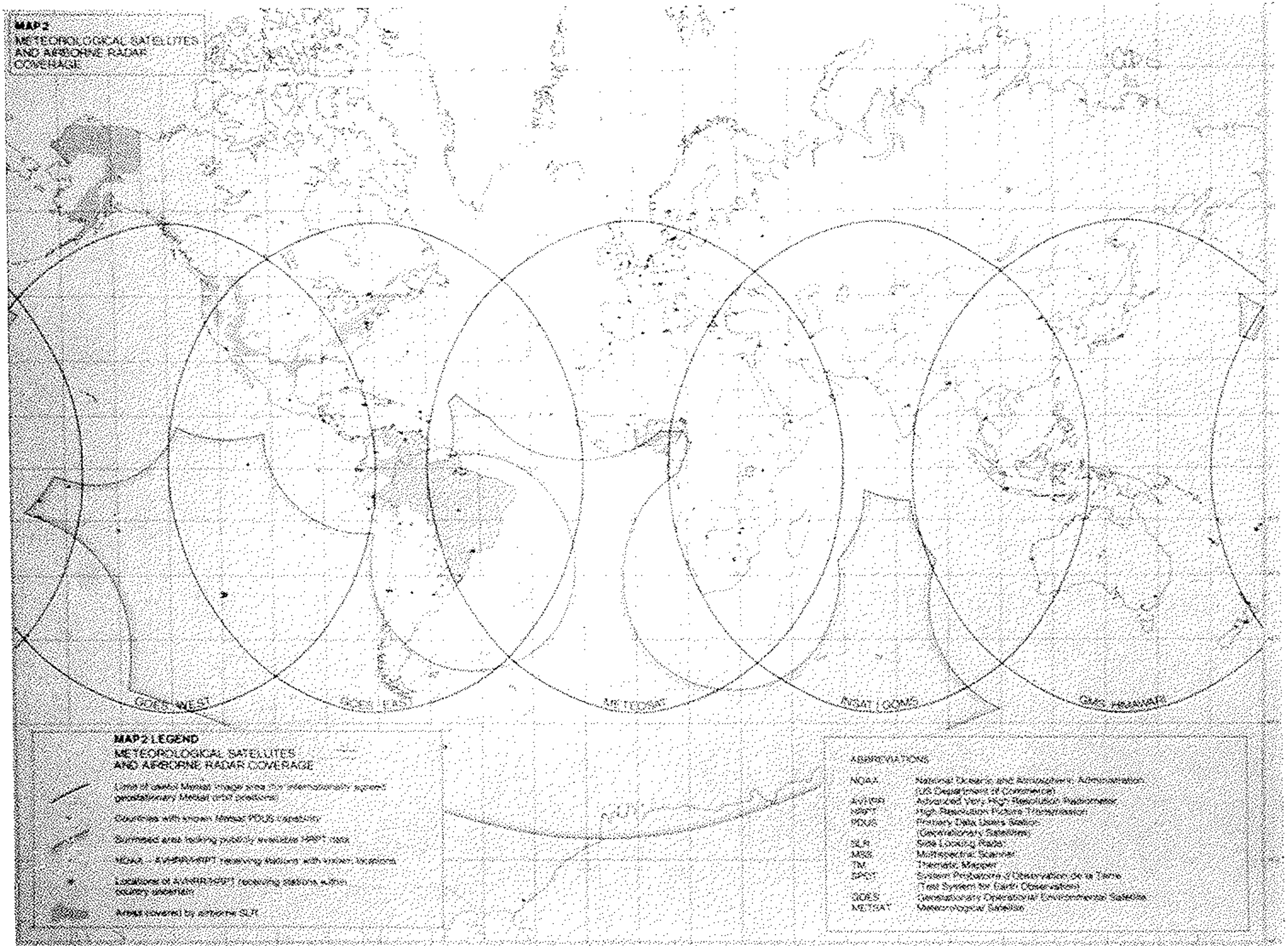
Instruments

Geostationary Meteorological Satellites - The classic instrument for these satellites is a radiometer, with two to three spectral channels in the visible and in the infrared. The ground resolution is of the order of a few kilometers (1 to 5). Typical data rates range from 100 to 300 kbits/sec. These satellites operate on a 24 hr. basis.

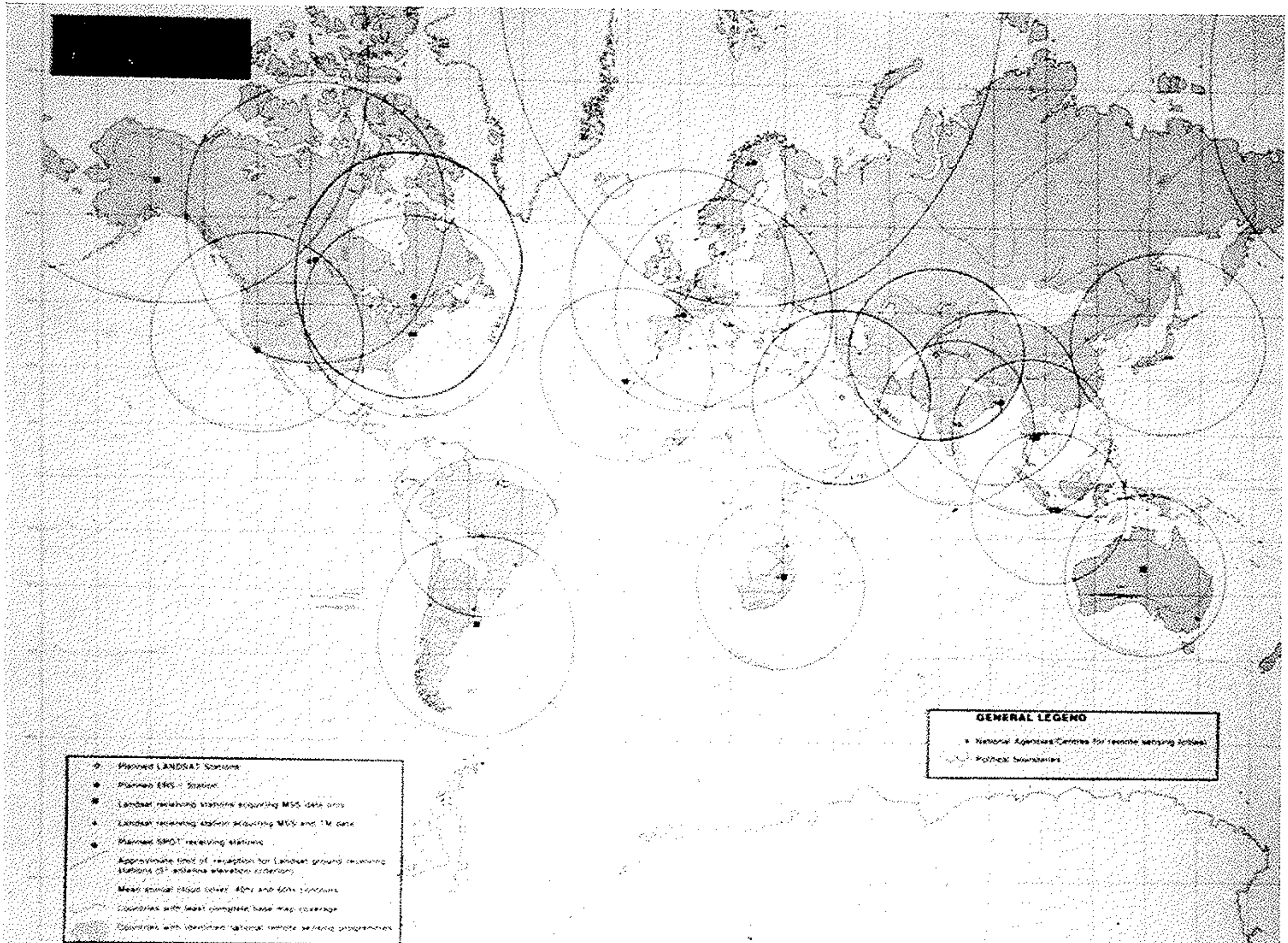
Low Orbiting Platforms - The instruments mounted, or planned to be mounted, on these platforms, constitute a large variety of remote sensors and are quite representative of the different ways in which man looks at his planet and environment.

Working by examples, Figures 3 to 5 present in brief the characteristics of the instruments mounted on three typical platforms:

— Landsat


MAP 2
METEOROLOGICAL SATELLITES
AND AIRBORNE RADAR
COVERAGE
GOES WEST
GOES EAST
METEOSAT
INSAT / GOMS
GMS HIMAWARI
MAP 2 LEGEND
METEOROLOGICAL SATELLITES
AND AIRBORNE RADAR COVERAGE
Areas covered by airborne SLR
ABBREVIATIONS

[redacted]



Planned LANDSAT Stations
Planned ERS - 1 Station
Landsat receiving stations acquiring MSS data only
Landsat receiving station acquiring MSS and TM data
Planned SPOT receiving stations
Approximate limit of reception for Landsat ground receiving stations (5° antenna elevation criterion)
Mean annual cloud cover: 40% and 60% contours
Countries with least complete base map coverage
Countries with identified national remote sensing programmes
GENERAL LEGEND
National Agencies/Centres for remote sensing activities
Political Boundaries

— Nimbus
— ERS-1

The instruments can be broadly classified into three categories as far as data rates are concerned:

— Low Bit Rate : 5 Mbits/sec
— Medium Bit Rate : 10 to 20 Mbits/sec
— High Bit Rate : 50 Mbits/sec and above.

Power constraints can influence the operational window of the instruments on a per orbit basis and on a daily basis. In particular, passive sensors operating in the visible and infrared spectrum can operate for a higher percentage of time than active sensors (radars) in the microwave domain. Symmetrically, the latter sensors can operate under all weather conditions, while passive optical instruments are affected by clouds which make useless for surface surveying as much as 50% in average of the captured data (the percentage is of course much higher over specific parts of the globe: northern countries, equatorial areas, etc.). Also the operations are constrained by the particular application for which the sensors are designed, e.g.:

— high data rate sensors are typically those which have higher spatial resolution on the ground (10-30 m) and are generally dedicated to land applications. With the exception of Africa, most land masses are within coverage of ground stations. But Synthetic Aperture radars (SAR: up to 7 m resolution on the ground, generating up to 120 Mbits/sec.) are extremely useful in oceanographic application and most ocean waters are out of the coverage of any ground station. This will obviously limit the SAR operations for ocean monitoring purposes to such areas as the North Atlantic.

Looking towards the time frame 1990-2000, sensors are going to be designed with higher data rates: one could think, in modular terms, of future instruments being equivalent to 2, 3 or more (10?) of the present instruments combined together, with the data rates multiplied accordingly, e.g.: a dual frequency radar would be equivalent, as far as data rates are concerned, to two one-frequency radars; an imaging spectrometer could be the equivalent of ~ 10 Thematic Mapper data streams.

LANDSAT 5 MAIN FEATURES

The satellite operates in a repetitive, circular, sun-synchronous, near-polar orbit at a nominal altitude of 705.3 km. The orbital period is 98.9 minutes. It completes 14-9/16 orbits per day and views the entire Earth every 16 days:

Orbital Parameter	*Value*
Semi-major Axis (km)	7086.127
Inclination (deg.)	98.252
Period (min.)	98.940
Time of Descending Node Equatorial Crossing (local time)	9:39 AM
Coverage Cycle Duration	16 days (233 revs)
Distance Between Adjacent Ground Tracks at Equator (km)	171.5

THEMATIC MAPPER BANDS AND APPLICATIONS

The TM sensor collects radiometric data in seven spectral bands. It offers a ground resolution of 30 by 30 meters in the six bands of the visible and the infrared, and 120m by 120m in the thermal IR channel.

Band	*Spectral range*	*Application*
1	0.45 - 0.52 μm	Water body penetration, coastal water mapping, differentiation of soil from vegetation.
2	0.52 - 0.60 μm	Measurement of visible green reflectance peak of vegetation for vigor assessment.
3	0.63 - 0.69 μm	It is a chlorophyll absorption band useful in discriminating vegetation.
4	0.76 - 0.90 μm	Determination of biomass content. Delineation of water bodies.
5	1.55 - 1.75 μm	Determination of vegetation moisture content and soil moisture. Differentiation of snow from clouds.
6	10.40 - 12.50 μm (thermal infrared)	Vegetation stress analysis. Soil moisture discrimination, thermal mapping.
7	2.08 - 2.35 μm	Discrimination of rock types. Hydrothermal mapping.

TM VERSUS MSS

	TM spectral data		*MSS (Multi-Spectral Scanner) data**	
Band	Spectral range, μm	Radiometric resolution, NE_p	Spectral range, μm	Radiometric resolution, NE_p
1	0.45-0.52	0.8%	0.5-0.6	0.57%
2	0.52-0.60	0.5%	0.6-0.7	0.57%
3	0.63-0.69	0.5%	0.7-0.8	0.65%
4	0.76-0.90	0.5%	0.8-1.1	0.70%
5	1.55-1.75	1.0%		
6	10.4-12.5	0.5 K NETD		
7	2.08-2.35	2.4%		

NE_p = Noise equivalent reflectance. NETD = Noise Equivalent Temperature Difference.

Fig. 3

THE NIMBUS-7 MISSION

- Satellite launched in October 1978.
- Data acquired and pre-processed at Lannion (France) and Maspalomas (Canary Islands) Stations from April 1979 and from September 1984, respectively.
- As of December 1984, acquisition and pre-processing is concentrated at Maspalomas.
- Earthnet's involvement in the NIMBUS-7 mission is limited to Coastal Zone Colour Scanner (CZCS) instrumentation. Scanning Multichannel Microwave Radiometer (SMMR) data acquisitions are carried out on request only.

Spacecraft Parameters

Orbital altitude:	955 km
Orbital inclination:	99°
Orbital period:	104 min. passing equator at 12.00h mean solar time
Number of orbits per day:	14
Resolution:	825 km × 0.825 km at nadir (sea level)
Swath width:	1566 km

The Payload

CZCS	Coastal-Zone Colour Scanner
ERB	Earth Radiation Budget
LIMS	Limb Infrared Monitor for the Stratosphere
SAM-II	Stratospheric Aerosol Measurement (II)
SAMS	Stratospheric and Mesospheric Sounder
SBUV	Solar and Backscatter Ultraviolet Spectrometer
TOMS	Total Ozone Mapping Spectrometer
SMMR	Scanning Multichannel Microwave Radiometer
THIR	Temperature Humidity Infrared Radiometer

The CZCS instrument is devoted to ocean and coastal-zone water monitoring.

The CZCS Experiment is designed to measure water colour and temperature providing quantification and qualification of suspended materials.

FIG. 4

ERS-1 — THE FIRST ESA REMOTE SENSING SATELLITE

- Presently Under Development, Scheduled for Launch the Last Quarter of 1989.
- 10 Esa Member Countries Participate to the Programme, Plus Austria, Norway and Canada.
- Mission Objectives:
  - To Increase the Scientific Knowledge of the Ocean, Coastal Zones Processes and Climate
  - To Develop and Promote Applications of Microwave Remote Sensing Data
- Main Feature: Quick Delivery (Within 3 Hours from Sensing) of the Following Products:
  - Wind Field
  - Wave Spectra
  - SWH (Significant Wave Height)
  - Sar Imagery of Selected Areas

ERS-1 ORBIT:

— Sun-Synchronous, Circular

— Height Around 777 km (Depending on Orbital Cycle)

— Local Solar Time at Descending Node: 10h30'

— Ground Track Repeatibility Within ≠ 1 km

— Reference Orbit: 3 Days Repeat Cycle up to 6 Demonstration Orbits are Foreseen with Repeat Cycles 7, 11, 17, 20, 29 and 35 Days

THE LBR SENSORS:

Wind Scatterometer - It measures the wind field with 50 km resolution and 500 km swath.

Wave Scatterometer - It measures wave spectra in 5×5 km regions at 200 km sampling intervals.

Radar Altimeter - It measures ocean and ice topography plus SWH (Significant Wave Height) and wind speed at nadir.

Along Track Scanning Radiometer/M - It measures SST (Sea Surface Temperature) with 1 km resolution and 500 km swath and water vapour content at nadir.

SAR SENSOR:

C-Band, VV Polarisation, 100 km Swath, 30 m resolution.

FIG. 5

Communications to the Ground

As previously stated, a remote sensing satellite will transmit information to the ground only when in visibility of a ground station. Geostationary satellites can therefore operate 24 hours a day. Low orbiting platforms would have to limit their operations to those portions of the globe which are "seen" by their sensors while the satellite is in visibility of ground stations. Since zones of interest do not coincide necessarily with station coverage areas, two solutions have been found and largely applied:

— data recording on on-board tape recorders

— use of transmission channels by geostationary data relay satellites (Figure 6).

On-Board Recording - For data rates up to 25 Mbits/sec, recording is presently possible on-board (e.g., the French SPOT satellite can record

BLOCK DIAGRAM OF FUCINO LANDSAT STATION
ACQUISITION AND PROCESSING CHAIN

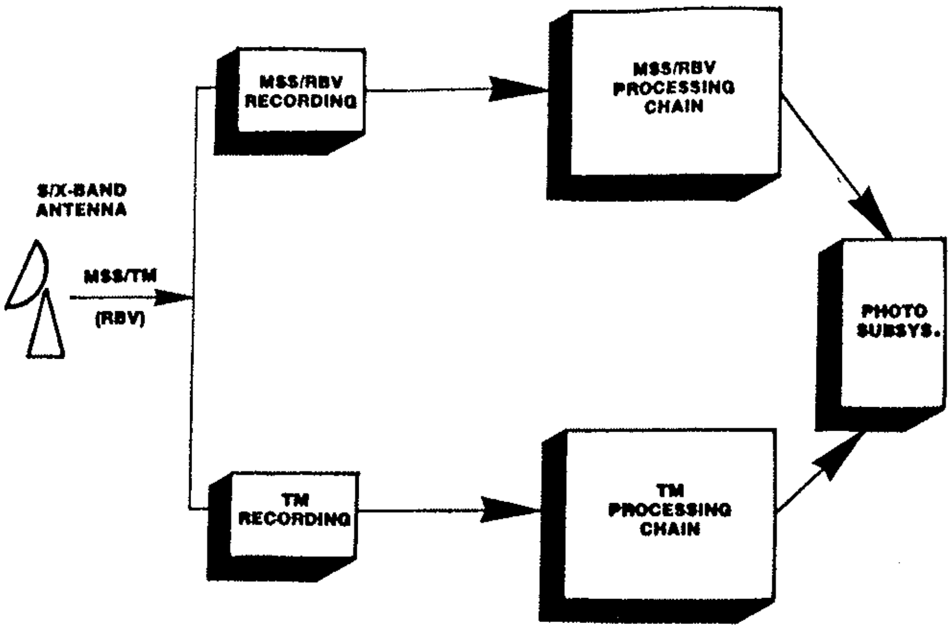


FIG. 6

up to 50 Gigabits on-board, corresponding to about 20 minutes of operations of the two sensors (~ 24 Mbits/sec each).

The scenario can therefore be presented as follows:

Today: Data from sensors with rates of up to 25 Mbits per second can be recorded on on-board tape recorders, allowing therefore operations outside the visibility of ground stations.

The data will then have to be played back to the ground when the satellite is in visibility of a station.

Future: Increased on-board recording capability (100 Gbits, perhaps more) will allow accommodation of higher through-put instruments, or larger operating times outside station visibility.

On-board recording will still be constrained by the playback of the tape recorders when in visibility of a station; visibility has a limited duration for each orbit (800 secs. maximum for SPOT, ~ 10 mins. for ERS-1). If substantial data quantities are recorded on-board, these have to be transmitted to the ground during these short periods and therefore necessitate once again high data rate links. Example: the ERS-1 low bit rate sensors (altimeter, wind scatterometer, wave scatterometer) have real-time data rates which sum up to ~ 1.5 Mbit/sec. When played back from the on-board tape recorder (6 G bits capacity) during a station overpass, the link has to accommodate 15 Mbit/sec., i.e., a factor of ten.

Data Relay Satellites - The data relay satellite scheme is based on a telecommunication satellite, or better, a set of satellites, placed in geostationary orbit. They are positioned, ideally, in such a way that the remote sensing low orbiting satellite is, in any orbital position, in visibility of one of them. The data are transmitted to the relay satellite and then retransmitted, through one or more channels, to the ground station which is permanently assigned to the relay satellite. Data can also be transmitted from one relay satellite to the other, in order to arrive at the ground station dedicated to their reception.

The system is obviously complex: full earth coverage by the Landsat satellites will be ensured only with the availability of 3 TDRSS type satellites, which also ensure full coverage of Shuttle missions and others.

The allocation of channels for the relay may become critical. Modularity will probably be the key for future systems: a reasonable high number of channels of different capacity, allocated to different data streams, e.g., 2 × 100 Mbits/sec. channels for a dual frequency SAR; 2 × 25 Mbits/sec. channels for two SPOT type instruments.

Along these lines, the European Data Relay Satellite System is being studied, and is planned to be available in 1993.

Acquisition Stations - Depending on the acquisition strategy selected (direct transmission, on-board recording, use of a data relay satellite), the location, number and size of ground stations may change.

In general they will all include receiving equipment (antenna(s), amplifiers, etc.) and recording equipment (tape recorders, etc.) in the front line. A typical scheme is in Figure 6. Since a long time, growing data rates no longer allow direct data input to computers for further processing; this is instead still possible for geostationary meteorological satellites.

Antennas may vary in size and cost, depending on the characteristics of the link. They also have different dynamics characteristics, depending on whether they are looking at a fixed spot (geostationary satellite) or they have to follow a rapidly moving low altitude satellite.

Location of an acquisition station for a low orbiting satellite is critical if only direct transmission is foreseen. It has to be at the center of the area from which it is intended to acquire data.

In case of on-board data recording, the case is less critical, but the location must be selected so as to allow playback from a maximum number of orbits. If the satellite operating agency intends to have exclusive access to on-board recorded data, it will have to ensure visibility of the satellite for a sufficiently long time and a sufficient number of orbits per day to allow playback of all data intended for recording. This is not always possible: the playback of the ERS-1 data required for the global oceanic coverage ($\sim$65 mins. per orbit) needs the use of three permanent stations (Kiruna, Maspalomas, Gatineau) and the occasional support of a fourth one. In this case too the satellite operators will have to rely on a ground system composed of multiple stations. We will later analyze the consequences of such complex networks.

The presence of a data relay satellite drastically alters the picture. From a purely logical viewpoint the possibility of a unique centralized ground station becomes a possibility. Nonetheless, a careful analysis of the implications of such a solution and its impact downstream on archiving and processing of data has to be performed. Appropriate trade-off criteria have to be established versus a decentralized option.

The analyst in this case has to take into account:

— the different type of services required from a user's viewpoint;

— the possibility that a data relay system, eventually made up of several satellites, may serve more than one remote sensing platform, and therefore instruments with substantially different characteristics;

— the consequent complexity in terms of equipment and operations required by the ground station;

— the possibility that, with the advent of more advanced platforms, increasingly complex instruments or a combination of instruments, are going to be flown.

As a consequence, for missions of little complexity, with well delimited objectives, the option of a centralized acquisition station takes precedence. When the complexity of the payload and those of all mission aspects, increases, the concept of a network within the footprint of the data relay satellite channels might have considerable advantages.

From an operational and technological viewpoint, an aspect of high interest is the recording subsystem. Data transmitted from the satellite have to be recorded in order to be later processed, and archived. Recording takes place today on high density tapes. Advantages are:

— high capacity,
— reasonably high recording speed,
— lower and controlled playback speed.

Disadvantages are:

— sequential access,
— high cost of tapes,
— difficulty of using the same recorders for different data rates,
— limited suitability as an archive medium.

Recording technology is evolving rather rapidly, and new media might be available in the next decade. They should be evaluated separately in terms of their suitability for recording data transmitted from satellites (high speed, dedicated recorders), and for archiving (efficient retrieval, low error rate, easy maintenance, low cost of media).

Archives

Recorded data have to be archived.

Processed data also have to be archived. If all data have been processed, raw data, as transmitted from a satellite, may not be archived, but it is generally preferred to preserve them. Media and equipment used for recording data incoming from satellites are often not the most suitable for long-term archiving and for efficient retrieval. The High Density Tapes, though used also for archiving in many cases for economic reasons, are far from being appropriate.

Again, technology may offer the answer in a reasonably short time. In any case some requirements are evident for remote sensing archives, however implemented:

— long-term storage with extremely low error rate of very large data quantities

— capability to accommodate both raw data and various levels of processed data

— capability to accommodate in an organized manner data originated from remote sensing instruments of a different nature, flying over the same or different platforms

— easy referencing systems ("catalogue"), accessible to a variety of users

— effective retrieval procedures, in particular in cases which require access to multisensor data sets

— capability to incorporate data other than those originated by remote sensing systems (ground collected information, statistics, administrative information, etc.).

Archives are going to be most likely distributed: each satellite operator is going to have a primary archive for his own satellite; each country is most likely going to maintain its own data base of administrative and ground truth information (e.g., digital terrain models, urban development plans, etc.).

The above requirements, in particular the last two, must be understood in the sense of:

— compatibility of access to catalogues and referencing systems,

— compatibility of information (products, data sets) in output from different archives.

Several international committees work in this direction, covering subjects like:

— standardisation of remote sensing product format

— standards for remote sensing product definition

— archive support media compatibility, etc.

Data transmission and recording pose challenging technical and operational questions, but archive organisation is going to be a rather more severe obstacle to the exploitation of the potential deriving from the integration of today, and tomorrow, remote sensing systems.

Data Distribution

Remote sensing data, after acquisition and recording, are processed in order to reduce them to a form more directly suitable for subsequent applications. This can be done in real-time, immediately after acquisition (ERS-1), or in delayed mode. Processing can also be systematic, on all acquired data (ERS-1, to a certain extent, Landsat in U.S.) or performed on request (Landsat in Europe).

In all cases processed data sets ("products") may be archived, but have also to reach some "user" for application or research purposes.

Mail may be suitable in some cases, but certainly is not when:

— a fast response is required, e.g.: real-time products, in particular those of interest for meteorological forecasts, crop monitoring data, etc.;

— data have to reach units on the field, often in not well served areas.

Ground and satellite-based digital links can provide the answer, but when important data quantities are involved, some limitations arise in standard networks:

— limited link capacity (in practice not above 1 Mbit/sec. over satellite channels)

— not satisfactory access time

— high cost.

Concepts of dedicated networks are being investigated (e.g., for ERS-1 fast delivery product distribution); the international nature of these networks, even at the European level, makes the technical definition problematic and the assessment of costs difficult.

3. Conclusions

Taking a global view of the picture of remote sensing systems today and in the foreseeable future (5-10 years), it can be stated that an impressive amount of high quality data is going to be generated by a multitude of sensors. The whole world is going to be covered, many and many times, every year by different instruments providing information on vegetation, soils, urban environment, atmospheres, oceans, ice caps, coastal areas, etc.

This impressive amount of information can, in several ways, as we have described, be collected on the ground. Processing systems have sufficient capacity to handle these data within adequate response times.

The bottleneck seems to be located at the level of the availability of these data to users, both via efficiently organised and coordinated archives, and by the use of effective distribution networks. National and international organisations, interested in the functional and operational application of this source of information can play a key role at this end of the system.

DATA ANALYSIS TECHNOLOGY

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ABSTRACT

Image analysis is an everyday activity of human beings. It is an essential process through which information is obtained from image data. Methodology or techniques facilitating the acquisition of accurate and reliable information, when identified and used would make difficult tasks easy. Principles of image analysis include methods for detecting, identifying, and measuring objects of interest from the aerial perspective. Image data may be obtained by special sensors sensitive to a particular electromagnetic spectrum. These sensors are categorized into photographic and non-photographic ones, depending on the medium used for recording the image data at the time of sensing. Image data is an important record in which all information is captured at the instant of sensing. It is necessary, then, that all the information be extracted from the image data and used to answer any questions of interest. The procedure for extracting accurate and reliable information from image data has been an important undertaking of military and civilian sectors of both developed and developing countries for a long time. Generally there are two approaches to image data analysis, namely, visual (manual) image analysis, and digital (machine-assisted) image analysis. Visual image analysis has been based on conventional photo interpretation. Methodology and necessary requirements for visual analysis have been clearly spelled out very well and there is not much room for improvement. Digital image analysis uses a similar approach and line of reasoning to

that of visual approach but they differ in data format being analysed, one being photographic and the other digital. Digital image analysis requires specialized knowledge and equipment for making analysis, display and permanent record, while the visual approach requires less sophisticated ones, but both require an experienced analyst or interpreter in order to yield accurate and reliable results.

Data analysis in the context of remote sensing technology has been intensified in wartime, especially in the developed countries. Civilian applications have increased recently. Digital analysis has made a leap forward due to new development in sensor-platform combinations yielding a large amount of data to be analyzed, and the development of computer hardware and software to handle these data.

1. Introduction

By definition, remote sensing is the art and science of obtaining information about an object or phenomenon from a distance by a sensor not having physical contact with that object or phenomenon. Obtaining information involves acquisition of image data and the analysis of the data in question to arrive at the right information in a usable format. Information contained in image data is valuable if available in a timely manner and for the subject of interest. For civilian purposes, information about a country's resources with respect to quantity, quality and location is vital for that country's economic planning for development. Because of its importance, image data analysis will be looked into in this presentation. There are two approaches to image data analysis, namely visual and digital means.

In the visual analysis approach, human perception is highly regarded as one of the factors for obtaining reliable information. It is along this line that methodology or techniques for visual analysis will be looked at from a conventional point of view and from the practice in some of the countries in the region. Digital image analysis requires specialized knowledge and equipment to carry out the process. Recently, this approach has been widely used even in developing countries. This is mainly due to the development in developed countries pushing satellite remote sensing and the digital analysis approach. Activities in developing countries have also been put in the same direction. This paper presents some of the activities in this area in developing countries.

2. Visual Image Analysis

Visual or manual image analysis makes use of human visual perception. Visual perception refers to the process whereby visual sensory stimulation is translated into organized experience. The way that humans perceive objects and phenomena can be used as a basis for analysis.

Generally, image analysis begins with the detection and identification of important objects. The objects may then be measured manually or with the aid of appropriate instruments. Measurements can then be followed by consideration of the objects in terms of information from the interpreter's special field of knowledge in a problem-solving context. The interpreter must then be able to communicate both his perception of objects and the significance of the objects. Figure 1 indicates the conceptual framework of image analysis.

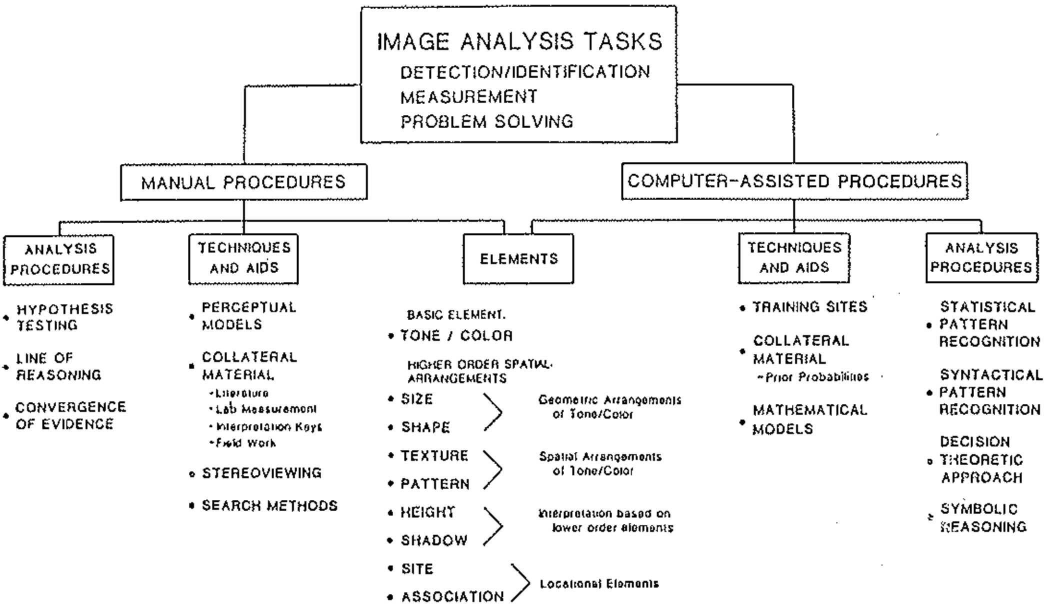

Fig. 1. Conceptual Framework of Image Analysis. A broad conceptual framework, or paradigm, by which human and computer-assisted image analysis procedures can be compared and contrasted. After tasks and basic elements, the two approaches diverge significantly, although analogs of the manual procedures can be seen in the more advanced computer-assisted procedures. (*From Manual of Remote Sensing*, Vol. 1, 2nd Edition).

Elements of Visual Image Analysis

Remotely sensed data represent energy reflected, emitted, transmitted, and scattered from many regions of the electromagnetic spectrum. The data may be recorded in many shapes, sizes, and scales. An understanding of the basic elements of image interpretation is essential to the efficient and effective use of these data. Inherent elements within an image that can provide an image analyst clues toward detection, identification, measurement, and problem-solving tasks of image analysis include: tone/color, size, shape, texture, pattern, height, shadow, site and association. A brief description of the mentioned elements is in order.

— *Tone and color*: Color perception is an important element of awareness of the environment. Different objects reflect, emit, and transmit different amounts of wavelengths of energy. These differences are recorded as either tonal, color, or density variations on an image. The difference in tone or color between objects, or between an object and its background leads to detection of the object. Tones and colors of objects are major clues to their identity or composition.

— *Size*: The size of an object is one of the most useful clues to its identity. By measuring an unknown object on an aerial photograph, the interpreter can identify various features or objects.

— *Shape*: The shape or form of some objects is so distinctive that their images may be indentified solely from this criterion. Shape delimits the class of objects to which an unknown must belong and it frequently allows a conclusive identification and aids in understanding of its significance and function.

— *Texture*: Texture, the visual impression of roughness or smoothness, is a valuable clue in interpretation. This can be especially true when analyzing side-looking airborne radar data and imaging passive microwave radiometry in which texture plays an important role in differentiating various classes of environmental phenomena.

— *Pattern*: Pattern, or repetition, is characteristic of many manmade objects and of some natural features. Some patterns in our environment are primarily cultural; others primarily natural. There are, however, few parts of the world that have not been affected by man, and most of the patterns visible from aerial perspective result from the interaction of natural and cultural factors.

— *Height*: Identification and detection of objects can be achieved by examining a single image which provides two-dimensional perception, length and width. A third dimension, height, will be an added advantage in identifying objects, which is the purpose of image analysis.

— *Shadow*: Shadows are familiar phenomena. In life we often judge the size and shape of objects by observing the shadows they cast. Shadows help the interpreter by providing a profile representation of objects. If objects are small or lack tonal contrast with their surroundings, sharp boundaries and shapes of shadows enable the analyst to identify objects at the threshold of recognition.

— *Site*: The location of objects with respect to terrain features or other objects is often helping in their identification.

— *Association*: Association is one of the most helpful clues in identifying man-made installations. Some natural occurrence also exhibits association. Some objects or features are so commonly associated that one tends to indicate or confirm the other. All the above elements are more or less useful to image analysis. Sometimes only one element is enough to identify an object, at other times it requires more or combinations of the said element to do the job.

Aids and Techniques for Visual Image Analysis

One of the definitions of image interpretation has been the act of examining photographs and/or image for the purposes of identifying objects and phenomena and judging their significance. In carrying out this task, the interpreter may use many more types of data or information than those recorded on the images in order to facilitate the analysis. These aids may be grouped under headings such as perceptual models, collateral materials, interpretation or analysis keys, handling of imagery, stereoscopic viewing, and method of searching which are all good techniques for obtaining maximum information in the most efficient manner.

Equipment for Visual Analysis and Information Transfer

Image analysis and information transfer require specialized equipment. This equipment is used for three general purposes: viewing (including enhancement), measuring, and the transferring of details which results in the generation of a new product or manuscript. The instrumentation or equipment required is determined by original types of information.

— *Viewing equipment*: Viewing equipment enables the interpreter to scan or study imagery visually under various magnifications. This equipment can be categorized under: stereoscopic viewing, non-stereoscopic viewing, and optical and electronic viewing instruments.

— *Measuring equipment*: Measuring equipment may be used to measure length, areas, heights and densities. Plotting measurers can be used to provide orthographic plots. Measuring equipment can be categorized under the following: linear measuring, area measuring, height measuring, plotting, and densitometric measuring.

— *Equipment for transfer of detail*: Details of information derived from image analysis are transferred through the use of instruments designed to do the job. These equipments are essentially tracing devices that incorporate means for changing scale in the process of compilation. In some types, provision is also made for an approximate rectification for tilt in photographs.

Miscellaneous Equipment

This equipment does not lend itself to any one area of interpretation, information transfer, or measurement, but supports all of these functions to one degree or another and can be used at any stage of a project. This equipment includes, but is not limited to: digitizers, dot counters, slide rules, copy camera systems, etc.

3. Digital Image Analysis

Digital image analysis or computer-assisted image interpretation has tasks similar to those of the visual analysis in that they have detection and identification, measurement, and problem-solving. The most common analysis procedure for computer-assisted analysis has been statistical pattern recognition. Other approaches are decision-free structures or layered classification up to so-called artificial intelligence procedure.

Image data obtained via remote sensing means is subject to many uncertainties in different forms. These uncertainties inhibit the extraction of information. It is necessary and important that the image be subject to

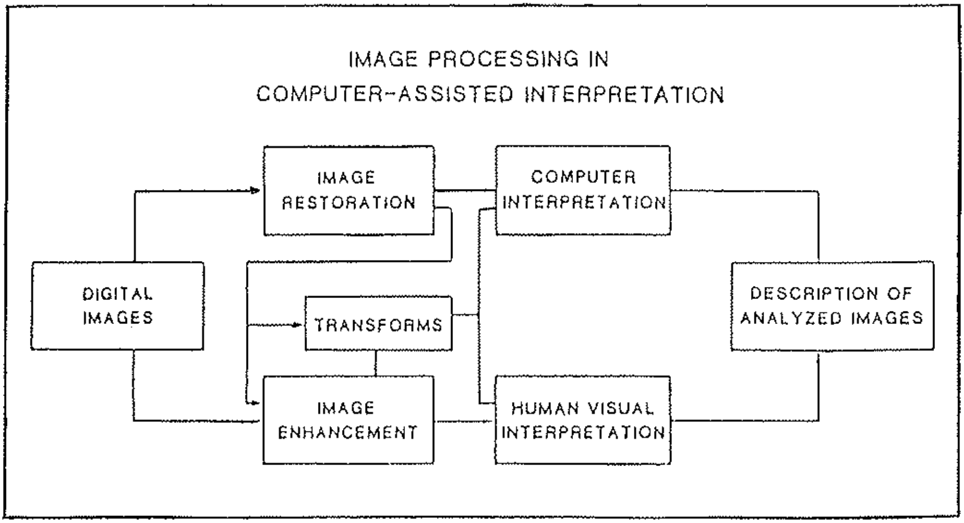

FIG. 2. Image processing in computer-assisted interpretation. (*From Manual of Remote Sensing*, Vol. 1, 2nd Edition).

various processes in order to improve or correct it so that it is as good an estimate as possible of the original scene before interpretation takes place.

Steps in Digital Image Processing

Digital image processing techniques can be divided into three activities: image restoration, image enhancement, and interpretation (Fig. 2). Based on the diagram in Figure 2, the purpose is based on two principal application areas:

— improvement of image information for human interpretation, and

— processing of scene data for computer-assisted interpretation.

The manipulation of a digital image by computer has been performed to prepare an image for display and human interpretation and/or to extract information from the image with computer interpretation. A brief description of the three processes is in order:

— *Image Restoration*: Image restoration requires significant human inputs, primarily specific *a priori* information to correct degradations.

Remotely sensed images are always degraded to some extent because of atmospheric effects and the characteristics of the sensing and recording systems. Image degradations may be grouped into radiometric and geometric distortions. Radiometric degradations arise from blurring effects of the imaging system, non-linear amplitude response, vignetting and shading, transmission noise, atmospheric interference (e.g., scattering, attenuation, and haze), variable surface illumination (e.g., difference in terrain slope and aspect), and change of radiance with viewing angle. Geometric distortions can be categorized into sensor-related distortions such as aberrations in the optical systems, non-linearities and noise in the scan deflection system, sensor-platform related distortions caused by changes in attitude and altitude of the sensor; and object-related distortions caused by earth rotation, curvature of terrain relief. It is therefore necessary to correct both the radiometric and geometric distortions before further processing and interpretation. The correction process is called radiometric and geometric restorations.

— *Image Enhancement*: Image enhancements are usually applied after image restoration. The goal of image enhancement is to aid the human analyst in the extraction and interpretation of pictorial information. Enhancement is achieved by the articulation of features or patterns of interest within an image and by a display that is adapted to the properties of the human visual system. Image enhancement implies a goal of improvement in image quality. Moreover, for an image to be enhanced properly, the information of greatest interest to the user must be optimally displayed. There are many approaches and purposes of enhancements; including contrast enhancement, filtering, edge enhancement, and image transformations (i.e., arithmetic manipulation, rationing, difference).

— *Image Classification*: Computer-assisted image interpretation through pattern recognition is the sorting or classifying of an image into pixel classes or categories using the remote sensing measurements. There are three steps in a typical spectral pattern recognition procedure in supervised computer-assisted interpretation. These steps (stages) are training, classification, and outputting stages.

· The training stage is where the analyst compiles an interpretation key, or signature-set, analogous to the spectral attributes for each feature of interest. This is generally performed by examining representative sample sites of known cover types called training areas.

· In the classification or interpretation stage, each pixel in the image data set is compared to each category in the numerical interpretation key and labeled with the name of the category it resembles, or is labeled unknown if insufficiently similar to any category. Then the multidimensional spectral image matrix is used to develop a corresponding map of interpreted category symbols.

· The results of the categorized data set are presented in the output stage commonly in the form of a map. The categorized data may also be used to generate tables of the areas of various cover types in the scene, or it may be recorded as computer-compatible inputs to a grid-based geographic information system.

An alternate to the supervised approach is unsupervised classification (clustering). Analyst specified training data are not used. The analyst's entry into the process is after the clustering is done to identify the spatial development of the spectral clusters. This is the process of cluster-labeling. Unsupervised classification can use an algorithm to examine a large number of unknown pixels and cluster them on the basis of natural spectral groupings present in the image gray values. The basis assumption is that values within a given cover type would be closer together in spectral space and that data from other classes would be separated.

Geographic Information Systems

Geographic or Geobased Information Systems (GIS) make use of spatially referenced data by computer systems. Geographic information systems are useful in land-resource planning and management. GIS will automate a large number of time-consuming and expensive manual processes in map creation, manipulation, and storage. As more complex environmental relationships were understood, data on the environment were used more effectively in combination than separately. The concept of Geographic Information Systems is based on a combination of data layers which yields new information layers. A data layer is a spatially registered data source describing a land area. Layers for a given area typically include data derived from remote sensing as well as maps of the physical environment. More information can be extracted from remotely sensed data when combined with such data layers. Geographic information systems provide the means to combine disparate data types in an automated fashion.

4. Remote Sensing Software and Hardware

Software Systems

A software system is considered to be a unified collection of computer programs which is designed to perform calculations or data processing tasks in support of remote sensing applications. Computer-aided analysis of multi-spectral images became feasible in 1965. The advance in computer development along with the techniques of pattern recognition analysis were the catalysts for rapid development of advanced remote sensing software systems. Currently there are many software packages available for analysts/users. These software systems provide batch and interactive processing capabilities, user friendly capabilities, and capabilities to perform all of the standard image processing functions normally required for remote sensing applications, with a thorough set of user and program documentation. Software packages are available with varying complexities and sophistications for microcomputers, minicomputers and large main-frame computers.

Hardware Systems

Remote sensing is moving from reliance on analogue photographic methods to systems which make extensive use of digital technology. Digital technology is an important factor in satellite tracking, guidance, ground data systems for sensor and spacecraft testing and integration as well as data telemetry and final product formatting. Digital technology is also used to manage and manipulate large amounts of information derived by digital image analysis. Hardware and software are two distinct components of image processing systems. Software consists of instructions which tell the hardware how to do its job. Image processing systems are made up of a number of discrete components, each of which has a particular function. Generally speaking, hardwares for image processing are made up of computer systems with Central Processing Unit (CPU) and Mass storage (disks and mag tapes). Peripherals to this are made up of other hardwares such as data acquisition devices (scanners, digitizers), data display devices (various kinds of CRTs), and outputting or hard copy devices (film recorders, plotter, line printers).

System Configurations

Computers and peripheral devices come in many different levels of capability, quality, and cost. Building or selecting an image-processing system is a matter of matching requirements and budget to the available hardware. Prices of image-processing systems are generally and comparatively commensurate with their capabilities. Classification of the image-processing systems can be done according to their cost as well as their associated capability. Three levels of image processing have been categorized, due to their costs, their capabilities and their association with computers of three different capabilities, i.e., micro, mini, and large main-frames. The systems are categorized under:

— Small Systems usually are based on microcomputers of 8 to 16 bit microprocessor. Usually one user at a time.

— Medium Systems: the systems need not rely on a host and can perform all major image-processing functions independently. They can support more than one user.

— Large Systems support many work stations at a time, with an extensive set of peripheral devices.

5. Trends and Futures

Image data analysis has entered into an era of more sophistication. That is to say that photographic interpretation has been made easier by the enhancement of image through the use of a computer. While procedures and methodology for photointerpretation may not have changed a lot in the last decade, they have been facilitated by the help of computers. Digital image processing and analysis seem to make good progress. Advances in computer technology, including the evolution of mini- and micro-computers, offer continued promise for lower processing hardware costs. Computer-aided analysis was initially limited by the basic processing speed of the early computers used in remote sensing applications. In recent years, the basic computing speed available for fixed dollars of investment has increased substantially. Also the cost of on-line data storage is declining, and storage density of digital storage devices is increasing. It is therefore anticipated that the use of digital image-processing techniques will be on the increase all around. Remote sensing technology is fast developing and changing all the time. It is required that interpretation or analysis procedures keep up with the technology. It is anticipated that the technology will move in the direction to achieve better data resolution and therefore the processing systems have to cope with large amounts of data generated by new sensor/platform combination.

6. Status and Trend of Remote Sensing in Developing Countries

Remote sensing has been practiced to a certain extent by countries in the developing world. The practice is intensified by the publicity of the recent development of the technology using orbital satellites. The need to use remote sensing is due to the fact that much of the developing world does not possess adequate information on extent and condition of their natural resources as well as the capability to determine or detect changes in those resources. There have been infrastructures set up in various places among developing countries for national and for regional purposes. Ground receiving stations have been established to receive, record, process, and distribute data to satisfy national and regional needs. Disciplinary agencies have been carrying out their requirements by incorporation of remote sensing as part of the tools. It has been our experience that the majority of the agencies have used or been familiar with visual analysis but new to digital image analysis. To apply remote sensing technology effectively requires specialized knowledge and equipment. The two issues are being addressed here:

— Training and education in remote sensing and related areas are being given attention by all developing countries. Personnel is being educated through short-term and long-term training up to formal education. Training institutes, national and regional, have been established for this purpose. Funds have been made available by various countries/donor agencies. There are still a lot of people to be trained in specialized areas. At the Asian Institute of Technology, Bangkok, Thailand, a regional training center has been established and has trained more than 250 resource scientists from 19 countries. More education, diploma and degree programs in remote sensing and natural resources development and management will be developed and implemented. The outlook for increased trained personnel in the region is positive from this standpoint.

National universities have incorporated remote sensing and related courses such as photogrammetry and cartography in their curriculum. Generally, departments of geography, forestry, and engineering would have remote sensing courses as part of the general curriculum. This also contributes to the positive outlook of more trained personnel in the marketplace.

National agencies that deal directly with training or education have also established or organized training courses, especially in their own specialized areas. This is also a positive indication.

It will still take some time to flood the market with the trained personnel in this specialized field because almost all the work force in the resource management area would benefit from additional knowledge of remote sensing.

— As for specialized equipment, it is always the case that the majority of developing countries are in a disadvantageous position in that they are behind in equipment technology. They have to rely on assistance from developed countries, and, to say the least, this has been deterring the progress of applying the technology. Fortunately, the general trend is that equipment is getting to be cheaper and easier to get. Private companies dealing with specialized equipment have been more helpful, and as a result many countries in the developing world have acquired some specialized equipment for their undertakings. The trend looks promising for agencies taking part in applying remote sensing.

The progress, however, will depend on other factors as well, especially the certainty of continuation of satellite systems, the cost of data derived from the satellite, etc. These factors will enable and encourage developing countries to enter into the technology and to invest in training and equipment.

7. Experience at the Asian Institute of Technology (AIT)

The Training Center

The Asian Regional Remote Sensing Training Center (ARRSTC) was established at AIT for the purpose of conducting remote sensing technology transfer. This technology transfer was planned to affect natural resource scientists and technicians of developing countries in Asia and the Pacific Region.

The Programs of Activity

ARRSTC programs of activity include:

— *Training and Education Programs*:

- a four-month short-term training program (one-term) — this has been an ongoing program which has been conducted three times a year;
- a two-term diploma program in applied remote sensing — this will be implemented in the September term of 1986;
- a five-term master's degree program in natural resources development and management — this program will be implemented sometime in 1987.

— *Special Programs*: Special programs will be of a continuing education type of activity with shorter periods of time. The purpose is to create awareness of the current development of the technology and to upgrade and update practical knowledge due to new development or advancement in technology. Generally these activities fall under seminars, conferences, workshops, etc.

— *Information Dissemination*: Plans are being drawn up for the establishment of information centers in remote sensing and natural resources management. Additionally, a newsletter has been published to communicate information on the Center to alumni and interested parties. News from alumni and others can also be heard through the newsletter.

— *Research and Projects*: AIT/ARRSTC faculty and staff have initiated several research projects both in-house and sponsored ones. Research and projects are an integral part of any educational institute, and AIT/ARRSTC follows the general practice and philosophy of any educational institute.

— *Advisory Services*: This service is considered part of technology transfer. Many consultations have been rendered to countries and government agencies of the region.

Faculty and Staff

The mandate of technology transfer requires that AIT/ARRSTC maintain adequate faculty and staff to conduct the necessary activities. Faculty and staff are of multinational and multidisciplinary backgrounds.

This is necessary because participants come from various countries with various backgrounds. Support staff are responsible to keep the facilities and equipment operational.

Facilities and Equipment

Technology transfer in the form of training and education requires that ARRSTC be provided with adequate facilities and equipment. The training and education program emphasizes both visual and digital analysis approaches. Facilities and equipment related to visual and digital analysis are described below:

— *Visual Analysis Laboratory*: The laboratory is ample for the purpose of conducting visual analysis. It is equipped with a color additive viewer, a zoom transferscope, a number of individual pocket stereoscopes, mirror stereoscopes, a stereoscopic plotter, drafting and cartographic aids, including light tables, drafting tables, etc.

— *Digital Analysis Laboratories*: These facilities include image processing systems based on micro, mini, and main-frame computers.

Two microcomputer-based image processing systems are maintained, i.e., an ERDAS/IBM-PC/XT system and a Pericolour 1000 system.

A mini-computer-based image processing system is maintained and is based on a Gould 32/6780 computer with two Comtal work stations operated by ATLAS software.

A main-frame computer-based image processing system is based on IBM 3083 (time-sharing) with two Ramtek work stations operated by DIMAPS software.

— *Photographic Laboratory*: A complete photographic laboratory will be installed in 1986, which will be equipped with full black and white and color processing capabilities for generating custom satellite imagery products for special applications.

Trainees and Participants in AIT/ARRSTC

Trainees in the four-month short-term training so far have come from some 19 countries in Asia and the Pacific Region. Almost all of them were under fellowships or assistantships provided by donor countries/agencies. More than 250 resource scientists and engineers from the region have completed the training program from AIT/ARRSTC.

— *Classification of Participants*: Experience gained through the span of time indicates that there have been three major groups of participants joining the training program:

· Professional people, these are people coming from disciplinary areas such as agriculture, forestry, geology, etc. Thes people normally come from government agencies that deal with resource development and management problems. Their objectives include the acquisition of new development and techniques for data analysis to solve resource problems. Some have the definite idea of getting acquainted with hardware and software systems in order to plan their own facilities in their own countries.

· New and potential people, these are people who are newly graduated and still looking for jobs. Their objectives are to broaden their knowledge and experience in their field of specialization. In doing so they hope to land a better job than those without additional training. The majority of this category are AIT alumni who have completed their master's degree from among the nine academic divisions of AIT.

· Academic people, this group of people comes from higher educational institutes and universities in the region. Their objectives include to learn and to gain more knowledge in remote sensing in both principles and applications. The aim is to be able to plan to incorporate remote sensing courses into their existing curriculum. Additionally, some of the people in this category took advantage of the opportunity to become acquainted with the use of equipment for their project of interest.

Curriculum

The short-term training curriculum consists of fundamentals of remote sensing, visual analysis, digital analysis, applied remote sensing, remote sensing project development and management. The training is accomplished through classroom lectures, laboratory assignments and hand-out exercises, plus field investigations for ground-truthing. Students are required to develop and conduct a small and practical project to be completed within the given time frame. These projects reflect their practical interest in the applications of remote sensing to their fields. Students are allowed to use any approach or procedure that is suitable for their project, within the context of the visual and digital approaches. The project approach proves to be interesting and fulfilling for students/trainees.

8. Impact in the Developing Countries Based on the Experience at AIT

With limited experience from limited programs conducted at AIT, it is possible to say that there have been some 75 people a year from the region who have more knowledge about remote sensing that is supplied through our four-month short course, 20-30 people more knowledgeable through our seminars or workshop activities. These people will be absorbed into the country's workforce. As a result, more facilities and equipment will be purchased and set up to carry out necessary work. This will enable developing countries, in the long run, to make adequate surveying and mapping of their countries, because of new development of equipment to handle a large amount of work in a shorter period of time.

9. Conclusion

This paper has described image data analysis in remote sensing. Conventional approaches have been looked into, including visual and digital approaches. Equipment required for each approach was briefly discussed. Trends and the future for the analysis were also looked at. Finally, the status of remote sensing in developing countries was mentioned. Issues on technology transfer and specialized equipment as factors affecting the progress of applications of remote sensing were mentioned. The overall picture reveals that progress is being made in a steady manner. This is due to the needs for adequate information on the natural resources of all these developing countries.

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FUTURE OUTLOOK

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1. Introduction

In 1978, the French government took the decision to have a civil Earth observation satellite programme, SPOT, *Satellite pour l'Observation de la Terre.* Conceived and designed by the French Centre National d'Etudes Spatiales, CNES, SPOT has been built by the French industry working in association with European partners, Belgium and Sweden. The SPOT system does encompass a space segment composed of one satellite, a ground segment comprising a mission and control centre and data reception and processing infrastructures.

Responsibility was given to a commercial entity, SPOT IMAGE, to market the satellite images as well as to negotiate reception and distribution agreements with foreign operators. Moreover CNES, GDTA,[1] *Groupement pour le Développement de la Télédétection Aérospatiale*, and SPOT IMAGE with various SPOT simulation exercises in the past and CNES and SPOT IMAGE with their joint *Programme d'Evaluation Préliminaire de SPOT*, PEPS, SPOT early assessment programme, going on, do maintain numerous cooperation endeavours worldwide. The flawless launch of SPOT 1 on 22 February 1986, from Kourou, French Guiana, by

(1) GDTA: CNES partners in the GDTA are:
— Bureau pour le Développement de la Production Agricole, BDPA.
— Bureau de Recherches Géologiques et Minières, BRGM.
— Institut Français du Pétrole, IFP, and
— Institut Géographique National, IGN.

Ariane, the almost immediate, high quality images obtained, the availability of an identical SPOT 2 satellite due to be launched in 1988, but ready from 1987, to ensure a full continuity of service to users, the decisions-to-be-taken on SPOT 3 and 4 mission characteristics have strengthened and will add new impetus to our relations with users.

2. The SPOT satellite

The SPOT satellite consists of two parts: a standard multi-purpose platform called the SPOT bus and a payload.

2.1 The SPOT bus hosts various subsystems which perform such essential functions as:

— precision control of the orbit,

— three-axis stabilization,

— electrical power supply,

— housekeeping telemetry transmission,

— command reception,

— monitoring and programming of the payload through an on-board computer with a memory loaded by ground control.

2.2 The SPOT 1 payload consists of two identical observation instruments and a package comprising two magnetic-tape data recorders and an image telemetry transmitter.

2.2.1 The two-observation instruments called HRV, *Haute Résolution Visible*, use static solid state arrays of detectors of the CCD, Charge-Coupled Device, type. The HRV instrument is designed to operate in either of two modes in the visible and near-infrared portions of the spectrum:

— a panchromatic mode, resulting from observation in a broad spectral band and a ground sampling interval corresponding to a ground element, pixel, of 10 m × 10 m,

— a multiband mode, resulting from observation in three narrower spectral bands and a ground sampling interval of 20 m × 20 m, in both cases for nadir viewing.

Light from the scene being viewed enters the HRV instrument via a plane mirror that is steerable by ground control thus enabling the viewing axis to be oriented in the plane perpendicular to the orbit and this in a range of ± 27° relative to the vertical (Fig. 1).

2.2.2 This off-nadir viewing capability along with the high resolution are two of the most innovative features of the satellite.

2.3 *Nadir and off-nadir viewing*

2.3.1 Though independent, the two HRV instruments can be pointed so as to cover adjacent fields. In this configuration the total swath width is 117 km, at nadir, and the two fields overlap by 3 km (Fig. 2).

2.3.2 By selecting the orientation of the pointing mirror, it is possible to observe any region of interest within a 950 km-wide strip centered on the satellite ground-track. At extreme off-nadir viewing (± 30°) the ground swath width is 80 km (Fig. 3).

2.3.3 Were the satellites instruments only capable of nadir viewing, the revisit frequency for any given region would be 26 days and that

Characteristics of the HRV instrument	Multispectral mode	Panchromatic mode
Spectral bands	0,50-0,59 μm	0,51-0,73 μm
. . . .	0,61-0,68 μm	
. . . .	0,79-0,89 μm	
Instrument field of view	4,13°	4,13°
Ground sampling interval (nadir viewing) . .	20 m × 20 m	10 m × 10 m
Number of pixels per line	3000	6000
Ground swath width (nadir viewing	60 km	60 km
Pixel coding format	3 × 8 bits	6 bits DPCM (1)
Image data bit rate	25 M bits/s	25 M bits/s

(1) DPCM (Digital Pulse Code Modulation) is a mode of data compression that does not degrade the radiometric accuracy of the image data (256 grey levels).

FIG. 1

NADIR VIEWING

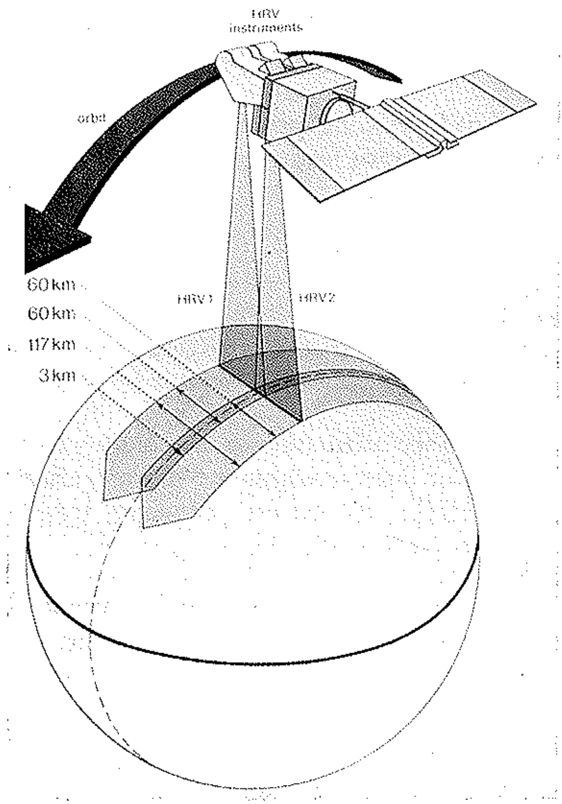

Fig. 2

interval is unacceptable for the observation of rapidly evolving phenomena. The off-nadir viewing capability partly alleviates that inconvenience and the cloud cover hindrance to data acquisition and makes it possible to obtain data on seven different occasions for a point located on the Equator and on eleven occasions if at a latitude of 45°, giving an average access time of respectively 4 and 2.5 days (Fig. 4).

2.3.4 Another important consequence of the off-nadir viewing capability is that of recording at different viewing angles stereoscopic pairs of images, with main applications in photogrammetry and photo-interpretation.

OFF-NADIR VIEWING

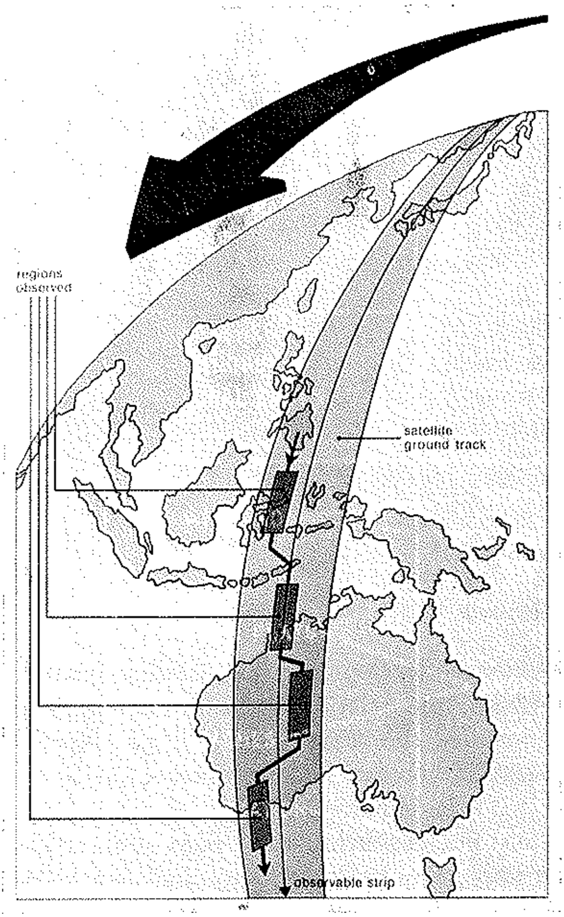

Fig. 3

2.4 *Image transmission*

The observation sequence is loaded every day into the on-board computer by the Toulouse mission and control centre; the direct data transmission occurs at 8 GHz with a rate of 50 Mbits/s for the two HRV; the satellite carries two on-board recorders with a 23 min capacity each, thus enabling to acquire approximately 330 scenes at each orbital period of 100 min.

REVISIT CAPABILITIES

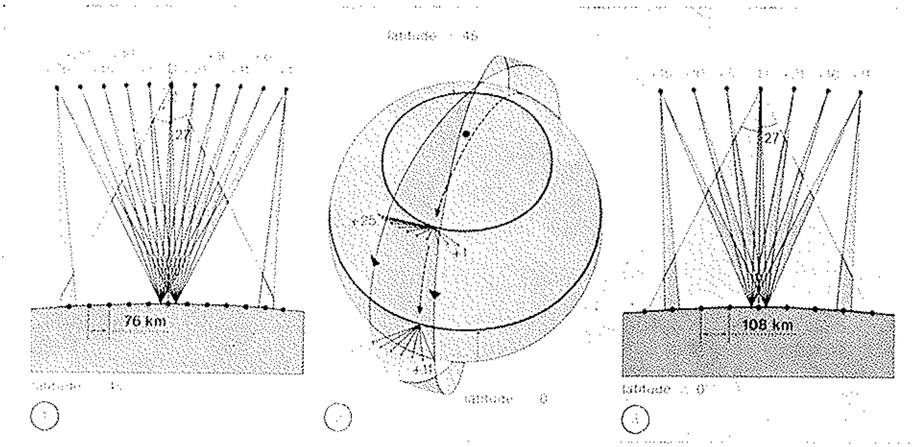

FIG. 4

3. THE RELATIONSHIP WITH THE USERS

While programme development and satellite operations remain the prerogative of CNES, the relationship with the users is of paramount importance and justified the creation in 1982 of a specific entity geared to ensuring system promotion and to operate on a commercial basis. SPOT IMAGE, with shareholders representing major fields of application, embodies this user-conscious attitude and aims at an efficient management of both satellite image acquisition capacity and data transmission, by the ground network of SPOT data receiving stations, in accordance with user requirements.

The dissemination policy for SPOT data meets the criteria spelt in the to-be-adopted principles on remote sensing on which consensus was reached among the member States of the United Nations Committee on the Peaceful Uses of Outer Space, and based on non-discriminatory access to data.

3.1 *The network*

The network consists of image receiving stations and image distributors.

3.1.1 In addition to the Toulouse and Kiruna, Sweden, stations, which are the only ones to "read" the data from the on-board recorders, SPOT image telemetry will be received at other locations such as Prince Albert and Gâtineau in Canada with full coverage of the continental United States; Dhaka, Bangladesh; Hyderabad, India; Islamabad, Pakistan; Beijing, P. R. of China; Cuiaba, Brazil; Riyadh, Saudi Arabia; Maspalomas, Spain, by the European Space Agency, etc.

The satellite is within a range of visibility aproximately 2600 km in radius. The transmission frequency, radiated power and bit rate specified for SPOT image telemetry are compatible with other Earth observation satellite systems and exchange of information on all technical parameters occurs within GOSS — *Groupe des Opérateurs de Stations SPOT* — as well as among satellite operators within CEOS — Committee on Earth Observation Satellites — a forum dealing with land and ocean observation programmes.

3.1.2 The distribution network stems over all continents permitting the widest, time-efficient and cost-effective dissemination of SPOT data: moreover SPOT IMAGE is prepared to bring assistance in the running of the national users' seminars by presenting at the request of the distributor, appropriate lectures focused on image characteristics, processing aspects or relevance to specific applications. Today more than 40 distributors around the world have entered into agreement with SPOT IMAGE.

3.2 *The products*

The basic unit for segmenting the image data stream at the ground receiving stations is the "scene" which corresponds to the totality of image data for an area 60 km in length — along the ground track — and 60 to 80 km in width — in the cross-track direction — depending on the instrument viewing angle. Each scene is referenced to a predetermined grid applied to the Earth's surface as well as by latitude and longitude.

In order to be interpreted, a number of processes should take place on the data. The correction processes applied include, and are not limited to:

— radiometric corrections taking into account the calibration factors for the detectors and the optical and telemetry systems,

— geometric corrections to take account of the viewing conditions: viewing angle, Earth rotation.

At Toulouse, such corrections take place at CRIS — *Centre de Rectification des Images Spatiales* — a joint activity of CNES and IGN.

Four main levels of preprocessing are available:

3.2.1 Level 1A is the closest form to "raw" data, the only processing performed being the equalization of detectors. Neither interband calibration nor geometric correction is applied.

3.2.2 Level 1B processing includes radiometric and geometric corrections: compensations of rotation of the Earth, satellite perspective effects, viewing angle and effects of satellite perspective effects, viewing angle and effects of the satellite forward motion, i.e., desmearing. The location accuracy is 1500 m (rms) for nadir viewing and the relative error 10^{-3}. This is the basic preprocessing level for photointerpretation and thematic analysis. Stereoscopic pairs, with different B/H ratios depending on instrument viewing angles are available at this level.

3.2.3 Level 2 is a precision processed level. Radiometric corrections are identical to level 1B. Geometric corrections involve bi-dimensional computation based on 6 to 9 ground control points per scene. The image is rectified according to a given cartographic projection.

The location accuracy is 50 m (rms) for nadir viewing. But this level does not take account of distortions due to relief. Thus, the closer the viewing angle to the vertical and the less pronounced the relief, the more accurate the final product.

3.2.4 Level 3 involves scene rectification relative to landmarks to ensure registration with another scene used as reference to within 0.5 pixel, i.e., to within 5 or 10 m depending on the imaging mode.

3.2.5 In addition to those basic preprocessing levels available at Toulouse, Kiruna, or at other centres attached to local receiving stations, there are further processed and value-added products such as:

— cartographic precision processed SPOT scenes: level 3 orthophotography using a Digital Terrain Model and level 4 production of contour level maps to be produced in France by IGN,

— radiometric enhancements: stretching, edge enhancements, etc.,

— channel combination: ratios, colour composites,

— geocoded products.

3.2.6 The SPOT products will be available by full scene or sub-scene:

— on computer compatible tapes at 6 250 or 1600 bpi,

— on floppy discs for scene extracts,

— on photographic films in the 241×241 mm format covering one full-scene at a scale of 1:400,000 for level 1B; to take full advantage of the fine details of SPOT imagery, the basic film format providing for the interpretation will be at a scale ranging from 1:200,000 to 1:100,000, on paper prints.

3.2.7 For easy reference and general quality assessment each scene acquired at any station worldwide will appear on a quick-look image.

A central catalogue of all SPOT data is maintained at Toulouse and available at several locations and open for consultation on a 24 h basis.

All acquired data are archived at their respective receiving station; a quick-look is generated for each data.

4. Cooperation activities

4.1 The cooperation activities in the field of remote sensing carried out by France with developing countries have been manyfold and have involved several government agencies. Even before the inception of the SPOT programme cooperation actions took place aiming at:

— setting up and/or strengthening regional or national training and user assistance centres,

— studying the feasibility of setting up or upgrading ground receiving stations and data processing centres,

— getting the satellite operator but primarily the end users acquainted with the image characteristics of SPOT through simulation exercises in West and East Africa, in Bangladesh and the South Pacific region. Moreover, simulation exercises were also carried out over western Europe and North America,

— encouraging methodological research through a hundred PEPS projects.

4.2 This dialogue has proven extremely useful, has modified the perception of and the relations to the user, and the decisions to be taken have, to various extents, been shaped by that interaction: choice of spectral bands for better distinction in the vegetation, choice of ground sampling interval to respect acceptance margins and to reach improved and new cartographic applications, choice of a price structure for greater flexibility in data ordering, choice of system compatibility, awareness of system continuity demand, etc.

5. Thinking ahead: the challenges of the end of the century

The continuity of the SPOT system being ensured with SPOT 1 and 2 until 1990, the decisions announced in 1985 to go ahead with SPOT 3 and 4 were of significant importance for the users' community.

The next decade will be characterized by additional systems coming from Japan, Canada, India, Brazil, the European Agency, etc. (thus complementing the present American and French programmes) and by the development in some countries of an extremely active and diversified sector composed of small engineering groups providing added-value and custom-tailored products.

The mere continuation of the SPOT programme on its today basis will not adequately permit the expansion in data dissemination and the adjunction of new fields of application. The following modifications are being studied for SPOT 4:

· Modifications induced by an increased life duration of the satellite.

In order to improve the economic balance of the programme and consequently product competitivity, an expansion of the life duration is a requirement and the target is to have a 4- instead of a 2-year duration. This objective could be achieved by improving the overall reliability and delaying the exhaustion of consumable on board.

The present technological endeavours in France concentrate on:

— a higher reliability of present gyroscopes,

— a decreased mean temperature on the platform leading to a better functioning of electronics,

— an increased electric power of the batteries and their longer duration,

— an increased solar-generator power,

— a larger quantity of hydrazine necessary for altitude control and orbit adjustment,

— improved on-board recorders with increased recording-capacity.

• Modifications induced by an evolution in mission characteristics.

SPOT privileged field of application in the 90's will be in agriculture and monitoring of natural vegetation. To answer those needs, the observation range of the HRV instrument will be extended to the mid-infrared portion of the spectrum around 1.6 μm, of special interest for the measurement of soil moisture, with the same resolution — i.e., 20 m — and perfect superposition to the present three channels.

This new configuration which will contribute to advance in thematic mapping will require:

— the adaptation of the telescope optics to a new range of wavelengths,

— the adaptation of the image chain to have the same data flow (bit rate) as on SPOT 1 in spite of the adjunction of a spectral band.

Moreover, it is envisaged to have a new *vegetation* instrument geared to the observation of chlorophyllian activity. This instrument will permit the frequent, permanent, worldwide and rapid monitoring of natural vegetation and cultures. This instrument will generate data which associated with the HRV data and the deduced areas will permit forecasting taking into account local meteorological conditions.

The "vegetation" passenger will be based on an optical wide field — 100° — system associated with a CCD concept of detectors in the same four (4) spectral bands of SPOT 4. The IFOV will be of the order of 1 km, an electronic memory will permit the recording of all images and their reception at Toulouse; direct reception by local stations worldwide will also be possible.

In conclusion, decision makers, in particular in developing countries, can now count on a reliable, performing and evolving system up to the year 2000. The contribution of SPOT to the inventory of natural resources, their subsequent monitoring as well as to improved and up-to-date medium scale cartography — thematic and topographic — will greatly enhance man's knowledge of planet Earth.

REMOTE SENSING:
FUTURE OUTLOOK IN THE SPACE STATION ERA

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Significant progress has been achieved recently in the development of improved remote sensing techniques for observing the Earth, including the atmosphere, the ocean, and the land. Likewise, a number of planning activities have been under way in order to develop science objectives and to define the priorities for future remote sensing developments. Such activities are in progress in the United States, in Europe, in Japan and in several other countries.

I will briefly summarize the current planning activities within the United States (U.S.) of America. Then I will briefly describe some of the current plans as they are viewed today with respect to future activities in remote sensing in the United States. I believe that there is developing a unified approach throughout the United States and Europe, in Japan, in Canada, and in other countries. This is very encouraging with respect to the outlook for global Earth observations in the future.

Within the United States the National Academy of Sciences/National Research Council Committee on Earth Sciences has recently published a two-part study, "A strategy for Earth Science from Space in the 1980's, Part. I: Solid Earth and Oceans (1982); Part. II: Atmosphere and Interactions with the Solid Earth, Oceans, and Biota (1985)", which describes a comprehensive set of scientific programs throughout the Earth Sciences which should be addressed in the immediate future. In addition, the U.S. Committee for an International Geosphere-Biosphere Program of the Commission on Physical Sciences, Mathematics, and Resources, National Research Council has just published a report entitled "Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP". This is part of a much broader effort associated with the International Council of Scientific Unions (ICSU), to define the U.S. elements of an integrated international program for studying the Earth during the decade beginning in the mid 1990's.

Within the National Aeronautics and Space Administration (NASA), a Scientific Working Group (SWG) was established to review what observing capabilities for Earth Observations might be achieved with the proposed Space Station Program with special emphasis on what opportunities might exist from the Polar Platform Component of the Space Station (S.S.). This committee has published a series of reports defining an Earth observing system (Eos) based upon the concept that such a system should be "An Information System established to meet the multi-disciplinary needs of Earth science that go beyond the currently planned research and operational observing programs" which would include data systems as well as observing systems.

Subsequently NASA and the National Oceanic and Atmospheric Administration (NOAA) joined together to study how a Space Station Polar Platform might serve both the research and the operational observational communities. A number of international meetings have occurred in the past eighteen months in which these efforts have been extended, with international cooperation, to incorporate studies being performed by other countries, and especially with those countries and organizations which have agreed to cooperate in the international Space Station development. Finally NASA, NOAA, and the National Science Foundation (NSF) have supported the Earth System Science Committee (ESSC) study to define the specifics for implementing a study of the Earth as a system in the next decade. The summary report of this committee was published in June, 1986.

The ESSC Committee has defined the "Goal" of this program to be: "To obtain a scientific understanding of the entire earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales".

The ESSC Committee has defined the "Challenge" for this program to be: "Changes that will occur in the next decade to century, both naturally and in response to human activity".

NASA, NOAA, NSF, and the National Academy of Sciences are currently reviewing the recommendations of this committee to determine how such a program, in the context of the broader ICSU "Global Change" Program, can be implemented and how the international requirements for such a program might be cooperatively achieved.

Figures 1 and 2 illustrate the currently approved and proposed NASA Earth Science and Applications missions for the next decade. The Upper Atmosphere Research Satellite (UARS) will measure the composition, energetics, and winds throughout the stratosphere. The development of this satellite and the construction of all ten separate instruments are proceeding well. This mission will provide the first comprehensive measurements of the various components that control the upper atmosphere and will provide the first long-term set of simultaneous measurements required to help resolve the "ozone depletion" question.

The Scatterometer to be flown on the Navy Remote Sensing Satellite (NROSS) is well under development. This instrument is an improved version of the instrument that was flown on SESAT and should provide

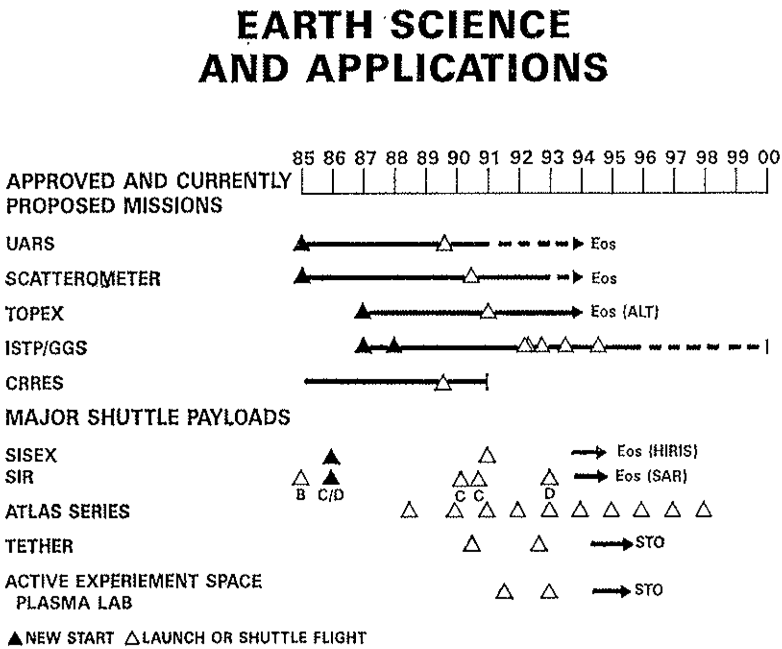

FIG. 1. Current ESAA Programs.

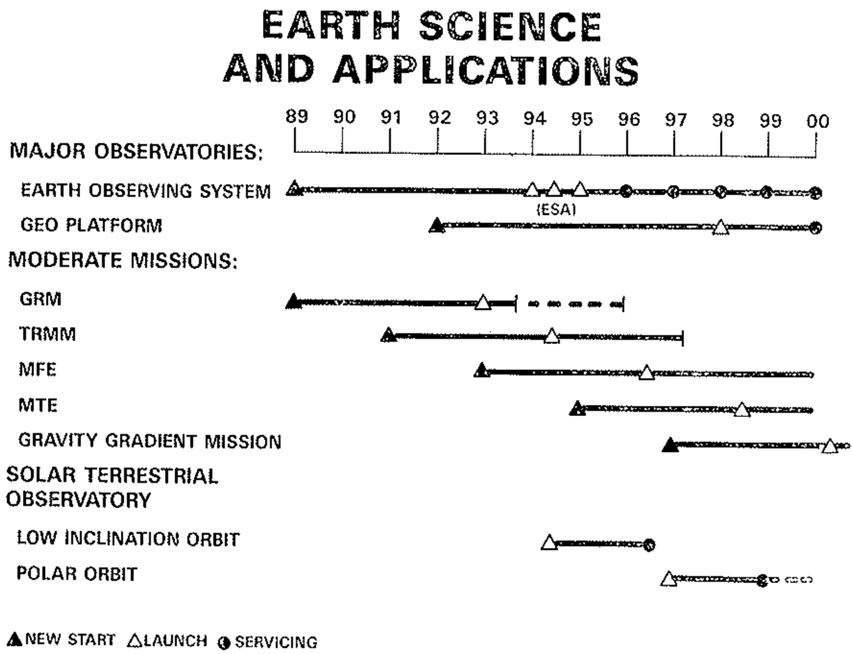

FIG. 2. Future ESAA Programs.

a significant improvement in the measurement of ocean surface winds on a global basis. (The solid triangles indicate new start approval, or planned approval, and the open triangles indicate the expected flight date).

Both TOPEX (actually TOPEX/POSEIDON, this is a joint mission between the U.S. and France, and TOPEX is just the U.S. contribution to the joint mission), an altimetry mission to determine very precisely the ocean height to a few centimeters on a global scale, and ISTP/GGS, the U.S. portion of the internationally supported International Solar Terrestrial Physics satellite program (GGS = Global Geosphere Science portion of this program) are candidate 1987 and 1988 new start missions within NASA. Japan and ESA have already received new start authority for the Geotail and the Soho and Cluster spacecraft, respectively.

CRRES is the joint NASA/Department of Defense Chemical Release/Radiation Effects Satellite which will release a number of chemicals (Ba, Li, etc.) into the magnetosphere and will also measure the effect of solar and galactic radiation on a number of newly developed solid state electronic components over an extended period of time.

The Shuttle Imaging Spectrometer Experiment (SISEX), an array imaging spectrometer, actually is composed of a number of instruments to be developed over the next decade with higher and higher levels of capability. The first instrument in this developmental series is the Airborne Imaging Spectrometer (AIS), which was initially flown in 1985. The instrument characteristics are listed in Figure 3. The next step in this evolutionary development is the Advanced Visible and Infrared Imaging Spectrometer (AVIRIS), also an aircraft instrument, with extended wavelength and number of channels, which will be available for flight in 1987. Later we plan to fly an improved version of this instrument on the Shuttle, and finally we plan to fly a further improved version of the shuttle instrument on the Eos platform (the High Resolution Imaging Spectrometer, HIRIS). The instrument characteristics for each of these instruments

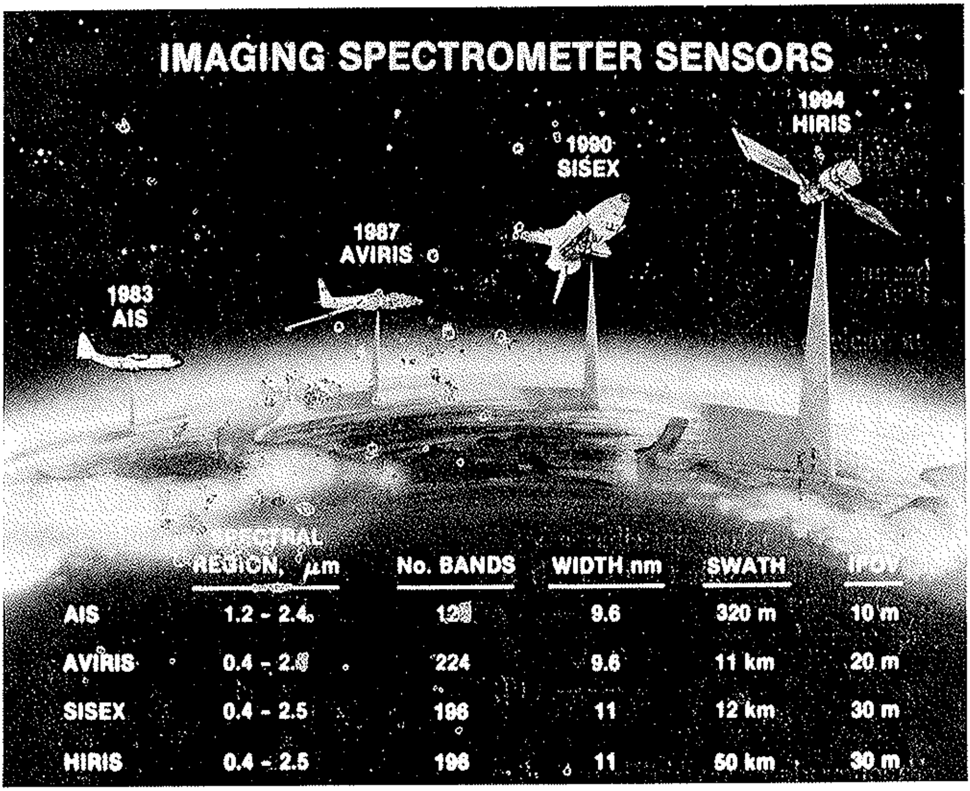

FIG. 3. Imaging Spectrometer Dev.

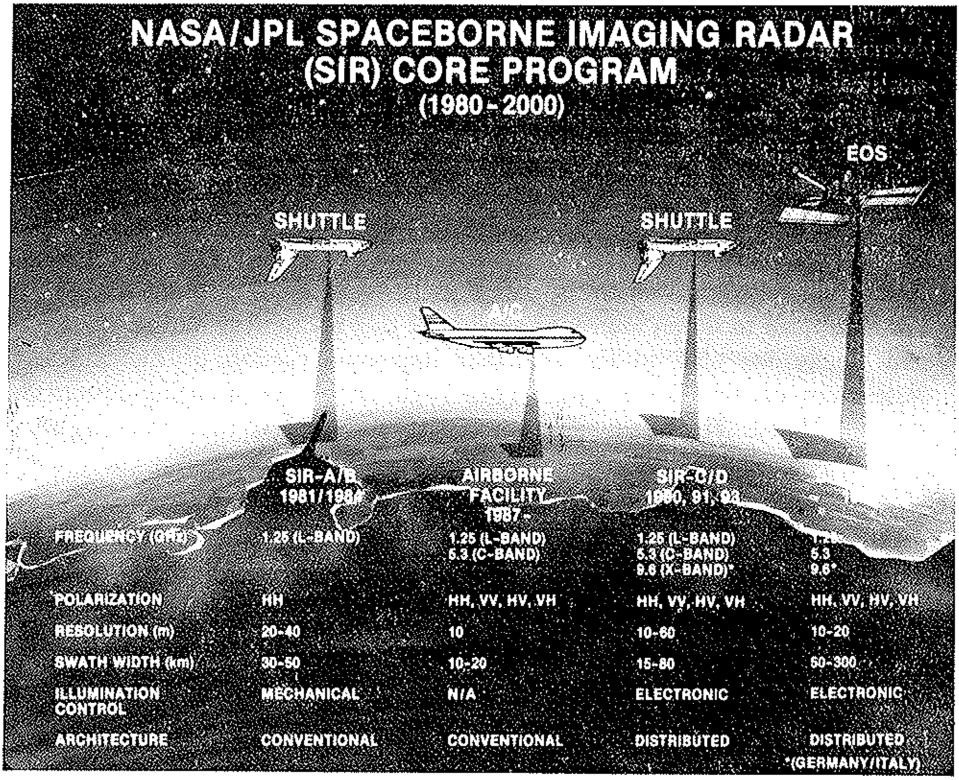

FIG. 4. SIR Program.

are listed in Figure 3. One of the most important points to keep in mind with these types of instruments is that the data rates are very high, the amount of information received back from these instruments is very large, and the techniques that are presently used to reduce and analyze the AVHRR, Landsat, and Spot-Image data must be significantly improved, or more probable, new techniques must be developed, in order to effectively utilize the information received from these instruments. It is very important that such data reduction, handling and analysis techniques be developed. Otherwise many resources will be wasted in the development of such instruments if we are not going to be able to effectively use these kinds, and amounts, of data in the next decade. I have not discussed the commercialization issues for any of these instruments; however, it is possible that, if commercially viable, such instrumentation might be commercially supported and operated in this time frame.

The ocean science community has recommended that one of the most useful instruments for the near future is an improved follow-on instrument to replace the Coastal Zone Color Scanner (CZCS) currently flying on the NIMBUS-7 satellite. Other elements of the science community have identified additional channels that would significantly improve the capabilities of the current AVHRR flying on the NOAA polar orbiting operational satellites. These additional channels would provide improved information about both the land surface and the atmosphere. A Science Working Group that was established to define the measurement requirements for the Eos time frame has recommended that a multichannel instrument, the Moderate Resolution Imaging Spectrometer (MODIS), be developed for the Eos Space Station Polar Platform. Two elements of this instrument, a tilting mode (MODIS-T) and a nadir mode (MODIS-N), could provide a 500 meter to one kilometer field of view capability that would significantly improve atmospheric, oceanic, and land information. This instrument would eventually replace the current AVHRR and the HIRIS-2 on the polar orbiting operational satellites and would provide a significantly improved ocean color and ocean temperature data set. The instrument characteristics for the MODIS instrument are listed in Tables 1 and 2. The tilting mode of this instrument could provide essentially continuous one day coverage of specific areas and could provide information at a number of sun/look angles, which is very important for many ocean and land observations.

TABLE 1 - MODIS-T *Whiskbroom Imaging Spectrometer.*

SPECTRAL CHANNELS	64 (CHOOSE ANY 17)
SPECTRAL BANDWIDTH	10 nm
DETECTOR ARRAY	64 x 64 (Si)
SCAN MIRROR	0.105 Hz (1 SCAN/9.5 sec)
OPTICS DIAMETER	5.0 cm
SWATH	1513 km
FOOTPRINT (705 km)	1000 m
SENSOR LOOK ANGLE	60 Degrees
DATA RATE	1.3 Mb/sec

TABLE 2 - MODIS-N *Scanning Radiometer.*

No. Channels	Wavelength (micro m)	Delta (nm)	Ifov Meters	S/N	Comments
6	0.4- 1.06	10-100	500	700-1700	LAND PROCESSES
8	0.4- 1.06	10	1000	500-1500	OCEAN COLOR
3	0.76	1.2	1000	900-1600	OXYGEN A-BAND
2	0.5	100	1000	2880	POLARIZATION
7	1.1- 2.3	20-50	500	200-1100	CLOUDS+PLANT STRESS
6	3.0- 5.0	50-90	1000	N/A	THERMAL
8	6.7-14.2	300-500	1000	N/A	THERMAL
40					

Swath	1513 km
Optics diameter	20 cm
Scan Mirror	0.8 Hz
Data rate	8.3 Mb/sec (day)
	1.5 Mb/sec (night)

As with the SISEX program, the Shuttle Imaging Radar (SIR) program is actually composed of a number of components. The first synthetic aperture radar (SAR) instrument flown in space, was the SESAT SAR. The SESAT SAR instrument characteristics were similar to those listed in Figure 4 for SIR-A except the angle of incidence was fixed at a lower angle. Next the Shuttle Imaging Radars — initial version (SIR-A, see Fig. 4) — followed by the second major improvement (SIR-B, single L-band, but with a tiltable antenna to look at a number of depression angles) — were flown on the shuttle. Now under development is the three wavelength, multiple look angle, multiple polarization version (L-, C-, and X-band in cooperation with Germany and Italy). Simultaneously we are developing an improved version of a dual band, multiple polarization aircraft SAR. Ultimately we plan, in cooperation with the international community, to fly one or more Synthetic Aperture Radars on the Space Station Polar Platforms as a follow-on to the European Space Agency (ESA) and Japanese ERS-1/SAR programs for both research and operational purposes.

There are a number of additional radar programs for which initial studies have been completed or are in progress. Some of these are summarized in Figure 5. They include a scanning radar altimeter for global

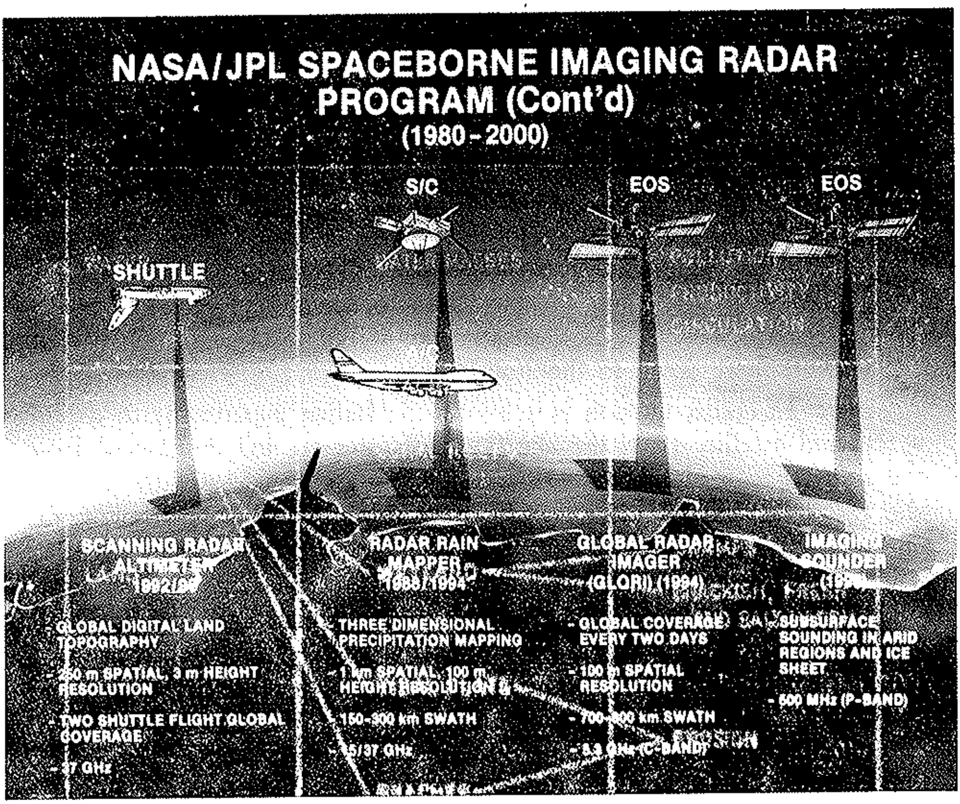

Fig. 5. Radar Programs.

digital topography mapping, a radar rain mapper, a global radar imager, and an imaging sounder, which will be especially valuable for ice mapping.

We also have a number of Laser ranging systems in operation (aircraft types), under development, or under study. These include relatively simple aircraft aerosol and cloud top lidars, aircraft differential absorption lidars (DIAL) for composition measurements (water vapor, ozone, etc.), aircraft Doppler lidars for wind measurements, shuttle lidars for aerosols, and several more complex systems for the shuttle and subsequently for the Space Station, both in the 28 degree and polar orbits. Such lidar systems can also provide very precise measurements of ice changes and the movements of tectonic plates, so important for better understanding earthquake phenomena.

The ATLAS series listed in Figure 1 corresponds to the series of missions formerly known as the EOM-Earth Observations Missions. This is a series of flights on the shuttle to calibrate a number of free flying spacecraft instruments such as the "active cavity radiometer (ACR)" flying on the Solar Maximum Mission and similar experiments on Nimbus-7 and the Earth Radiation Budget Experiment (ERBE) satellites. This series of missions will also include such experiments as the ATMOS — a high resolution (0.015 wave number) infrared absorption interoferometer which operates in the 2-16 micrometer wavelength range to measure upper atmospheric composition and to help calibrate experiments on the UARS. This instrument has also demonstrated the ability to measure winds from the thermosphere down to the troposphere.

The TETHER mission is a joint U.S./Italian experiment to deploy a tethered satellite from the shuttle (both upward and downward from the shuttle) to study: (1) the dynamics of two coupled satellites and (2) the region of the thermosphere from ± 100 km above and below the shuttle, which is a very difficult region to study by conventional satellites. The Active Experiment Space Plasma Laboratory will incorporate a number of experiments aboard the shuttle in which the magnetosphere will be actively perturbed by optical and radio-frequency radiation. Such perturbations will then be measured by combined remote and *in situ* experiments aboard and near-by the shuttle.

The remaining three near time major missions listed in Figure 2 include the study for a very high precision gravity and magnetic field measurement, the Geopotential Research Mission (GRM) which we hope to initiate within the next few years. Currently these missions are being jointly studied by a combined U.S. and French team. The Tropical Rainfall Mapping Mission (TRMM) is a small Explorer class Satellite which has been proposed, using active and passive microwave techniques, to map precipitation in the low latitudes. This mission is very important because of the important contributions to the Earth's energy and moisture budget. Currently discussions are under way with Japan, Italy, France, England, and other countries about potential cooperation in this mission.

The other "major" mission in the near time frame is the Earth Observing System (Eos) which I mentioned above. The scientific community has concluded that the synergistic measurements obtained from such a multisensor platform offer many advantages over separate instruments on separate spacecraft with the data from each such instrument being obtained at different times with different coordinates. Table 3 lists the U.S. version of the combined NASA/NAA payload that we would

NASA-Eos/NOAA BASELINE SCENARIO

"824/540"

PLATFORM INSTRUMENTS	1 824 km - PM	2 540 km - PM	3 824 km - AM	GROWTH
IOC: RESEARCH	*ADCLS *CR *F/P-INT *GLRS *HIRIS *LASA-A *MODIS *PMR	*MAG *MPD *SAR	*SCM *SUSIM	
ANTICIPATED OPS.	AMSU (2) ARGOS AVHRR (2) ERBI HIRS (2) LFMR S&R SEM SSMI DB		AMSU (2) ARGOS AVHRR (2) HIRS (2) LFMR MLA S&R SEM SSMI DB	
RESEARCH/ POTENTIAL OPS.	ALT ATSR GOMR OCI SCATT		ALT ATSR ERBI SCATT SEASAR	
IOC + 2: RESEARCH	*AMSR *NCIS *TIMS			
ANTICIPATED OPS.	~~LFMR~~			
IOC + 4: RESEARCH	*LASA-B	*CIS *F/P-INT *IR-RAD *MLS *SUB-MM *VIS/UV		
IOC + 5: RESEARCH				*DOPLID *ESTAR

Key

* NASA PROVIDED
MLA COMMERCIAL PLACE HOLDER
(2) REDUNDANT INSTRUMENTS
—— INDICATES REMOVAL

TAB. 3

hope to implement a few years after the Space Station Polar Platform is initially implemented. As I indicated earlier, the S.S. Polar Platform will be a joint effort by all the participating Space Station partners and there is now agreement between all the partners that ESA will provide the a.m. platform and that the United States will provide the p.m. platform containing the operational instruments. Research instruments from many countries will be located on all platforms. A list of acronyms is provided in Appendix A, which defines all the instruments listed in Table 3. A (2) in Table 3 indicates that two of these specific instruments will be included on that particular platform to reduce the frequency with which the platform must be serviced, i.e., those instruments, such as the AVHRR, are defined as critical operational measurements. Exact resource allocations are under discussion with all partners at the current time. A joint, or internationally coordinated, Announcement of Opportunity (AO) is planned to be released in early 1988 soliciting Principal Investigator experiments and investigators for the facility class and operational instruments. Figure 6 indicates that we expect a wide variety of users to actively interact with the Eos "data and information system", and one of our prime objectives is to develop this system in a user-driven environment with continuous inputs by the wide range of expected users. [It should be noted that in Figure 6 we have put the users at the top of the diagram and not at the bottom, as is the usual case.] The proposed Eos Information System (EOIS) is more than an observing system. EOIS is conceived to be an information system that includes space observations

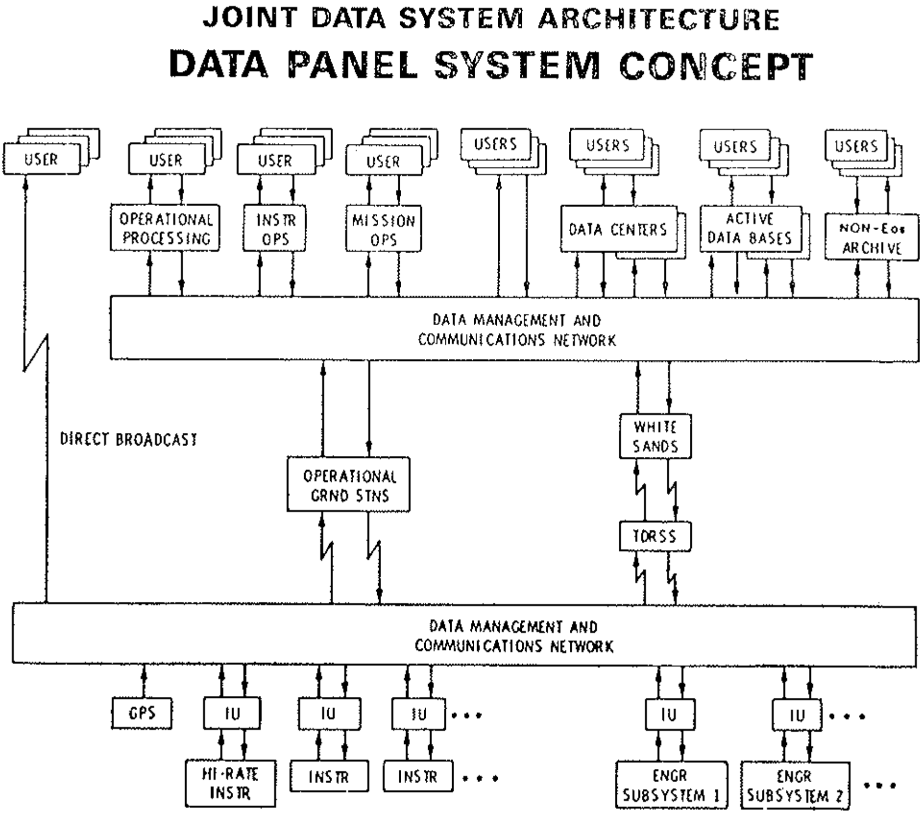

FIG. 6. Data System Architecture.

TABLE 4 - EOIS Information System.

0 CONTROL CENTER OPERATIONS
- TOTAL END-TO-END DATA SYSTEM PERFORMANCE EVALUATION
- PLATFORM STATUS
- SUBSYSTEM/PAYLOAD/INSTRUMENT STATUS
- CENTRAL CONTROL FOR TELESCIENCE OPERATIONS

0 REAL TIME DATA
- NOAA, etc.
- QUICK LOOK PROCESSING FOR RESEARCH GROUPS
- TARGET OF OPPORTUNITY REQUESTS
- SUPPORT RESEARCH FIELD EXPERIMENTS

0 ARCHIVAL DATA
- ACTIVE GROUPS WITH KNOWN REQUIREMENTS
- GROUPS WITH KNOWN ATTRIBUTES
- OTHER
- RETROSPECTIVE RESEARCH

0 INGEST AND PROCESS DATA
- AVERAGE OF 120 MBPS PER PLATFORM (300 MBPS PEAK)
- FOUR PLATFORMS AT 600 MBPS FROM TWO TDRSS SA LINKS

0 STORAGE
- TWO DAYS RAW DATA AT 10E13 BITS/DAY/PLATFORM
- ACTIVE DATA BASES OF 4 x 10 E 15 BITS/YEAR/PLATFORM
- TWENTY YEAR ARCHIVE

0 SUPPORT USER COMMUNITY
- UP TO 200 ACTIVE AT ONE TIME
- UP TO 10,000 TOTAL

and ground data, linked by a capable information network with access to Eos missions operations, Eos data, and other relevant data sets.

Ultimately this information syystem is intended to be a multiagency data system. Conceptually, it will integrate the Eos science, operational, and applications sensors into a total data system with access to past NASA satellite data sets; NOAA, USGS, the Earth Resources Operational System (EROS) Data Center, and Earth science data from other agencies (e.g., NSF and DOE), the NASA UARS data sets, relevant DMSP data, such as that from the SSMI; and the European Space Agency's and Japanese ERS-1 and the Japanese MOS data when available. This system will be internationally accessible, with many kinds of computer hardware, and will handle many of the routine, but important, tasks of calibration, registration, remapping, etc. The system must also be able to quickly transfer high volumes of data around the network. Also required will be remote access to super computers and certain analysis software on line with the appropriate documentation. Table 4 lists the EOIS system characteristics. We believe that the experience we have obtained with current operational data distribution networks, the Pilot Climate Data System, the Pilot Ocean Data System, the developing Pilot Land Data System, and especially the United Nations Environmental Program's Global Resource Information Data base (GRID) project will provide significant insight into the development of EOIS.

Table 5 and Table 6 list examples of global data acquisition that are currently being collected, or that are planned to be collected, from current and approved programs and from proposed future programs, respectively. Table 7 contains representative examples of proposed satellite measurements. These data were compiled by the ESSC as part of their summary report and recommendations. Appendix "A" contains an extensive list of acronyms that are currently in use by the Earth Science and Applications community and which have been used in many of the Tables and Figures in this paper.

TABLE 5 - Observational Programs for Global Data Acquisition: Representative Examples of Proposed Future Programs.

Representative Space Programs

Program	Agency/ Status	Objectives
TOPEX/POSEIDON: Ocean Topography Experiment	NASA-CNES (France)/Start 1987, Launch 1991	Ocean surface topography
POES: Polar-orbiting Operational Environmental Satellite system — follow-on missions (NOAA K, L, M)	NOAA/ Planned	Advanced capabilities for weather observations
GOES: Geostationary Operational Environmental Satellite system — follow-on missions (e.g., GOES-Next)	NOAA/ Planned	Advanced capabilities for weather observations
RADARSAT - Canadian Radar Satellite	Canada/Start 1986, Launch 1991	Studies of arctic ice, ocean studies, Earth resources
MOS-2: Marine Observation Satellite-2	NASDA (Japan)/ Launch about 1990	Passive and active microwave sensing
GRM: Geopotential Research Mission	NASA/Start 1989, Launch 1992	Measure global geoid and magnetic field
Individual instruments for long-term global observations:		
OCI: Ocean Color Imager	NASA-NOAA/ Planned	Ocean biological productivity
ERB: Earth Radiation Budget instrument	NASA/ Planned	Earth radiation budget on synoptic and planetary scales
Carbon-Monoxide Monitor	NASA/ Planned	Monitor tropospheric carbon monoxide
Total Ozone Monitor	NASA/ Planned	Monitor global ozone
GLRS: Geodynamics Laser Ranging System	NASA/ Planned	Crustal deformations over specific tectonic areas
Laser Ranger	NASA/ Planned	Continental motions
Scanning radar altimeter	NASA/ Planned	Continental topography
Eos: Earth Observing System/Polar-Orbiting Platforms. NASA-NOAA program:	NASA-NOAA/ NASA Start 1989, Launch 1994	Long-term global Earth observations
NASA research payloads	NASA/ Planned	Surface imaging, sounding of lower atmosphere; measurements of surface character and structure; atmospheric measurements; Earth radiation budget; data collection and location of remote measurement devices
NOAA operational payloads	NOAA/ Planned	Weather observations and atmospheric composition; observations of ocean and ice surfaces; land surface imaging; Earth radiation budget; data collection and location of remote measurement devices; detection and location of emergency beacons, monitoring of space environment
European Polar-Orbiting Platform (Columbus)	ESA/Planned	Long-term comprehensive research, operational, and commercial Earth observations
Rainfall mission	NASA/Start 1991, Launch 1994	Tropical precipitation measurements
MFE: Magnetic Field Explorer	NASA/Start 1993, Launch 1996	Secular variability of Earth's magnetic field
MTE: Mesosphere-Thermosphere Explorer	NASA/Start 1995, Launch 1998	Chemistry and dynamics of upper atmosphere
GGM: Gravity Gradiometer Mission	NASA/Start 1997, Launch 2000	Gradient in Earth's gravitational field

Representative International Programs for Measurements *In Situ*

Program	Organization/ Status	Objectives
WOCE: World Ocean Circulation Experiment (World Climate Research Program)	WMO-ICSU-IOC-NSF-NASA-NOAA/ 1987 enhancement	Detailed understanding of ocean circulation
IGBP: International Geosphere-Biosphere Program (Global Change)	ICSU/ Proposed	Study of global change on timescale of decades to centuries
GOFS: Global Ocean Flux Study	NSF-NOAA-NASA/ Enhancement	Production and fate of biogenic materials in the global ocean
GTCP: Global Tropospheric Chemistry Program	NSF-NASA-NOAA/ Enhancement	Tropospheric chemistry and its links to biota
Ocean Ridge Crest Processes	NSF-USGS-NOAA/ Enhancement	Chemistry and biology of deep-sea thermal vents, plate motions, crustal generation
Sensing of the Solid Earth	NSF-USGS-DoD-NASA/ Enhancement	Large-scale mantle of continental convection, studies lithosphere
Ecosystem Dynamics	NSF/ Enhancement	Studies of long-term ecosystems, biogeochemical cycles
Greenland Sea Project	ICSU/Planned	Atmosphere - sea ice - ocean dynamics

TABLE 6 - Observational Programs for Global Data Acquisition: Representative Exam of Approved and Continuing Programs.

Representative Space Programs

Program	*Agency/ Status*	*Objectives*
POES: Polar-orbiting Operational Environmental Satellites (e.g., NOAA-7)	NOAA/ Operating	Weather observations
GOES: Geostationary Environmental Satellite System	NOAA/ Operating	Weather observations
DMSP: Defense Meteorological Satellite Program	U.S. Air Force/ Operating	Weather observations for Department of Defense
METEOSAT: Meteorology Satellite	ESA/ Operating	Weather observations
GMS: Geostationary Meteorology Satellite	NASDA (Japan)/ Operating	Weather observations
METEOR-2: Meteorological Satellite-2	USSR/ Operating	Weather observations
LANDSAT: Land Remote Sensing Satellite	EOSAT/ Operating	Vegetation, crop, and land-use inventory
LAGEOS-1: Laser Geodynamics Satellite-1	NASA/ Operating	Geodynamics, gravity field
ERBE: Earth Radiation Budget Experiment	NASA-NOAA/ Operating	Earth's radiation losses and gains
GEOSAT: Geodesy Satellite	U.S. Navy/ Operating	Geodesy, shape of the geoid, ocean and atmospheric properties
GPS: Global Positioning System	U.S. Navy-NOAA-NASA-NSF-USGS/ Completion 1989	Geodesy, crustal deformation
SPOT-1: Système Probatoire d'Observation de la Terre-1	France/ Operating	Land use, Earth resources
IRS: Indian Remote Sensing Satellite	India/ Operating	Earth resources
Representative Space Shuttle instruments:		
ATMOS: Atmospheric Trace Molecules Observed by Spectroscopy	NASA/Current	Atmospheric chemical composition
ACR: Active Cavity Radiometer	NASA/Current	Solar energy output
SUSIM: Solar Ultraviolet Spectral Irradiance Monitor	NASA/Current	Ultraviolet solar observations
SIR: Shuttle Imaging Radar	NASA/ Current/In development	Land-surface observations
MAPS: Measurement of Air Pollution from Shuttle	NASA/ Current/In development	Tropospheric carbon monoxide
SISEX: Shuttle Imaging Spectrometer Experiment	NASA/Planned	Spectral observations of land surfaces
LIDAR: Light Detection and Ranging instrument	NASA/Planned	Surface topography, atmospheric properties

Program	*Agency/ Status*	*Objectives*
MOS-1: Marine Observation Satellite-1	NASDA (Japan) Launch 1987	State of sea s and atmospher
LAGEOS-2: Laser Geodynamics Satellite-2	NASA-PSN (Italy) Launch 1988	Geodynamics, g field
SPOT-2: Système Probatoire d'Observation de la Terre-2	France/ Launch 1988	Earth remote s
UARS: Upper Atmosphere Research Satellite	NASA/ Launch 1989	Strotospheric chemistry, dyna energy balance
ERS-1: Earth Remote Sensing Satellite-1	ESA/Launch 1990	Imaging of oce ice fields, land areas
N-ROSS: Navy Remote Ocean Sensing System	U.S. Navy/ Launch 1991	Ocean topograp Surface winds, ice extent
JERS-1 Japan Earth Remote Sensing Satellite-1	NASDA (Japan)/ Launch 1991	Earth resource

Representative International Programs for Mea ments *In Situ*

Program	*Organization/ Status*	*Objectives*
GEMS: Global Environment Monitoring System	UNEP/ Begun 1974	Monitoring of global environm
World Ozone Program	WMO-NASA-UNEP/ Operating	Atmospheric composition
Crustal Dynamics Project	NASA-23 nations/Begun 1979	Tectonic plate movement and deformation
Man and the Biosphere	UNESCO/ Operating	Ecological studi
International Biosphere Reserves	UN/Operating	Long-term ecol studies
ISCCP: International Satellite Cloud Climatology Project (World Climate Research Program)	WMO-ICSU/ Begun 1983	Measure interac of clouds and radiation
ISLSCP: International Satellite Land Surface Climatology Project (World Climate Research Program)	WMO-ICSU/ Begun 1985	Measure interac of land-surface processes with climate
TOGA: Tropical Ocean Global Atmosphere Program (World Climate Research Program)	WMO-ICSU/ Begun 1985	Variability of gl interannual clin events
GRID: Global Resource Information Database	UNEP/ Begun 1985	Information on global resource

TABLE 7 - Representative Examples of Proposed Satellite Measurements *.

Measurement	*Implementation: Current Era*	*Implementation: Space Station Era*
Solar energy output	ERBE, UARS	Eos
Ice extent, dynamics	DMSP, N-ROSS, ERS-1, JERS-1	Eos, DMPS, RADARSAT
Weather and climate: physical parameters	POES, GOES, DMSP, MOS-1, N-ROSS, ERS-1, JERS-1, (WWW)	POES, GOES, DMSP, MOS-2, Eos, RADARSAT, (WWW)
Stratospheric ozone chemistry and dynamics	UARS, POES	Eos
Tropospheric Chemistry	CO Monitor	Eos
Ocean surface winds and ocean currents	N-ROSS, TOPEX/POSEIDON, ERS-1, GRM, MOS-1, GEOSAT, (TOGA) (WOCE)	MOS-2, Eos, (TOGA), (WOCE)
Ocean spectral reflectivity, ocean productivity	OCI, (GOFS)	Eos
Precipitation, rainfall rates	Concept and technique development	Rainfall mission over tropics, Eos, GOES
Surface spectral reflectivity, land-surface biology, continental geology	LANDSAT, Shuttle instruments, SPOT, (ISLSCP)	Eos, EOSAT, SPOT
Geopotential field and mantle circulation	GRM, (Global Digital Seismic Network)	(Global Digital Seismic Network)
Continental topography	Scanning radar altimeter	Eos
Magnetic field	GRM	MFE
Vegetation cover	LANDSAT, SPOT, JERS-1	Eos
Crustal deformation and plate tectonics	LAGEOS-1, LAGEOS-2, GPS, Laser Ranger, Shuttle instruments, (VLBI)	GLRS, Eos, GPS, LAGEOS-1, LAGEOS-2, (VLBI)
Land-surface energy and moisture budgets	Concept and technique development	Eos
Biome extent and productivity	Concept and technique development	Eos
Winds, especially in tropics	GEOS, Concept and technique development	Eos

* Programs of complementary measurements *in situ* appear in parentheses; e.g., (WOCE).

APPENDIX A

ACRONYMS AND ABBREVIATIONS

ACR	=	Active Cavity Radiometer
ADCLS	=	Automated Data Collection and Location System
ALT	=	Radar Altimeter
AO	=	Announcement of Opportunity
APACM	=	Atmospheric Physics and Chemistry Monitors
ARGOS	=	French Tracking System
ATMOS	=	Atmospheric Trace Molecules Observed by Spectroscopy
AVHRR	=	Advanced Very High Resolution Radiometer
CRRES	=	Chemical Release and Radiation Effects Satellite
CZCS	=	Coastal Zone Color Scanner
DCLS	=	Data Collection Location System
DMSP	=	Defense Meteorological Satellite Program
EOM	=	Earth Observations Missions
EOS	=	Earth Observing System
EOIS	=	The Eos Information System
EOSAT	=	The EOSAT Company
ERB	=	Earth Radiation Budget
ERBE	=	Earth Radiation Budget Experiment
ERBS	=	Earth Radiation Budget Satellite
ERS-1	=	Earth Remote Sensing Satellite # 1 (ESA)
ERS-1	=	Earth Remote Sensing Satellite # 1 (JAPAN)
ESA	=	European Space Agency
ESMR	=	Electronic Scanning Microwave Radiometer
DOE	=	Department of Energy
DOI	=	Department of Interior
ESSC	=	Earth System Science Committee
GARP	=	Global Atmospheric Research Program
GEMS	=	Global Environmental Monitoring System
GEO PLATFORM	=	Geostationary Platform
GEOS-3	=	Geodynamical Experimental Ocean Satellite
GEOSAT	=	Geodesy Satellite
GGM	=	Gravity Gradiometer Mission
GGS	=	Global Geoscience Satellites (part of ISTP)
GLRS	=	Geodynamics Laser Ranging Satellite
GMS	=	Geostationary Meteorological Satellite
GOES	=	Geostationary Operational Environmental Satellite
GOFS	=	Global Ocean Flux Study
GPS	=	Global Positioning System
GRID	=	Global Resource Information Data base System
GRM	=	Geopotential Research Mission
GTCP	=	Global Tropospheric Chemistry Program
GSFC	=	Goddard Space Flight Center
HIRIS	=	High Resolution Imaging Spectrometer
HMMR	=	High Resolution Multifrequency Microwave Radiometer

HQ	=	NASA Headquarters
ICSU	=	International Council of Scientific Unions
IGBP	=	International Geosphere-Biosphere Program
IOC	=	Initial Operating Configuration (Space Station)
IOC	=	International Oceanographic Commission
ISCCP	=	International Satellite Cloud Climatology Project
ISLSCP	=	International Satellite Land Surface Climatology Project
ISTP	=	International Solar Terrestrial Physics Program
JERS	=	Japan Earth Remote Sensing Satellite
JPL	=	Jet Propulsion Laboratory
LAGEOS	=	Laser Geodynamics Satellite
LANDSAT	=	Land Remote Sensing Satellite
LaRC	=	Langley Research Center
LASA	=	Laser Atmospheric Sounder and Altimeter
LIDAR	=	Light Intensificatoin Detection and Ranging System
LIMS	=	Limb Infrared Monitoring System
MAPS	=	Measurement of Air Pollution from Space
MLA	=	Multispectral Linear Array
METEOR	=	Meteorological Satellite (USSR)
METEOSAT	=	Meteorology Satellite (ESA)
MFE	=	Magnetic Field Explorer
MODIS	=	Moderate Resolution Imaging Spectrometer
MOS	=	Marine Observing Satellite
MTE	=	Magnetosphere - Thermosphere Explorer
NAC	=	NASA Advisory Council
NAS	=	National Academy of Sciences
NASA	=	National Aeronautics and Space Administration
NASDA	=	Japan Space Agency
NIMBUS	=	NIMBUS Satellite
NOAA	=	National Oceanic and Atmospheric Administration
NRC	=	National Research Council
N-ROSS	=	Navy Remote Ocean Sensing System
NSCAT	=	N-ROSS Scatterometer
NSF	=	National Science Foundation
OCI	=	Ocean Color Imager
POES	=	Polar Operational Environmental Satellite System
PSN	=	Piano Spaziale Nazionale (Italian National Space Plan)
RADARSAT	=	Radar Satellite (CANADA)
S & R	=	Search and Rescue
SAM	=	Sensing with Active Microwaves
SAR	=	Synthetic Aperture Radar
SAR	=	Search and Rescue
SBUV	=	Solar Backscatter Ultraviolet Spectrometer
SCATT	=	N-ROSS Scatterometer
SEASAT	=	Sea Satellite
SIR	=	Shuttle Imaging Radar
SIS	=	Shuttle Imaging Spectrometer
SISEX	=	Shuttle Imaging Spectrometer Experiment
SISP	=	Surface Imaging and Sounding Package
SMMR	=	Scanning Multifrequency Microwave Radiometer
SPOT	=	Système Probatoire d'Observation de la Terre
SSM-1	=	Support Systems Module
SUSIM	=	Solar Ultraviolet Spectral Irradiance Monitor

SWG	=	Science Working Group
TIROS	=	Television and Infrared Observing Satellite
TM	=	Thematic Mapper
TOGA	=	Tropical Ocean Global Atmosphere Program
TOPEX	=	Ocean Topography Experiment (U.S./France)
TOPEX/POSEIDON	=	Ocean Topography Experiment (U.S./France)
UARS	=	Upper Atmospheric Research Satellite
UN	=	United Nations
UNEP	=	United Nations Environmental Program
UNESCO	=	United Nations Educational, Scientific, and Cultural Organization
USDA	=	United States Department of Agriculture
USGS	=	United States Geological Survey
VLBI	=	Very Long Baseline Interoferometry
WCRP	=	World Climate Research Program
WMO	=	World Meteorological Organization
WOCE	=	World Ocean Climate Experiment
WWW	=	World Weather Watch

REMOTE SENSING AND TRAINING: A SHORT REVIEW OF ACTIVITIES

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1. Introduction

During the last few decades Remote Sensing Techniques (RSTs) have proved to be a very powerful means to conduct studies and applications in many environmental disciplines, such as:

— *Geology* (tectonic features and lineament detection);
— *Hydrology* (soil moisture analysis, river flood monitoring, snow cover evaluation);
— *Land-use* (urban growth, change detection);
— *Cartography* (map up-dating);
— *Meteorology* (weather forecasting, atmospheric circulation).

Furthermore, the most recently launched satellites and sensors have greatly improved their performance, e.g., current scanners have a geometric resolution close to 20m and many spectral bands; it is also possible to have stereoscopic views of the same area, etc.

At this time it is not difficult to note the following important aspects:

1. RSTs have been developed primarily in the most technologically advanced countries;

2. the same countries have received the major benefits in terms of both technological fall-out and advantages coming from applications.

Keeping in mind that in many Developing Countries there is not yet adequate scientific background on remote sensing, at least not enough to manage their own renewable resources (often they have not even sufficient cartography), it results very clearly that RSTs constitute a much more powerful means for those countries.

Furthermore, we must realize that more detailed knowledge of the RSTs results in their more fruitful applications.

In the Developed World such a knowledge has grown gradually during years of study and experience, strongly supported by expensive and complex facilities. These facilities very often are not available in Developing Countries.

At present the actual situation for many of those countries could be characterized by two contrasting aspects:

a) Strong requirements of remote sensing applications;

b) Poor availability of both knowledge and facilities.

In this context it is simple to see the role of primary importance that training activities can play when people coming from Developing Countries are involved. At the same time this is a very delicate role, because the aim should be not only to train them, but also, to assist them to conduct effective local applications and provide them appropriate facilities to work with, i.e., data acquisition and processing systems. In our opinion this is the only way to translate training into aid.

This report contains a short, surely not exhaustive, review of the main training facilities existing in Developing Countries and open to international attendance. A deeper view into remote sensing educational activities carried out in Italy will follow.

2. Review of Training Centres in Developing Countries

We will start our review with African countries, whose fight against hunger, drought and desertification calls for major attention.

Kenya: Regional Remote Sensing Facility (RRSF), Nairobi

This facility was designed to provide support and assistance to users of remote sensing data and offers:

— 3-week short courses for introducing RSTs to professional staff in government departments, public organizations and universities. Courses deal with hydrology, cartography, geology, etc., and are well equipped.

— 3-5-day technical information seminars and on-the-job training. Most of the time is spent in the requesting country.

— Technical assistance activities, including user assistance for image interpretation and organization of specific remote sensing projects.

Burkina Faso: Centre Régional de Télédétection de Ougadougou

It offers the following kinds of courses and also acts as a centre for reproduction and distribution of LANDSAT imagery:

— 1-3-week introductory courses to provide participants with a general understanding of remote sensing and its applications.

— Practical introductory courses (3 months). Applications are conducted in disciplines such as geology, hydrology, forestry, agronomy and land-use planning.

— Advanced courses (3-6 months) take place after completion of introductory courses. Specific projects in fields of interest.

— On-the-job training for enabling personnel to work with the centre's staff.

In South America at present there is no centre acting strictly on a regional basis, but there are some national centres offering training courses in some way open to foreign participants.

Panama: Defence Mapping Agency, Inter-American Geodetic Survey, Cartographic School (DMA-IAGS), Fort Clayton

Since 1952, IAGS Cartographic School trains people in mapping technology using RSTs. It also co-sponsors with EROS Data Center a 5-week introductory course on the use of LANDSAT imagery recorded on CCT's (Computer Compatible Tape). The school designs and offers courses upon specific requests as well.

Colombia: Centro Interamericano de Fotointerpretación (CIAF), Bogotá

This is a government Institution whose activities started in 1968 in cooperation with the International Institute for Aerospace Survey and Earth Science (ITC) and, at present, is one of the main training and user-assistance centres in Latin America.

It offers regular courses in geology, forestry, etc., in which remote sensing and photointerpretation are integrated. They last 40 weeks and are open to professionals from Latin American countries. CIAF also cooperates with international bodies in organizing symposia and seminars.

Argentina and *Brazil* are very active in remote sensing, respectively through the Comisión Nacional de Investigaciones Espaciales (CNIE) and the Instituto de Pesquisas Espaciais (INPE). Both are responsible for their own ground-receiving and processing station and distribute LANDSAT data as well. They organize training activities but not on a regular basis and only occasionally open to foreign people.

In *Asia* there is only one educational facility operating actually as a regional centre and this is located in Thailand.

Nevertheless some other ESCAP (Economic and Social Commission for Asia and the Pacific) countries give further training opportunities.

Thailand: The Asian Regional Remote Sensing Training Centre (ARRSTC), Bangkok

The U.S. and Thai Governments set up this facility for technical training and user assistance. Courses are conducted for participants coming from the ESCAP region.

India: National Remote Sensing Agency (NRSA) and the Indian Institute of Remote Sensing (IIRS)

These two Indian Institutions are both involved in educational activities, the latter, in particular, offers regularly opportunities of short and long courses in photointerpretation techniques, also open to participants from the ESCAP region.

3. Review of Italian Educational Activities

From a general point of view activities on remote sensing expanded greatly in Italy in recent years, using systematically satellite data to detect and evaluate natural resources and to know the environmental situation. At the present time several Ministries, Organizations and Institutions are involved.

Moreover, the importance of training in remote sensing has been fully recognized and specific activities have been established. In the following a description is presented of these activities, outlining those carried out in and for Developing Countries.

Activities by Ministry of Public Education

In this framework, many Italian universities give degrees with special courses connected with remote sensing (environment analysis, agriculture, meteorology, geology, space activity, sensors, etc.). Further, there are some Specialization Courses in which aspects of remote sensing are included.

In 1983 the new "doctorate program" started in many Universities, often with "Consortia" embracing several Universities for a specific doctorate. Some of these doctorate programs contain curricula devoted to or connected with remote sensing. As an example, a consortium among Florence, Padua, Pisa and Trieste Universities for a doctorate in "electronic and information engineering" offers a curriculum mainly devoted to remote sensing.

It is important to mention that all the previous activities and training programs are open to foreign students and researchers, in particular those coming from Developing Countries; indeed several students from those countries are already attending such programs.

Remote sensing, under different headings, is present in several curricula of the following courses, leading to the "laurea" (a degree equivalent to the "master's degree"):

Physics (4 years); Civil engineering (5 years); Electronic engineering (5 years); Architecture (5 years); geology (4 years).

Several post-graduate students, especially from Developing Countries, are spending their fellowships granted by the Italian Ministry of Foreign Affairs, on training stages at University Departments and Institutes.

Activities by National Research Council

In the framework of The National Research Council (CNR), the Italian National Space Plan (PSN) is actively developing projects on remote sensing, for land and water investigations, for implementation of advanced sensors and for efficient processing of remote sensing data. PSN is also studying a program for training in remote sensing, open to participants from Developing Countries.

Institutes and Laboratories of CNR are open to foreign visitors under specific cooperation agreements. That is especially true for those Institutes directely involved in remote sensing such as IROE and IATA in Florence, IEI in Pisa, ITS and IGL in Milan, IESI in Bari.

Furthermore CNR has recently established a special commission on "Science and Technology Against World Hunger", also taking into account the contribution of remote sensing.

Activities of the Ministry of Foreign Affairs

The Ministry of Foreign Affairs, through the Department for Co-operation in Development, is actively engaged in education-training programs for Developing Countries, in particular in the remote sensing area.

In recent years, in cooperation with the Food and Agriculture Organization of the United Nations (FAO), a remote sensing training program was established in three large regions (Africa, Middle East, Latin America), to prepare local personnel for receiving and processing satellite data. The main goal of the program, already attended by about 200 operators from Developing Countries, is to get a better use of local natural resources.

As a specific example of cooperation, the Kenyan Government has recently proposed to the Italian Government a detailed agreement including a remote sensing program, in which training of Kenyan operators is planned.

The Ministry of Foreign Affairs has also some Institutes giving specific courses, related to remote sensing and open to students from Developing Countries. An interesting and significant example is represented by the graduate course (six months) on "Photogrammetry and Remote Sensing for Resource Management" held for many years at the *Istituto Agronomico per l'Oltremare* (IAO) in Florence, which also develops a part of the training activities directly in Developing Countries.

In 1985 a 4-month training course has been carried out jointly by the Foreign Ministry and by the OMM-TEAM group of Genova for 12 researchers from the Republic of China.

Activities developed by other Organizations, Institutions, Industries and Associations

Many other Italian organizations, institutes, industries and associations are developing activities on remote sensing, also with training programs.

The Italian Air Force Meteorological Service (*Servizio Meteorologico dell'Aeronautica*) in Rome is distributing meteorological data (in particular from METEOSAT satellite), using an advanced data processing system and many remote terminals. This system can be very useful for training programs.

ENEA (*Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative*) in Rome has started activities related to remote sensing applications for energy plant siting and environment analysis, implementing an advanced image processing system and organizing specific meetings on the topic, with indications useful also for Developing Countries.

Several industries and firms (*Telespazio, Selenia, Italeco, Aquater, SMA, VDS...*) are strongly involved in remote sensing activities, developing on-board sensors, ground instrumentation and receiving-data processing systems.

These firms, in connection with transfer of their systems to Developing Countries, organize specific courses for training local operators. A Consortium (*Telespazio, Aquater, Italeco*) developed a study for the Italian Ministry of Agriculture and Forestry with the aim of assessing the benefits deriving from the inclusion of satellite data in a multi-stage information system, which could be operationally used for agricultural resource management at the national level. In particular, the developed end-to-end system for crop production forecasts can constitute a very good opportunity for Developing Countries, in which efficient management of agricultural resources is of vital importance: a training in this system could be very useful.

In Italy projects are developed regarding small portable and simple-use ground-receiving stations from satellites, in particular of meteorological type, to be widely employed in Developing Countries.

The CSATA (*Centro Studi e Applicazioni in Tecnologie Avanzate*), located in the new Technopolis centre in Bari, is carrying out activities in remote sensing, with training programs also for Developing Countries, in particular based on their multiple data processing system.

Two scientific Associations, AITA and SITE, were established several years ago in Italy for scientific, cultural and professional activities in remote sensing and environment analysis. In the last years these Associations strongly cooperated in the organization of a National Annual Meeting on Remote Sensing and a course on Remote Sensing and its Applications, open to foreign participants also from Developing Countries.

Finally, the very important activity of the remote sensing centre of FAO in Rome should be mentioned. FAO, in cooperation with the Italian Government, organizes regular courses on remote sensing and related applications for technicians from Developing Countries.

Activities in the European Communities and International Cooperation

Italy is actively cooperating in European Programs in Remote Sensing (European Communities — EC and European Space Agency — ESA).

The EC is promoting a wide education-training activity on different aspects regarding remote sensing. At the Joint Research Centre of EC in Ispra, courses are organized each year, in particular on remote sensing data processing, open to EC and Developing Country participants.

ESA, developing its space activity in Europe, is also promoting training activity. In 1976 the European Association of Remote Sensing Laboratories (EARSeL) was established, under the auspices of the EC, ESA and the Parliamentary Assembly of the Council of Europe. One of EARSeL's activities, having a specific Working Group (with Italian participants), regards the education-training in remote sensing and connected branches and in recent years, great attention has been given to the problems of Developing Countries.

Italy is participating in the Project "Remote Sensing from Space" in the international framework of the Working Group on Technology, Growth and Employment (TGE) set up by the Economic Summit. The general project objective consists in the improvement of multilateral cooperation concerning remote sensing activities.

In particular, for decision makers and experts from Developing Countries, a specific International Conference is planned in Berlin next September. The Conference is titled: "Remote Sensing for Development: Experiences with and Requirements for User Assistance in Training" and was jointly prepared by the Economic Summit Members with the main goal of providing:

— direct and detailed information on the importance of remote sensing in Developing Countries;

— information on decisions to apply RSTs in Developing Countries;

— definitions of ways to apply RSTs;

— definitions of user assistance and training needs for remote sensing.

4. Conclusions

RSTs surely are becoming of increasing interest all over the world, and for Developing Countries they are a very useful tool for improving their level of life, helping them to fight hunger and natural distresses like desertification.

But in order to obtain such fruitful results, RST applications must become fully accessible to those countries. Therefore remote sensing training activities are a very crucial point, especially when they are application-oriented.

As previously outlined in the report, there are already international training centres and educational activities which are constantly increasing in number and diversifying their content for a better fulfillment of more specialized needs.

However, a great request persists from those countries. Then all the industrialized countries must jointly make further efforts in order to reach both:

— a better diffusion of information on the training opportunities, in such a way that interested people from Developing Countries can attend the most suitable courses for satisfying their respective needs;

— a deeper harmonization of all the activities in order to make them more effective.

As for Italy, in particular, we must outline the strong commitment and current financial support of the Italian Government to help the Developing Countries fight against hunger and its causes, for which purpose we do believe that RSTs will give a strong contribution.

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REMOTE SENSING APPLIED TO RENEWABLE NATURAL RESOURCES

REMOTE SENSING IN FOOD PRODUCTION

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The Pontifical Academy of Sciences convened a study week on the impact of space exploration on mankind in October 1984. At this very important meeting, a number of specialists examined the role of the aspects of space technology in the improvement of the quality of life for all mankind. There were discussions on the entire range of space applications from satellite communication to disaster forecasting. Today, we come back to take up the very special aspect of the previous study - Remote Sensing as Applied to Agriculture. In my presentation at that meeting, I took up the question of the Conquest of Hunger. Perhaps, it will be opportune for me to recapitulate some of the thoughts I put forward at that time and look forward to a concrete plan of action for the future.

A Hungry World

In the year 2015, eight billion people will be living on this earth. In a very short span of forty years, the world's population will have doubled from the four billion of 1975.

Not only will there be twice as many people to feed in 2015 as there are now, but the demand for diets that are more nutritious and varied will be much greater than it is today. The higher standard of living that many people will have at that time will make this an inevitable research. The implication is therefore formidable. Farmers, livestock keepers, food processers, and distributors will not only have to produce, process, and distribute twice as much food as they do now, they also will have to change the mix among cereals, meats, and vegetables as well as increase production and distribution by perhaps as much as another 100 per cent to satisfy the greatly expanded demand in developing countries, for other than the simplest of diets based primarily on the major cereals.

A Global Problem

Increasing world food production three- to four-fold in some forty years, is a global problem. The nature of the problem, its size, the potential solution and the prospects for success, differ markedly from major region to region, from country to country, and indeed from area to area within countries. In fact, no human endeavour devoted to a single broad objective operates within the extremes or faces the diversities, that farming and animal husbandry face worldwide. The number of internationally important crops on which attention must focus for the greatest impact is not large and totals fewer than two dozens. Perhaps this very factor might make it easier to handle from a global point of view. The concentration, therefore, that is required from us would be on those major items that constitute important aspects of the diet of the people.

Major animal types are even less numerous, and so are major climate, crop zone, categories. However, when these relatively few variables are multiplied by ranges in farm size, soil type, number of individual crop varieties, the length of the growing season, changes in local climates at particular times, type and population of pests, degree of mechanization, cultivation practices, the level of education, etc., the permutations are indeed exceedingly great.

In spite of the resulting complexities, certain generalizations are possible. The developed countries, for example, should easily increase food production to satisfy populations that are growing relatively slowly and at the same time continue to provide diversity in the diets which will be nutritionally balanced and aesthetically pleasing.

Developing Nations

Developing countries in the meantime face a much less optimistic future. Many of them depend heavily on imports to meet their needs of food. The limit will soon be reached at which the relatively few developed countries can produce more food to make up the deficiencies in the much more numerous poorer regions of the world. Therefore, the developing nations will have to become almost self-sufficient as a group, if they are to meet their increasing demands for both basic nutrition and for diets that are more varied. Much of the increase in food production needed for the balance of this decade and the early nineteen-nineties can be achieved by combination of technology transfer and technology adaptation.

From one point of view, the world has achieved impressive success in food production during the past two decades. The specific examples of remarkable achievement are India, which tripled the production of wheat in twenty years: Indonesia, which doubled its rice production in ten years; and Colombia, which doubled its rice production in five years. Sri Lanka has, after four hundred and fifty years of history, for the first time become self-sufficient in rice.

However, a notable and tragic exception to this performance is Africa, where South of the Sahara, the annual growth of agricultural output has declined from 2.7 per cent in the sixties to only 1.3 per cent in the seventies. This occurred at a time of greatly increased population growth. In fact, Africa's population growth rate of more than 3 per cent annually is unparalleled, representing a doubling every twenty years. Even African countries with an impressive economic growth have not kept pace with population growth. For example, the agricultural output of Zambia increased 2.8 per cent a year in the seventies, one of the highest rates in Africa, but was considerably below the 3.5 per cent annual population increase.

In spite of all our efforts, Africa is producing less food per person today than it did twenty years ago.

Research and Development

The increasing production that can be reasonably expected from research and development in agriculture in developing countries should meet much of the need for more food in the near term. However, there is no assurance that these efforts will permit a 100 per cent increase in world food production by 2015 or whenever the population reaches eight billion, much less provide the three- to four-fold increase, if rising expectations are also to be met.

It is therefore vitally important that projects of fundamental nature be assigned the highest priority possible. If they are, then perhaps findings will be available within the next decade, that will lead to increase in food production not in inadequate successive steps, but in jumps of 50 per cent or 100 per cent.

Success can by no means be promised. However, the world risks truly severe short falls in food production to meet both the group populations and growing expectations, unless such basic programmes are supported adequately in the years ahead.

The Forward Edge

A number of opportunities are available to us. The best of these, which may provide production gains of 50 per cent and 100 per cent or more, may lie in the fields of genetics and plant physiology. Much of the increase in food production in developing countries is due to the high yielding varieties of wheat, rice, and maize, developed in the sixties and the seventies by the international agricultural research centres and cooperating national programmes. The green revolution led to an extraordinary increase in agricultural output in those fortunate locations for which the seeds were suited, areas with good water supply, adequate supply of plant nutrients, pest and disease management programmes, and areas where agro-chemicals such as herbicides and insecticides were used together with the improved seed.

While it is generally believed that more than a few high yielding cereal varieties are needed to meet the food requirements of the developing nations, the world has come far closer to its goal for its food production than would have been possible without the green revolution. However, in order to take the next quantum jump, we may need to leap from the green revolution to the gene revolution.

Biotechnology

The research projects that can be classified under the broad rubric of genetic engineering in laboratories of all types worldwide, have implications for world food supplies that are more profound than in any other category of research. Since genetic processes control all characteristics of plants, gaining an understanding of different genetic processes should in time allow scientists to tailor food and feed crops for maximum yields at higher efficiencies and maximum resistance to pests and environmental conditions.

In order to provide advances much greater than traditional incremental gains, scientists will need to emphasize research that increases fundamental knowledge of plant biology and biochemistry if they are to realize the potential of genetic engineering.

The major barrier to progress lies in the difficulty in transmitting genetic materials into plant systems except through the sexual cycle. Because there are constraints in identifying genetic characteristics at the biochemical level and the inability to regulate gene expression, a major way in which research can lead to large gains in yields and other desirable characteristics lies in plant physiology studies.

Plant Growth Regulators

Most important, research on plant growth regulators offers the very real prospect of modifying in a major way the photosynthetic rate per unit of solar energy absorbed, the ability to fix nitrogen and control transpiration.

We may indeed be able to improve on mother nature. Because of the complexity of plant physiology processes and the present lack of fundamental knowledge, understanding will not be achieved rapidly. Intensive research will be needed before numerous practical applications will occur. The potential is so great, however, that laying the base must receive greater support now, so that major gains in yields and other important plant characteristics indeed become possible in the long term.

Major delays will occur if government agencies and private institutions neglect the long-term need to increase food production for everyone, while they attempt to cope with short-term needs posed by today's problems of starvation and malnutrition. Welfare and relief to prevent suffering are extremely important, but they must not be allowed to undercut long-term efforts.

Soil and Crop Management

Most of the increase needed to feed double today's population will have to come from the developing countries. Moreover, virtually all the increase will have to come from the land, since 98 per cent of the world's food needs are met by land crops and animals. Fortunately, the potential is great for increasing food production on the land of the developing countries. The difficulties, however, are also enormous.

In discussing the role of science and technology in soil and crop management, we have to focus on the developing countries of the tropics where the problems are the greatest but where the gains can also be the greatest. Although most tropical developing countries have a few farms that produce yields comparable to those in developed countries, yields on the average are very low. Rice yields, for example, average two metric tons per hectare and wheat and maize about 1.5 metric tons. On farms in the high latitude countries the averages range around 6 metric tons per hectare. Yields at both levels, however, are far less than the maximum under optimum laboratory environments, where yields of wheat and rice approach 14 metric tons per hectare and those of maize 22 metric tons.

Developing countries continuously lose crop lands because the fertility is exhausted, erosion depletes them, salination makes them unsuitable for cultivation, and they are diverted to other uses. In addition, subsistence cultivators and landsmen increasingly invade marginal lands that have inadequate rain or that have thin soils and steep slopes. As a result, increasingly greater zones of destroyed forests and steep watersheds erode under subsistence agriculture and over-grazing. Irrigation systems face increasing hazards from flooding and salination, and serious shortages of wood or fuel will occur. As farmers and landsmen turn more and more to dung for fuel, they hamper further their ability to maintain soil fertility.

Inter-tropical Convergence Zone

Finally, what is known as the Inter-tropical Convergence Zone dominates tropical agriculture. This climate condition results from an unstable trough between northeast and southeast trade winds, that causes a variable and uncertain pattern of intense radiation and heavy rainfall. Droughts and floods are endemic. Inadequate supply and balance of plant nutrients and adverse soil conditions can also be major constraints for corp yields. Good practice, therefore, calls for proper tillage, planting on contours, controlling runoffs, constructing irrigation and drainage systems, where necessary, to provide good environment for root growth. Individual farmers in tropical developing countries can take some of these steps, but the more important need is for resources to be organized on the scale of river basins and sub-water sheds.

Regional Efforts

Regional efforts at watershed management are beyond the capability of groups of farmers. Governments of developing countries in the tropics must therefore give priority to controlling watersheds to provide the physical conditions under which the farmers can benefit from agricultural products and processes developed by modern science. Given good land use patterns and watershed control, the short-term solution for tropical developing countries to increase food production will be to adopt as quickly as possible the intensive farming practices that have been so successful in the agriculturally advanced countries.

There is a substantial potential for expanding food production in the developing countries by bringing new land into cultivation, land not prone to erosion but flat land and with the potential for high productivity. In Africa and Latin America only a fraction of the potentially arable land is now being cultivated, leaving open the possible way of significant future expansion.

Rice

When we consider rice, 90 per cent of the world's rice is grown and consumed in Asia, and about 100 million hectares of potential rice lands in Asia are uncultivated and uninhabited or sparsely populated. These lands have attracted attention in recent times. A more universal means of accelerating food production throughout the developing world is to increase crop yields and increase intensity of cropping on the land that is already cultivated. This may be the only approach open in Asia, where three quarters of the world's under-nourished people live.

In fact, in some parts of Asia ecological considerations, as well as practical agricultural economics, suggest that the land presently under annual crop cultivation should actually be reduced to permit the reforestation of hillsides that are presently being cultivated and concurrently devastated by erosion.

Problem Soils

Another aspect to be considered is in regard to problem soils that need special management to produce economically valuable returns. The low productivity of such soils may be due to the presence of plant toxins, nutrient deficiencies, nutrient imbalance, and unfavourable physical properties. Further, we understand that almost all the thirteen billion hectares of the world land area have soil problems in varying degrees. About five million of these hectares of land suffer severe climatic stresses and are uncultivated. Further, five to seven million hectares of cultivated land are going out of production annually because of salination, erosion, and denudation. The idling of vast areas of potentially cultivable land, often within easy access of some of the most densely populated areas in South and Southeast Asia, is largely due to soil problems.

Remote Sensing and Rice Production

In the presentation I made in these very halls two years ago, I pointed out the potential role that remote sensing might have in the production of rice. Because of its importance as a staple diet in more than 90 per cent of the people in the developing countries, and because of its importance in international trade, rice must be viewed in the global context. From the perspective of increasing rice production, the most important areas of the world are those where water is not a limiting factor. However, from a global economic perspective, the important areas of the world are those where production varies widely from year to year.

Rice is extremely adaptable to the environment, growing from tidal marshes to latitudes exceeding three thousand meters, from 35 degrees south to 50 degrees north in latitude. It is adapted to wide ranges of rainfall, from 100 mm per year to more than four thousand five hundred mm per year.

Temperature during the growing season can vary from 17 degrees to 33 degrees centigrade. As a result of this adaptation, it is a very complex crop to model in either biological or econometric terms.

It is clear that when properly supported by the existing national government infrastructure, satellite remote sensing, including both land and atmospheric remote sensing, has the potential to enable the global programme to be developed to inventory and monitor rice. Major elements of the technology are in an advanced state of development but have not yet been tested adequately on rice. Many but not all elements of this science are ready to be used in any such programme.

A Five-year Plan

At our last meeting two years ago, I outlined the five-year plan for remote sensing developed at Hyderabad in September 1981 by the group of space technologists and rice scientists gathered together. This was further refined in 1984 at the International Rice Research Institute in Manila. Let us describe it as the Hyderabad-Manila blueprint for action. Five special areas were outlined for our attention: crops, soil, water, pests, and modelling. In each area action could commence while research would fill in the gaps of our technology and knowledge.

Water will play a major role. It is important to detect and monitor water because the yearly distribution of rainfall is so variable. The primary driving factor for rice production requires the largest amount of water. Snow, humidity, groundwater, the intensity, amount and duration of rainfall need to be monitored. Remote sensing could assist greatly in optimizing water use for increased and standardized rice production. The state-of-the-art technology can be used to contribute substantially to the data requirements in this area.

In crop studies an environmental plan and a production plan were outlined. The determination of area parameters, yield parameters, and the monitoring of crop development, constitute an important part of the scheme.

The LANDSAT series, LACIE, AGRISTARS, SPOT, and meteorological satellites will provide data for area and yield studies.

In the study of soil, remote sensing has enormous advantages over conventional ground methodology. It can cover vast inaccessible areas synoptically and repeatedly. It is objective, faster, and cheaper.

In densely populated countries of Asia, where both food and arable land are scarce, there are about 100 million hectares of land which are suitable for rice cultivation lying idle, largely because of soil problems. The lack of data on the extent and distribution of these lands is a serious obstacle to their utilization.

Conclusion

We are thus at a point where a meaningful plan can be triggered into action. We, in the Third World, have the problem. You, in the north, have the technology. Is it possible that the technology and the problem could be brought together? In 1982 at the UNISPACE Conference in Vienna, the United States proposed to the world a massive programme entitled "Global Habitability" where all the knowledge that we have of space technology could be used to improve the quality of life. Such a programme was intended to embrace agriculture, climatology, land management, water resources, the oceans, communication, health, and education. Our precious globe would be observed from outer space. Our knowledge of the biology would be coordinated. However, very little has happened since that euphoric meeting.

I wish to propose a concrete plan at this very august assembly. Let us, as members of the Third World Academy of Sciences under the leadership of Dr. Abdus Salam, together with the Pontifical Academy, which has made a commitment to the improvement of the quality of life of the poorer nations, get together and interface with NASA and ESA and implement a plan.

Perhaps the rice project could be taken as a test case. We need a focal point around the region to work on this. The Arthur C. Clarke Centre for Modern Technologies, established in Sri Lanka to celebrate the greatest space scientist of our time, Arthur C. Clarke, who participated with us at the last Pontifical Academy Workshop on Space Technology, can be used as a basis for such activity. I hope that before this meeting breaks up a task force can be set up to implement some of these plans. Members of the Academy and learned friends, let such a plan be the best outcome of this workshop that we are conducting now, gathered under the sponsorship of the Pontificia Academia Scientiarum.

REMOTE SENSING APPLICATION TO FORESTRY IN THAILAND

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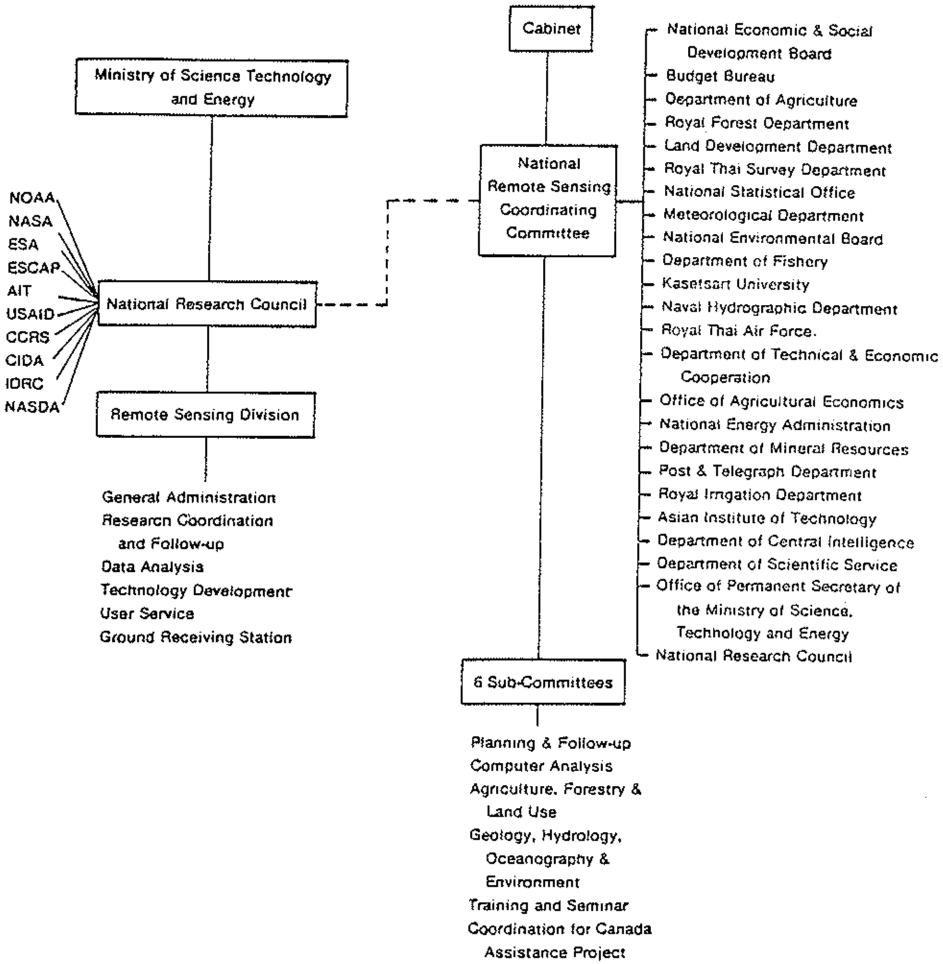
1. *Introduction*

In Thailand, the remote sensing activities are coordinated by a National Remote Sensing Coordinating Committee appointed by the cabinet as early as September, 1971. Twenty-four agencies comprising the planning, financing and user components are presently represented in the Committee. This Committee is entrusted with the responsibilities in coordinating remote sensing activities ranging from the acquisition of data, the dissemination of the data, application support and technology transfer. Thailand Remote Sensing Center is the focal point which, besides acting as the secretariat of the Committee, operates the Thailand Landsat Station (TLS), disseminates Landsat data to users both inside and outside the country, provides user assistance in visual and digital image processing and analysis, conducts regular training courses, and promotes the use of remote sensing data through the provision of research funds, organizing seminars, and issuing newsletters. The organization of the Thailand National Remote Sensing Program is shown in the following chart. Functionally, Thailand Remote Sensing Center is the Remote Sensing Division under the National Research Council of Thailand (NRCT).

The applications of remote sensing data in various disciplines are conducted by the user agencies through the coordination of working sub-committees under the guidance of the National Remote Sensing Coordinating Committee. The applications to forestry are handled by the

Organization of The Thailand National Remote Sensing Program



Sub-Committee on Agriculture, Forestry and Land Use. The technology transfer is accomplished through the coordination of Sub-Committee on Training and Seminar. The Planning and Follow-up Sub-Committee provides support in the research and development including guidance in the accomplishment of action-oriented activities by allocating funding for specific purposes. In forestry applications, most of the work is being conducted by the Royal Forestry Department, which has a strong interest in using the remote sensing data and also has an efficient and capable group of scientists and technicians to handle the assignment. The Faculty of Forestry of Kasetsart University in Bangkok also engages in research and technology transfer with a small but well equipped remote sensing laboratory. The National Research Council of Thailand performs data analysis in forestry applications, especially within the concept of multi-stage remote sensing and the geographic information system.

2. *Thailand Landsat Station* (*TLS*)

As a contribution from Thailand to the proposed establishment of the Asian Regional Remote Sensing Training Center to be located in Bangkok for the supply of Landsat remote sensing data, the Royal Thai Government in 1979 approved a budget of some U.S. 6 million dollars for the setting up of Thailand Landsat Station to be managed by NRCT. The Station was commissioned in late 1981. Since then the Royal Thai Government has been providing an annual budget of about U.S. one to two million dollars for the operating cost of the Station. As shown in Table 1, Statistics of Landsat Data Distribution for calendar year 1985, the sale from Landsat data is only about U.S. $ 150,000, which amounts to only one quarter of the current NOAA access fee which NRCT must pay to NOAA. Another important fact is that international users comprise the largest user group and surpass the Royal Thai Government agencies. Thus, Thailand Remote Sensing Center is a regional center supplying Landsat data to countries in South-east Asia and several other non-Asian users, although it is fully supported by the Royal Thai Government budget.

With the commercialization of Landsat and the same nature for SPOT, it is rather difficult to upgrade TLS to receive and process Landsat TM and SPOT HRV data without the assistance of developed countries or international organizations. However, NRCT is in the process of negotiating with NASDA of Japan to receive and process data from the

TABLE 1 - *Statistics of Landsat Data Distribution of Thailand Landsat Station.*

PROFILE OF USERS FOR CALENDAR YEAR 1985

Users	Frames/Reels	Percent	Approx. US$	Percent
1. Government Agencies	987	43.52	46,840.00	31.48
2. State Enterprise	8	0.35	259.00	0.20
3. International Organization	1,155	50.93	96,302.75	64.72
4. Private Sector	118	5.20	5,360.00	3.60
TOTAL	2,268	100.00	148,797.75	100.00

LANDSAT DATA DISTRIBUTION FOR CALENDAR YEAR 1985

Products	Amount/Frames/Reels	Percent	Value (US$)	Percent
B & W Photos	1,717	75.71	59,722.80	40.14
Color Photos	407	17.94	21,157.85	14.22
MSS CCT Scenes	144	6.35	67,917.10	45.64
TOTAL	2,268	100.00	148,797.75	100.00

Marine Observation Satellite (MOS-1) to be launched next year. Such cooperation would ensure data supply to countries in the South-east Asian region.

3. *Application of Landsat Data to Forestry*

Almost fifty years ago, a large portion of the country was covered with dense forest distributed all over the country except the great central plain, where forest had long been replaced with agricultural land. The increasing population in the past few decades at a high rate of 3.0 per cent per annum led to the exploitation of forest land for agricultural purposes. However, in order to sustain economic growth, a rational utilization of natural resources including forestry must be properly maintained. Such realization that forest is an integral part of the eco-system which must be preserved led to the government policies to maintain the forested area at a suitable percentage of the total land area and to manage the watershed area more wisely. Satellite remote sensing data, especially Landsat, is considered to be useful in assessing the forest land resources and in monitoring the change. Results of the Landsat data derived interpretation have been used by policy makers to plan more effectively for the preservation of forest area, for the reforestation scheme and rehabilitation of watershed on the major catchment basin areas.

Most of the interpretations of Landsat data were done visually, using Band 5 and Band 7 at 1:250,000 scale and diazo-color composite transparency at 1:1 million scale. Digital anlaysis started with the establishment of Thailand Landsat station and became quite popular since 1983 with the acquisition of DIPIX Image Analysis System. The majority of work has been accomplished by the staff of the Royal Forestry Department, Forest Management Division with manpower of about 30 who had been well trained and equipped with necessary instruments and adequate budget including expenses for ground survey. In fact, the greatest contribution of our data from Thailand Landsat Station up to now has been in the field of forestry applications. If we were to conduct a nationwide survey of existing forest by air reconnaissance, the effort would take three years and cost about four million U.S. dollars, because only three months a year are suitable due to haze and cloud cover, and Thailand has a total land area of about 514,000 square kilometers. The last nationwide air survey was conducted in 1961 for forest inventory.

4. *The Forest of Thailand*

Thailand is divided by physical characteristics into five regions as follows:

— The Northern part is made up mainly of highlands and steep mountains surrounding rich alluvial valleys.

— The Northeastern part is a generally low-lying zone with Korat Plateau having a height of a few hundred meters above mean sea level.

— The Central region comprises the Chao Phraya Plain and its tributaries connecting to the Gulf of Thailand.

— The Eastern part consists largely of a broad coastal zone with a hilly hinterland.

— The Southern region is a long narrow peninsula extending towards Malaysia.

Being under the influence of monsoon climate conditions, the vegetation of Thailand is a humid tropical one with vast areas covered with forest. Basically, the forest of Thailand can be classified into two broad categories of Evergreen and Deciduous.

The Evergreen Forest is composed of a great proportion of the non leaf-shedding species and covers about 60% of the total forested area. It can be subdivided into the following three types:

— Tropical Evergreen Forest or Tropical Rain Forest
— Coniferous Forest
— Mangrove Forest

The Deciduous Forest can be subdivided into the following three types:

— Mixed Deciduous Forest
— Dry Deciduous Dipterocarp Forest
— Savanna Forest.

The forests in the Northern region of Thailand are of Teak (*Tectona Grandis Linn.*) bearing type. The forests are rich in timbers of commercial value such as bamboo, rattan, wood oil, gums and incense wood. Most of the forests are Tropical Mixed Forest with many valuable species. This type is very dense with considerable understoried plants and climbers making ground inventory very difficult, if not all inaccessible.

5. *Rate of Forest Depletion*

The forested area of Thailand by means of the interpretation of Landsat data conducted in 1973, 1976, 1978, 1982 and 1985 was shown in Table 2. It is evident from the results that in 1985, the forested area of the whole country was depleted to approximately 29.05 per cent compared to the figure of 43.21 percent in 1973.

The rate of forest depletion since 1973 was highest in the Northeastern region at 4.35 per cent per annum and the lowest in the South at 1.33 per cent per annum, and at 2.73 per cent per annum for the whole country.

The high rate of forest deterioration is mainly due to population increase, political, economic, and social pressures, which can be attributed to the following:

i) The increase of the population growth in Thailand has been at a high rate of 3 percent per annum.

TABLE 2 - *Forested Area by Region of Thailand in* 1973, 1976, 1978, 1982 *and* 1985.

Region	Total Area	Forested * Area 1973		Forested ** Area 1976		Forested *** Area 1978		Forested **** Area 1982		Forested ***** Area 1985	
	Km^2	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%
North	169,644	113,595	66.96	102,327	60.32	94,937	55.96	87,756	51.73	84,126	49.59
Northeast	168,854	50.671	30.01	41,494	24.57	31,221	18.49	25,886	15.33	24,224	14.35
East	36,503	15,036	41.19	12,631	34.60	11,037	30.24	8,000	21.92	7,990	21.89
Central	67,399	23,970	35.56	21,326	32.38	20,426	30.31	18,516	27.47	17,228	25.56
South	70,715	18,435	26.07	20,139	28.48	17,603	24.89	16,442	23.25	15,485	21.90
TOTAL	513,115	221,707	43.21	189,417	38.67	175,224	34.15	156,600	30.52	149,053	29,05

* Source: Landsat-1 imagery, taken in 1973
** Source: Landsat-2 imagery, taken in 1976
*** Source: Landsat-3 imagery, taken in 1978
**** Source: Landsat-3 imagery, taken in 1982
***** Source: Landsat-4-5 imagery, taken in 1985

ii) Due to the population increase, the land badly needed for food production is getting more and more scarce and this leads to the high pressure on land, leading to forest destruction.

Forest invasion can be divided into 4 main groups as follows:

— Hill tribe people practising shifting cultivation in the watershed areas.

— Migrated people from neighbouring countries.

— Capitalists who sent their labourers to open the fertile forest land.

— Indigenous people, especially the poorer farmers who do not have enough land and hired farmers who have no land of their own.

iii) Demand for timber is much higher than what the forest can supply. In 1972, FAO conducted a study on the supply and demand from forest resources in Thailand. The result showed that at present a deficit of growth over annual cut has occurred.

iv) The weakness of forest law.

v) The Royal Forest Department has not enough forest rangers and financial support for forest protection programme.

vi) With increasing industrialization, some forested areas were destroyed for industrial sites.

vii) In the past, there had been no forest development plan. The Royal Forest Department carried out all functions as temporary measures for facing the problems. But now, forest policy would have to follow the governmental policy concerning the specific forest development plan in order to slow down the rate of forest destruction and prevent unwise land use. This action is the result of the remote sensing data being used by the highest decision-makers in the country.

6. *Impact of Remote Sensing on Forest Management*

A study conducted by Kasetsart University in 1977 using Landsat-2 imagery revealed that of the existing forest area in Thailand of 38.48 per cent, only 25.68 per cent was classified as productive and about 12.80 per cent was classified as disturbed non-productive forest. The government policymakers were informed of the alarming rate of forest depletion and plans were drawn up to correct this trend. Subsequently, the Five Year Social and Economic Development Plan included the plan for the forestry sector. The current Plan calls for the following targets to be met.

— Maintaining the forest area of the country up to the maximum level of 40% of the total land area.

— Lowering the forest destruction rate.

— Acceleration of the replanting program with an annual planting area of 80,000 hectares and reduction in planting cost by using new method.

— Expansion of the forest protection program and controlled logging operation in restricted areas.

— Rehabilitation of the watershed on the major catchment basin areas, especially in the North and Northeast regions.

It is important that those deteriorated areas should be restored to the original state, either in the form of productive forest area, watershed area, national park, or wildlife sanctuary. And one of the solutions to achieve the desired target of 40% is by setting up the forest plantation program. It was evident that in 1978 with the existing forest area at 34.15% and if the replantation of 500 km^2 per year was carried out, it would take up to 60 years to reach the 40% target. Another measure is the land rehabilitation and resettlement, both in the highland development and the lowland development. Remote sensing plays a very vital role in monitoring the reforestation program and the rehabilitation effort. Optimum forest land-use planning and management by incorporating the remote sensing data in multi-level structure using Landsat, some air-photos and ground survey are being carried out in a routine manner by the Royal Forestry Department. Such a scheme is also being executed in other ASEAN countries, for example, the Philippines and Indonesia.

7. *Conclusion*

The forest is one of the few renewable natural resources. With careful planning and management and efficient reforestation programs, we can harvest timber and derive economic benefits indefinitely. The forest land use should be planned in conjunction with the master plan for land use. The information obtained from remote sensing data showed a sharp decrease of forest land and at present the total forest area of Thailand is much lower than the desired target. This indicates that Thailand's forest has now reached a critical stage. The government has initiated plans and actions to correct the situation. Monitoring of such efforts by remote sensing is an effective and economic way. With the increasing use of digital image processing, the different types of forest can be classified, which would provide information for the forest management. Better resolution data from current satellite sensors and future satellites would enhance the benefits of remote sensing to forestry. Regional cooperation, either through UN bodies or multilateral agreement should be strengthened. The commercialization of remote sensing systems should take into account the cost-effectiveness and the economic and technological condition of the developing countries.

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REMOTE SENSING FOR FOOD SECURITY

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1. Introduction

Almost 50 percent more food will have to be grown by the year 2000, if only to meet the minimal present levels of food security. Additional food supplies will be needed by the end of the century, to conquer famine and malnutrition and to accommodate the requirements for improved nutrition as well as the demands arising from higher incomes (Dudal, 1982). By the end of this century, the world population will surpass 6 billion and probably reach 10.5 billion by 2110 (Sala, 1981) against less than 3 billion twenty years ago and 4.8 billion in 1984. Eighty-seven percent (cf. 72% in 1972) will live in developing countries, and the population density will become acute in some areas (e.g., an estimated 140 million in Java).

Resulting primarily from the current population explosion, probably more serious than the future threats of pollution, will be major changes in patterns of land use and the accelerating threats to agriculture caused by deforestation, soil erosion, declining soil fertility, salinity and, in some regions, increased desertification. In North Africa alone, the loss of land to desert encroachment has been estimated as exceeding 100,000 ha a year (Le Houérou, 1970). Also, preliminary land degradation assessments indicate that unless conservation measures are introduced on all cultivable land, 544 million hectares of potentially productive rain-fed crop land could be lost to agriculture by the year 2000 (Higgins *et al.*, 1982).

Such are the challenges posed to a sector where agriculture is the dominant factor of the economy in many developing countries, where output is determined by the naturally built-in limits to biological growth and where many decisions taken today can affect production only in the next decade (vide FAO, 1981; Howard and Mitchell, 1986). Major land development schemes may require twenty years from the time they are decided on, before they are in full production. Moreover, agriculture is not only technical; it is the core around which socially complex human cultures have evolved: for peoples to change their land tenure and cultivation practices, so as to permit the full modernization of their farming, is a task of decades.

2. State-of-the-art of Remote Sensing Technology

This is the man-made scenario into which remote sensing technology is being increasingly introduced, with many successes but at the same time with some disappointments. As we will be aware from other papers presented in this study week, remote sensing or teledetection is concerned with the capture of data at a distance and the analysis of the collected data. The analysis of remote sensing data for food security involves both analogue and digital techniques. Often the visual interpretation of computer-processed imagery has proved to be the most effective. The collected data, after processing to provide information, will be found to be synoptic, timely, of very low cost per unit area of land, as compared with rural surveys relying entirely on data collected on the ground and often unique in character. Over 40 years ago, it was recognized that the introduction of aerial photography into land-use survey reduced several times the cost of survey per unit area (Howard, 1970).

When we speak of remote sensing applied to food security we are concerned not only with satellite remote sensing, but airborne methods and techniques and sometimes the use of light reconnaissance aircraft or a ship. Until the early 1970s aerial photography, combined with aerial photogrammetry and aerial photointerpretation, was the only space tool available to provide data and information useful to food security.

Black-and-white panchromatic aerial photography and the interpretation of the processed prints provide the traditional approach to the applications of aircraft remote sensing, which began 73 years ago with aerial photography in North Africa. In recent years, spectacular advances in conventional aerial photography, due to the much improved resolution of camera lens and careful choice of the film filter combination (e.g., colour, infrared colour), provide new opportunities. Light high-wing aircraft using miniature cameras (35 mm, 70 mm) are used for aerial reconnaissance, for point and strip aerial photography, and to provide data to complement remote sensing information sources from other platforms and sensors. High altitude jet aircraft equipped with modern survey cameras can provide complete colour infrared photographic coverage in stereo of 10,000 km^2 to 20,000 km^2 a day with a resolution of ground objects as small as 1-2 m. This rapid coverage enables extensive areas with only short cloud-free periods to be covered by aerial photography. For example, Sierra Leone was covered on 15 days, whilst conventional coverage of the country had taken 8 flight missions over a period of 14 years (Howard and Schwaar, 1978).

Two other major airborne sensors are airborne imaging radar and multispectral scanners. Side-looking airborne radar (SLAR) and synthetic aperture radar (SAR) with their cloud penetrating capability, have been used for over twenty-five years to provide small-scale planimetric maps (e.g., 1:100,000, 1:250,000) of areas unsuited to aerial photography and to provide information about land-use (e.g., forest versus non-forest), flooding, drainage patterns and landforms. Other than providing small-scale thematic maps, there seems at present little opportunity for food security to benefit from radar technology.

Secondly, airborne multi-spectral scanning (MSS), including thermal sensing, has been used for about twenty years to provide imagery beyond the aerial photographic spectrum; but, with the exception of the thermal sensing of forest fires, volcanic activity, some urban studies and water temperature differences associated with pollution, fresh-water discharge and ocean currents, airborne MSS scanning has remained experimental. Unfortunately, the flying height required to provide MSS imagery with the same resolution of ground objects as aerial photography is several times lower. Furthermore, processing of MSS imagery is more complex. This thereby restricts MSS technology use in food security.

On the other hand, satellite sensed data is most frequently collected by multispectral scanner systems. In the new SPOT satellite the scanner is replaced by CCD Sensors ("coupled charged devices"). At the present time, satellite remote sensing technology is used mainly in an experimental or quasi-operational mode for application related to food security, but potential operational uses are increasingly being identified. Satellite sensing is much more cost-effective for repetitive coverage of the same ground areas than airborne sensing. In comparison, aerial photography of the same ground area can seldom be justified financially more often than every 5-10 years, which limits its usefulness to food security. Complete ground coverage of an area by satellite imagery may be a thousand times cheaper than aerial photography or SAR; but the resolution of ground objects by aerial photography may be five to fifty times finer than by using earth resources satellites. Thus the airborne and satellite systems are complementary, and recognition of this fact is now favouring multistage and multiphase sampling techniques using both aerial photographs and satellite imagery in combination with field collected data and occasionally DCPs (data collection platforms).

The family of satellites currently ranges from the geostationary (e.g., Meteosat, GOES 1-2, GMS), the polar-orbiting earth resources satellites (e.g., Landsat, SPOT), the polar orbiting environmental NOAA satellites Tiros, Nimbus) and manned spacecraft including Salyut/Solyuz, Skylab in 1977 to the Space Shuttle (Spacelab) in 1984 with its metric and large-format cameras. The geostationary satellites provide the lowest spatial resolution (i.e., 2.5-5 km), but the highest temporal resolution (e.g., every 30 minutes for Meteosat). Data from polar-orbiting environmental satellites with higher temporal resolution (NOAA/Tiros/AVHRR: 1.2 km^2, 15 km^2) are receiving increased attention for food security, particularly as the purchase price of data is much lower than that of the earth resources satellites and new types of useable information are obtainable. Nimbus with its coastal zone colour scanner (CSCS) has demonstrated the usefulness of this type of system in marine studies; and in 1990 ERS-1 carrying SAR can be expected to provide a wealth of new data, some of which may be useful to food security.

The earth resources polar-orbiting satellites (Landsat-5, the planned Landsat 6, SPOT-1, SPOT-2 and ERS-1), are expected to provide global coverage, albeit at higher cost for imagery, into the early 1990's. These experimental satellites, particularly the earlier Landsats 1-4, have demonstrated the increasing uses to which data, collected in several spectral bands by scanner systems, can be adopted, although often restricted by problems of cloud cover and their relatively low temporal coverage (e.g., Landsats 1-3, every 18 days) and ground resolution (80 m, MSS; 30 m, Landsat Thematic Mapper). Although SPOT-1 passes over the same ground area every 26 days (10 m, 20 m resolution), by using its side-looking capability, it can sense obliquely the same ground area every 2-5 days. This side-looking capability of SPOT, combined with its spectral characteristics and improved ground resolution, may prove increasingly useful (e.g., detection of crop areas, crop types, crop condition); but data flow to the user and the purchase price of data may prove to be major constraints.

3. Application of Remote Sensing Technology to Food/Feed Security

The application of remote sensing to food security and feed security for livestock calls for the matching of the needs of the growing world population with advances in appropriate technology and the skills of the experienced imagery analyst using analogue and digital techniques. Table A summarizes the scale/resolution of imagery applicable to food security activities and Table B summarizes sensor platforms.

Whilst the skill of the aerial photo-interpreter demands the extraction of information from a mass of data contained in aerial photographs, satellite analysis requires the maximum use to be made of very limited data contained in the satellite imagery. The overall approach to photo-interpretation and satellite imagery analysis is to proceed from the general to the specific, using deductive reasoning.

The application of remote sensing to food/feed security implies using the technology to provide data and information extracted from the remotely sensed imagery, which is timely, useful and directly or indirectly used in monitoring agricultural changes, in assessing the land and crop condition and in planning the better use of the landscape. Remotely sensed inputs may take the form of estimating the agricultural crop areas, assessing crop and rangeland conditions, counting livestock, obtaining information about the landscape and environmental factors influencing crop growth and crop yield, including agro-meteorological data, and providing information useful in assessing agricultural productivity in the short, medium and long term.

Agricultural Crops: For many years, large-scale aerial photography has been demonstrated as useful to identifying a range of agricultural crops, including cereals (e.g., Brunnschweiler, 1957; Bomberger *et al.*, 1960; Anuta and MacDonald, 1971), and for assessing their areas and the crop condition, including incidence of disease (e.g., Colwell, 1956; Brenchley and Dodd, 1962; Howard and Price, 1972). In general the successful interpretation of the areas relies not only on spectral radiance differences as in Landsat analysis but also on textures, pattern, shape,

TABLE A - *Scale/Resolution of Imagery for Food/Feed Security* (X: applicable - Activities).

Scale Res.	Land-use	Land-use Change	Simple Land System Maps	Agro-Ecol. Zones	Veget. Index	Agric. Crop Area	Agric. Model Yields	Precip. Estims.	Area Samp. Frame	Livestock count	Rangeland condition	Inland Fisheries	Marine Fisheries	Water Resources	Eros./soil degradation	Soil Survey	Drought	Floods	Temperature
1/2000AP										X									
1/5000AP						X								X	X				
1/10000AP	X					X			X			X		X	X	X			
1/15000AP	X					X			X			X		X	X	X			
1/25000AP	X					X			X			X		X	X	X			
1/50000AP	X		X			X			X			X		X	X	X		X	
1/80000AP (1 m. res.)	X		X			X			X			X			X	X		X	
1/120000AP (2 m. res.)			X			X			X		X				X			X	
10 m. res. (e.g. SPOT)			X						X					X	X			X	
20 m. res. (e.g. SPOT)	X	X	X		X	X			X		X			X	X	X	X	X	
30 m. res. (e.g. LANDSAT TM)	X	X	X	X	X	X			X		X			X	X	X	X	X	
80 m. res. Landsat MSS	X	X		X	X	X			X		X					X	X	X	
NOAA LAC 1 km.² approx res.				X	X		X				X						X		X
Meteosat/GOES 2.5/5 km res.								X			X		X						X
NOAA GAC 16 km² approx. res.				X	X						X								X

TABLE B - *Platform associated with Food Security Activities* (X: applicable).

Scale Res.	Activity																	
	Land-use	Land-use Change	Simple Land System Maps	Agro-Ecol. Zones	Veget. Index	Agric. Crop Area	Agric. Model Yields	Precip. Estims.	Area Samp. Frame	Livestock count	Rangeland condition	Inland Fisheries	Marine Fisheries	Water Resources	Eros./soil degradation	Soil Survey	Drought	Floods
Low-level AP	X	X				X				X		X						
AP for Topo mapping	X		X			X			X			X		X	X	X		
High altitude AP	X		X			X									X			
EARTH Resources Satellite (Landsat MSS)	X	X	X	X	X	X			X		X	X		X		X	X	X
2nd generation ERS (TM, SPOT)	X	X	X			X			X		X	X				X	X	X
Polar orbiting Env. sats				X	X		X	X			X		X				X	
GEO stationary Satellites							X	X					X				X	
Aerial reconn.	X									X	X	X			X		X	X
DCP support							X	X						X				X

and sometimes height. Unfortunately, the regular airborne monitoring of agricultural crops has generally not proved cost-effective, and airborne monitoring is therefore usually confined to emergency situations. However, new inputs to monitoring and the timely acquisiton of data are provided by the environmental and the earth resources satellites; and considerable progress has been made on evaluating satellite remote sensing systems for monitoring rangelands and for assessing crop condition, which when combined with crop area provide inputs to crop production models (i.e., crop production = crop area × crop yield).

We know that the coarse resolution of satellite imagery, the problem of cloud cover in the crop-growing season, and often the delivery time between data capture and processing and the supply of imagery and information to the agricultural user, are major constraints in the direct use of earth resource satellites, including assessing agricultural crop production. Whilst Landsat-5 continuously covers the same area of the earth's surface every 16 days, relatively cloud-free imagery may be obtained only once or twice in the crop-growing season. It seems that even if there are major advances in satellite remote sensing technology, the effective regional monitoring of specific cereal crops using earth resources satellites may still not be practicable. The identification from imagery of specific cereal crops, their separation from other land-use classes (e.g., green pasture in Argentina) and the resolution of small areas are major constraints. For example, for rice in the Far East, the field sizes are often very small (e.g., 0.1 ha), the rice crop in the same locality may be at several stages of growth (e.g., in Java, five stages of growth in 1 km^2) and multiple cropping may be common practice (e.g., beans and maize in Africa). Even if a specific agricultural crop has a distinctive reflective signature, it may require a minimum cluster of nine pixels for its satisfactory identification. This amounts to an area of about 0.5 ha for SPOT MS, 4 ha for Landsat MSS; and about 140 km^2 for the vegetation index imagery derived from NOAA AVHRR GAC data.

For over a decade satellite data has been increasingly incorporated in crop production studies, and its importance to food security in the near future can be expected to be linked with improved field sampling, improved inputs to crop yield models and in planning agricultural studies associated with crop production. Work at the FAORSC in the mid 1970s, for example, showed that Landsat MSS imagery can be applied in place of maps to delineate complex/compound land-systems as a base to land-use planning and to define the strata of the area sampling frame. Now, Landsat TM and SPOT imagery with their higher resolution enable simple land-systems to be identified and mapped.

The first major attempt at applying satellite data to agricultural crop production was the LACIE programme conducted in the USA between 1974 and 1978. Its objective was to demonstrate that the earth resources satellite Landsat (MSS), could be applied to forecasting wheat production. The programme was later extended to other cereals and combined the assessment of crop areas with historical wheat yield statistics and climatic and weather data. Provided the field sizes are very large and the cropping pattern simple, an accuracy acceptable to many developing countries (i.e., 85% to 90%) is achieved; but this is still well below the operational standard of the USDA Crop Reporting Service using the area sampling frame. Using Landsat imagery under ideal conditions in North Dakota, the area under small grain was inventoried with an accuracy of 96.5%. The study of weather data as part of the programme stimulated interest in the development of yield models in which environmental satellite data was later introduced as a variable.

This was followed in 1980 by the "Agriculture and Resources Inventory Survey through Aerospace Remote Sensing" (AGRISTARS). The overall goal of AGRISTARS is to determine the feasibility of integrating aerospace remote sensing technology with USDA acquisition systems. The usefulness of timely and inexpensive meteorological data acquired by the NOAA polar-orbiting and geostationary operational environmental satellite (GOES) was recognized and integrated into the crop yield models.

The current strategy of the United States Department of Agriculture (National Agricultural Statistics Service) in introducing remote sensing for estimating crop areas (Vogel, 1986) recognizes that remote sensing is another method of data collection that can supplement the existing field data collection system, but not replace it. To improve crop acreage estimates, the goal is to integrate the two data collection systems through rigorous statistical methodology and by developing resource-effective techniques. An annual survey is conducted in the USA by NASS to measure the area under cultivation for the different crops during late May and early June each year. The primary sampling unit is an area frame. The first step in constructing the area frame is to identify categories of land use that will improve sampling efficiency. The Landsat imagery is photo interpreted to determine land use while the county maps provide physical features to use as stratum boundaries. A random sample of about 16,000 segments of land across the United States is selected from the frame, and their physical location is identified on county maps and on aerial photographs. During the survey, interviewers who have received training on interviewing and map reading procedures locate the sample segments and personally interview each farm operator with land in the segment. In recent years, this procedure has been used to construct new area frames in many U.S. states as well as in several other countries including Morocco, Thailand, Sudan, Zaire. The use of satellite imagery can yield significant improvements in sampling efficiency when it aids defining "crop specific" strata. Examples are the separation of dry land from irrigated areas and the identification of areas with concentration of a specific crop.

Livestock: Another aspect of remote sensing in which remote sensing can be applied directly to the feed security of livestock is for range-land planning and management. Currently there exists the possibility of obtaining estimates of forage and production of large areas through the use of satellite remote sensing techniques even if only a low precision is possible, and for over twenty years the usefulness of light aircraft reconnaissance in counting livestock has been demonstrated to be efficient and often as accurate as ground counts. Sampling procedures are adopted which are commensurate with the range-land characteristic measurements taken in the field. Many characteristics of range-land, such as herbage production and livestock production, vary greatly even over short periods of time, whilst shrubs and trees and human densities change much slower. Generalization of localized information on the vegetation, which forms the backbone of range-land surveys, to more extensive areas, is achieved by classifying the range-land by types and then sampling in each type.

The application of remote sensing to range-land studies favours firstly the interpretation of the vegetation on aerial photographs and photomosaics and then the use of the differential reflectivity of red and near infrared radiation by green vegetation and other surfaces, as recorded by the satellite scanners. Various ratios have been constructed by the combination of the recorded reflectivity data of the red and near-IR spectral bands which are referred to as vegetation (greenness) indices (VI). A more complex index (i.e., normalized difference vegetation index) is frequently used by NASA (Goddard Space Centre) in the analysis of NOAA AVHRR data (local area coverage - LAC; global area coverage - GAC). LAC data can be correlated with vegetation data collected in the field (i.e., plant cover, green biomass) and then used as training sets.

Once an acceptable mathematical correlation is achieved between the satellite recorded spectral reflectivity and the data collected at the field sites, the relationships are extended to the overall area as recorded on the satellite imagery. It is doubtful if the same procedure can be advocated for the much lower resolution GAC imagery, in which each data will cover an area of approximately 16 km^2.

In Botswana, through the FAO range-land project, high correlations were established between the vegetation index and ground samples for green herb cover and bare ground cover. NOAA AVHRR imagery derived from using the normalized vegetation index techniques was observed to correlate well with the ground samples and Landsat data (Astle, 1984). A similar study is now proceeding in the Sudan. In Senegal (van Praet, 1984) false colour imagery of the NOAA satellite's AVHRR data has been used to monitor the growth of the standing crop through the rainy season. Measurements collected at the same time as the satellite's passage, by clipping grass in the field, allowed the project to compare the false colours shown on the imagery with the true primary production, and thus to produce maps (scale 1:500,000) of the standing crop biomass. These maps are of particular interest in the comparison of carrying capacity with stocking rate, and in the determination of spatial distribution of forage. Two obvious applications are in the provision of early warning to future movements of livestock (which depend in large measure on the availability of pasture) and in indicating areas of potential fire hazards.

Fisheries: Turning to coastal and inland fisheries, the rapid changes in the area and shape which can take place in lakes, on riverine flood plains or in coastal lagoons and estuaries are usually not recorded on available maps. Aerial photography, or occasionally SLAR, may be used to detect these changes in flooded areas, such as SLAR in one FAO project on the Magdalena River in Colombia (FAO, 1982). The high resolution imagery of Landsat TM and SPOT can be expected to play an increasing role in obtaining this type of information, including identifying the exact location of small dams established by farmers and suited to the introduction of lake fish.

Considerable use has also been made of visual observation and miniature camera photography from light aircraft to monitor fixed fishery installations, such as the brush parks in coastal lagoons in Benin, for the enumeration of temporary fishing camps and the number of boats or fishery units in use. When combined with ground sampling, economic production and productivity data can then be derived (FAO, 1982).

Remote sensing using satellite imagery and aerial photographs is assisting in the mapping of coastal features and shallow-water bottom topography, including reefs. Satellite imagery, particularly Landsat and SPOT MSS simulation, gives a valuable synoptic view. In Bangladesh, for example, Landsat was used to determine what flood plain lakes retained flood water throughout the dry season. In a recent SPOT simulation study in coastal Kenya, the imagery was found to facilitate the location of sites for acquaculture.

With marine fisheries, however, dynamic phenomena take place against a dynamic background in which it is difficult to provide a fixed frame of reference for remotely sensed data. Information must be passed on very rapidly if any practical benefits are to be obtained. This therefore has been a major constraint to the use of satellite imagery; but timely results are now being obtained as diverse as the Californian and Southwestern Australian coasts. In marine fisheries, FAO has been heavily involved through the use of hydro-acoustic equipment for the assessment of fish populations and the direct location of fish concentrations. Fishermen also benefit from the contribution of space and airborne remote sensing to the monitoring and forecasting of the weather and of ice conditions and to general science of the sea, particularly biological and physical oceanography. Satellite remote sensing has been used to detect experimentally chlorophyl in phytoplankton concentrations. Thermal sensing (e.g., Nimbus Coastal Zone Color Scanner) has been used to map ocean upwellings and cool/warm water interfaces, which are well known as centres of fish productivity; and now, by using navigation satellites, the exact location of these areas can be plotted on the Admiralty and other sea navigation charts. In a study in the Maldives, which has a very small land area to sea area, Landsat TM will be used to establish the map base of the atolls, and supplementary information on the land use and coastal zone will be obtained from small-format low-level light aircraft photography. It is planned for this to be integrated with satellite Doppler positioning system to establish cartographic accuracy.

Rural disasters: as significantly influencing food/feed security, these can be categorized firstly into those with short-term sudden effects, such as floods, earthquakes, storms, forest fires and the explosive growth in numbers or mass movements of migratory pests. Rural disasters are also associated with short-term cumulative effects such as flooding from prolonged rainfall, local and regional droughts, and those with long-term effects such as climatic changes, soil degradation and desertification (Howard, Barrett and Hielkema, 1979). Satellite data can be used, for example, to improve our knowledge on annual rainfall and the isoline mapping of areas having erratic or scanty rainfall, e.g., Oman (Barrett, 1977), and for mapping floods (e.g., Pakistan, Sudan).

Timely and accurate information concerning the location, extent and intensity of rainfall and vegetation development in the locust recession areas is a major requirement of the FAO programme carrying out the strategy for the prevention of desert locust plagues. The desert locust potentially threatens crops and range-land resources over some 30,000,000 km^2 in many countries in Africa, the Near East and South West Asia, impinging upon the livelihood of a fifth of the world's poorest population. The first study using Landsat and NOAA imagery was initiated in 1976 by the writer in consultation with the FAO Desert Locust Surveillance Unit. Now using Meteosat data to assess precipitation, NOAA AVHRR imagery in vegetation index format to monitor vegetation development and sometimes including supplementary Landsat MSS data, this enables a comprehensive regional picture to be obtained of the prevailing ecological conditions. This allows for the selection of specific areas for ground surveys and aerial spraying (Hielkema, 1984).

In developing satellite-based techniques for drought monitoring over large areas of Africa, it is becoming apparent that specific techniques can be singled out. The most efficient system of drought monitoring in Africa will probably be to integrate the precipitation monitoring by METEOSAT, the vegetation greenness condition monitoring by NOAA AVHRR and ground meteorological data. The advantage of the satellite contribution is that it permits regular and frequent observations of large areas over a long period of time. The satellite observation system functions even when the ground-based reporting is disrupted. Thus satellite-derived information on precipitation patterns provides early warning of drought before data from other sources may be available and supplements conventional data, particularly in areas from which the reporting is inadequate.

The Food and Agriculture Organization of the United Nations utilises Meteosat as the primary source of information from which quasi-operational maps ("precipitation estimates") are prepared. In turn these maps are used by the FAO Food Security and Information Service (ESCF) as one of the inputs into the pool of data from which early warnings of food shortages and crop failures are derived (Kalensky *et al.*, 1985). Although these data can only be used for a broad assessment of agricultural conditions, they provide systematic and objective coverage of the area, regardless of its remoteness or accessibility. The actual rainfall totals calculated from the rain-gauge and satellite data for 7-10 day periods (according to the local reporting periods) are compared with the long-term averaged rainfall totals for the same area and time period. Results expressing a relative change in total amount of the actual rainfall as comapared to a long-term average are grouped into five broad classes and plotted on charts.

In the United States NOAA integrates data from NOAA's polar-orbiting and geostationary satellites, geographic information, agronomic models and economic models to monitor land and marine resources (Hock, 1984). Climatic assessments and food security for developing countries in the tropics include weekly rainfall, weather analyses and climatic impact assessment models for more than 400 agroclimatic regions. The results of these assessments are used in an "early warning system" of impending crop failures. Already these agricultural monitoring activities have provided advanced warning of the crop failures which affected the Sahel and east African countries and parts of southern Africa.

Other associated applications

The following examples, drawn from FAO activities, extend from the land-use and monitoring forest cover, which, when degraded, may adversely affect agricultural security through erosion and micro-climatic changes, increased surface run-off, erratic stream flow and soil erosion to the mapping and estimating the area of land units potentially suitable to agriculture and assisting in identifying and delineating ecozones suited to specific crops.

In *land resource* investigations, FAO has combined Landsat imagery analysis with the land unit approach, which, using aerial photographs, was first proposed by Bourne in 1927 and later developed by the Australian CSIRO Division of Land Research (1946) and others in Australia, Canada, South Africa and UK (Howard and Mitchell, 1986). Methods depend upon the interpretation of aerial photographs and satellite imagery supported by "ground truth", the identification and delineation of land units, each of which is characterized by a particular combination of physiographic and natural vegetation characteristics. These land units of varying magnitude identified by remote sensing imagery, may then be aggregated according to soil types, current land use and land potential. For example, Landsat-1 imagery was used to carry out a land unit classification in four months of the Kingdom of Jordan (Mitchell and Howard, 1978). Land systems were defined and mapped at 1:250,000 scale on the basis of photogeomorphic subdivisions, recognizable on the imagery by changes in tone, colour, texture and drainage patterns. A similar basic approach was applied to the soil and land use mapping of the central region of the Yemen Arab Republic (Pacheco, 1978).

FAO, on behalf of the UN, has also used remote sensing imagery to provide a preliminary assessment of potential land suitability of Namibia as a basis for future development planning. Since the circumstances in the country preclude any direct access to field data, it has been necessary to rely entirely on satellite imagery analysis supplemented by published sources of information. Visual interpretation was undertaken of Landsat prints at 1:1,000,000 scale. The land potential map at 1:4,000,000, combined with a Landsat mosaic of the entire country at 1:1 million, is expected to be published shortly. In Ethiopia, the new land use and land cover map at a scale of 1:1,000,000 results from a combination of manual interpretation of Landsat imagery, field surveys and existing information. Landsat provided the backbone of data generation, using the imagery elements of colour, tone, texture and pattern. Imagery of both wet and dry seasons was used. The map has a total of 31 mapping units derived from twelve major classes (Henricksen, 1984).

Aerial photographs have been used for many years in *soil surveys*, namely to serve as small-scale soil surveys, to help locate the position on the ground of sample strips and sample points and to extrapolate the soil information obtained from these points or strips to the overall area. FAO work has indicated that small-scale soil mapping can be achieved by using Landsat imagery coupled with minimal, but carefully organized, ground truth collection of quantitative data (FAO, 1982). For example, Landsat imagery was used to produce small-scale or exploratory soil maps of six provinces of Central Sudan covering an area of about 570,000 square kms (Pacheco and Howard, 1977). The primary purpose was the regional inventory of the soil resources to enable a broad assessment of land potential to be made. In China recently a soil survey at a scale of 1:250,000 has been completed of the Beijing area using a combination of Landsat imagery and aerial photographs (Morain, 1985; Lin Pei, 1986).

As a contribution to combating soil degradation, FAO has prepared from Landsat imagery a *soil degradation* map at a scale of 1:5,000,000.

A methodology was developed for use with Landsat and a legend was evolved as the first stage input by mapping representative areas in Africa and the Near East, which provided transects from the humid tropics, to arid and semi-arid areas. A remote sensing world legend was developed and tested by applying it to the mapping of Iran. Landsat imagery was shown to be capable of providing accurate boundaries to geomorphological, hydrological and biotic features, notably snow lines, drainage networks, slope lengths, rock types, saline areas, wind action, vegetation density and land use types.

The assessment of the *water resources* and the change of these resources with time, including water quality, are subjects of great and growing importance, as the population of the world increases, thereby placing greater stress on existing water supplies. Remote Sensing can provide synoptic observation with high observational density over relatively large areas and thus has been increasingly used in all aspects of water resources assessments and monitoring. Many applications of remote sensing techniques to water resources studies have been conducted. FAO, for example, has applied remote sensing to lineaments analysis of the crystalline area of Burkina Faso, to locate potentially groundwater-storing fractures; the location of groundwater areas in the People's Democratic Republic of Yemen using fracture analyses and vegetation types, and the recent study in the Philippines (Bohol Island), in which multistorage remote sensing techniques were used to identify tropical karst "waterways" (Travaglia, 1986).

As related to food security, forest cover influences the agricultural crop environment. A matter of world-wide concern is the rapid rate of destruction of forest cover in tropical countries, the need for this to be monitored at world and country levels, and its future impact on agriculture. Maps of forest and other vegetation cover were prepared initially by FAO for the whole of Benin and Togo at 1:500,000 and of the southern two-thirds of Cameroon at 1:1,000,000, using a multistage procedure by which keys derived from ground survey, reconnaissance flights and aerial photo-interpretation over limited areas were extrapolated with the interpretation of Landsat cover of the entire area (Baltaxe, 1980). This approach to monitoring changes in forest cover is now being extended to south-east Asia and other parts of Africa.

4. Conclusions

Thus remote sensing has an established and expanding role in helping to strengthen feed/food security (cf. tables A and B). The wider recognition of its role appears to come more from the newer field of satellite remote sensing than the more traditional airborne remote sensing (i.e., aerial photography). In the next few years both airborne and satellite remote sensing can be expected to be of increasing importance to food security in developing countries and associated regional programmes. Recognizing this, a recent FAO expert consultation (1985) has urged that an international meeting be held soon on remote sensing applied to food security in the next decade.

Satellite remote sensing, with its expanding range of resolution, spectral signatures and temporal frequency, is providing, as indicated, a range of data, some of which is readily adaptable to the needs of food security. Already, it is providing inputs valuable to desert locust surveillance, and the experimental results related to the extensive range-lands of Africa are encouraging. For the semi-arid and mesic rain-fed agricultural areas, results indicate the usefulness of environmental satellite data in providing information on precipitation, rainy days and agricultural drought. With the introduction of higher resolution earth resources satellite data, its role, at least in the near future, would seem to be that of complementing environmental satellite data, to provide information on land use and land use changes and to form an integrated part of multistage agricultural statistical sampling (e.g., area sampling frame). The usefulness of satellite data in crop yield models is increasingly recognized but the operational identification and the precise measurement of the area of specific crops, except under ideal conditions, is yet to be achieved.

As indicated in this paper, remote sensing can be expected to benefit food security in developing countries by providing information related to land use/land potential, by providing early warning of food shortages and disasters, in providing inputs helpful to immediate, medium-term and long-term relief measures. This in turn will call for the strengthening of "centres of excellence" in developing countries, in providing decision makers in developing countries with a practical awareness of remote sensing applications, in developing management skills and in training and stabilizing in employment younger technical staff. Skills will be increasingly needed in the art and science of extracting meaningful information from the ever-increasing volume of readily available remote sensing data, in providing high quality photographic products to the users and ensuring that data products are geocoded for ready use in geographic information systems.

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REMOTE SENSING APPLICATIONS TO COASTAL ZONE RESOURCES

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Introduction

Ecologically, the coastal zone is the transition place from terrestrial to marine influences. In this narrow interface area thrive various open and interactive ecosystems such as marshes, seagrass beds, rocky coasts, islands, mangroves, coral reefs and flats, river deltas, sand beaches, etc. Some of these major ecosystems (mangroves, seagrass beds, coral reefs, and marshes) are among the most productive, providing life-support systems to fisheries and aquatic resources.

From the economic standpoint, coastal zones are productive economic units for management and planning because of their richness in both renewable and non-renewable resources. They are used for various economic development activities such as fishing, transportation and navigation, human settlements, mining, port development, land reclamation, agriculture, and waste disposal. Coastal zones are therefore distinct management units where natural resources can be exploited to optimize economic returns, while safeguarding that degradation of these resources can be held to a minimum and sustainability over time of renewable resources can be achieved.

However, due to pressure of an ever-increasing coastal population and urbanization, coastal zones in developing countries are subjected to resource overexploitation, beach erosion and sedimentation, pollution, and non-sustainable land and water uses.

In terms of resource endowment, the coastal zones do not have absolute or fixed boundaries, whether inland or seaward. The demarcations depend both on the level of economic activity and ecological influences and homogeneity associated with use and conservation. For example, in most archipelagic islands with rugged terrain, the coastal zone inland might just be a small strip of beach, whereas a coastal area with gently flowing slopes, river deltas, and streams can have several kilometers of coastal zone inward. Towards the sea, the coastal zone can extend up to territorial waters (3-7 km) or up to the measurable edge of continental shelves. In these days of 200-mile economic zones, in accordance with the Law of the Sea provisions, economic activities and control of coastal areas can extend to the limits of territorial waters, depending on the capability of countries to control, plan, and implement economic activities therein.

General Remote Sensing Applications to Integrated Coastal Zone Planning and Management

Integrated coastal zone planning and management for various economic development purposes is an effective tool for harmonizing economic development with ecological conservation. It provides a rational allocation of land and water uses/resources in coastal areas without upsetting resources sustainability over time. Figure 1 shows a systematic view of integrated coastal zone planning and management which considers the various development goals and alternatives for the optimal use of coastal zone resources. This integrated concept of development considers the interaction of various natural systems or ecosystems such as mangroves, coral reefs, seagrass beds, marshes, etc., on the productivity and functioning of the coastal zone, as well as integrating development objectives of coastal zone management with sectoral goals in forestry, fisheries, water management and with national and local development goals.

The most crucial supportive activity in integrated coastal zone planning and management is the generation of baseline ecological and environmental data in the form of maps and statistics. Remote sensing technology, using various platform-sensor combinations, provides a major tool for generating data for identifying coastal zones and delineating their boundaries, mapping and assessing coastal resources and existing uses, and proposing ideal or planned land and water resources development activities. Examples of such data are land use, vulnerable habitats, types of fisheries and aquatic resources, sedimentation and erosion, water quality, current platforms

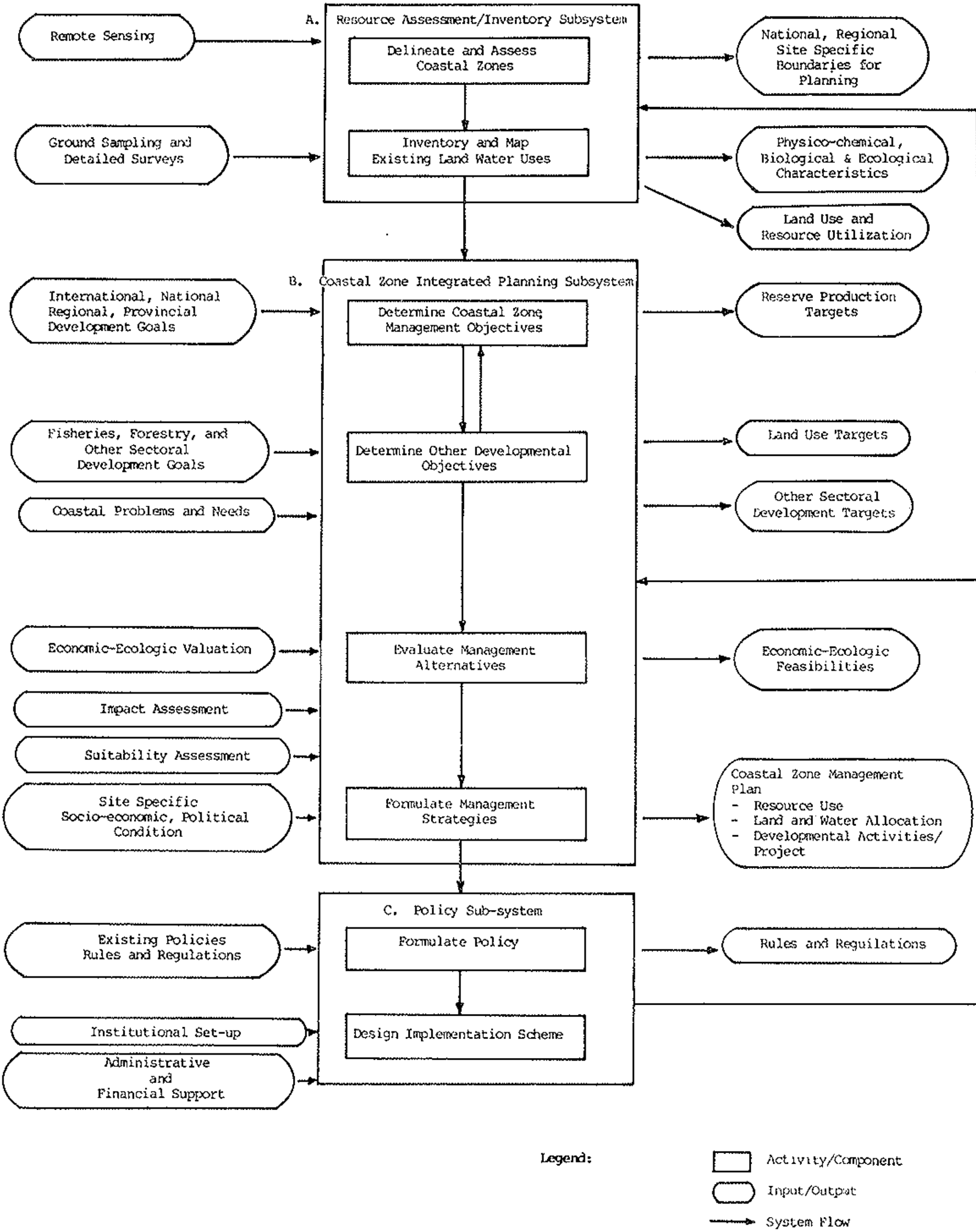

FIG. 1. System View of Integrated Coastal Zone Planning/Management.

and distribution, shallow water topography and physiography, vegetation types and a host of other ecological data which in the case of developing countries are to be gathered for the first time.

The traditional use of cameras (with panchromatic, color, and infrared color films) aboard aircraft platforms for small, intermediate and large-scale analysis of earth features has been very effective for several decades in developing countries in spite of its limitations in flying time (dictated by weather conditions), small area coverage, tedious interpretation, and increasing costs. The applications of these platform-sensor combinations are already well known and tested, hence the focus of data generation in coastal areas presented in this paper will be on more recent and promising developments in satellite remote sensing and their optimal combinations with other remote sensing schemes in the conduct of multi-stage and multi-sensor remote sensing. At the moment, the recently commercialized LANDSAT series remains as the most widely used for various earth resource observations. The French SPOT series of high resolution satellite imageries will complement and improve the capability for earth resource assessment and monitoring as soon as data distribution is operationalized.

Environmental satellites like the NOAA series and NIMBUS with coastal zone color scanner and others, as shown in Table 1, can be of assistance to coastal zone management since they can provide water resource data, atmospheric data, and are capable of monitoring prevailing weather and climatic conditions. However, these environmental satellites have very low spatial and spectral resolutions even if images come more frequently. At the most, they can provide additional systems for monitoring coastal zone features and phenomena.

The multispectral characteristics of LANDSAT MSS allow the application of this "terrestrial designed" satellite for assessment of land-sea interface in coastal zones. Nearshore shelves where fishery is highly productive can be highly visible at Band 4, which operates at wavelength 0.5-0.6 microns with penetration at clear water of up to 20-30 meters. On the other hand, Band 7, which operates in the near-infrared region of wavelength 0.8-1.1 microns of the electromagnetic spectrum, can be very useful in the sea-land interface or brackishwater areas. Combination of bands such as MSS Band 4, MSS Band 5, and ratio of MSS 4/MSS 5 can characterize physiographic features of coral reefs in the tropics. Combination of MSS Bands 4, 5, and 7 can clearly indicate processes of sedimentation and siltation in coastal areas. Table 2 depicts MSS bands

TABLE 1 - *Sensors flown on satellite with potential application in resource exploration.*

Satellite	Sensor	Wavelength or Frequency	Spatial Resolution
Nimbus I-VII	High-resolution, infra-red radiometer (HRIR)	Thermal IR	8 km
NOAA 1-4	Scanning radiometer (SR)	Visible and thermal IR	7 km
NOAA 1-6	Very high resolution radiometer (VHRR)	Visible and thermal IR	1 km
Tiros-N	Advanced very high-resolution radiometer (AVHRR)	Visible and thermal IR	1 km
Landsat 1-2	Multispectral scanner (MSS)	Four channels, visible and reflected IR	70 m
Landsat 3-4	Multispectral scanner (MSS)	Visible and thermal IR	70 m, 100 m (IR)
Landsat 5	Thematic mapper (TM)	Seven channels, visible, near infrared and thermal infrared	30 m 120 m (IR)
Nimbus-G	Coastal zone color scanner (CZSC)	Six channels, visible, reflected and thermal IR	500 m
Nimbus-5	Electronically scanned microwave radiometer (SMMR)	19 GHz	15 km
Seasat-A	Scanning multi-channel microwave radiometer (ESMR)	Five channels: 6.6, 10, 18, 21 and 35 GHz	15-140 km
Skylab, Geos 3, Seasat-A	Short pulse altimeter (Alt)	13.9 GHz	2 km
Skylab, Seasat-A	Radar wind scatterometer (Scatt)	13.4 GHz	25 km
Seasat-A	Synthetic aperture radar (SAR)	1.4 GHz	25 m
Socyuz-22	Multispectral camera (MKF 6)	0.45, 0.54, 0,60, 0.66, 0.72, 0.84	About 10 m

Source: Karl-Hanz Szekielda (1984).

TABLE 2 - *MSS Bands Useful for Various Natural Resource Application Areas.*

Information About Application Areas	MSS Band 4 5-6 μm Green	MSS Band 5 6-7 μm Red	MSS Band 6 7-8 μm Near-Infrared	MSS Band 7 8-1.1 μm Near-Infrared
Large horizontal concrete surfaces		X		
Lithology		X		
Marshes			X	
Metamorphic rock				X
Rivers			X	X
Roads	X	X		
Serpentine outcrop				X
Shallow water	X			
Shoals	X			
Shores			X	X
Small lanes				X
Snow detection	X			
Soil associations		X	X	
Soil discrimination		X		
Soil moisture detection		X		
Stream channels			X	
Stress		X		
Surface water			X	X
Tectonic features			X	
Topography		X		
Turbidity	X	X		
Urban areas	X	X	X	X
Water boundaries			X	
Water depth	X	X		
Water pollution	X	X		
Water sedimentation	X	X		
Wetlands			X	X
Wooded areas	X	X		
MSS water penetration				
Band 4-9 m	Band 6-1/4 m			
Band 5-3 m	Band 7-1/8 m			

useful for various natural resource applications. On the other hand, thematic mapper spectral bands 5-7 provide additional capability for vegetation moisture measurement, thermal, and hydrothermal mapping, which might be useful in coastal features analysis, especially coastal vegetation and nearshore fishing areas.

At the current state of application, LANDSAT MSS can provide a data base for multisectoral, multidisciplinary planning of coastal areas. Even with the limited water depth penetration of MSS bands, LANDSAT can provide a synoptic overview and produce acceptable thematic maps on a regional scale of up to 1:250,000 (both visual and digital processing) containing information on geographic location, area, and possibly condition of:

1. Extent of tidal flats (littoral and sub-littoral)
2. Inventory/assessment of fishing habitats such as mangroves, coral reefs, seagrasses, etc.
3. Detection of sediment, silt, and pollution from various sources, including shore reclamation
4. Shallow water bathymetry and bottom topography
5. Existing land use and land use changes in coastal zone
6. Water quality assessment and monitoring
7. Fish productivity indications from color, turbidity, and water circulation system, chlorophyl boundaries, salinity, and plankton blooms.

To maximize the capability of LANDSAT MSS for coastal zones development planning, multilevel and multisensor approaches with remote sensing systems can be applied. Aircraft photography and aircraft thermal sensing data provide larger, detailed ground information that makes possible a better understanding of the population and productivity dynamics of fisheries and changes in the coastal zone and shallow continental shelves. These aircraft-borne sensors (IR and microwave radiometers) offer highly accurate information on upwelling areas, current boundaries, eddies and water mass circulation patterns, chlorophyl and plankton. The interfacing of various remote sensing data is a good basis for detailed studies on estimating fisheries model/productivity and constructing a planning model for fishing ground and coastal areas based on various marine, brackishwater, and tidal flat parameters discernible from LANDSAT. Data from meteorological satellites are important in the interfacing process because while these are very low in resolution, they can provide invaluable information on ocean dynamics and the physical-biological properties of the oceans.

General examples of application areas in coastal zone management using LANDSAT MSS include the inventory of littoral and sub-littoral mudflat (which are habitats of molluscs, mud clams, etc.) in the Gulf of Thailand using bands 4, 5, and 7. The results showed an estimate of littoral mudflats of 910 km^2 and sub-littoral mudflat of 3,700 km^2.

In Indonesia, coastal applications using LANDSAT MSS include study of coastal landforms, sediment and erosion rates, land use changes, and water circulation patterns.

In the Philippines, a multidisciplinary program on conducting pilot studies for coastal resources and environment using LANDSAT MSS data has been completed. The program focuses on the information generation capability of existing LANDSAT systems for the fisheries and aquatic resources, forestry and vegetation, geology and hydrology, land use sectors of the pilot study areas in Lingayen Gulf, Northern Luzon. This multi-disciplinary information will be used for future integrated coastal zone management programs of the government.

Specific Case Examples

Multilevel Remote Sensing for Mangrove Area Conservation/Preservation

To date the multilevel remote sensing approach is popularly applied to provide the different levels of information needed for specific mangrove-related management decisions in the country. The Natural Resources Management Center (NRMC), in support of the government's national mangrove program, has initiated assessment studies using LANDSAT data and selected reconnaissance survey.

During an early mangrove resource assessment study, Bina *et al.* (1980) grouped the remaining mangrove forests in the entire country according to their proximity to the nearest fishing grounds, on the assumption that mangroves play important ecological roles in the marine productivity of the outlying bodies of water. Using data on surface current, the boundary of each fishing ground was delineated on a 1:1,000,000-scale map. The premise was that the extent of ecological influence of mangroves to the marine waters is more or less defined by the prevailing current in the area. Each fishing ground, together with the mangrove areas within its periphery, was designated as an "ecosystem unit" identified by its traditional name. Using topographic charts at a scale of 1:250,000 as reference, the percentage of the remaining mangrove forests in each defined fishing ground was estimated using the data on computer-generated thematic maps obtained from digital processing of LANDSAT imageries. Fishing grounds with less than 50% of the original mangrove stands were eliminated from further assessment on the assumption that fishpond development and other land uses have expanded in the area. Only those with more than 50% mangrove cover were considered for more detailed survey and mapping. A total of 15 out of the 45 traditional fishing grounds in the country passed the 50%-plus forest cover criterion. The coastal areas where these fishing grounds are located were further surveyed via low-level aircraft reconnaissance, whereby coastal features such as mangrove forests, denuded areas, reclaimed areas, fishponds, and other land uses were documented using 35-mm hand-held cameras. Land use/cover changes were also noted in the coastal areas by referring to the 1:50,000 topographic charts carried in flight.

The information obtained from these aerial surveys was integrated with the data extracted from LANDSAT imageries in order to produce 1:50,000 scale land use maps of the areas surveyed. The maps generated from the activity not only updated the mangrove statistics of the country but also served as reference in identifying particular mangrove areas within the fishing grounds that need to be conserved and preserved. Based on the existing ecological and socio-economic parameters noted during the conduct of the study, guidelines have been formulated for the selection of mangrove areas to be preserved as wilderness, those to be conserved as forest reserves, and areas which can be released for other purposes (Table 3).

The results of the study also paved the way for the creation of two conservation laws passed on December 29, 1981 (Presidential Proclamation Nos. 2151 and 2152) which allocated some 78,594 hectares of mangroves for preservation and conservation. PP 2151 declared certain islands and/or parts of the country with a total area of 4,326.5 hectares as wilderness areas off-limit to unauthorized entry, sale, human settlements, fishpond development or any kind of exploitation. On the other hand, PP 2152 declared the entire province of Palawan and certain parcels of the public domain and/or parts of the country as mangrove swamp forest reserves, covering an aggregate area of 74,267.9 hectares. Utilization of forest products other than trees may be allowed in these

TABLE 3 - *Guidelines for the selection of mangrove areas for preservation, co servation, declaration as forest reserves, and release for fishpond develo ment.*

Location	Proposed Action	Reason for Proposed Actio
1. Adjoining major river system	Conserve; not release for fishpond	Maintenance of ecological balance.
2. Adjacent to productive fry and fishing grounds	Conserve; not release for fishpond	Insure breeding, spawning a nursery grounds of fishes a shellfishes.
3. Adjacent to populated areas or urban centers	Conserve; not release for fishpond	Insure continuous use for minor forest products.
4. Places with significant hazards if developed	Preserve	Protection against storms, erosion, floods, etc.
5. Primary and dense forest growth regardless of location	Preserve or declare as forest reserve	Maintenance of ecological balance; protection agai riverbank erosion; uses wildlife sanctuaries and f education and research.
6. Around small islands	Preserve	Maintenance of ecological balance.
7. Others (exclusive of Nos. 1-6)	Release for development	Fish production and other la uses, whichever is mo compatible.

Source: MNR Committee Report, October 1979.

reserves, but subject to strict regulations. These documents now serve as the main basis for approving/disapproving Fishpond Lease Agreements (FLA's) and Mangrove Timber Licenses (MTL's) entered into by either private individuals or corporations with the government.

Coral Reef Assessment and Mapping

In the Philippines, digital analysis of LANDSAT MSS was used to map out coral reefs which are known to influence fisheries productivity.

The major physiographic zones and bottom cover of Apo Reef in Mindoro Island, Philippines, were categorized and mapped out, using combinations of unsupervised (without ground truth) and supervised (with extensive ground truths using transects, bounce dives, underwater sled transects, and shallow surface reconnaissance) techniques of digital processing, using interactive computer-assisted processing systems.

False colour composites of MSS bands 4, 5, 6 and 7 were derived from December 1972 computer compatible tapes taken at low water level.

Before conducting a detailed mapping of coral reefs, the major bottom and bathymetric variations of the reef's surface were first determined and mapped to arrive at more detailed categories and also to provide quantitative and qualitative information on the reef's major structures.

The digital ratioing of the two most water penetrating bands of LANDSAT (MSS 4/MSS 5) produced a set of signals related to depth changes. These signals were digitally superimposed with raw MSS 4 and MSS 5 data to obtain a digital image, with pixels characterized by bottom-related signals. This computer-enhanced imagery was used for processing and classifying through automatic clustering algorithms using a combination of maximum likelihood and Euclidian distance functions.

The actual stratification and classification of submerged features of a coral reef can be a difficult and tedious process. Reflectance features defining coral reefs represent a summation of signals due to bottom reflection and signals due to sea surface and atmospheric influences. Thus, for MSS bands 6 and 7 with little or no water penetration, background signals (not bottom reflection) are detected. To remedy this, band zoning has been necessary in which the resolution elements (pixels) of a given reef are assigned to a specific band zone in which they are significant. In this application project, band zone mapping was done by assigning pixels in the 4-band category into categories or zones with band signals above the background signal level in the following spectral regions: MSS 4-7 (Zone 1), MSS 4-6 (Zone 2), MSS 4-5 (Zone 3), and MSS 4 (Zone 4).

To synthesize the derived spectral clusters into bottom-cover categories and correlate them with ground truth data, the band signal counts of bottom cover types taken from imagery, with depth derived from ground survey, were determined via a clustering algorithm approach. Each of these clusters was then assigned to a bottom type category by matching its mean band signal counts with the derived bottom cover depth-signal values.

The major physiographic features of the Apo Reef were identified and measured, through the digital clustering of combined MSS 4, MSS 5 and ratio of MSS 4/5. Features identified and measured were sand flats (3-6 m), rock/coral/sand (1-3 m), deep lagoon and mixed substrata (2-3 m), sand substrata (1-2 m), and shingles and rubble ramparts (1-2 m). These categories were verified using the available ground data which were further superimposed on a band zone map.

On the other hand, bottom type categories for each channel along the Apo Reef were stratified according to four band zones after doing the unsupervised digital processing. Band Zone 1 representing reef bottom covers in the intertidal and emergent areas was determined by using pixels with 4-channels signals (MSS 4, MSS 5, MSS 6 and MSS 7), Band Zone 2 representing bottom covers in very shallow (0.5 m) areas was determined by using pixels with 3-channel signals (MSS 4, MSS 5 and MSS 6), Band Zone 3 representing bottom covers from 0.5-3 meters was determined using pixels with 2-channel signals (MSS 4 and MSS 5), and Band Zone 4 for areas from 3-9 meters deep using pixels with 1-channel signals (MSS 4).

This application project showed that unsupervised clustering of combined MSS 4, MSS 5 and ratio of MSS 4/MSS 5 can thematically map major physiographic features of coral reefs without a training area. This approach can be useful in planning for an extensive ground survey and establishing stations for surveys. Moreover, the gross information derived from this unsupervised clustering technique can provide data needed for fisheries planning, including gross morphology, approximate depth ranges of the reef's surface, gradual slopes, intertidal zones, and shallow and deep lagoons. Band zone mapping assists in generating more accurate thematic information on major physiographic and bottom cover of reefs.

Multidisciplinary Coastal Zone Studies

In 1979, the NRMC, with financial assistance from the National Science and Technology Authority (formerly the National Science Development Board), launched a three-year research program entitled "Coastal Resource and Environment Survey Using LANDSAT Multispectral Scanner Data." The primary goal of the Program was to establish the maximum amount of information derivable from the synoptic and repetitive multispectral scanner data of LANDSAT for resource and environmental survey and monitoring of our coastal zone through the actual conduct of ground surveys in selected pilot areas. Likewise, the Program was envisioned to develop new computer-digital programs for processing LANDSAT imageries that would provide the target resource and environmental information at minimum time and cost. The Program's goal was geared towards the facilitation of vital data to be used during the formulation of measures that would properly manage and protect the country's coastal zone and its resources.

A total of seventeen (17) sectoral studies have been accomplished during the project duration which can be grouped into five major disciplines: Geological and Hydrological Studies, Land Use and Agricultural Studies, Botanical Studies, Marine Resource and Oceanographic Studies, and Fishery Studies.

The geological and hydrological studies placed emphasis on the use of LANDSAT imageries as a potential tool for locating minerals through the study of landforms and geological structures, determining geologic hazards; mapping of detectable hydrologic parameters for water resource assessment; and monitoring dynamic processes such as coastal erosion, river erosion and siltation. Data extracted from 1:250,000 and 1:100,000 LANDSAT image scales and aerial photographs of 1:250,000 scale were used during the structural mapping of the Pangasinan-Ilocos Region. Results of the activity served as baseline information during the conduct of further geologic hazard studies and in pinpointing mineral potential areas. The capability of the technology to investigate seismotectonic and sand-encroachment hazards along the coastal areas of La Union and Ilocos Norte provinces has also been successfully demonstrated. Lithologic and structural data extracted from LANDSAT imageries together with the available earthquake recurrence and land use maps were used as parameters during the quantification of probability of hazard occurrence and in the production of landslide susceptibility maps showing varying degrees of probability of occurrence. On the other hand, hazards imposed by the sand encroachment were identified using manual and digital interpretation of LANDSAT imageries taken on different dates during a six-year time span (1972 to 1978). In mapping all the geological hazards, comparative analysis of LANDSAT data was made on multidated imageries. This was done particularly on outlined high risk areas to assess the possibility of detecting changes that may reflect the occurrence of hazards. Ground surveys and low altitude oblique air photography were used to confirm or reaffirm results. Moreover, another activity under this component was the determination of flood prone and non-flood prone areas in Pangasinan province using the spectral signature difference of both areas as reflected in LANDSAT imageries. The principal objective of this particular study was to provide flood-hazard information that would assist officials and private interests in making decisions and alternative plans concerning the development of areas near the coasts which are subject to flooding.

Land use studies for the pilot areas were mainly devoted to agricultural activities with rice, being the major crop, as the center of interest. Two studies were devoted to this particular crop, one which establishes a correlation between satellite data and the crop's phenological stages, and another which explores the various preprocessing functions useful for identifying rice from other crops being grown in certain areas near the coast. Imagery analysis was started by extracting subscenes of the various test areas from LANDSAT computer-compatible tapes. Preprocessing was employed primarily to reveal homogeneous riceland areas. The activity involved contrast stretching of temporal data to improve the tonal variations on the imagery and ratioing to delineate rice lands from other features. Spectral signatures were extracted from the various features found in the riceland area of all test sites using single pixel training and single cell programs. In consonance with the land use mapping, soil association mapping was also done to determine the land suitability and capability of the selected study sites. The results of the study, especially that which involved the identification and mapping of major crops, were envisioned to serve as input to a growth model that would predict the harvesting season and/or detect pathological characteristics.

Oceanographic and marine biological studies, which were concentrated mainly in the Lingayen Gulf, were aimed to maximize the use of LANDSAT imageries for detecting and monitoring dynamic processes in coastal waters such as water movement, changes in water quality, bathymetric configuration and siltation. The suspended sediments coming out of the rivers were used to determine the spatial extent of marine life that can be affected by mine tailings dumped in rivers. Mapping of major underwater biotic communities in shallow waters was also of particular interest since such information has been useful in delineating areas for mariculture and in assessing our marine resources. The different studies conducted under this sector have as a whole established a methodology on the future characterization of the saltwater bodies in the project areas, from mapping the bottom of shallow waters to determining the quality of water above it.

The botanical studies were mainly concerned with the mapping of natural vegetation using LANDSAT MSS data in contrast with cultivated crops; discriminating major plant communities and determining their growth conditions, and studying the effects of the seasonal changes in the spectral signatures of natural vegetation. Both aerial photographs and LANDSAT imageries were used in these activities. While LANDSAT imageries were extensively used in extracting the features of natural vegetation in the project areas, low oblique aerial photographs were valuable in the collection of ground information, especially since natural vegetation and agricultural crops were mixed together in a very complex manner in the areas of study. The slope of the topography also to some extent affected the correctness of digital analysis. Results of the analyses have been very useful during the assessment of the land resources as well as in determining the optimum land use and locating new areas for agricultural expansion.

The fishery resource studies, the last component of the three-year program, involved the discrimination and delineation of various types of fishponds for inventory purposes using LANDSAT imageries and correlating LANDSAT spectral properties of marine water with planktonic production for possible use to fish stock assessment. Also included is the integration of all parameters detectable from LANDSAT imageries to predict the fishery potentials of selected coastal sites.

Monitoring of Brackishwater Fishponds, Coves and Bays

Scattered over the major islands along the coastal areas in the Philippines are extensive areas of brackishwater fishponds. Pond aquaculture is now one of the leading industries in several coastal provinces in the country. During the last few years, as a result of improved technology, this sector of fisheries has produced a very significant percentage of our total annual fish harvest. For the proper planning, management and development of this coastal resource, it is necessary that studies be conducted on how these areas can be effectively surveyed and monitored. And because fishponds are constructed on mangrove swamps, which causes the destruction of mangrove forests, results of such studies can be used to properly monitor their expansion so that further development could be controlled and be limited only to areas open for such purpose.

Presently, it is difficult to conduct an assessment of the potential production capacity of our fishpond resources because of the lack of important information such as the real extent of this resource base. A good assessment depends on timely and reliable information which, unfortunately, is difficult and very expensive to obtain using conventional means. Therefore, LANDSAT remote sensing data have been used to determine important information like the areal extent of fishponds and their distribution, which can be readily measured from the imageries. Visual interpretation of LANDSAT photo products has indicated that these two important parameters can be extracted using properly selected date of coverage. LANDSAT data taken particularly during the dry season are found to be very useful for such purpose. During this time, fishponds can be easily segregated from the adjacent rice fields when the latter are dry and not under water. Using LANDSAT MSS Band 7 data for the Manila Bay area, the expanse of fishponds can be easily determined. The location and distribution of fishponds are easily measured, and areas where there is heavy concentration of fishpond operations can be readily identified. More detailed information on fishponds, however, is not yet possible to obtain and segregation of developed and underdeveloped ponds is not feasible. But given a complete and recent remote sensing data coverage, the actual extent and distribution of fishponds can be measured, and such information can be used as one of the many inputs in the study and assessment of the potential production capacity of the country's fishponds.

With the advancement of culture technology, especially on prawn culture, high pond productivity is now easily achieved. Prawn culture has now become a highly profitable business. With this development, many entrepreneurs now and in the near future will search for areas where they can establish pond operations. Fish farming is already heavily concentrated in some areas and, therefore, if ever expansion is allowed, other areas where pond operations can be established should be identified. Remote sensing data, particularly the new generation high resolution images, will be an important tool to map areas of heavy, medium and low concentrations of operations.

In the Philippines, fishponds are mainly constructed on areas formerly devoted to mangrove or nipa swamps. As a result, the country's once extensive mangrove areas have diminished in hectarage, principally due to fishpond conversion. Although conversion to aquaculture use is a profitable venture, the negative impacts upon the environment of this activity have made it imperative to regulate and monitor the areal expansion of fishponds. Certain areas of mangrove forests in the country have been demarcated and declared off-limits to any form of exploitation, particularly conversion to fishponds. Remote sensing technology is also used to monitor activities in such areas which can be very useful for identifying recently cleared areas.

Remote sensing data is also being used in the study of changes occurring in the country's bay areas. Multitude imageries are being used to study and measure environmental changes. Due to the demand for more land space for human settlements, commercial centers, tourism and recreational areas, our coastlines have been modified and portions of bays have been reclaimed. Through the course of time, significant changes have occurred in several bays in the Philippines, particularly along the coastlines. In Manila Bay, extensive areas have been reclaimed and filled and are now occupied by hotels, business offices, trading sites, recreational facilities and others. LANDSAT data will be used to determine the extent of the reclaimed land in the bay area.

Soil erosion has also been identified as a critical environmental problem in the Philippines. Caused mainly by intensive farming, mining, deforestation and other forms of human activities, soil erosion contributes to the siltation/sedimentation of our bays. The deposition of silts on the bottom environments is identified as one of the major culprits in the destruction of our coral resources. Analysis of LANDSAT imagery of Manila Bay and surrounding area taken during the rainy season at the time of heavy rainfall showed the heavy load of silts being carried by the waters into the Bay. The extent or affected area of sedimentation can be easily delineated as well as the dispersion patterns of silts on that particular day.

Conclusion

At the current level of usage, LANDSAT MSS has been proven to be a cost-effective, acceptable, and useful management tool for decision-making in integrated coastal zone planning and management. In spite of limited water penetration, it can provide synoptic overview and acceptable information on major productive ecosystems such as corals, mangroves, seagrasses, and marshes. Dynamic coastal processes such as land use changes, sedimentation, land accretion, and pollution can also be detected, assessed, and monitored.

The case examples conducted in the Philippines showed that multi-level remote sensing with satellite imagery as the overview level can actually maximize the use of other information and ancillary aircraft reconnaissance flights for coastal zone planning and management. A procedure has been evolved for assessing coral resources, and legislations were formulated and implemented on mangrove conservation and preservation using multilevel remote sensing. Further, the multidisciplinary researches conducted on a pilot area in the Philippines for various coastal zone applications showed both promising and operational results which can be used for integrated coastal zone management, the conservation and assessment of critically important coastal natural systems like the mangroves, and researches and assessment of overall coastal productivity.

Future directions in remote sensing applications point to the need for more interfacing of various remote sensing data to provide detailed studies on things like fisheries productivity modelling and interactive models for various coastal zone ecosystems. This interface should include the use of low resolution environmental satellites, the current high resolution remote sensing provided by the French SPOT and LANDSAT Thematic Mapper and aircraft borne sensors, principally microwave sensors.

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MARINE AND COASTAL RESOURCES MONITORING WITH SATELLITES

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1. Introduction

Oceans are major reservoirs of heat, and their dynamics, therefore, play a significant role in determining global as well as regional climate. Over half of the solar radiation, along with the surface wind stress, is the ultimate energy source for a variety of physical processes in the ocean. The absorption of solar radiation is primarily responsible for the existence of a warm surface mixed layer of the order of 100 meters. The exchange of the ocean's heat with the atmosphere occurs over a wide range of time scales, and largely determines the relative importance of other physical processes in the ocean for climatic change. Some of this heat is used for surface evaporation and is eventually deposited in the atmosphere as latent heat during cloud formation; some is stored in the surface layers; and some is moved downward into deeper water by various dynamic and thermodynamic processes. The most energetic motion scale in the oceans is that of the mesoscale eddy, which can last a few months and has a horizontal wavelength of the order of several hundred kilometers.

The total length of coast in the world is approximately 280,000 miles. Assuming an average width of 50 miles for the coastal areas, of which 50% is land, then the land component of the coastal areas is 12% of the world land area or about 7 million square miles; the waters of the

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coastal areas can be approximated by the shallow seas and waters of the world's continental shelves, which cover an area of 29 million square miles.

The rapid growth of large-scale activity in coastal regions takes place in relatively narrow and limited areas (see Fig. 1). The coastal areas of industrialized countries have already been significantly developed. For example, 40% of the United States coastline is now exploited, while 75% of the coast of the Netherlands is currently being exploited.

Important activities are being planned and continue to increase in the coastal areas, such as:

— Large-scale urbanization with concentration of trade and industry around the major port cities;

— Extraction of marine resources, both living and non-living;

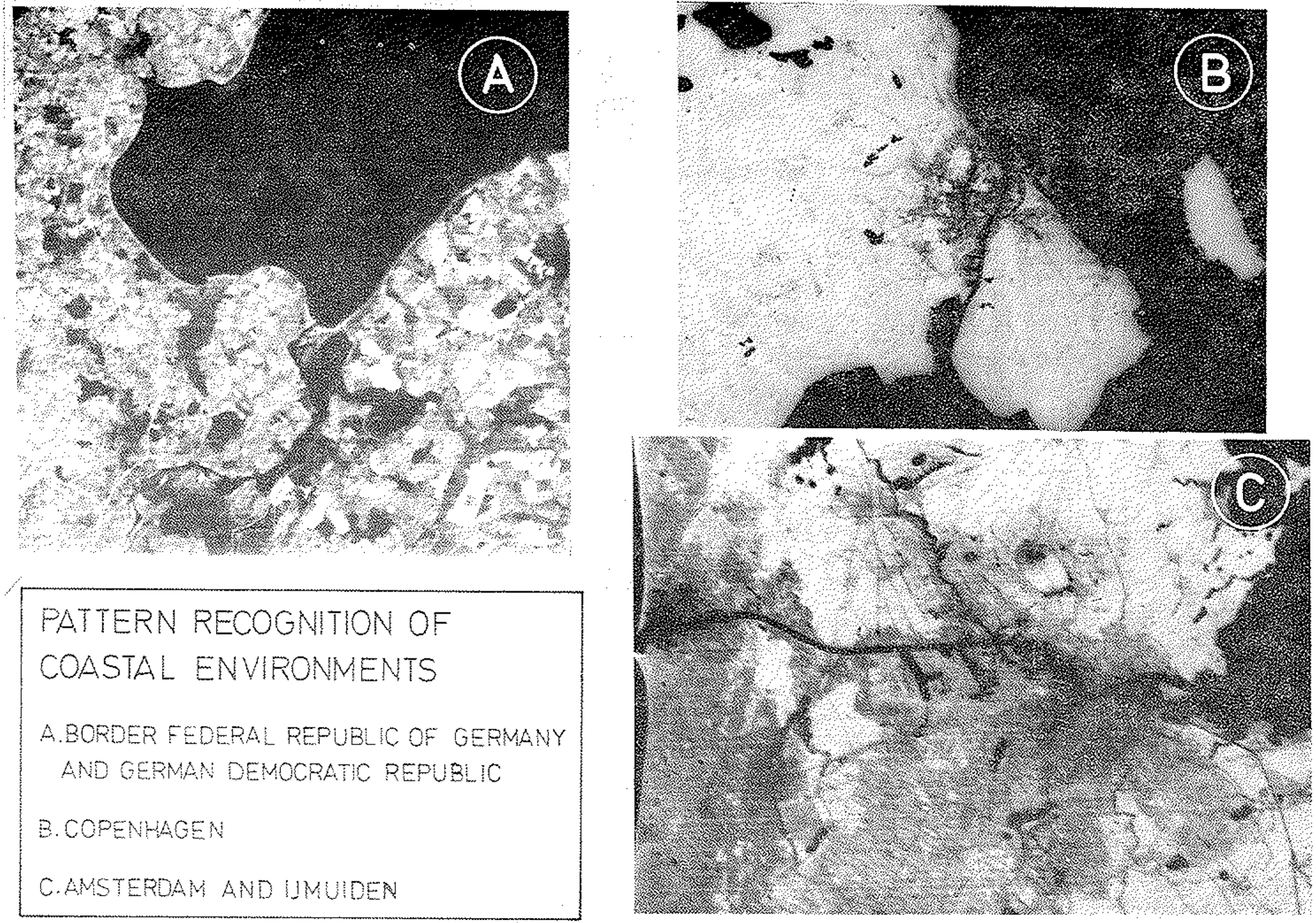
— Tourism and recreation.

The multidisciplinary use of coastal areas requires a well-balanced management. Although the management of resources has been a great concern for many countries, ocean management is only now becoming of great importance as well. Attention is aimed at controlling the types and levels of activities in these areas and to determine how every marine resource contributes to the state of the entire resource system.

To consider the management and development of marine resources, the simultaneous and compatible development of different resources in the coastal region should also be taken into account so as to effectively supply, support or provide facilities for the exploitation of resources.

Specific missions for marine-related investigations and resources inventories have so far been flown on Nimbus 7, Seasat and the Global Operational Environmental Satellite (GOES). Other satellites have also shown the application of infrared, microwave and visible data in the marine field, although they were not built exclusively for the marine discipline. Of further importance have been the experimental flights, especially on the Space Shuttle. On an experimental basis, these satellites have been used to collect data for suspended sediment, current boundaries, bathymetrics, ice conditions, surface winds and sea surface temperature.

For more details on satellite programs for marine research, see for instance, Epstein *et al.* (1984) and for data availability, Kidwell (1984) and Needham (1986). A summary of the satellites which provide a data basis for marine-related investigations is given in Table 1.



PATTERN RECOGNITION OF
COASTAL ENVIRONMENTS

A. BORDER FEDERAL REPUBLIC OF GERMANY
AND GERMAN DEMOCRATIC REPUBLIC

B. COPENHAGEN

C. AMSTERDAM AND IJMUIDEN

TABLE 1 - *Marine-related sensors on environmental and oceanographic satellite*

MARINE-RELATED SENSORS ON SUN-SYNCHRONOUS ENVIRONMENTAL SATELLITES

Name	Sensor	Channels	Derived product	Estimated accuracy
Landsat 3	multispectral scanner (MSS)	0.5-0.6 μm 0.6-0.7 μm 0.7-0.8 μm 0.8-1.1 μm	visible and infrared signatures of terrestrial, aquatic and nearshore marine regimes	N/A
Landsat D	thematic mapper	0.45- 0.52 μm 0.52- 0.60 μm 0.63- 0.69 μm 0.76- 0.90 μm 1.55- 1.75 μm 10.04-12.05 μm	same products as landsat-C plus surface temperature	
ITOS-1 NOAA 2-5	very high resolution radiometer (VHRR)	0.6- 0.7 μm 10.5-12.5 μm	day and nighttime cloud cover sea surface temp. (SST)	SST-0.5°C sensitivity to relative changes
TIROS-N Series (NOAA-A THRU G)	advanced VHRR (AVHRR) Note: NOAA Series Channel 1 0.55-0.68 Channel 5 only on D, F and G.	0.55 - 0.90 μm 0.725- 1.10 μm 3.56 - 3.93 μm 10.5 -11.05 μm 11.5 -12.05 μm	day and nighttime cloud and surface mapping, surface water delineation SST	SST-0.2°C sensitivity to relative changes
NIMBUS-7	scanning multi-channel microwave radiometer (SMMR)	6.63, 10.69, 18.00, 21.00, 37.00 GHz dual polarization	SST sea surface wind speed	≈ 1.5°C ≈ 1 m/s
	coastal zone colour scanner (CZCS)	0.43- .45 μm 0.51- .53 μm 0.54- .56 μm 0.66- .68 μm 0.70- .80 μm 1.05-2.50 μm	marine chlorophyll and sediment distribution sea surface temp.	parameters presently under investigation
DMSP Block 5D	operational line-scan system (OLS)	0.41-1.1 μm 8-3 μm	same as Tiros-N	somewhat lower than Tiros-N

(Table 1 continued)

Marine-Related Sensors on Sun-Synchronous Oceanographic Satellites

Name	Altitude	Orbit period	Inclination	Instruments	Data products	Estimated accuracy
Geos-3	843 km	101.7 min 14.2 orbits per day	115°	radar altimeter	marine geoid	± 1-2 m
					significant wave height	± 10%
					sea surface topography	± 20 cm
Seasat	790 km	100.8 min ≈ 14 orbits per day.	108°	radar altimeter		
				synthetic aperture radar (SAR)		
				radar scatterometer (SASS)		
				scanning multi-frequency radiometer (SMMR)		
				visible i.r. radiometer (VIRR)		

Source: J. Sherman, NOAA-NESDIS.

2. Theoretical background

Coastal resources require measurements of water features as well as parameters over land and the air/sea/water boundaries. Land surveying with the most recent sensors, such as SPOT and the Landsat Thematic Mapper (TM), is theoretically operational, while for the oceans, at the present time, only large temperature mapping is operational.

Water quality and particle load have been monitored with Landsat and NOAA data. More specific substances, such as chlorophyll, however, need a more complicated approach.

Gordon *et al.* (1980) used a regression analysis which relates the concentration of chlorophylls and phaeophytin-a to the radiance ratios at different wavelengths:

$$R_1 = Lw^{143}/Lw^{550} \text{ and } R_2 = Lw^{520}/Lw^{550} \text{ through}$$

$$\log C_i = \log a + b \log R_i, \; i = 1 \text{ or } 2 \qquad (1)$$

where log a and b are coefficients with values for R_1 of -0.297 and -1.269, respectively; for R_2, the corresponding values are -0.074 and -3.975.

The method to remove the aerosol effects is based on the approximation that the total radiance L^λ observed by the sensor at wavelength λ can be partitioned into Rayleigh-scattering (L_R^λ), aerosol-scattering (L_A^λ), and the radiance backscattered out of the ocean (L_W^λ) as transmitted through the atmosphere. This can be written as:

$$L^\lambda = L_R^\lambda + L_A^\lambda + t^\lambda L_W^\lambda \tag{2}$$

where t^λ is the diffuse transmittance of the atmosphere.

As the aerosol-scattering phase function is assumed to be independent of λ, then L_A^λ at one wavelength will be approximately proportional to that at another wavelength. If equation 2 is applied at two wavelengths λ_1 and λ_2, we obtain:

$$t^{\lambda_2} L_W^{\lambda_2} = L^{\lambda_2} - L_R^{\lambda_2} - \alpha(\lambda_1, \lambda_2)\left[L^{\lambda_1} - L_R^{\lambda_1} - t^{\lambda_1} L_W^{\lambda_1}\right] \tag{3}$$

where $\alpha(\lambda_1, \lambda_2)$ is a constant which can be related to the optical properties of the aerosol through the single scattering approximation. If λ_1 is chosen such that $L_W^{\lambda_1 \sim 0}$, then $L_W^{\lambda_2}$ can be determined for any λ_2, provided $\alpha(\lambda_1, \lambda_2)$ is known. Of the Coastal Zone Color Scanner (CZCS) bands, 0.670 μm is the most suitable, except in regions of very high turbidity. In the analysis of CZCS data as reported by Gordon *et al.* (cited above), $\alpha(\lambda_1, \lambda_2)$ has been determined from equation 3 by direct *in situ* measurement of L_W^λ at one location in the image, and these values are used throughout the entire image.

With respect to the spectral properties of pure water, water covered objects, such as algae beds or coral reefs, and suspended material, it is important to estimate the photon penetration depth in water.

Charnell and Maul (1973) made calculations in order to determine the percent of energy that penetrates the sea surface in different spectral intervals. These calculations were made by solving the intensity equation:

$$I = \int_0^\infty \Phi_\lambda \, I_{0\lambda} \, e^{-\alpha_\lambda z} \, d\lambda$$

where I is the intensity observed at a depth z through a band-pass filter $\varnothing_\lambda$, which is normalized over the region of wavelength λ for the spectral intervals; $I_{0\lambda}$ is the intensity at the sea surface, and α_λ is the spectral attenuation coefficient.

The calculations show that a perfect reflector at a depth of 2 m would return 86% of the incident energy for the 0.5-0.6 μm spectral region, 55% for the 0.6-0.7 μm spectral region, 11% for the 0.7-0.8 μm spectral region, and 2% for the 0.8-1.1 μm spectral region. These results indicate, on the other hand, the shortcomings of remotely detected chlorophyll or sediment concentration from satellites, because a thin layer of a low concentration of sediments may cause a similar spectral response as a deeper water body with higher concentrations.

With cloud-free conditions, satellite infrared sensors can readily be used to detect thermal gradients and monitor accurately sea surface temperature (SST). For large scale mapping, however, statistical methods need to be applied to eliminate atmospheric contribution to the measurements. So far, the most advanced large scale mapping system is the Multichannel Sea Surface Temperature Method, which provides data on a large grid, but, compared to ship measurements in the southern oceans, has a very dense monitoring grid (Strong and McClain, 1984).

In examining SST measurements, one needs to take into account that the radiation observed by a sensor is a function of the radiation emitted from the target, the interaction of the emitted radiation with the atmospheric components and the radiation reflected from the surface. Due to the high emissivity of water, a value of unit can be assumed which concludes that reflection is negligibly low.

Mathematically, the component sources of radiation in a clear atmosphere can be written as:

$$N_s = \int_{\lambda_1}^{\lambda_2} e_s(\lambda)\, \beta(\lambda, T_s)\, d\lambda$$

where N_s is the total energy emitted by a radiating surface in a bandwidth (λ_1, λ_2), at a temperature T_s, β is the Planck radiance and e_s is the surface emissivity, and

$$N_a = \int_{\lambda_1}^{\lambda_2} \int_{P_o} \beta(\lambda, T(P))\, \frac{d\tau(\lambda, P)}{dP}\, dP d\lambda$$

where N_a is the positive energy contribution of the atmosphere in the bandpass (λ_1, λ_2), T(P) is the temperature of the atmosphere at pressure level P, and T(λ, P) is the atmospheric transmittance from pressure level P to the top of the atmosphere. P_o is the atmospheric pressure at the surface. The total energy, N(T), over the bandpass measured by the sensor viewing an ocean surface is then given by:

$$N(T) = N_s \tau_s + N_a = N_s - (N_s \alpha_s - N_a)$$

At microwave frequencies, the brightness temperature over the oceans is relatively small compared to the shorter wavelengths. The intensity of the brightness temperature depends on salinity, temperature, surface roughness, frequency, polarization and the angle of incoming radiation, as has been shown, for instance, by Tomiyesu (1974). The brightness temperature T_B can generally be expressed as:

$$T_B = e\, T_W$$

where *e* is the emissivity, and T_W the absolute temperature of the sea surface.

As shown by Nordberg *et al.* (1971), in the 1.55 cm microwave emission, the brightness temperatures in the nadir direction increased almost linearly with wind speed from 7 to 25 m · sec^{-1} at a rate of about 1.2 C (m · $sec^{-1})^{-1}$. At 70° from nadir the rate was 1.8 C (m · $sec^{-1})^{-1}$. This increase was determined to be directly proportional to the occurrence of white water on the sea surface. At wind speeds < 7 m · sec^{-1}, essentially no white water was observed, and brightness temperatures in the nadir direction were ~ 120 K; at wind speeds of 25 m · sec^{-1} white water cover was in the order of 30% and average brightness temperatures at nadir were ~ 142 K. Maximum brightness temperatures for foam patches large enough to fill the entire radiometer beam were 220 K. This is based on the fact that the emissivity of foam covered water may change from about 0.4 to almost 1. Since foam cover and wind speed are correlated, it is possible to estimate the wind speed by microwave techniques.

The plotted brightness temperature (T_B) results from radiation components received by the radiometer-radiation emitted to the aircraft by the sea surface, the radiation emitted to the aircraft by clouds and atmospheric water vapor, and atmospheric radiation reflected toward the aircraft by the sea surface:

$$T_B = \epsilon T_{W\tau H} + (1 - \epsilon)\, T_{S\tau H} + \int_0^H T_A(h)\, (\partial\tau/\partial h)\, dh$$

where T_W is the water surface temperature, T_S the sky brightness temperature, T_A the atmosphere temperature, τ the atmosphere transmissivity, ϵ the surface emissivity, h height above surface, and H aircraft altitude. The first, second and third terms correspond to surface emission, reflected atmospheric radiation and atmospheric emission, respectively.

3. Categories and feature classification of the marine and near coastal environment

Essential and prominent in coastal management programs are the identification of the ecosystems to be managed and evaluation of environmental information on them. Environmental systems which could be examined in a management program are:

1. Shoreline systems

a. Exposed shorelines, such as rocky shores and cliffs, sandy beaches, barrier beaches

b. Sheltered shorelines, such as rocky shores and cliffs, sandy beaches, salt marshes, mud flats;

2. Estuarine systems, such as large bays, tidal rivers, coastal lagoons and ponds, and neritic systems, such as open coastal waters and sounds; and

3. Open ocean, whereby upwelling, convergence zones and currents could be considered.

The coastal area is an important resource area for many countries. The exploration and exploitation of coastal areas, however, have led to many conflicts and resulted in the degradation of these areas. These conflicts may be kept to a minimum by applying proper management procedures in the various disciplines or by categorizing the different activities and establishing an integrated approach in the planning and development of the various coastal zones.

The coastal area can be defined as that area of interaction between the land and the sea which generally includes the landward component, the submerged lands of the continental shelf, and the superjacent waters. Examples of landward physical boundaries are coastal mountain ranges, coastal roads and watersheds. The use of a watershed can be practical; however, it can result in the use of a very large land area, as is the case in urban centers located around a bay or estuary. On the seaward side, a typical physical boundary is the edge of the continental platform and the superjacent waters. The problem with this type of boundary is the fact that there is no globally recognized measurement of the continental shelf or platform.

A definition of the coastal area using physical criteria can be easily understood; however, such a definition may or may not respect existing political boundaries, and may require special legislation to be enacted. Use of the continental shelf edge as a seaward boundary encompasses most economically significant marine resources, such as fishing, and offshore oil and gas. In many cases, such boundaries coincide with physical processes such as currents and upwelling.

Three basic zoning categories have been considered by Johnson, Barloga and Barney (1972) for land and near coastal water use:

Category	*Activity*
1. Preservation	No development
2. Conservation	Limited development
3. Development	Intensive development

The activities in these categories create different types of regions of which parameters can be monitored from space.

Preservation areas are in general protected regions where ecologically sensitive flora and fauna and areas such as beaches, marshes and dunes are the main features. Conservation areas, on the other hand, are characterized by extensive land use. Finally, development zones include lands already developed, undeveloped lands vacant for intensive development, and undeveloped lands with some physical limitations.

Considering common characteristics of the different categories in the coastal areas, three primary levels, namely water, the interface land-water, and land, can be established. A possible further breakdown into secondary and tertiary levels is indicated in Table 2.

All three levels can be recognized and/or interpreted from satellite data. In some cases computerized classification is necessary in order to distinguish on the tertiary level small differences in patterns caused by phenomena with similar optical characteristics. In addition, to detect the

TABLE 2 - *Feature hierarchy for coastal investigations.*

PRIMARY LEVEL DIFFERENTIATION	SECONDARY LEVEL RECOGNITION	TERTIARY LEVEL INTERPRETATION
WATER	WATER MASSES	FISH SCHOOLS SUSPENDED MATTER POLLUTION PRODUCTIVITY CIRCULATION
BOUNDARIES AND INTERFACE	BEACHES MANGROVES CORAL REEFS	DEPOSITS RESOURCES
LAND	WETLAND TIDAL FLATS BEACHES VEGETATION LAND USE	SWAMPS BRACKISH, FRESH AND SALT MARSH EROSION CROPS RANGELAND URBAN TRANSPORTATION

tertiary level from spacecraft altitudes, more detailed information on the ground is needed to differentiate between oceanic phenomena, such as circulation, turbidity and chlorophyll distribution. Wetland classes at the secondary hierarchy level can be determined with a high degree of repetition, and marsh classification tends to remain spectrally separable from most other classes.

4. Monitoring of marine resource systems

Shoreline systems

The land/sea interface of shoreline systems can be mapped in all parts of the electromagnetic spectrum (EMS) where significant gradients in the reflected or emitted energy are present. More recently, SIR-A data have indicated potential for mapping purposes and for resource investigations. Figure 2 is an example of coastal shoreline surveying with the SIR-A.

The sea component of the shoreline system undergoes very fast changes and the dynamic processes involved have a time span of minutes to hours. The dynamic processes of the environment and the changes in currents in the near shore region over a tidal cycle can easily be studied from satellite images, as for example, for the German Bight (see Figures 3 and 4). From this example, tidal flats can be seen to undergo a dramatic change over short periods of time. Taken from Landsat observations, three different tidal stages are shown in Figures 5 to 7 for the near-shore area.

In tropic areas, coastal environments show great diversity, such as mangrove forests, reefs and beach areas. An example and a case study is the Portland Bight in Jamaica (see Fig. 8).

The Portland Bight has produced an area of high resource value for marine life and birds, and based on its special environment has been identified as a site for a national park. In conflict, however, to this planned project, tanker traffic in the Bight has caused damage to the ecology of the West Harbor and Peake Bay areas. In addition, broken oil pipelines have affected sea grass beds and shorelines in the region around Port Esquivel. The mangroves, coral reefs and the fishing industry have been adversely affected by the spill and need protection in the long-term. Aerial photography along with the use of space images can monitor such conditions.

Although SIR-A data have not been applied specifically for coastal zone management programs, Fig. 9 shows the potential for landuse mapping and detection of geological features, such as lineaments in the coastal areas. Of greater importance is the air-sea interface which can be altered by the sea state due to different wind speed and also by organic material (see for example Fig. 10).

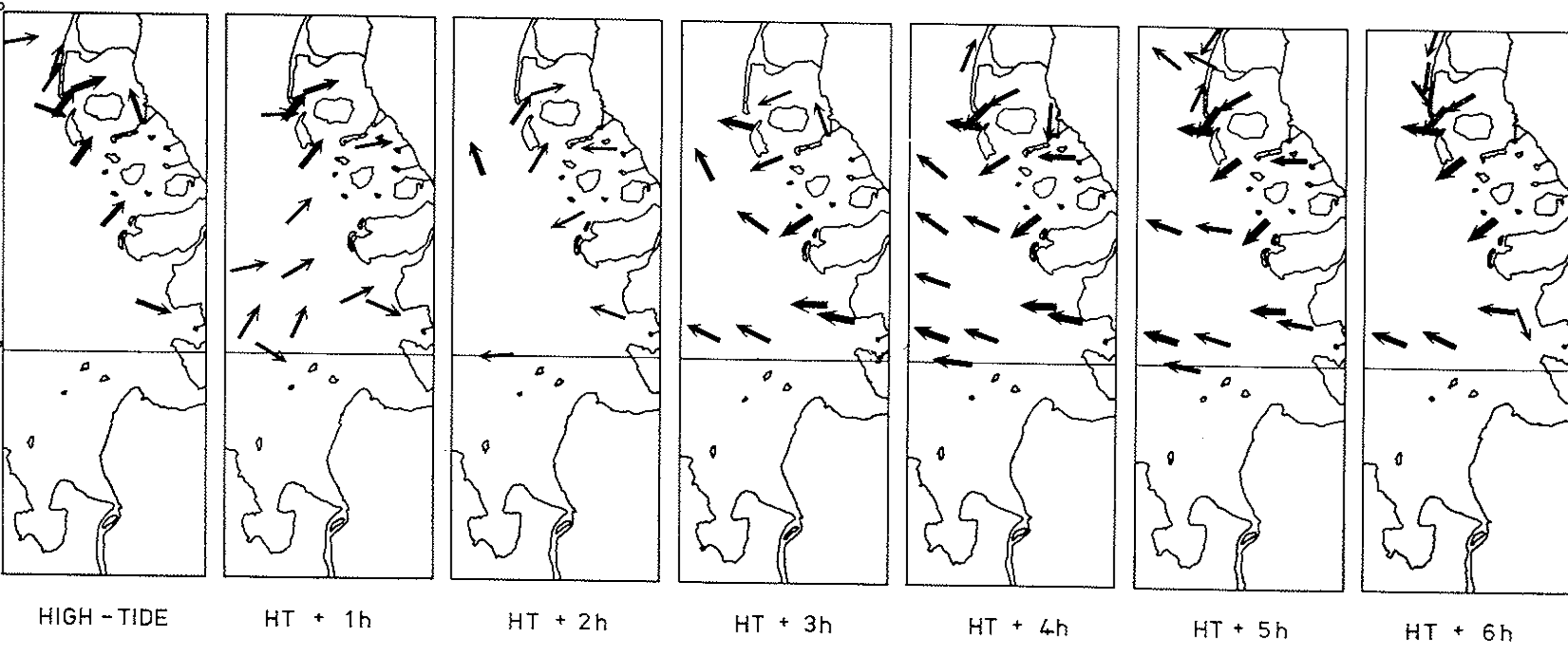


FIG. 3. Currents in the near-shore region of the German Bight compared to high tide at Heligoland.

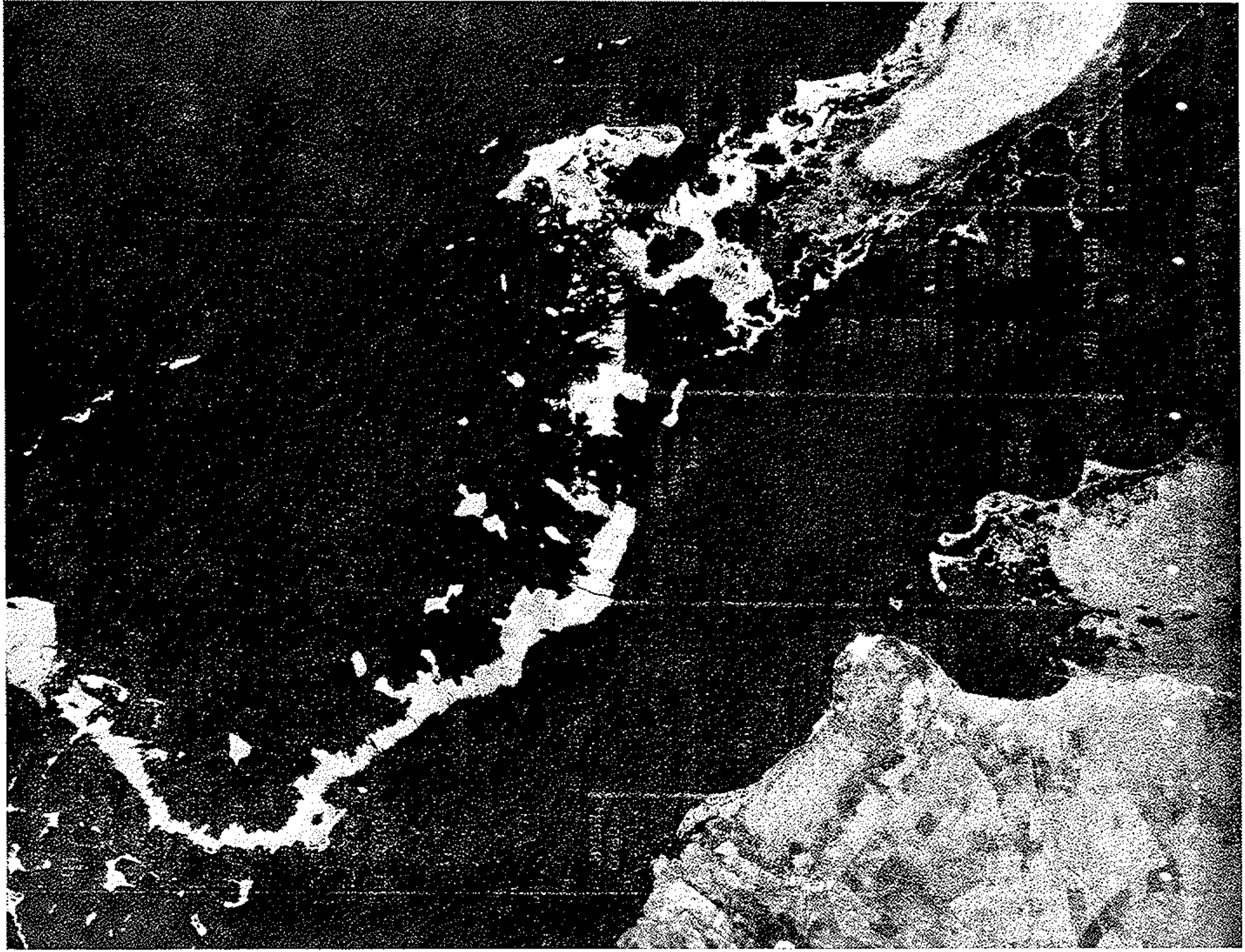


FIG. 2. Coastal area mapping with SIR-A.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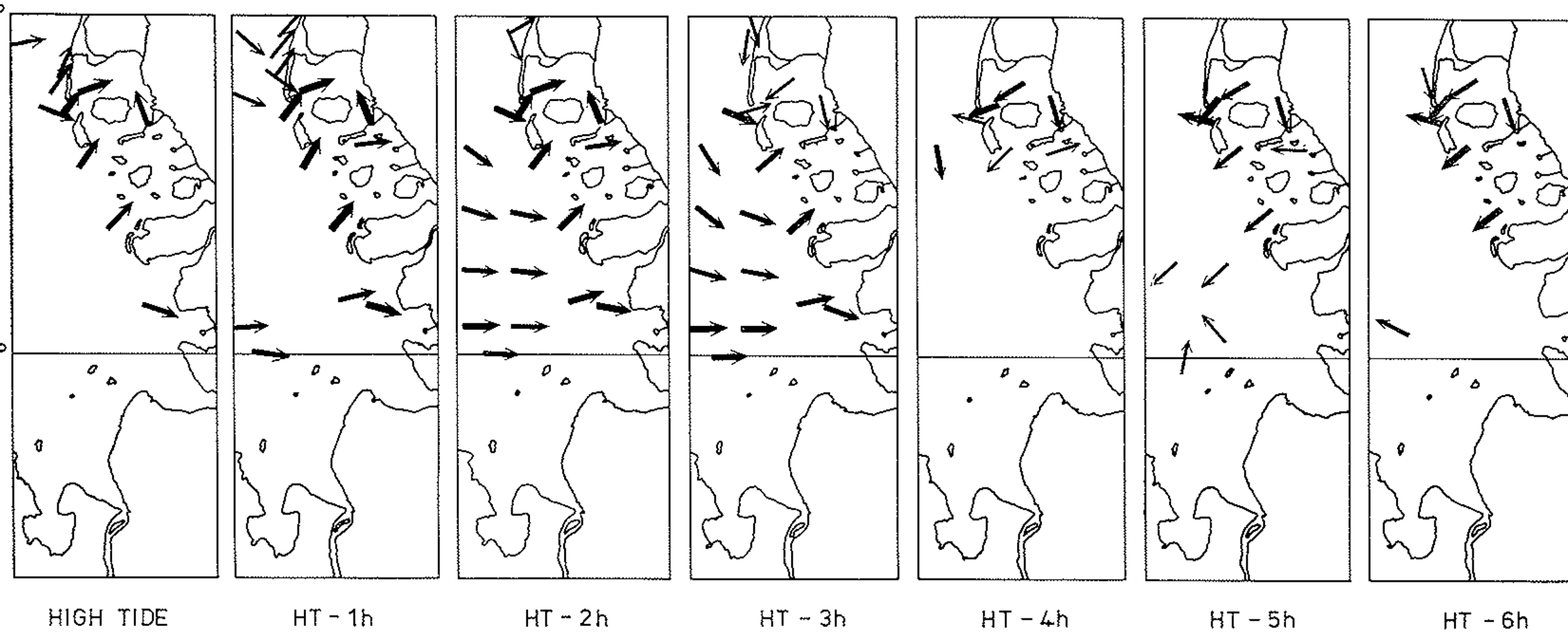

FIG. 4. (Continuation of Fig. 3).


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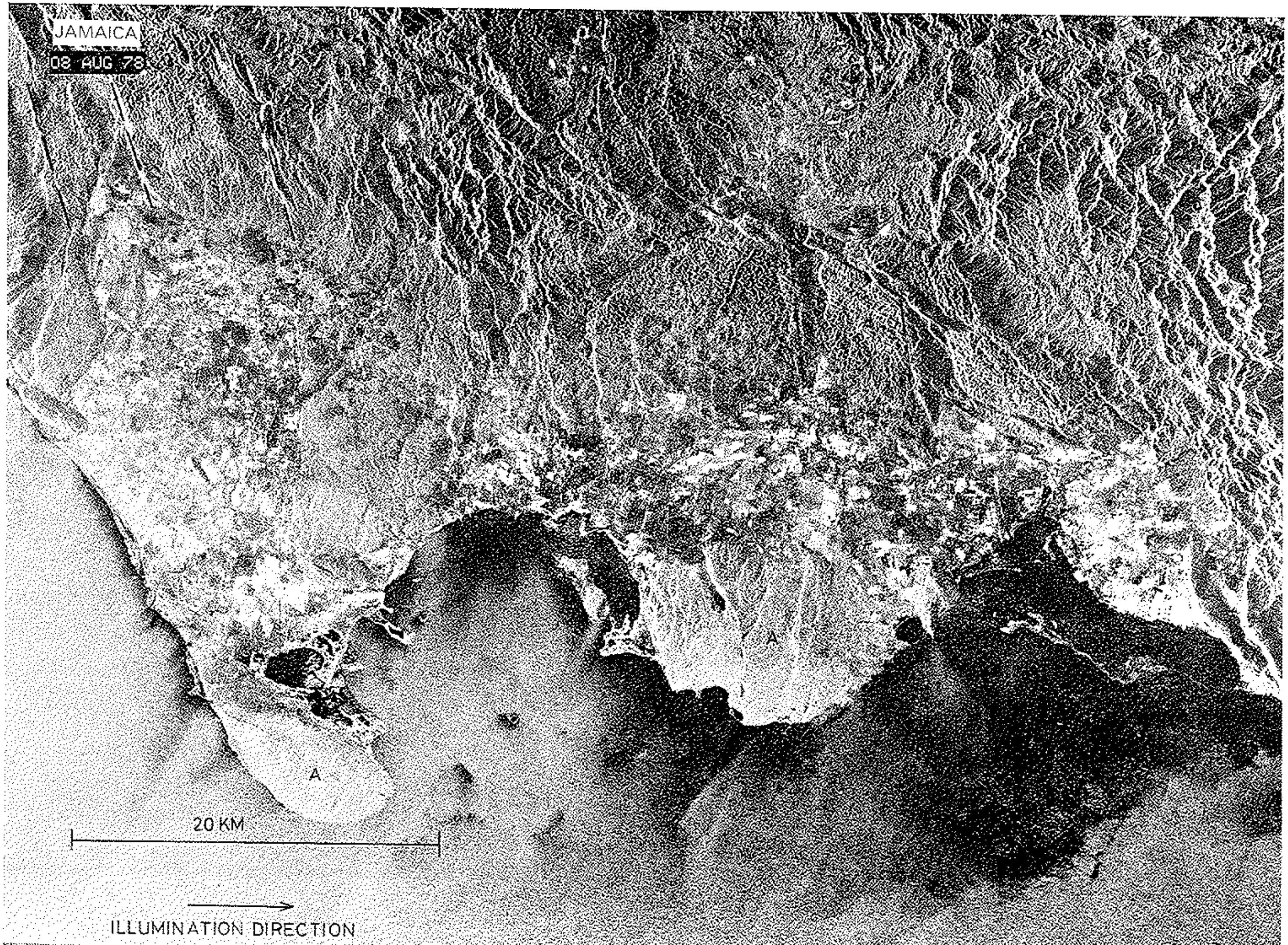
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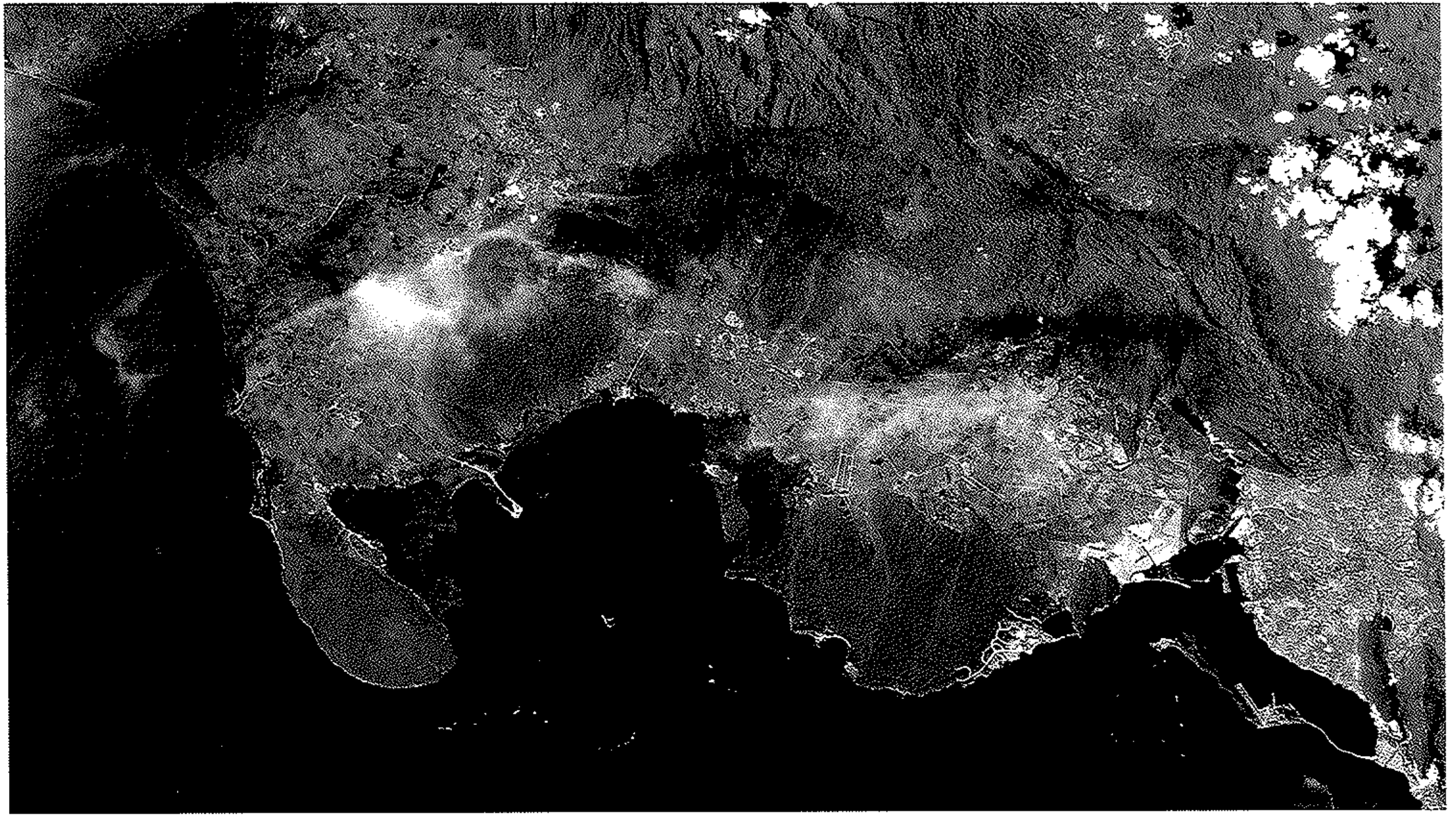


FIG. 8. Coverage of Jamaica with the Metric Camera on the Space Shuttle. Portland Bight is on the left portion of the image.

Estuarine and neretic systems

River runoff forms a low salinity in the upper layer of an estuary and tends to move seaward, while the sea water that has been entrained into the surface water is replaced by deeper sea water with a movement toward the river. Lateral and vertical mixing causes sea water to be added to the effluent which is carried in an offshore direction. Vertical mixing in an estuary is rapid and directly involves river water of negligible salt content and sea water of high salinity. In moving seaward through the estuary, the upper layer is continuously increasing in volume and salt content. Deeper water rises to replace that which is carried seaward in the surface layers, whether entrained into the overlying surface layers or frictionally driven by the stress exerted by the overlying seaward flowing surface layers. This process describes river-induced upwelling. In addition, wind-induced upwelling may drastically influence the hydrographic conditions in the estuary or the characteristics of the effluents.

In an estuary and within the effluent of a river, the relationship between plankton and the dilution process is increasingly complicated by variable light conditions, sedimentation of organic material and the recycling of nutrients from the salt wedge. In a river effluent, highly stratified in a very thin layer of about ten meters with respect to physical, chemical and biological parameters, even small scale processes such as wind stress, fluctuations in current shear, etc., will not only influence the distribution patterns of organic matter but also change the conditions for recycling of nutrients and primary production. The heterogeneity in the offshore region in the outflowing water of a river can be demonstrated with an example from a study of the Changjiang in Figure 11.

Within the effluents, maximum concentrations of plankton have been observed at the outer part of the plume surrounding the estuary in a "circular fashion", an example evident from satellite data for the Amazon effluent (see Fig. 12). This observation is under the assumption that a continuous outflow of the river water is present under normal or average conditions, and recycling of nutrients appears along the salt wedge.

A study of a neretic system is demonstrated with investigations in the Yellow Sea. The changes in the system connecting the Bohai Sea, Huanghai Sea and the East China Sea are predominantly influenced by the seasons and prevailing wind conditions. The most important influence on the hydrography of the Huanghai Sea is the warm Kuroshio Current, coming from the South.

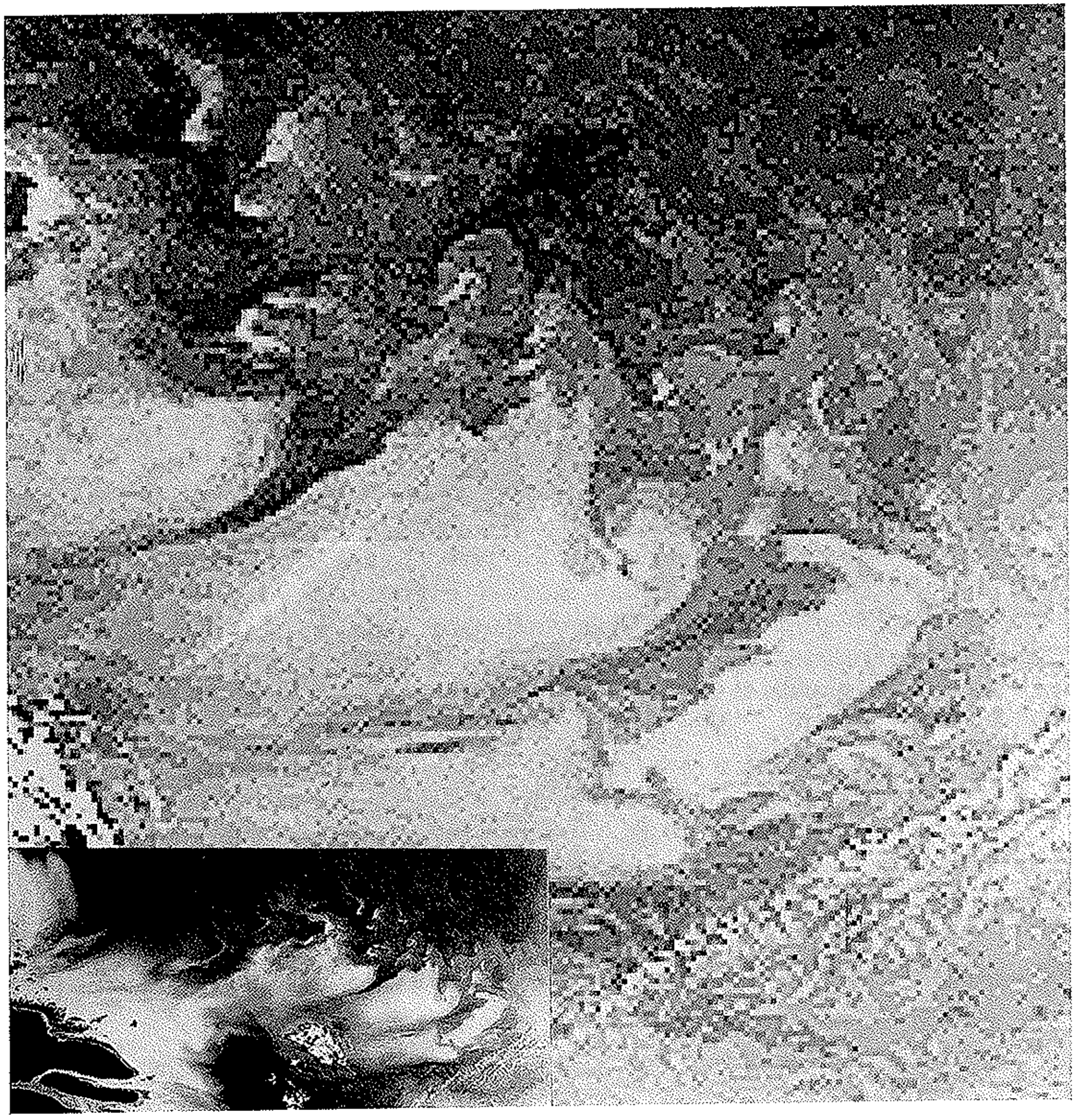


FIG. 11. Patches generated from the Changjiang (after Szekielda and McGinnis, 1985).

An infrared image for March 9, 1982, in Figure 13, shows the effect of the major current system with a branch of the Kuroshio carrying warm water of about 9°C to the North. Most probably, under the influence of the northern winds, cold water is carried by the coastal current of the Huanghai Sea with local low temperature of < 4°C when the current leaves the coast, creating upwelling. The outflowing water from the Changjiang is marked by lower temperatures compared to the adjacent water. Reflected and emitted energy is shown in image format in Figure 14. Visible are the warm current of the Huanghai Sea going north to the Shandong Peninsula, the coastal current and part of a coastal upwelling system. Along the Korean peninsula, cold water enters the sea from the coast. Based on the infrared observations, the visible data can be interpreted with respect to the origin and fate of particulate material. The river water has relative high temperatures and flows in a southern direction. The cold coastal water leaves the coast and carries a high concentration of suspended material which originates in the northern part of that region. It is also worth noting that the concentration further upstream at Tang-Chia has a low reflectance level indicating that the offshore region has higher particle load. This is also evident by the offshore pattern, which besides showing a complicated structure in the distribution pattern, shows higher reflectance than the near-shore. The offshore patterns are directly in the axis of the cold water; therefore, it can be speculated that the patches do not reflect Changjiang diluted water.

Besides having a quasi-synoptic view of the main features of the hydrography in the Huanghai Sea, the transport, origin and production of particulate matter can be identified. The patchiness shown in the data further indicates that with conventional data, the impact of the Changjiang outflow on the hydrography may be misinterpreted. What may look like Changjiang water, especially in the offshore region, may be discharge water from the sand banks north of the river mouth.

Open ocean

According to the scale of the water mass, the appropriate measuring grid has to be identified. For instance, global ocean features in connection with large scale atmospheric ocean interaction would need a rather coarse sampling compared to near coastal investigations for resources development.

A global coverage of SST based on a daily coverage with a grid resolution of 100 km, as shown in Fig. 15, displays temperature gradients connected with major currents, convergence zones and upwelling areas. With regard to fishing zones, upwelling and its time-dependent behavior can be monitored even on such scales. For example, the Peruvian upwelling, the upwelling regime along the NW and SW coasts of Africa can be identified by their low temperatures. Major current systems such as the Kuroshio, Gulf Stream, Benguela Current, Falkland/Malvinas Current and the convergence zones in subtropical regions are evident by their horizontal temperature gradients at the surface. The temperatures compare well with ship observations, and statistical analysis of the data gives an accuracy which is better than the intake measurements aboard vessels.

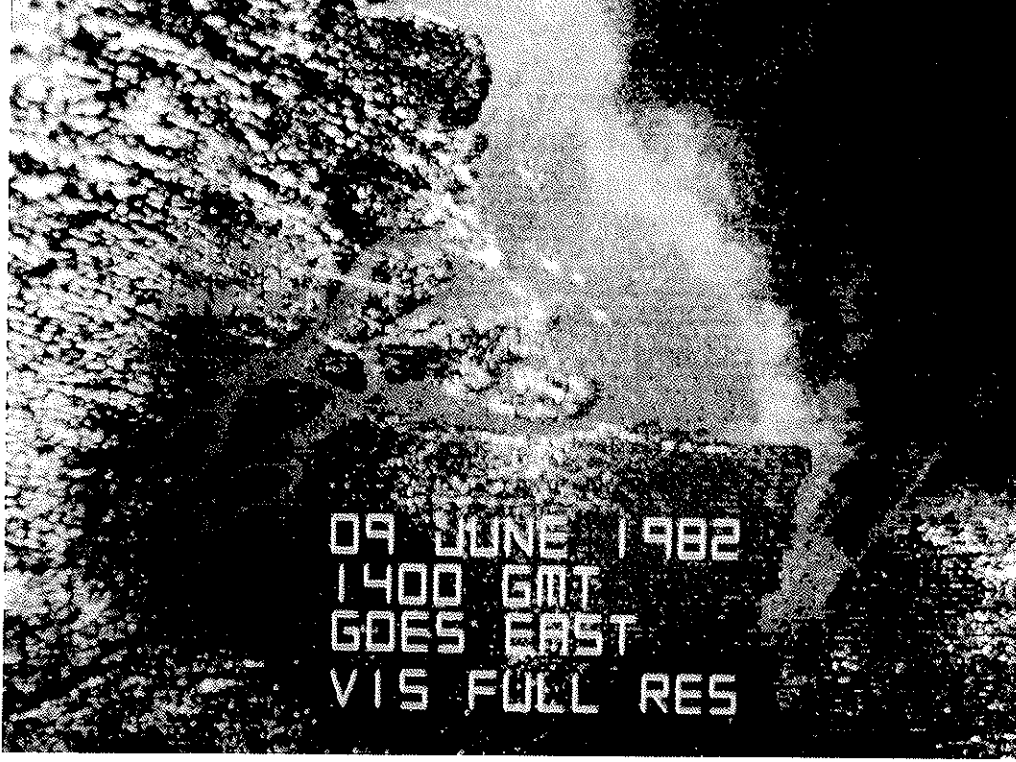
Air-sea interaction is the most driving force for weather systems. For instance, the Indian Ocean responds drastically to the changes from the SW to the NE monsoon, and vice versa. This can be shown by comparing temperature maps in Fig. 16 for the SW monsoon, and vice versa. This can be shown by comparing temperature maps in Fig. 16 for the SW monsoon and the NE monsoon periods.

Of great concern is the large scale phenomena of El Niño, whose immediate impact has been studied especially for the western coast of Latin America.

Weisburd (1986) showed that signals of a developing El Niño include warmer-than-normal waters extending from the Peruvian coast north to the equator, and sea surface temperatures rising at a faster rate than usual. Equatorial temperatures west of the date line are, at this time, also higher than normal. The southern oscillation, or the atmospheric pressure "seesaw" between the SE Pacific Ocean and the Australian-Indian Ocean region, swings in a direction consistent with the development of El Niño.

Recently, observations have shown that the waters west of Peru have gradually changed from below normal values in late 1985 to above normal in January and February, this region of above normal SSTs expanded northward, then westward along the equator to around 120° W. Rainfall was also above normal over the region of above normal SST south of the equator. While the SST anomalies are presently relatively small, their rate of increase in magnitude and extent during the past few months is of concern (Oceanographic Monthly Summary, 1986).

In the western equatorial Pacific between 150°-170° E, anomalously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1400 GMT
GOES EAST
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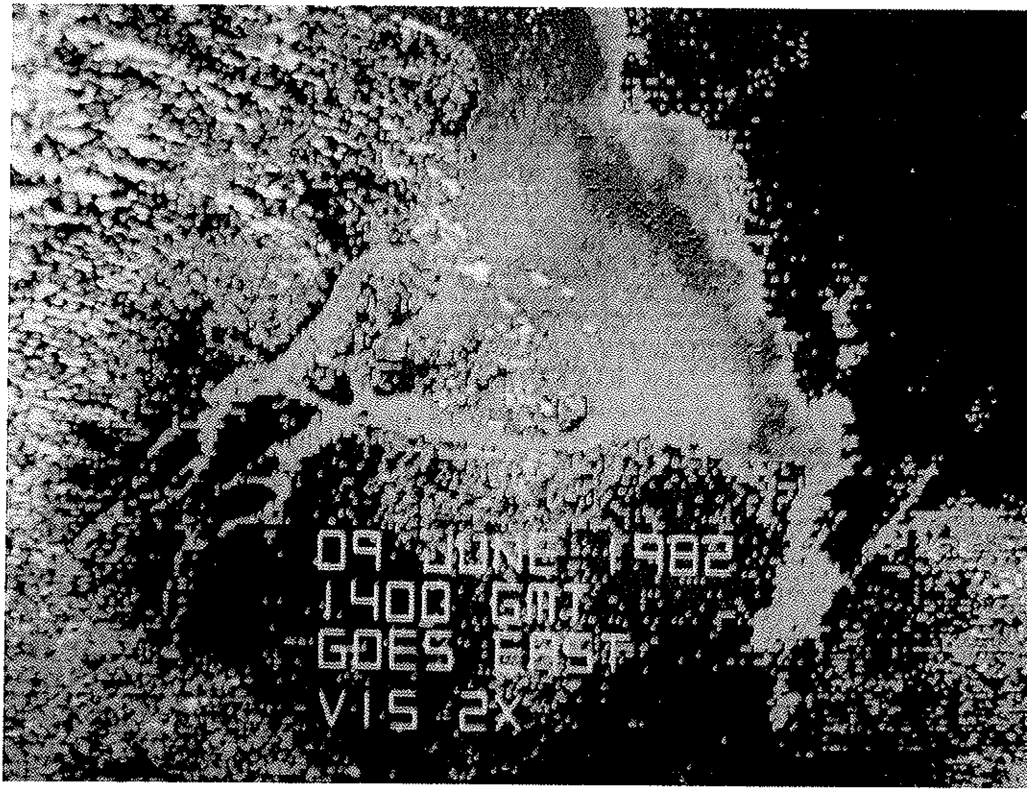
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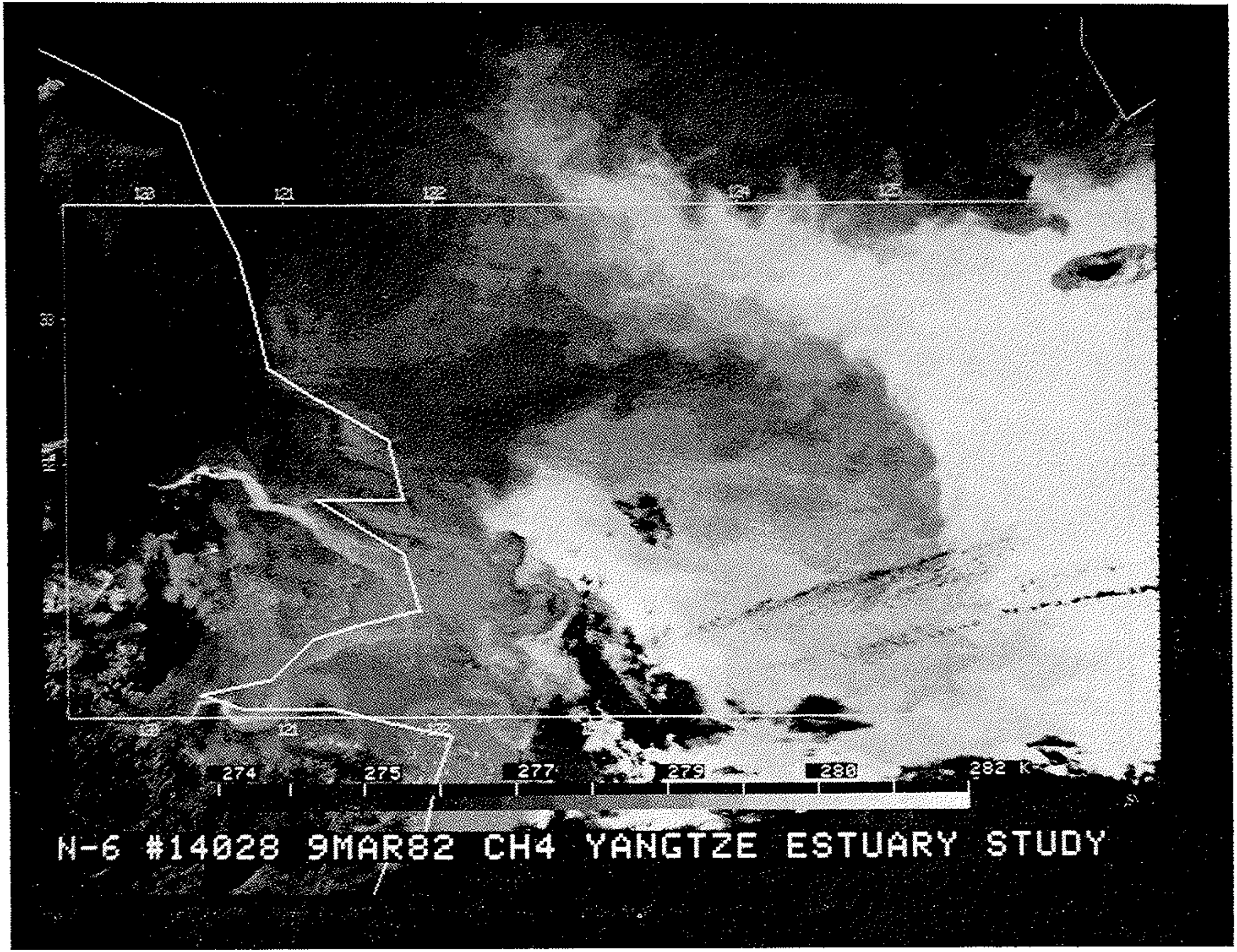

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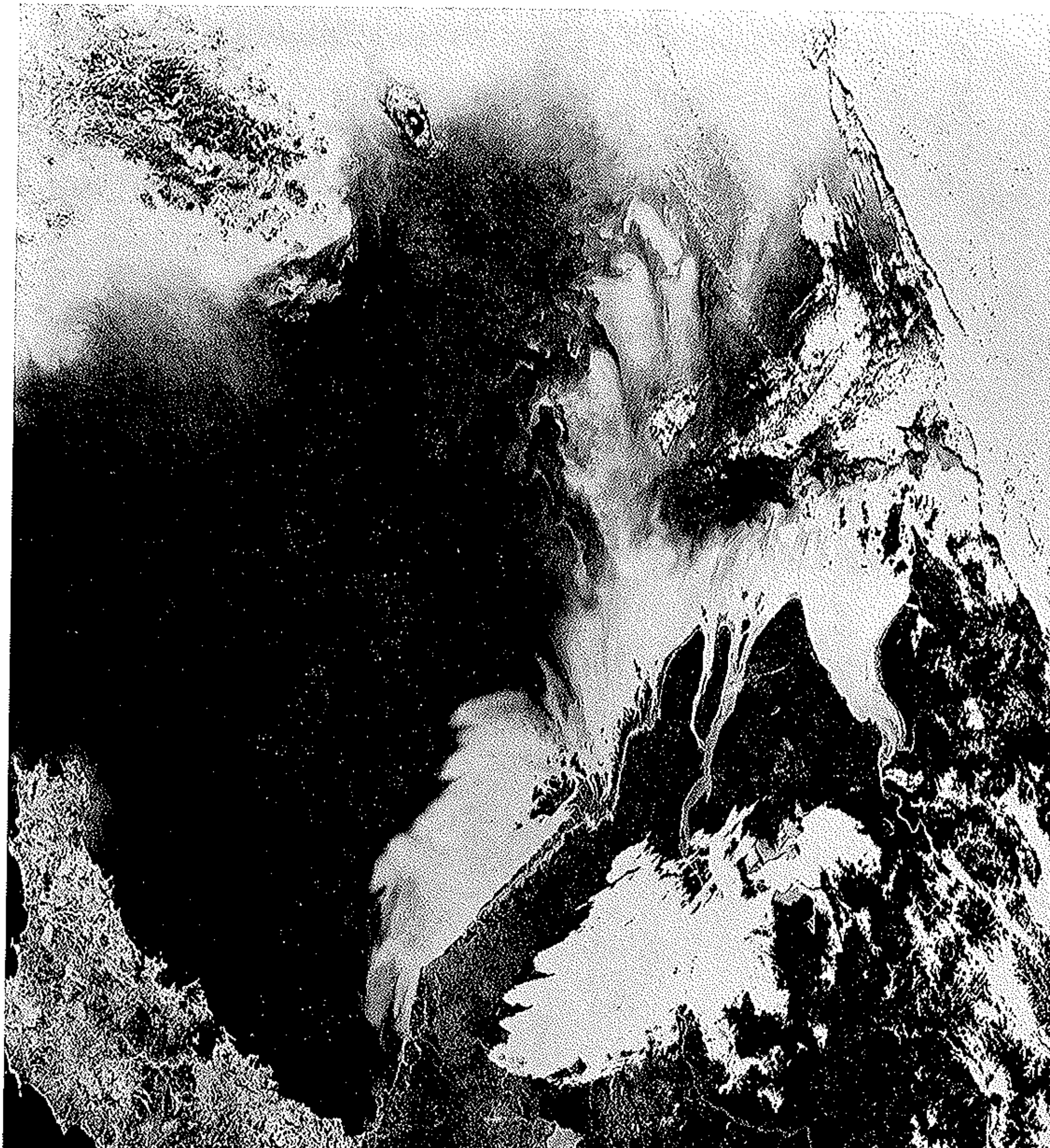


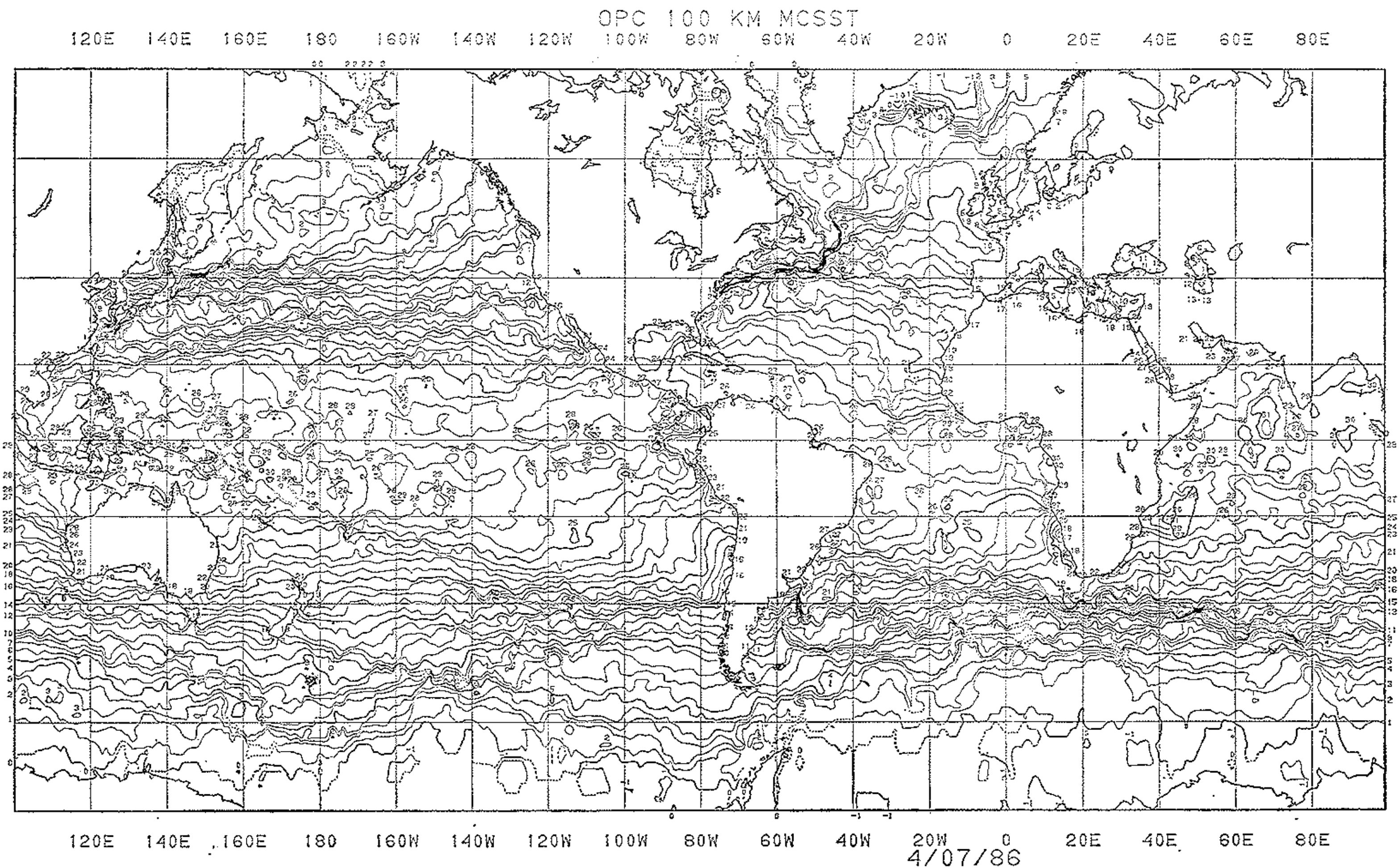
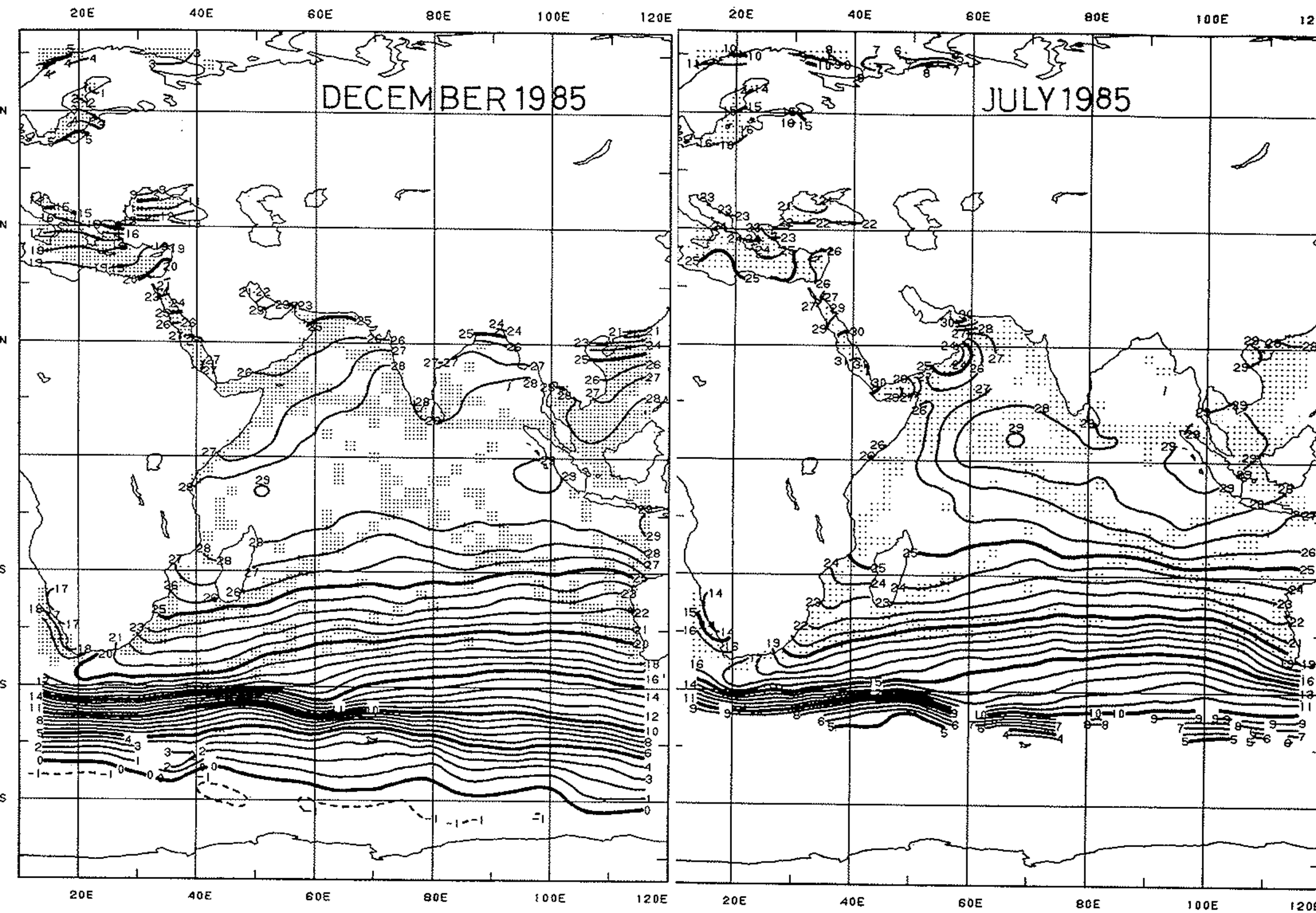


FIG. 15. Multichannel sea surface temperature map with a grid resolution of 100 kilometers. For 7 April 1986.


DECEMBER 1985
JULY 1985
20E
40E
60E
80E
100E
120E

high SSTs have also developed during the past few months. Ocean surface temperatures in this region are normally quite high, but current SSTs (30°C, more than 1°C above normal) are rarely exceeded. There are indications that this area of positive SST anomalies has migrated slowly and irregularly eastward during the past few months. As this took place, anomalous westerly surface winds developed to the west of the area of warmest water. As a consequence, the temperature field fluctuated, as shown in Figures 17 through 20.

The accumulation of warm water in the SE Pacific down to depths of 200 m and more, as was the case during the 1982-83 El Niño, the decrease in vertical and horizontal transport and the modifications in water density are the principal factors which determine changes in the marine ecosystem. The lack of nutrient replenishment and the existence of any process which depresses the thermocline to zones of phytoplankton concentration and the less intense light reduce the productivity (Jordán, 1985).

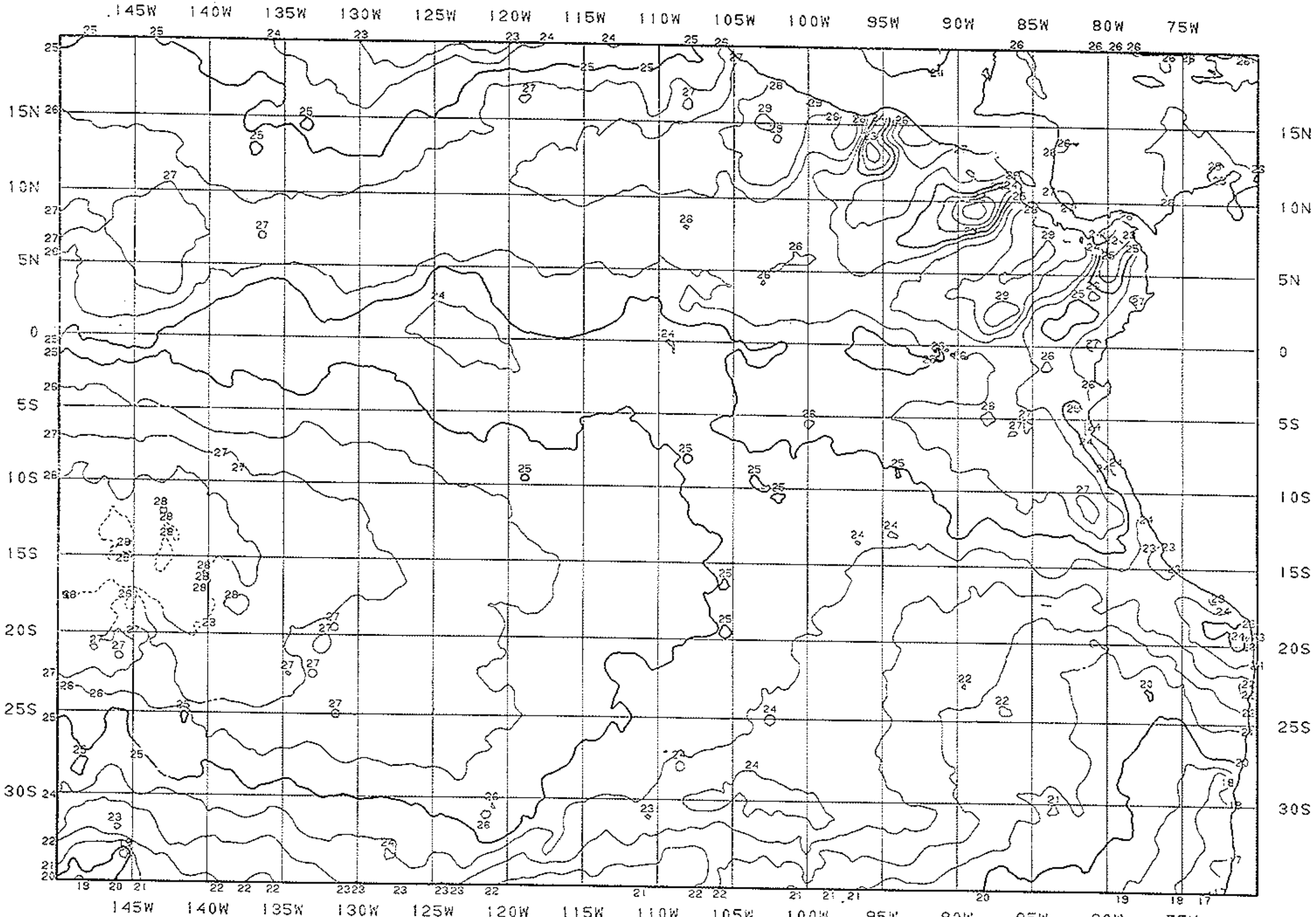
The reaction of fish populations to El Niño depends on their biomass, intensity of exploitation, and the magnitude of El Niño. For example, the 1957-58 El Niño occurred when fishing was at a start; however it did not affect the anchovy population. The 1965 El Niño, on the other hand, was moderate but affected both the fishing activity and the biomass a great deal. The 1972-73 El Niño occurred when the capture levels reached, and even surpassed, the permissible levels, so that it affected dramatically the reproductive process and larvae mortality, and led to the collapse of the fishing industry.

In view of the disastrous consequences of El Niño (see Table 3), a real time monitoring system of SSTs is therefore an important tool for large scale observations for the purposes of both monitoring and forecasting.

Some of the upwelling regimes in the oceans are not yet fully exploited and need further study, for which satellite monitoring can be of useful importance. One of those regions is the Somali upwelling, which responds to the changes of the monsoons.

In response to the wind system over the Arabian Sea, the Somali Current changes its direction of flow from northeast to southwest along the east African coast. The changes appear after the onset of the SW monsoon and the NE monsoon, respectively. In response to the onset of the SW monsoon, the current builds up from essentially no transport to $\approx 60 \times 10^6$ m^3/sec, which is of interest in time-dependent studies. The zone of extremely high velocities > 300 cm sec^{-1} is within the upper 50 m

OPC 50 KM MCSST



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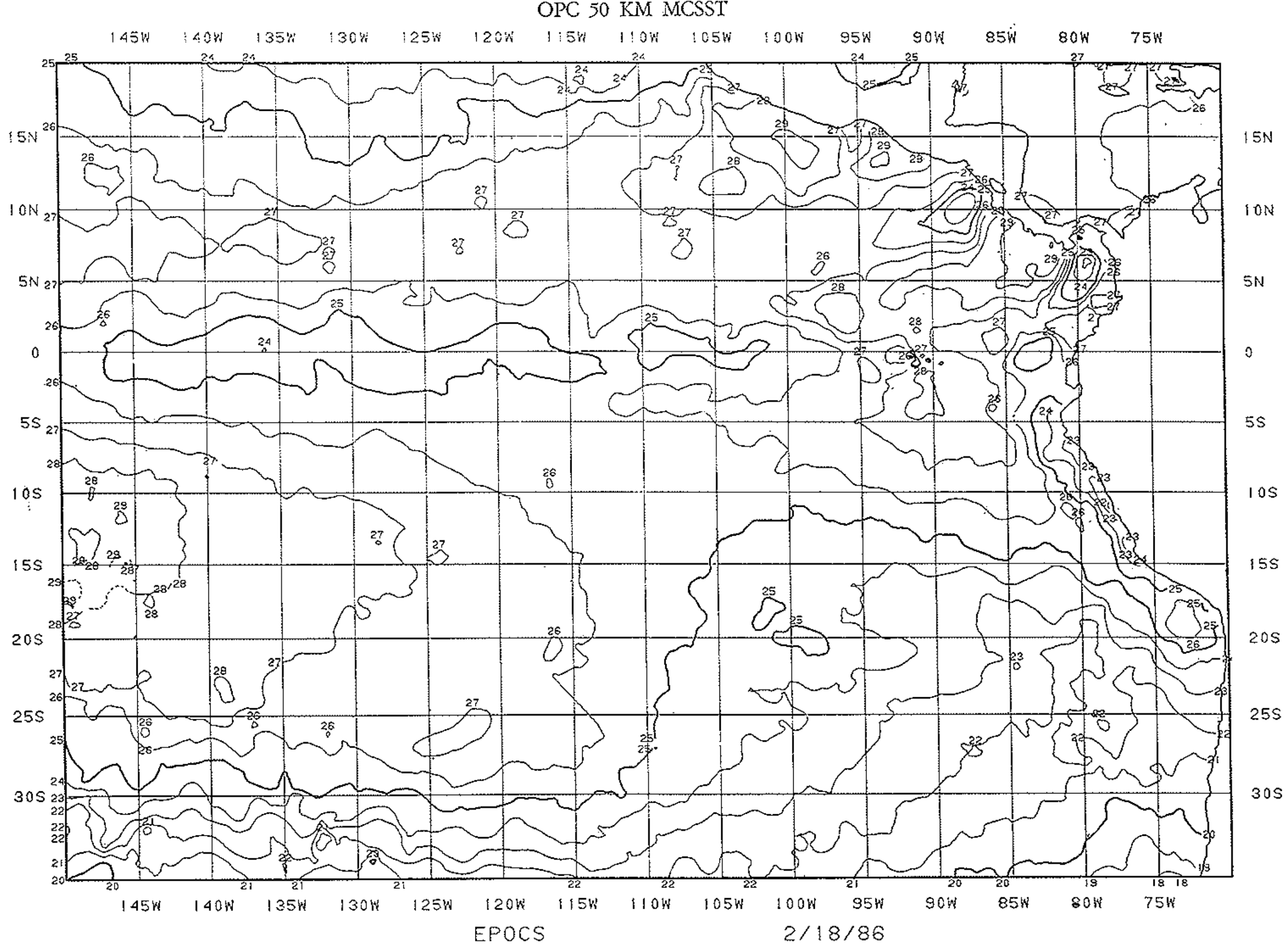
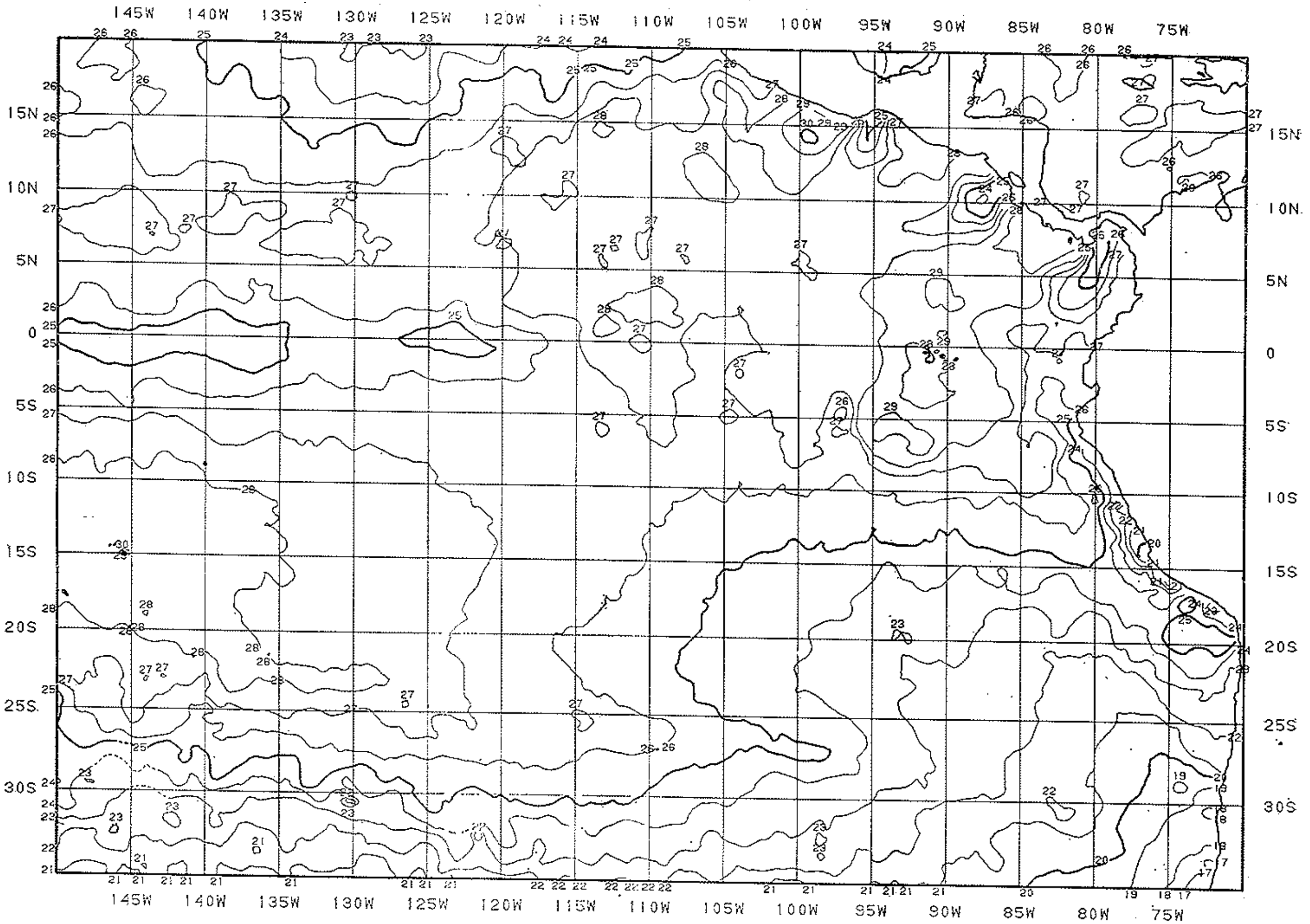


FIG. 18. Multichannel sea surface temperature maps for the Pacific Ocean, during 18 February 1986.

OPC 50 KM MCSST



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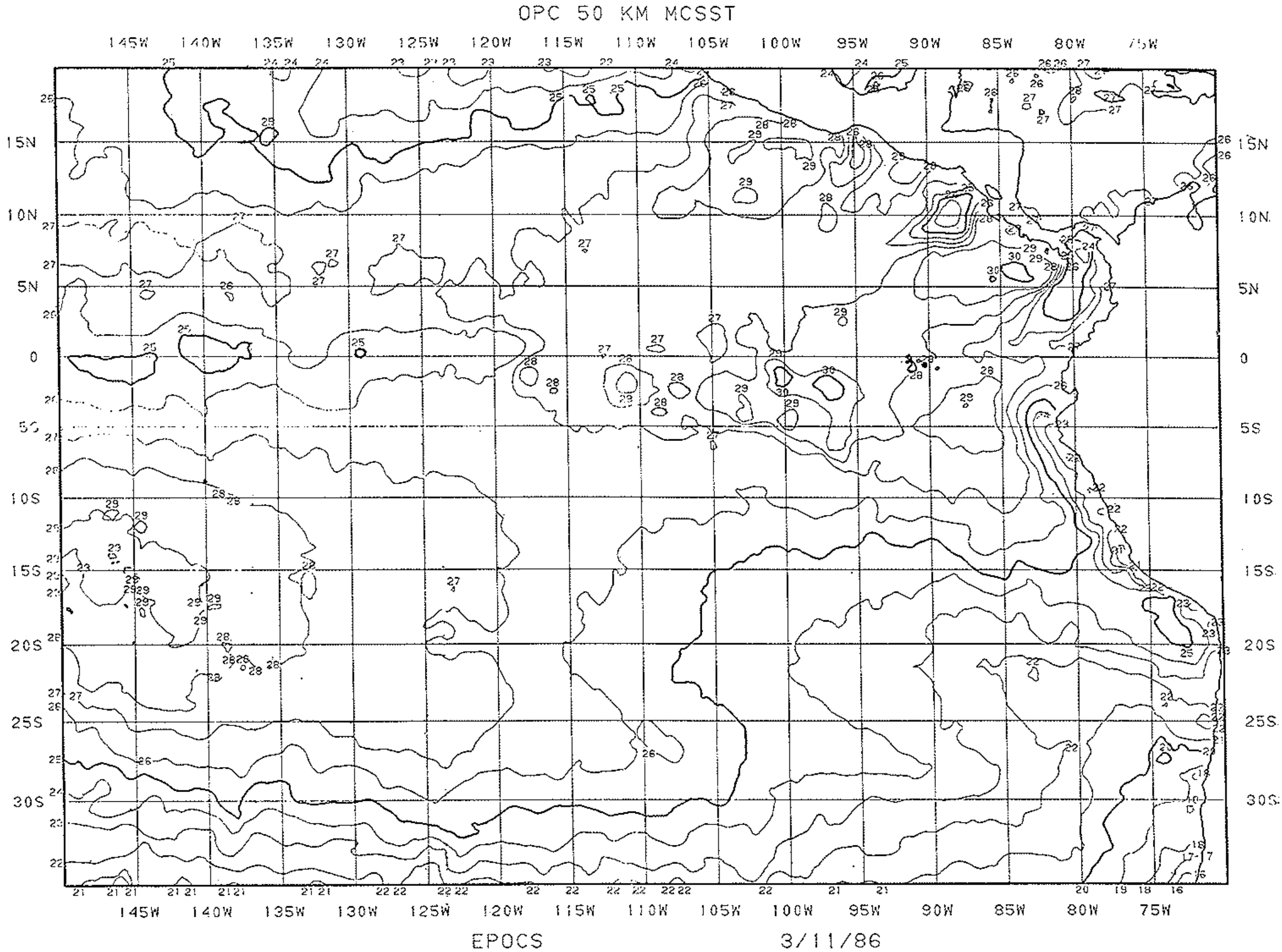


Fig. 20. Multichannel sea surface temperature maps for the Pacific Ocean during 11 March 1986

TABLE 3 - *Evaluation of physical damages caused during the 1982-83 El Niño in Ecuador, Peru and Bolivia* (after Jordán, 1985).

(In millions of US Dollars)

	Ecuador *	Peru **	Bolivia *
Agribusiness	233.8	649.0	716.0
Fishing	117.2	105.9	—
Industry	54.6	479.3	—
Electric energy	—	16.1	—
Mining	—	310.4	—
Transportation and communications	209.3	303.1	98.0
Housing	6.3	70.0	17.8
Health, water and sewage systems	10.7	57.1	4.7
Education	6.6	5.9	—
Archeological remains	—	without appraisement	—
Others	2.1	—	—
TOTAL	640.6	1,996.8	836.5

Source: * CEPAL.
** INP and CEPAL.

of the Somali Current and appears as a narrow stream close to the coast (see Fig. 21). The sharp temperature gradient which is associated with the upwelling area along the Somali Coast, may be easily monitored from space and also detected in the imagery material of infrared recordings. The time-dependent development of horizontal temperature gradients at the sea surface serves as an indicator for the formation of the baroclinic structure of the Somali Current. A comparison was made with the simultaneous development of the SW component of the monsoon wind as derived from ships' observations. The results in Fig. 22 show that the temperature gradients during the early formation stage are directly proportional to the wind speed. The phase lag between the development of wind and temperature gradient is surprisingly short during the development of the boundary current, ranging between 3 and 10 days. During the decay period in late summer and autumn, the temperature gradients lag 14 to 40 days behind the wind. The observations suggest that two

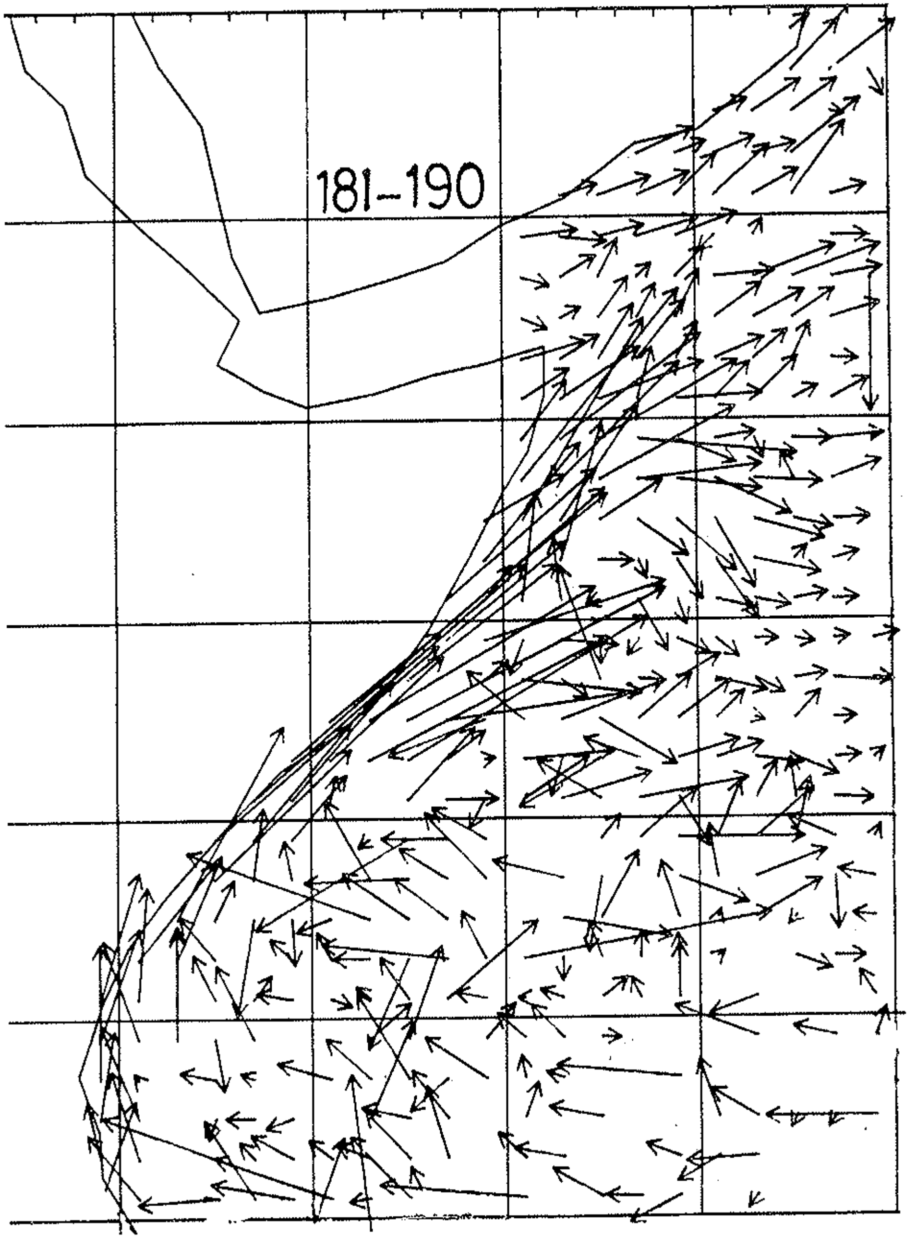


FIG. 21. Major currents during the SW monsoon in the Somali Current (extracted from Cutler and Swallow, 1984).

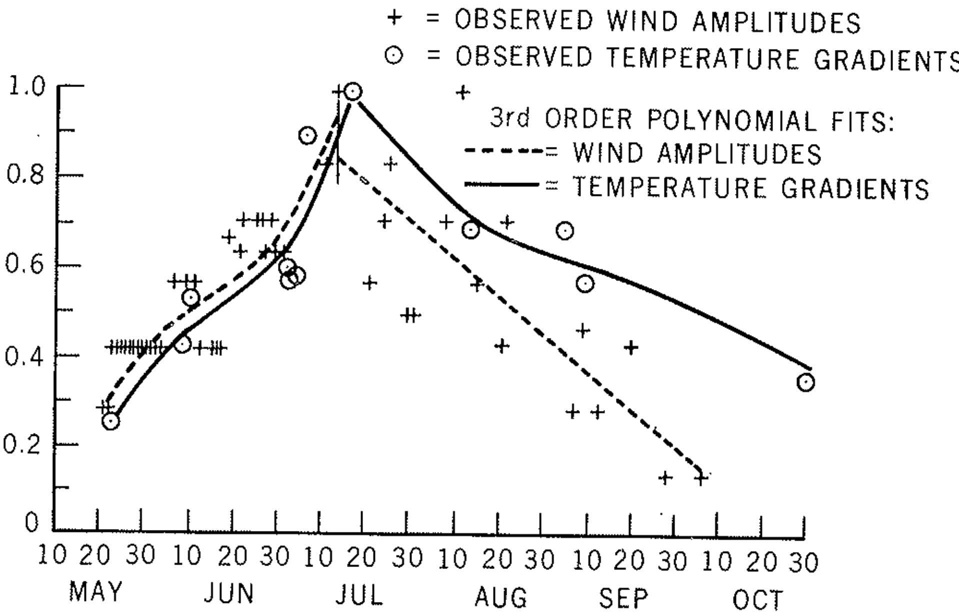


FIG. 22. Comparison between wind amplitudes and temperature gradients observed by satellites (after Szekielda, 1978).

phenomena of different spatial scales play an important role during the formation of the Somali Current: in the early stage (May, June), local wind-induced upwelling seems to be the more important source of baroclinicity; in the later stage (July), large scale geostrophic effects seem to dominate.

More recent observations with Multichannel Sea Surface Temperature (MCSST) data using a resolution grid cell of 50 km make it possible to monitor in detail the development of the cold water of the upwelling at the surface. A sample of a present ongoing study for the Indian Ocean and the Somali upwelling is given in Fig. 23, demonstrating the fast development of upwelling which is generally characteristic of this coastal regime.

Another example of an important upwelling regime with commercial fishery impact is along the NW coast of Africa. In this region upwelling appears throughout the whole year and, in consequence, chlorophyll concentrations are high in the coastal regions (see Fig. 24). Analysis of data taken with the Coastal Zone Color Scanner (CZCS) (see Fig. 25) shows the complicated structures in the distribution of parameters monitored

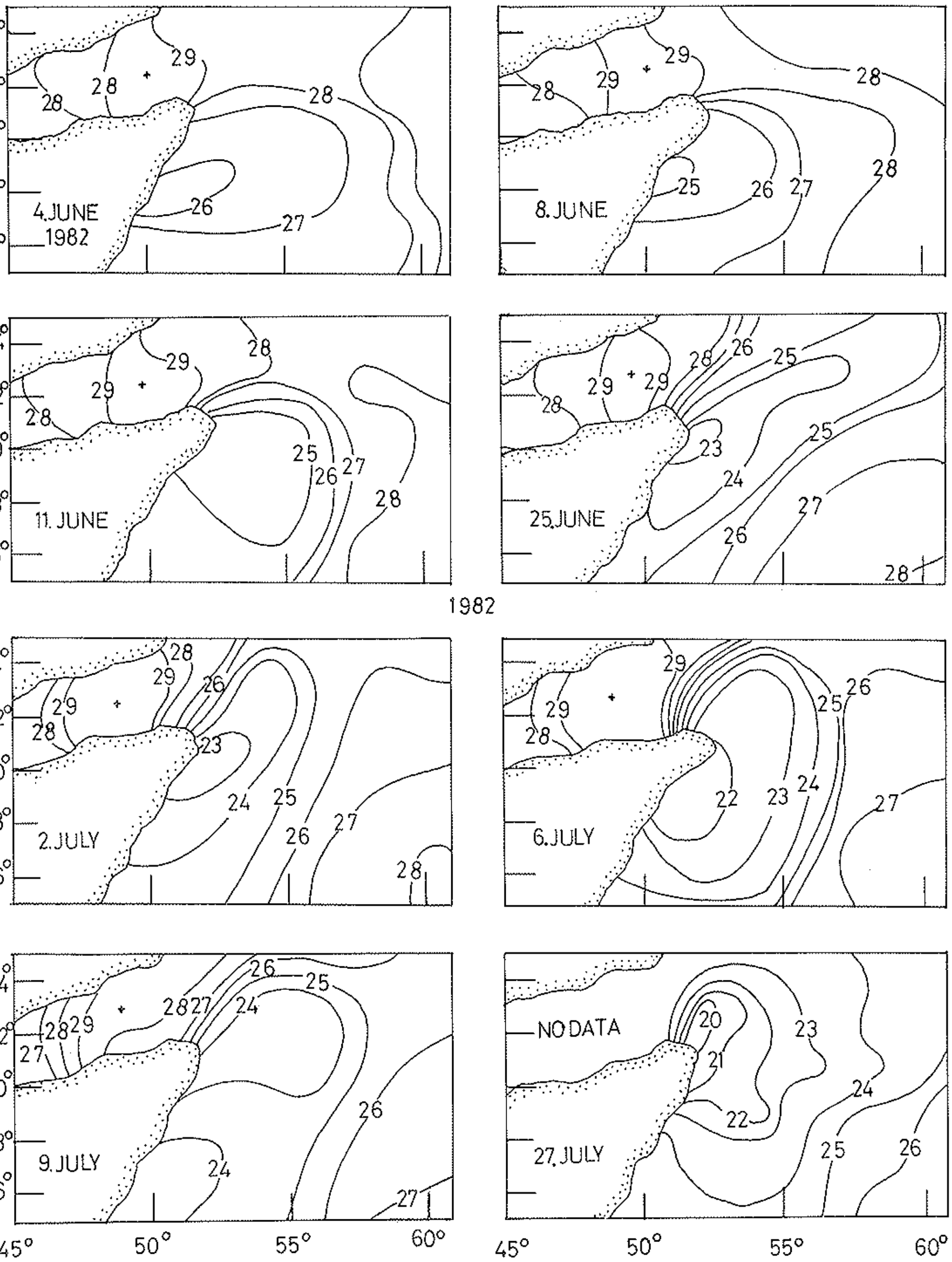
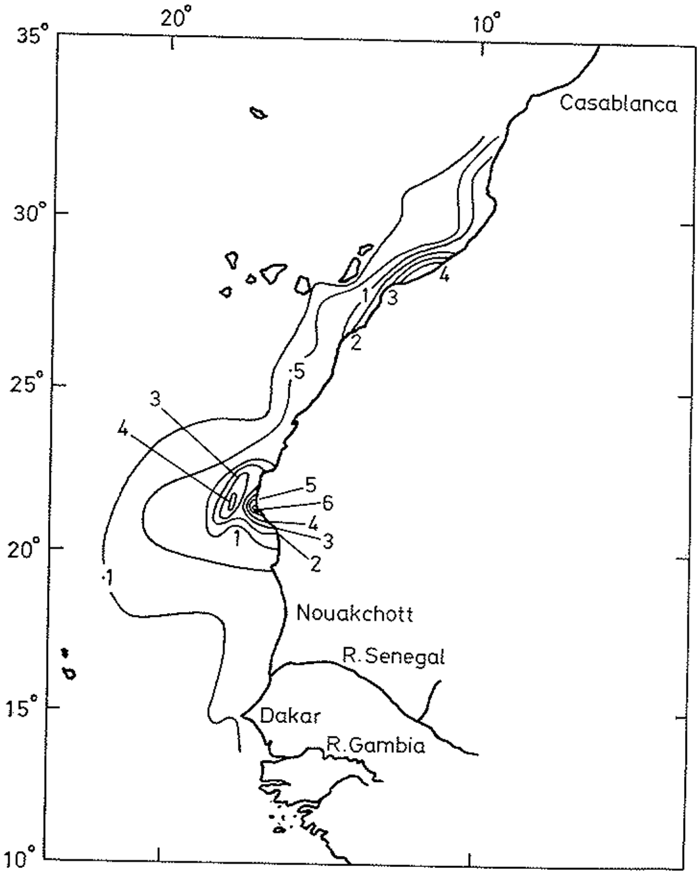


FIG. 23. Development of upwelling along the Somali Coast based on MCSST, during 1982. Based on an ongoing long-term study by the author.



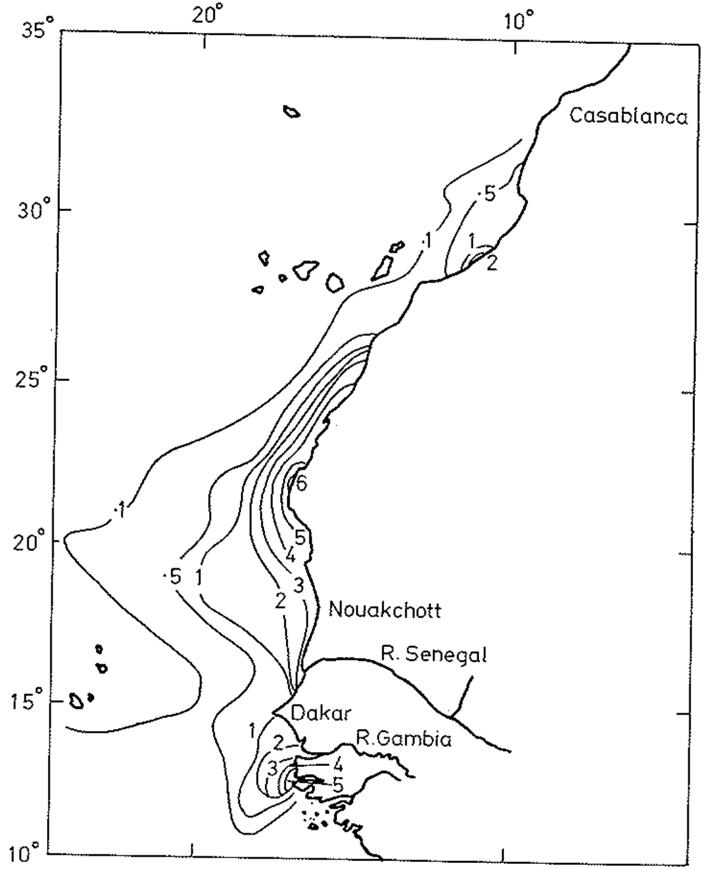


FIG. 24. Composite of chlorophyll concentrations in mg · m^{-3}. Left for the months January to June; right for the months July to September (after Szekielda *et al.*, 1977).

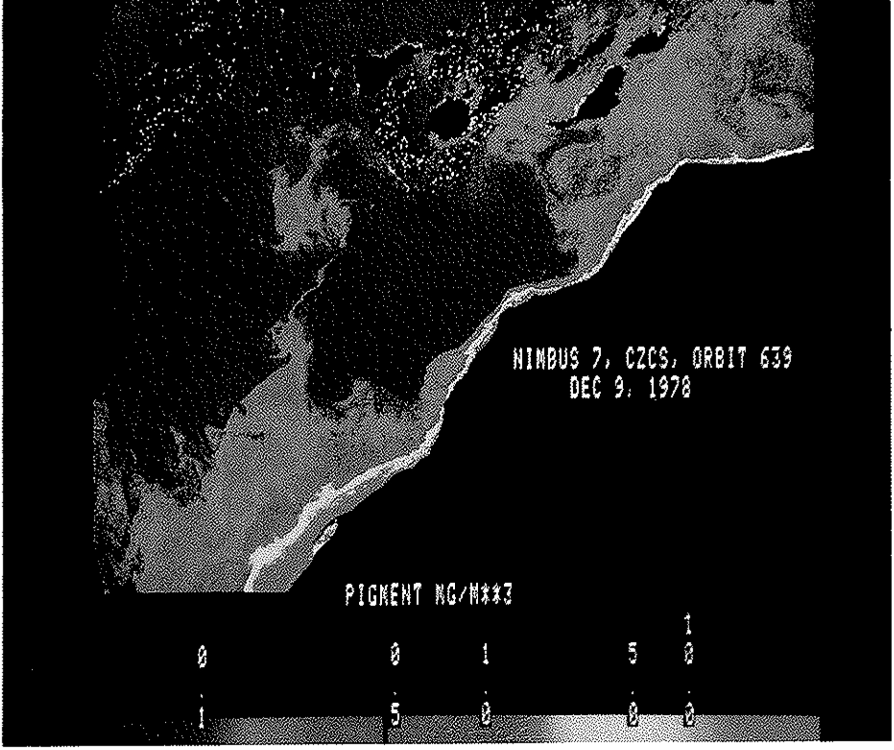
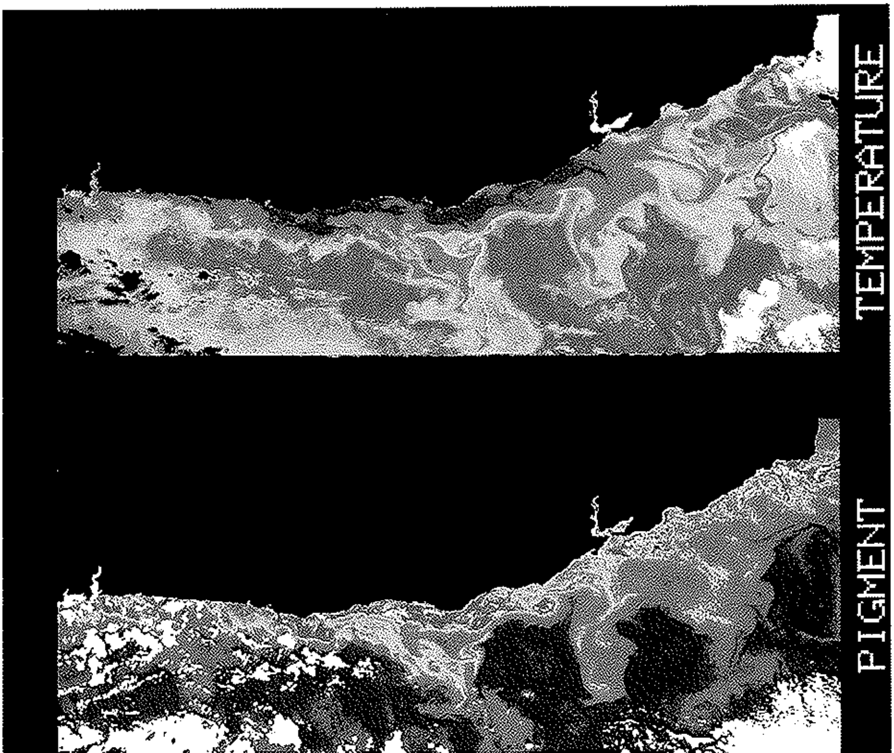


FIG. 25. Estimates of photosynthetic pigments based on measurements with the CZCS on Nimbus 7. (Courtesy J. Zaitseff, NOAA).



by satellites in the region, which was investigated earlier (see Szekielda, 1973 and Szekielda *et al.*, 1977).

Eastern boundary currents have also long been known to be regions of high productivity and major fisheries, a result of generally favorable conditions for upwelling of nutrient-rich water into the euphotic zone. One such system is the California Current System off the west coast of North America, which is shown with its patches in temperature and in chlorophyll distribution in Figure 26 (NASA, 1985).

Patches as observed over the last years in satellite data have contributed to a new concept in considering the ecological impact into the food chain of the marine environment. Generated patches range in scale from the molecular level to patches as large as 300 km in diameter. From pure physical impact alone, it is evident that if one considers a conservative parameter, the patchiness is determined by the factors involved in the mixing processes. In another dimension, namely the growth of organisms or the decomposition of organic material, the situation becomes more complex. It has been shown that the size of a generated patch is one of the factors that controls the development of the food chain or the breakdown of an existing biological system. This means that a diffusing phytoplankton patch in the effluent is affected by eddies larger than the patch size as a whole, while smaller eddies disperse the phytoplankton. Shear and/or spatial variations in the velocity field of eddies with similar size as the plankton patch also deform the patch by advecting one part of the patch relative to another.

A summary of the data on life span of patches observed with satellites is given in Figure 27. In comparison with the time scale of biological growth, patches only in the range of kilometers and upward may be of statistical significance, although it should be kept in mind that if steady state conditions appear, development of a plankton bloom may occur in much smaller patches (Szekielda and McGinnis, 1985).

The satellite data include processes over all the possible ranges and henceforth represent a more realistic observation on patches than the extrapolation of dye experiments into large scale mixing processes.

It can be concluded from the given data that a certain patch size is required in order to develop euthophication, for instance, in the effluent of a river. This, however, is a function of the stability of a water mass; i.e., mixing processes initiated by wind stress, for example, may locally vary the potential for plankton development and, on the opposite side, a steady state may develop maximum plankton concentrations.

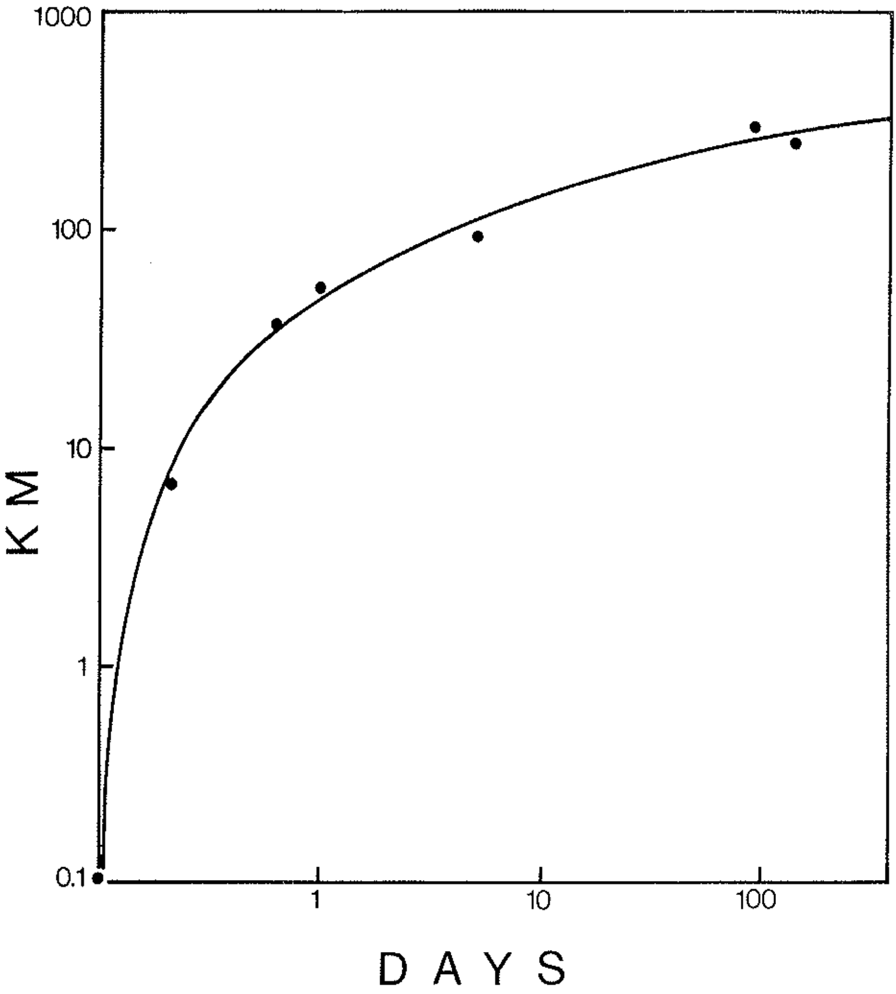


FIG. 27. Relationship between patch size and life span (after Szekielda and McGinnis, 1986).

5. Final remarks

With the presented data, it has been shown that space technology can monitor parameters and processes that are vital for our understanding of marine resource areas. Although many sensors are still in the experimental mode, others are operational and deliver, for instance, a global SST coverage on a daily basis. Other parameters, such as most probably photosynthetic pigments, will also be mapped operationally on either a regional or global scale. Time series have also been recommended (NASA, 1985) in order to address questions concerning both biological and physical processes.

With respect to large scale operations in international programs, ocean forecasting, as an operational observation system using satellites, can provide regional and global information for the management of marine resources (GOFS, 1986). Such programs could consider, for instance, the following:

- *Global climate/CO_2 problem.* Determine ocean productivity estimates for use in understanding the global carbon cycle and the ocean's role in climate.

TABLE 4 - *Ocean-Related Spacecraft: Next Decade.*

Satellite	Sponsor	Ocean-Related Sensors/Comments	Launch	Status
GEOSAT	USN	ALT	1985	Approved
DMSP	USAF	MR	1985	Approved
	NASA	MR Data Receiving/Processing Facility		Approved
MOS-1	JAPAN	CS, IR, MR	1986	Approved
ERS-1	ESA	ALT, SAR, SCAT, IR	1989	Approved
	NASA	SAR Data Receiving/Processing Facility		Approved
NROSS	USN	ALT, MR	1990	Approved
	NASA	Contribute SCAT		Approved
TOPEX	NASA	ALT	1990	Proposed
ERS-1	JAPAN	SAR	1990	Proposed
	NASA	Utilize SAR Data Facility		Proposed
SPOT-3	CNES	Piggyback ALT	1990	Proposed
	NASA	Piggyback CS	1990	Proposed
RADARSAT	CANADA	SAR	1991	Proposed
	NASA	Contribute LAUNCH		Proposed
	NOAA	Contribute SCAT		Proposed
	UK	Contribute BUS		Proposed
GRM	NASA	Satellite-to-Satellite Tracking	1992	Proposed

· *Fisheries research and applications.* Predict fishing locations, as well as upwelling and other high productivity regions optimal for fish larvae growth.

· *Offshore petroleum and marine mining.* Monitor ocean currents and eddies for use in drilling and mining operations.

· *Exclusive economic zone.* Estimate optical properties and phytoplankton abundance marine resource and habitat assessment.

· *Environmental quality.* Provide observations of pollution and sediment inputs to the coastal zone and their effects on the marine food web.

Other sensors applied in the monitoring of coastal areas from operational systems, such as Landsat and SPOT, have been successfully used in resources development and planning. It can be anticipated that within the next years more satellite systems will be in an operational mode for continuous monitoring of the marine environment and its resources. In this context, in order to carry out properly the programs, it would be necessary to train resources specialists immediately in the use of the data which may be derived from the future ocean-related spacecraft expected to be flown within the next decade (see Table 4, after Simmons, 1985).

Acknowledgements

The principal concept of the paper goes back to the 1970's when I was involved in coastal zone management while being with the United Nations. Under contract with the University of Hamburg and GKSS in the Federal Republic of Germany, the data for the North Sea have been processed. Research on eutrophication of coastal regions using the NOAA satellites was done with Dr. D. McGinnis of NOAA-NESDIS, and digital data for the SST studies were supplied through Dr. Pichel of NOAA.

Special thanks go to my wife, who did the editing of the manuscript.

ACRONYMS

ALT	Altimeter
CNES	France's National Center for Space Studies
CS	Color Scanner
DMSP	Defense Meteorological Satellite Program
ERS-1	ESA's Remote Sensing Satellite # 1 and Japan's Earth Resources Satellite # 1
ESA	European Space Agency
GEOSAT	Geodetic Satellite
GRM	Geopotential Research Mission
IR	Infrared Radiometer
MOS-1	Marine Observational Satellite # 1
MR	Microwave Radiometer
NROSS	Navy's Remote Ocean Sensing System
SAR	Synthetic Aperture Radar
SCAT	Scatterometer
TOPEX	Ocean Topography Experiment

SPACEBORNE OCEAN-SENSING TECHNIQUES

ALTIMETER (ALT) - a pencil beam microwave radar that measures the distance between the spacecraft and the earth. Measurements yield the topography and roughness of the sea surface from which the surface current and average wave height can be estimated.

COLOR SCANNER (CS) - a radiometer that measures the intensity of radiation reflected from within the sea in the visible and near-infrared bands in a broad swath beneath the spacecraft. Measurements yield ocean color, from which chlorophyll pigment concentration, and diffuse attenuation coefficient, and other bio-optical properties can be estimated.

INFRARED RADIOMETER (IR) - a radiometre that measures the intensity of radiation emitted from the sea in the infrared band in a broad swath beneath the spacecraft. Measurements yield estimates of sea surface temperature.

MICROWAVE RADIOMETER (MR) - a radiometer that measures the intensity of radiation emitted from the sea surface in the microwave band in a broad swath beneath the spacecraft. Measurements yield microwave brightness temperatures, from which wind speed, water vapor, rain rate, sea surface temperature, and ice cover can be estimated.

SCATTEROMETER (SCAT) - a microwave radar that measures the roughness of the sea surface in a broad swath on either side of the spacecraft with a spatial resolution of 50 kilometers. Measurements yield the amplitude of short surface waves that are approximately in equilibrium with the local wind and from which the surface wind velocity can be estimated.

SYNTHETIC APERTURE RADAR (SAR) - a microwave radar similar to the scatterometer except that it electronically synthesizes the equivalent of an antenna large enough to achieve a spatial resolution of 25 meters. Measurements yield information on features (swell, internal waves, rain, current boundaries, and so on) that modulate the amplitude of the short surface waves; they also yield information on the position and character of sea ice from which, with successive views, the velocity of sea ice floes can be estimated.

GEOSAT This is a U.S. Navy-sponsored mission to provide the Defense Mapping Agency with a larger quantity of altimeter data of Seasat quality. There will be an initial 18-month geodetic mission to map the marine geoid, one map being produced in six months and having an 18-km equatorial track spacing. Following this, there will be an 18-month oceanographic mission, with an orbit having a 20-day-repeat cycle and a 150-km equatorial track spacing. In general, the mean sea surface data from the initial 18-month geodetic mission will be classified, with the residuals from this surface being unclassified.

DMSP This is a series of U.S. Air Force operational meteorological satellites in sun-synchronous orbit. For those satellites planned for launch between 1985 and 1991, there will be a microwave radiometer (the Special Sensor Microwave Imager, or SSMI) aboard having four frequencies over the range from 19 to 85 GHz. As SSMI data are useful in characterizing sea ice, snow cover, surface winds, and atmospheric water, NASA plans to acquire them for research purposes. (Unfortunately, the SSMI data are not useful in estimating sea surface temperature).

MOS-1 The purpose of this mission is to establish Japanese technology for Earth observations and to carry out practical observations of the Earth, primarily focused on the oceans. MOS-1 is all passive, has a two-year design life, and will be in a sun-synchronous orbit. MOS-2 is being considered as a tentative follow-on; however, the sensor complement and orbital characterictics are as yet undecided.

ERS-1 This is an ESA marine science and applications mission whose purpose is to establish, develop, and exploit ocean and ice applications of remote sensing data. A sun-synchronous orbit is planned. The ESA member states have agreed to proceed with full implementation of the ERS-1 mission and have begun Phase C studies. ERS-2 is being considered as a tentative follow-on and would utilize spares from ERS-1.

NROSS This is a U.S. Navy mission with NASA and NOAA participation. The NASA (provision of a scatterometer) and Navy components have been approved in the FY-85 budget. The Navy currently plans to use the DMSP bus. This mission is viewed as an applications demonstration of how well spaceborne ocean observations can meet operational Navy needs. The spacecraft will be in a sun-synchronous orbit, have a three-year design life, and will be an element of the overall DMSP program. In addition to the SSMI, it will carry a lower-frequency microwave radiometer for estimating sea surface temperature. Data from the NASA scatterometer will be used to complement TOPEX data in addressing the general circulation of the oceans.

ERS-1 — This is a Japanese spacecraft with the same acronym as ESA's ERS-1. Its objective is to establish SAR technology for Earth observations and to carry out observations of the Earth, primarily focused on terrestrial applications. It will be in a sun-synchronous orbit and will have an L-band SAR with a two-year design life. Preliminary design and definition studies are under way.

TOPEX — The Ocean Topography Experiment is a dedicated altimeter mission whose data — when combined with data from the NROSS scatterometer — will be utilized to advance our understanding of the general circulation of the oceans. The orbital characteristics are: inclination of 63 degrees, altitude of 1300 km, equatorial track spacing of 300 km, and track repeat of 10 days. Tracking will be provided by DMA's Tranet system, and a Shuttle launch is one of two options being considered. Satellite design studies have been completed, and according to present schedules, TOPEX could be launched to provide a 20-month overlap with the NROSS mission.

POSEIDON — This is a CNES program to develop and utilize satellite altimetry and an associated tracking system (DORIS) for ocean and ice studies. One of two options being considered is piggyback deployment aboard the French SPOT-3 spacecraft. This program is viewed as developing the basis for a low-power, low-cost, and long-term ocean and ice monitoring package deployable on spacecraft of opportunity.

TOPEX/POSEIDON — The other option being considered for TOPEX and POSEIDON is to conduct a joint mission between NASA and CNES. Joint implementation studies have been completed whereby NASA will provide the satellite and TOPEX sensors and CNES will provide an Ariane launch and the POSEIDON sensors.

OCI — NASA is considering the launch of an improved version of the Coastal Zone Color Scanner (known as an Ocean Color Imager, or OCI) presently deployed aboard Nimbus-7. Two spacecraft are being considered for flight of the OCI: the NOAA-K operational meteorological and French SPOT-3 satellites.

GRM — This is a mission designed to improve our understanding of the Earth's gravity and magnetic fields; it is planned to extend our knowledge of these fields down to horizontal scales on the order of 100 km. GRM is planned as a two-satellite system flying at a 160-km altitude.

RADARSAT — This is a mission employing a C-Band SAR to monitor sea ice characteristics off the northern slope where the Canadians are interested in developing a petroleum field. It would provide the basis for sea ice forecasting. The Canadian government has approved funding to support detailed design studies both for Radarsat and its ground segment (which will also be used with ESA's ERS-1). NASA is considering participation in this mission by providing a Shuttle launch and NOAA by providing a scatteromater.

SPOT — This is a French version of the U.S. Landsat series. In addition to the terrestrial-oriented visible radiometers, SPOT 3 and 4 can each carry one or two additional sensors. SPOT 3, proposed for launch in mid-1990, is being considered as a platform for POSEIDON and OCI.

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REMOTE SENSING OF COASTAL RESOURCES IN DEVELOPING COUNTRIES

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ABSTRACT

During initial applications of remote sensing in developing countries, much emphasis was placed on agriculture, forestry and geology. To transfer remote sensing technology, regional and national centers were set up which were staffed and equipped to handle Landsat imagery. More recently, developing countries are showing an increasing interest in applying remote sensing to the management of renewable and non-renewable coastal resources, including fisheries and mangrove habitat.

The synoptic and repetitive coverage of satellites is particularly well suited for monitoring the properties and managing the resources of large coastal and ocean areas. Recent developments in marine-related remote sensing, such as synthetic aperture radar for wave studies, thermal infrared radiometry for sea surface temperature measurements, and narrow-band multispectral scanners for ocean chlorophyll or mangrove biomass mapping, will require a concerted effort by national and international agencies to set up regional centers, sponsor joint research programs, and conduct workshops for transferring this technology at the level at which each country is able to absorb it. Otherwise, the transfer of marine-related remote sensing technology will continue to lag well behind the transfer of Landsat techniques used in agriculture, forestry and geology.

Introduction

Economic pressures to extract oil and other deposits, to increase the harvest of food and, at the same time, to protect the coastal environment are creating a need to monitor the properties of large ocean and coastal water bodies. As a result, efforts to accumulate data concerning biological coastal and marine resources have recently come to rely significantly on remote sensing techniques, which are being applied with varying degrees of success to accomplish the following objectives:

— mapping wetland habitat size, plant species diversity, and productivity;

— monitoring man-made and natural changes in the coastal zone, including the impact of land use change on estuarine habitat;

— mapping chlorophyll and nutrient-rich upwelling regions important to fisheries resources management;

— charting current circulation, fronts and other dynamic properties important to studies of phytoplankton, zooplankton and fish egg/larvae circulation;

— determining the identity, concentration, and dispersion of certain natural substances and pollutants, such as suspended sediment and oil slicks.

These applications of remote sensing require a wide assortment of data analysis techniques ranging from visual photointerpretation of color infrared film for wetland mapping; to standard digital techniques for thermal infrared charting of coastal upwelling; and to sophisticated multispectral analysis methods for studies and quantitative determination of marsh biomass and chlorophyll concentration in water. The objective of this paper is to provide an overview of useful remote sensing techniques and to suggest how they could be employed to solve coastal resource management problems in developing countries.

State of the Art Overview

Table 1 summarizes the present capability of aircraft and satellite remote sensors to provide data on coastal land and water properties. Even though the ratings assigned are somewhat subjective, depending on environmental conditions, availability of ground "truth" and mode of operation,

Table 1 - *Performance of Remote Sensors for Coastal Studies.*

Sensor	Platform	Veg. & Land Use	Biomass & Veg. Stress	Coastline Erosion	Bottom Feat. SAV	Depth Profiles	Susp. Sed. Ptrns.	Susp. Sed. Concen.	Chlorophyll Concen.	Oil Slicks	Surf. Temp.	Water Sal.	Curr. Circ. Ptrns.	Wave Spectra	Surf.
m Cameras	A	3	1	3	3	2	2	1	1	2	0	0	2	2	1
	S	2	1	2	2	1	2	1	1	1	0	0	2	2	1
ltispectral	A	3	2+	3	3	2	3	2	2+	3	0	0	2	2	1
nners	S	2	2	2	2	2	3	2	2	2	0	0	2	2	1
ermal IR	A	1	1	1	0	0	1	0	0	3	3	1	2	0	1
nners	S	0	0	0	0	0	1	0	0	1	3	0	2	0	1
ser	A	0	0	1	3	3	1	0	0	1	0	0	0	3	1
ofilers	S	0	0	1	1	1	0	0	0	0	0	0	0	2	0
ser	A	1	0	1	0	1	1	2	3	3	1	1	1	0	0
orosensors	S	0	0	0	0	0	0	1	1	1	0	0	0	0	0
crowave	A	1	0	1	0	0	1	1	1	3	3	2	2	1	3
diometers	S	0	0	0	0	0	0	0	0	1	2	1	1	0	2
aging Radar	A	2	1	3	0	1	1	0	0	3	1	1	2	3	2
AR or SLAR)	S	1	0	2	0	1	0	0	0	2	0	0	1	2	1
DAR (Radar)	G	0	0	0	0	0	0	0	0	0	0	1	3	2	2
DS (Acoustic)	G	0	0	2	3	2	2	1	0	1	0	0	2	1	0
V Camera	G	0	0	2	3	2	2	1	1	1	0	0	1	0	0

ting

= Reliable (Operational)
= Needs Additional Field Testing
= Limited Value (Future Potential)
= Not Applicable

Platform

A = Aircraft (Medium or Low Altitude)
S = Spacecraft (Satellite)
G = Ground (Boat or Field)

this table provides a good idea of the relative ease or difficulty for remotely sensing coastal and oceanographic features which will be discussed in this paper.

As shown in Table 1, the species composition and condition of coastal vegetation can be mapped from aircraft or satellites using color films or multispectral scanners. With digital analysis of Landsat Multispectral Scanner (MSS) data, the classification accuracy of coastal vegetation types can be raised above 90%, especially if images from two different seasons are employed. Identical techniques apply to land use change mapping (Klemas *et al.*, 1975).

Vegetative biomass of both *Spartina* marshes and mangrove swamps can be determined using ratios and differences of Landsat MSS or Thematic Mapper (TM) red and near infrared bands (Table 2). For instance, the MSS band 7/band 5 ratio was found to correlate strongly with *Spartina alterniflora* biomass (Bartlett and Klemas, 1979, 1980; Butera, 1983). Variations in biomass in salt and brackish marshes were also highly correlated with spectral radiance, expressed as the vegetation index or infrared index, based on differences and ratios of TM bands 3, 4 and 5 (Hardisky *et al.*, 1983 a, b). Negative stresses like increased soil salinity and increased concentrations of copper or zinc yielded reductions in biomass which were detected spectrally. Positive stresses like freshwater and sewage effluent additions produced an increase in biomass which also were detected using spectral data. The demonstrated detection of biomass from spectral data was expanded spatially and temporally to estimate net primary productivity of a salt marsh. Remote sensing estimates of production ranged from 5 to 20% of estimates from harvest data (Hardisky and Klemas, 1983; Hardisky *et al.*, 1983 c).

Coastal erosion and coastal geomorphology have been studied successfully using aircraft film cameras and Landsat (Dolan, 1973; Dolan *et al.*, 1977; Stafford and Langfelder, 1971). The advantage of aircraft photography is that it provides the high resolution required for accurate measurement of beach erosion or accretion. Landsat MSS, however, can provide a geologic overview of an entire coastline, including underwater features. Bathymetric maps have been successfully prepared by extracting water attenuation and bottom reflectance from digitally processed Landsat MSS data (Rogers *et al.*, 1982; Lyzenga, 1978, 1979). The water depth algorithm used calculates water depth from Landsat MSS 4 (green light) and MSS 5 (red light) data values for Landsat pixels that are judged by a threshold test to be water. The threshold test is performed on MSS 7

TABLE 2 - *Characteristics of Landsat MSS, TM and SPOT.*

	Landsat MSS	Thematic Mapper (TM)	SPOT/HRV
Launch	1 1972 2 1975 3 1978 4 1982	1982	1986
Altitude (km)	920 (1-3) 695 (4)	695	822
Spectral Bands (μm)	4 0.5-0.6 5 0.6-0.7 6 0.7-0.8 7[2] 0.8-1.1	1 0.45- 0.53 2 0.52- 0.60 3 0.63- 0.69 4 0.76- 0.90 5 1.55- 1.75 6 10.40-12.50 7 2.08- 2.35	1 0.50-0.59 2 0.61-0.68 3 0.79-0.89 p 0.51-0.73[3]
IFOV (m)	76 x 76 (1-3) 80 x 80 (4)	30 x 30 (bands 1-5,7) 120 x 120 (band 6)	20 (bands 1-3) 10 (p)
Pixel Interval (m)	57 x 82 (1-3) 57 x 80 (4)	30 x 30 (bands 1-5,7) 120 x 120 (bans 6)	20 (bands 1-3) 10 (p)
FOV (km)	185 x 185	185 x 185	60 x 60[4]
Pixels/Scene (x 10^6)	28	231	27 (bands 1-3) 36 (p)
Bits/Pixel	6	8	8 (bands 1-3) 6 (p)

(near infrared). Pixels whose MSS 7 data values are less than the threshold are judged to be water. The bathymetry software calculates depth values using two algorithms, one for deep water and another for shallow water. In deep water, signals from MSS 4 only are used. In shallow water, signals from MSS 4 and 5 can be used in a ratio algorithm to calculate depth, minimizing the effects of changing bottom reflectances. If the water is too deep, the MSS 4 signal approaches the deep water signal. Following depth processing, depths are aggregated into intervals (generally two meters) and assigned arbitrary colors for filming. Typically, 7-10 intervals are filmed, depending on the maximum depth of penetration.

As shown in Table 1, water depth can also be measured by the time difference between laser pulses from the water surface and the bottom. Such laser profilers use green wavelengths which penetrate reasonably clear waters (Hoge *et al.*, 1980). Visible images from aircraft or satellites can help provide relative depth profiles which may then be calibrated with airborne laser profilers. Even though powerful laser pulses penetrate the water column to several Secchi depths, a major limitation is their inability to reach bottom in turbid coastal waters. For instance, the turbidities of Chesapeake Bay and Delaware Bay are such that less than half the total area could be mapped with the most powerful laser profiler available.

Suspended sediment concentrations are of interest to marine geologists and biologists, since sediment relates to coastal erosion/siltation and affects sunlight penetration and marine productivity. With appropriate surface "truth" data, suspended sediment concentrations have been mapped from aircraft and satellites (Johnson, 1975; Moore, 1978; Munday and Alfoldi, 1979; Maul *et al.*, 1974). To enable one to calibrate the imagery in terms of suspended sediment load, one must obtain not only concentration measurements on the ground, but also data on the grain size distribution. Atmospheric corrections are required for both sediment and chlorophyll concentration mapping (Wilson *et al.*, 1978). On the other hand, if one is looking only for suspended sediment patterns (qualitative information), film photography with appropriate filters and Landsat MSS bands 4 and 5 can be quite useful. The same discussion applies to mapping pollutant concentrations in coastal waters (Whitlock *et al.*, 1981). To map pollutant concentrations, good ground measurements are required and fairly sophisticated data analysis techniques may have to be used with multispectral scanner data (Philpot and Ackleson, 1981; Klemas and Philpot, 1981).

Chlorophyll concentration strongly influences ocean color (Figure 1) and is a good indicator of ocean productivity. The Coastal Zone Color Scanner (CZCS) on Nimbus 7 has been used with considerable success to map ocean color and chlorophyll-a concentrations over open ocean areas (Hovis, 1977; Wilson *et al.*, 1978) (Tables 3, 4, 5). Despite difficult atmospheric corrections, chlorophyll-a concentrations have been mapped with a factor two accuracy. In turbid coastal waters, it is more difficult to map chlorophyll concentrations using passive techniques. Water masses dominated by dissolved carbon, particulate carbon and inorganic sediment have been differentiated with aircraft multispectral scanners (Klemas *et al.*, 1981).

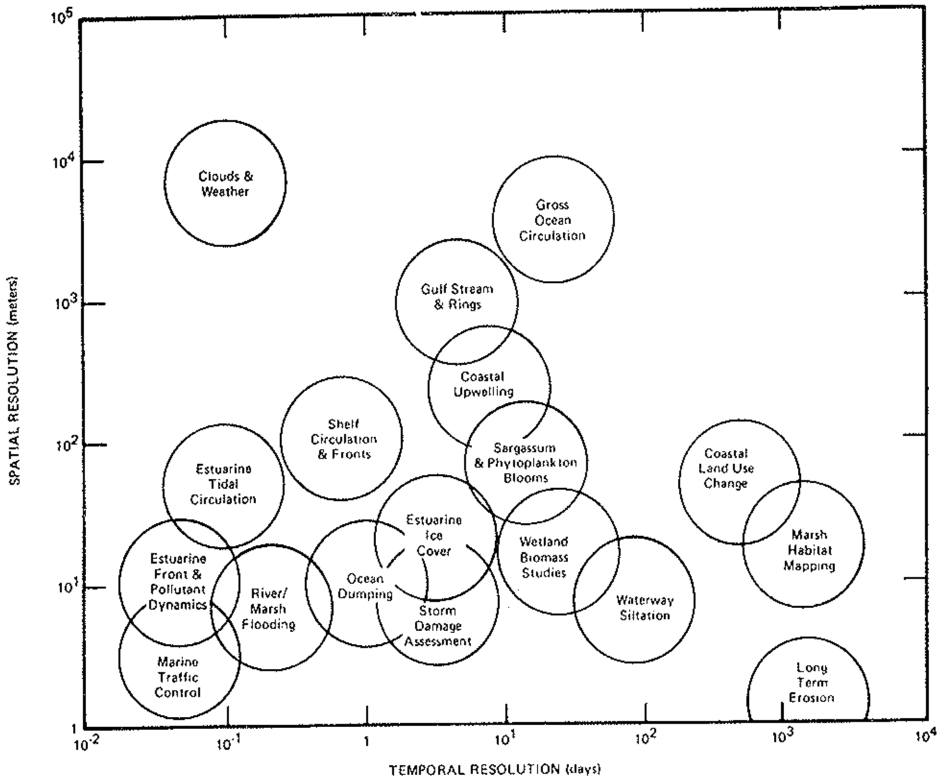

FIG. 1. Spatial and temporal resolution requirements for coastal studies.

Chlorophyll and other pigments have been detected in turbid coastal waters using laser fluorosensing techniques. Chlorophyll concentrations and dispersed oil can be determined using low-altitude airborne lasers operating in the fluorosensing mode (Jarrett *et al.*, 1979; O'Neil *et al.*, 1980). Oil slicks which have not been emulsified and mixed in the water column can be mapped with film cameras, multispectral scanners, thermal infrared and microwave devices (Catoe, 1972). In the visible region, oil has a higher index of refraction than background water; in the thermal infrared and microwave bands, its emissivity differs and radar can detect it primarily because oil slicks dampen small surface waves. However, only microwave devices and laser fluorosensors offer hope for measuring oil slick thickness.

Thermal infrared scanners have been very effective for mapping

TABLE 3 - *Comparative Spectral Bands* (μm) *of Selected Sensors.*

Nimbus-7 Coastal Zone Color Scanner (CZCS)		
Band 1:	0.43- 0.45	Blue
Band 2:	0.51- 0.53	Blue-Green
Band 3:	0.54- 0.56	Green
Band 4:	0.66- 0.68	Red
Band 5:	0.70- 0.80	Near IR
Band 6:	10.5 -12.5	Thermal IR
NOAA-7 Advanced Very High Resolution Radiometer (AVHRR)		
Band 1:	0.58 - 0.68	Visible
Band 2:	0.725- 1.1	Near IR
Band 3:	3.55 - 3.93	IR
Band 4:	10.5 -11.3	Thermal IR
Band 5:	11.5 -12.5	Thermal IR
Landsat 1, 2, 3, 4, 5 Multispectral Scanner (MSS)		
Band 4:	0.50-0.60	Green
Band 5:	0.60-0.70	Red
Band 6:	0.70-0.80	Near IR
Band 7:	0.80-1.1	Near IR

Cost/Unit Area of NOAA and Landsat Data

Sensor	Approximate Cost/km²
Landsat MSS	$ 0.02
Nimbus CZCS	$ 0.0001
NOAA-AVHRR	$ 0.00001

ocean surface temperatures with about ± 1°C accuracy and for studying coastal surface currents (Legeckis, 1975, 1978). Thermal infrared scanners on NOAA satellites, together with multispectral scanners such as the AVHRR and CZCS, have been used to study coastal upwelling and estuarine properties (Gagliardini *et al.*, 1984; Karszenbaum *et al.*, 1983) (Tables 3, 4, 5). Estuarine fronts and their effects on oil dispersion have also been investigated with Landsat (Klemas, 1980). Several aircraft and ground-based radar techniques are being developed for measuring currents (Shuchman *et al.*, 1979). Currents can also be measured using dyes and

TABLE 4 - *Characteristics of Selected Satellite Sensors.*

	CZCS[a]	AVHRR[b]		MSS[c]	
	Nimbus 7	NOAA 6	NOAA 7	Landsat 1-3	Landsat 4,5
No. of Visible/Near IR Bands	5	2	2	4	4
Orbit Altitude	955 km	850 km	850 km	920 km	750 km
Equator Crossing	12:00	7:30	14:30	9:30	9:30
Nadir Ground Resolution	825 m	1100 m	1100 m	79 m	83 m
Swath Width	1566 km	2250 km	2250 km	185 km	185 km
Field of View	± 39°	± 56°	± 56°	± 5.5°	± 7°
Effective Repeat Coverage	6 Days	2 Days	2 Days	18 Days	16 Days

[a] Coastal Zone Color Scanner.
[b] Advanced Very High Resolution Radiometer.
[c] Multispectral Scanner.

TABLE 5 - *CZCS and OCI Pertinent Sensor Characteristics.*

Spectral Bands (nm)	Band	CZCS (Nimbus-7) Wavelength (Bandwidth)	OCI (NOAA-K) Wavelength (Bandwidth)	OCI (SPOT-3) Wavelength (Bandwidth)
	1	443 (20)	443 (20)	443 (20)
	2	520 (20)	490 (20)	500 (20)
	3	550 (20)	520 (20)	565 (20)
	4	670 (20)	565 (20)	665 (20)
	5	750 (100)	620 (20)	765 (40*)
	6	11.5μm (2μm)	665 (20)	867 (45)
	7		765 (40*)	
	8		867 (45)	
	9			11μm (1μm)
	10			12μm (1μm)
IFOV (Instantaneous) Field of View) (mrad)		0.865	0.988	0.988
Ground Resolution (m) (Footprint at Nominal Altitude)		825	1100	1100
Scan Tilt (Degree) (Sun Glint Avoidance)		± 20	± 20	± 20
Radiometric Signal Digitization		8-bit	10-bit	10-bit

* Notched for O_2 band 759-770nm.

drogues tracked from shore or from aircraft (Klemas *et al.*, 1974, 1977). There are also photogrammetric methods for surveying tidal currents (Keller, 1963).

Large area measurements of ocean salinity are of considerable value to oceanographers investigating the coastal zone. Such data are useful in determining the estuarine impact of river flooding for shellfish-bed health monitoring and in detecting coastal water masses where mixing of different bodies of water occur that could affect fish distribution. Changes in salinity and temperature patterns can identify the presence of large-scale turbulence and currents. The data are also helpful in refining circulation and pollution models in bay areas. However, salinity is one of the most difficult properties to sense remotely. L-band microwave radiometers employed from low altitude aircraft have been able to map salinity (Swift, 1980; Swift and McIntosh, 1983) with an accuracy of less than one part per thousand at 25°C. Open-ocean salinity sensing requirements are more stringent by at least one order of magnitude. One of the principal needs relates to the measurement of mass density, as inferred from simultaneous temperature and salinity measurements. Such data identify regions of upwelling and resultant predictions of circulation patterns.

As shown in Table 1, sea state and wave spectra are best obtained using laser profilers from aircraft, radar mappers (SAR) and radar altimeters (Panicker, 1974; Ross *et al.*, 1970; Born *et al.*, 1979; Schule *et al.*, 1971). Imagers such as synthetic aperture radar or film cameras are particularly effective for wave studies if the data is analyzed using Fourier analysis techniques (Stilwell, 1969). Since surface winds induce capillary waves which influence microwave emission and reflectance, microwave sensors, particularly radar scatterometers such as the one on SEASAT, have been tested for surface wind determinations (Born *et al.*, 1979). SEASAT sensors were particularly designed for measuring and mapping ocean waves, surface winds, currents and other features (Am. Geophys. Union, 1983). The accuracies of the measurements are remarkable, considering they were made from satellite altitudes.

New Systems and Requirements

(a) *Spatial and Temporal Resolution*

Spatial and temporal resolution requirements for coastal and deep-ocean studies are shown in Figure 1. Note that as one moves further offshore, both the spatial and temporal resolution requirements become less stringent. For instance, observation of tidal-induced estuarine fronts requires one-half hourly observations at about 10 meter resolution; fronts and ocean-dumped waste plumes on the continental shelf can be tracked about every four hours with 50 meter resolution, while Gulf Stream meanders and warm core rings beyond the shelf can be sufficiently mapped twice a week with 1 km resolution.

Tidal estuarine observations offer the most serious challenge since both the spatial and temporal resolution requirements are severe. Ironically, Landsat MSS and TM offer the best spatial resolutions, yet are totally inadequate to catch hourly tidal changes. On the other hand, synchronous orbit satellites can make continuous observations (providing an image every 20 minutes), but have a spatial resolution of only 1-8 km (Table 6). Therefore, at the present time, one must supplement satellite data with frequent aircraft overflights. The same is true for coastal erosion studies where resolutions of fractions of a meter are required, and flights may have to be conducted immediately after a storm to assess storm damage as well. Similarly, Nimbus CZCS and NOAA AVHRR are ideal for shelf studies

TABLE 6 - *SMS/GOES* *

Launch:	1974 (105°W) 1975 (135°W)	1975 (75°W) 1977	
Orbit:	Earth-Synchronous 35,800 km	(Geostationary)	
Coverage:	60° N-S (Once Every 30 Minutes)		
VISSR:	(Visible IR Spin-Scan Radiometer)		
	8 Visible Channels	0.55- 0.70μm	0.8 km
	2 IR Channels	10.5-12.6	8.0 km
	(Radiance Temp. Meas. 180°K to 315°K)		
	(Sensitivity = 0.5°C)		
Space Environment Monitor			
Data Collection from Meteorological Platforms Every Six Hours			

* Synchronous Meteorological Satellite/Geostationary Operational Environmental Satellite.

and certain estuarine observations, but their spatial resolutions of about 1 km are not sufficient for detailed studies of estuarine fronts, circulation patterns, pollution plumes and interactions with the surrounding marshes (Tables 3, 4, 5). In summary, the ultimate space system for estuarine and marsh studies would be a synchronous orbit satellite providing data every thirty minutes at an MSS or TM resolution (80 meters and 30 meters, respectively). As shown in Figure 1, the system would be used at less than full capacity for continental shelf, open ocean and certain land use observations. For instance, if short intervals of a specific tidal cycle need not be resolved, but typical data over different tidal cycles are sought, NOAA/TIROS-N, AVHRR and Landsat MSS offer good results for studies of estuarine fronts, turbidity patterns, circulation patterns and discrimination of different water types. For studies of wetland vegetation and biomass, Landsat MSS is adequate, and considerable improvements are offered by the Thematic Mapper and SPOT sensors (Table 2). Small water features, such as pollution plumes or estuarine fronts, are also more easily detected by TM and SPOT (Ackleson *et al.*, 1985).

(b) *Spectral Band Requirements*

Results obtained with TM bands 1, 2, 3 and 4 (Table 3) indicate that they are quite effective for mapping coastal vegetation, land cover, marsh biomass and submerged vegetation (Ackleson and Klemas, 1983). As a matter of fact, for coastal land use studies, including wetland vegetation, I would be hard pressed to recommend better bands than the one on the Thematic Mapper. The only application that requires more and narrower bands in wetlands would be an attempt to relate small spectral changes of marsh vegetation due to stresses induced by changes in salinity or pollutants in the water or soil.

While the CZCS bands were quite suitable for mapping chlorophyll-a in the open ocean, the spectral complexity of turbid coastal waters suggests the need for more and narrower bands. To discriminate dissolved carbon, particulate carbons, chlorophyll-a, other pigments and inorganic suspended sediments, the CZCS bands might have to be narrowed down and doubled in number. This is where the scanning imaging spectrometers being designed by JPL and NASA/Goddard could be most useful. One other alternative is the laser fluorosensor system, including tunable dye lasers, being developed by NASA (Hoge *et al.*, 1980). Unfortunately, laser fluorosensors are currently confined by the atmosphere and beamwidth to low aircraft altitudes. As CZCS degrades in its orbit, there is hope that a new sensor, the Ocean Color Imager, will be launched in the future. This system will have more spectral bands as shown in Table 5.

At the present time, fixed wavelength lasers (e.g., pulsed neon gas laser at 540 nm) are employed for bathymetry. Since the wavelength for maximum penetration varies with the concentration and type of suspended/dissolved matter, a laser system capable of switching bands for better penetration in turbid coastal waters should be investigated.

Although SEASAT was operational for only three months, its sensors collected a wealth of oceanographic information (Am. Geophys. Union, 1983). Two new microwave sensing satellites are being planned: the Navy Remote Ocean Sensing System (NROSS) by the United States, and the ESA Remote Sensing Satellite by the European Space Agency. Similarly to SEASAT, both satellites will be able to measure wind fields, wave spectra, etc. (Table 7).

For airborne salinity measurements in the microwave region, the L-band has so far yielded best results. Since salinity is an important oceanographic parameter, more work needs to be done to increase the accuracy of the technique.

(c) *Radiometric Sensitivity*

The dynamic range of water radiance is about an order of magnitude smaller than that of land targets. Furthermore, in coastal studies one frequently needs to distinguish water masses having only small differences in particulate or dissolved content, and therefore small differences in the amount of backscattered light. As a result, more radiometric sensitivity is required for coastal water studies than those of land. One solution is to increase the number of quantization levels, such as going from 64 on MSS to 256 on TM. Another approach is to decrease the dynamic range of the sensors and to match them more closely to the reflectance extremes of the known water types around the globe. The dynamic ranges of MSS, AVHRR and CZCS are compared in Table 8. Obviously, AVHRR and CZCS are designed to be more sensitive to small radiance variations from different water types than Landsat MSS.

(d) *Image Analysis Systems*

Computer systems for image analysis have decreased in cost and have become more user-friendly. A high-quality interactive image analysis

TABLE 7 - *ERS-1 Parameters and Performance Specifications.*

Main Geophysical Parameter	Range	Accuracy	Main Instrument
Wind Field			
— Velocity	4-24 m/s	± 2 m/s or 10% whichever is greater	Wind Scatterometer and Altitude
— Direction	0-360 deg	± 20 deg	Wind Scatterometer
Wave Field			
— Significant Wave Height	1-20 m	± 0.5 m or 10% whichever is greater	Altimeter
— Wave Direction	0-360 deg	± 15 deg	Wave Mode
— Wavelength	50-1000 m	20%	Wave Mode
Earth Surface Imaging			
— Land/Ice/ Coastal Zones etc.	80 km (minimum swath width)	Geometric/Radiometric Resolutions: a) 30 m/2.5 dB b) 100 m/1 dB	SAR Imaging Mode
Altitude			
— Over Ocean	745-825 km	2 m Absolute ± 10 cm Relative	Altimeter
Satellite Range		± 10 cm	PRARE
Sea Surface Temperature	500 km Swath	± 0.5 K	ATSR (IR)
Water Vapor	At Nadir	10%	Microwave Sounder

system can now be purchased for about $50,000, and the cost is continuing to drop. For instance, in our laboratory, an ERDAS system, developed by Earth Resources Data Analysis Systems of Atlanta, Georgia, is used to analyze satellite data interactively. Based on an IBM/PC/AT and a Tele-Video CRT console, the system features a high resolution 19-inch color display, a joystick-controlled crosshair cursor for screen coordinate sensing and location, Anadex graphics and Polaroid color printers for hardcopy products and utility printing. The system is interfaced with the main-frames of the University's Computing Center through a dedicated data line.

The ERDAS' menu-driven "Landsat" software package enables the user to interactively display, enhance and analyze multi-band digital imagery. The ERDAS has been used effectively with Landsat MSS, TM, SPOT and AVHRR imagery. Complete control over the display screen and color look-up tables enable the user to interactively explore and enhance the imagery. Band ratioing, filtering, edge enhancement and geometric corrections are also some of the options available. The ERDAS supports two major means of classification. Supervised classification entails defining signatures with the joystick on the displayed image. Unsupervised classification employs a powerful spectral clustering algorithm. Images displayed on the 512×512 pixel display can be annotated and stored independently. The output of the classification routines is classified image files. These can be displayed on the color monitor in the 512×512 mode in 32 colors selected interactively from over 16 million. The GIS (Geographic Information System) package on the ERDAS facilitates proximity analysis, overlaying for multi-temporal change detection, reclassifying, and the creation of multi-layer geographic data bases to which logical and arithmetical functions can be assigned. The ERDAS is completely programmable in several high- or low-level programming languages and has a large applications software library, making it a very powerful and adaptable research tool.

TABLE 8 - *Radiometric Sensitivity* (mw/cm^2-sr-µm per count) *for the Different Systems.*

Band	MSS (Landsat 1)	AVHRR (NOAA-7)	CZCS (Gain 3)
1		0.052 (0.58 -0.68µm)	0.021 (0.433-0.453µm)
2		0.034 (0.725-1.1 µm)	0.014 (0.501-0.530µm)
3			0.011 (0.540-0.560µm)
4	0.185 (0.5-0.6µm)		0.005 (0.660-0.680µm)
5	0.166 (0.6-0.7µm)		0.093 (0.700-0.800µm)
6	0.126 (0.7-0.8µm)		
7	0.40 (0.8-1.1µm)		

Technology Transfer and Training Requirements

In developing countries, the term "remote sensing" has become almost synonymous with "Landsat". This is understandable in view of the long-term success Landsat has enjoyed in agricultural and geological applications in the United States and overseas. The governments of developing countries, in particular, with strong support of such agencies as the U.S. Agency for International Development, the World Bank and the Inter-American Development Bank, have successfully fostered Landsat-related investigations of land use, food resources and mineral deposits, including desertification, irrigation, crop management, deforestation, and exploration for minerals and metals. As a result, about seventy countries and more than five international organizations are involved in Landsat investigations. Landsat data receiving stations or data analysis centers have been set up in a number of developing countries, including Argentina, Chile, Brazil, Egypt, Kenya, India, Thailand, the Philippines and Zaire.

The backbone of U.S. A.I.D.'s technical assistance program has been the development of regional centers that become focal points for remote sensing activities (Conitz, 1978). The first of these centers was established in Kenya in cooperation with the new Regional Centre for Services in Surveying and Mapping, sponsored by the Economic Commission for Africa. The Nairobi Center began operation in 1977. Other centers were developed in West Africa, Asia and Latin America. A.I.D., in cooperation with the National Science Foundation, supported a center in Egypt that expanded to supply assistance to countries in North Africa and the Middle East. Each center was staffed by specialists representing different disciplines and by local technicians. Each center contained analytical equipment, imagery files, a technical library and groundtruth equipment. In addition to being able to provide workshops and other training, each center will have a strong outreach or extension capability. The staff was encouraged to acquire familiarity with the needs of the countries of the region to provide the kind of assistance that will satisfy those needs directly.

The regional centers became focal points for the development of networks and linkages. They were important contact points between local resource managers and experts in the United States and elsewhere. The personnel of the centers are working closely with national universities in the introduction of remote sensing into their curricula. Remote sensing is seen as a tool in resource management, just as mathematics is a tool in science or engineering, and the objective is to have remote sensing taught as an integral part of any resource-oriented curriculum.

When we turn to coastal and marine applications of remote sensing in developing countries, the results appear far less encouraging. Landsat's optical sensors have limited application to coastal and marine studies which require thermal infrared and microwave sensors as well. Whereas most developing countries are covered by the various satellites, most of these countries neither receive nor analyze thermal infrared or microwave satellite imagery. Thus, the impressive system set up by U.S. A.I.D. and other international agencies for transfer of remote sensing technology pertains primarily to Landsat technology for agricultural and geological studies, and usually neglects transfer of thermal infrared and microwave technology for oceanographic applications. For instance, several countries, including Chile, Peru and India, have long-standing involvements in satellite tracking networks or meteorological data analysis, receiving and analyzing low-resolution (8 km) thermal infrared imagery from satellites such as the Geostationary Operational Environmental Satellite (GOES). However, these stations and new remote sensing centers set up in Argentina, Brazil, Chile, Ecuador, Egypt, Syria, Kenya, Thailand and the Philippines have only limited capability to receive or analyze high-resolution thermal infrared data from NOAA-type satellites or microwave data from SEASAT-type satellites. Yet this is the type of data required for coastal and oceanographic studies.

In view of the present slow transfer of available technology in spacecraft oceanography, the outlook for adapting more advanced techniques appears even more difficult, unless national and international organizations seek more effective means for transferring this technology. Such organizations include the U.S. National Science Foundation, the U.S. National Oceanic and Atmospheric Administration, the Intergovernmental Oceanographic Commission Working Committee for Training, Education and Mutual Assistance, the International Council of Scientific Unions Committee on Science and Technology in Developing Countries, and the Committee on Space Research. These organizations already sponsor conferences, training workshops and joint research projects which allow foreign scientists to glimpse the advanced techniques used in the United States and Europe. Conferences and training workshops are relatively inexpensive and can be arranged on short notice. However, they lack continuity and continuing support, and sometimes train the wrong specialists. Joint research projects developing and demonstrating major applications of the technology are usually conducted under expert control and produce tangible results for a commitment that is limited in time. However, the success is not always transferable and the research in the developing country is frequently used by the expert to test his approach in a new environment, author a paper and move on to other investigations without having truly interacted with the local scientific establishment.

To transfer this technology effectively may require that, just as in the case of Landsat, regional centers be established for applying remote sensing to coastal and oceanographic problems on a permanent basis. The advantage of regional centers is that they establish continuing local access to the technology, involve local support and insure long-term program continuity. The disadvantage of centers is that they require expensive long-term commitments and are affected by regional politics.

Finally, I believe that remote sensing technology should be transferred at the level at which a developing country is truly able to absorb it. To differentiate South American countries according to their technological development in remote sensing, Adrien and Bartolucci (1978) have divided them into three groups, the most advanced of which receive and analyze digital satellite data. They found that five out of twenty-four Latin American countries are participating in technology transfer at the highest level, including multispectral digital analysis. Seven more countries can absorb techniques of moderate complexity, such as visual analysis with optical enhancement of aircraft or satellite imagery. The ratio of technologically advanced centers to total numbers of centers is somewhat lower in Asia and Africa, even though there are some fairly advanced laboratories in the developing countries of those continents, such as in Egypt, India, Kenya, the Philippines, Thailand and Zaire. In the many workshops and joint research experiments I have conducted in South America and Asia, I have always emphasized inexpensive techniques. For instance, a small single-engine aircraft in radio contact with a small boat can help guide the boat to optimum stations for sampling water properties and can synoptically expand the data obtained by the boat to cover a large coastal area. Inexpensive drogues tracked by small aircraft and boats are frequently more practical to use for current measurements in developing countries than sophisticated current meter arrays.

Conclusions

As shown in Table 1, remote sensing techniques are being applied with considerable success to provide the following data for coastal studies:

— mapping coastal vegetation and its biomass;

— monitoring man-made and natural changes in the coastal zone, including land use change;

— hydrographic charting;

— mapping geomorphic features, including submarine bars and coastline erosion;

— charting current circulation, waves and other dynamic properties influencing coastal erosion, navigation and harbor design;

— detecting coastal freshwater springs;

— mapping chlorophyll and nutrient-rich upwelling regions important to fisheries resources management.

Recently, the use of remotely sensed data has expanded due to the availability of low-cost, user-friendly microcomputer systems for satellite image analysis.

Developing countries are showing an increasing interest in remote sensing technology for the development of their renewable and non-renewable resources. Although most of the early applications have been in agricultural and geological areas, the synoptic and repetitive coverage of satellites seems particularly well-suited for monitoring the properties and managing the resources of large coastal and marine regions. The transfer of remote sensing techniques to developing countries is aided considerably by regional and national centers staffed and equipped to handle Landsat technology.

Landsat sensors, however, are limited to the visible and near infrared reflective region, and were designed primarily for land-related studies. Marine and coastal applications require sensors in the thermal infrared and microwave regions as well. New developments in marine-related remote sensing, such as synthetic aperture radar for wave studies, microwave radiometers for salinity measurements, thermal infrared radiometers for mapping sea surface temperatures and currents, and special multispectral scanners for measuring ocean chlorophyll and wetland biomass mapping, will require a concerted effort by national and international agencies to set up regional centers, sponsor joint research programs and conduct workshops for transferring this technology to developing countries at a level at which each country is able to absorb it. Otherwise, the transfer of marine-related remote sensing technology will continue to lag well behind the transfer of Landsat technology for agricultural and geological applications.

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REMOTE SENSING AS APPLIED TO SOIL STUDIES IN NEPAL

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Introduction

Soils are an irreplaceable resource, and mounting pressure upon land is making resources more and more valuable in Nepal. There is a need in all planning to examine not only how land resources and soils are presently used but how they can best be used and managed in the fragile ecosystem of Nepal. This calls for an area-wide soil survey which would show the geographic location of the various kinds of soils, identify their properties and interpret these properties for land use planning and management.

Soil is a collective term for all soils, just as vegetation is used to designate plants. "A soil", as the term is used in soil science and classification, is an individual body on the surface of the earth. It has depth and shape. A soil is the meeting place of the soil beneath and the influence of the changing atmosphere and biosphere above. Plants grow in soil, their roots push the soil particles around. They extract nutrients and water. Micro-organisms and animals live and burrow in it. The soil takes in and holds moisture from the atmosphere. Most of the organic wastes of nature are decomposed on it or within it. All its many properties and functions interact with one another. Soil changes during the season even from day to night. The living matter, the plants, microorganisms, and animals change; so does the soil, with geological changes that effect the erosion cycle.

The properties of soils vary widely from place to place. For example, on steep slopes the soil is generally not deep and productive as when it is formed on gentle slopes. Where it has developed from sandstones, it is more sandy and less fertile than where it has formed from rock such as shale. Its properties are quite different when it has developed under tropical climates as compared to temperate or Arctic conditions. Therefore soils are an integral part of an environment, are discrete bodies produced by interaction of climate and vegetation changing surface geologic material into geomorphic landscape.

Man is dependent on soils, and to a certain extent good soils are dependent upon man and the uses he makes of them. Soils are the natural boundaries on which plants grow. Man enjoys and uses these plants because of their ability to supply fiber, food and timber for human beings and the animals he keeps.

While wise management of good soil may have helped civilizations to flourish, poor management may have been a primary cause of their demise. Present population pressures have influenced a great deal land masses and it dictates the need to look for modern and new techniques that may lead to a better and more rapid approach, not only for delineating the soil boundaries but also to find what changes have occurred or are occurring in order to apply appropriate techniques to keep and maintain the soil condition.

Methodology

In the mountain region of Nepal, factors such as elevation, slope, and aspect contribute to soil and vegetative varieties. In these areas the plant communities play a dominant role in affecting spectral response. Elevation, slope, and aspect interrelate with the distribution of vegetative communities. The northerly aspect exhibits denser moisture and different vegetation and different vegetation species from the southern aspect; vegetation also changes with changing elevation. Steep slopes are more susceptible to erosion and wind-swept slopes exhibit less dense vegetation and more rock at the surface.

Most of the attributes of the physical parameters that contribute to soil formation can be derived from the Landsat imagery. Land form is recognised as a basis of ecological unit and it is closely associated with the drainage system. In the formation of different types of land form, geology plays the vital role and this information can be derived through the geology maps and satellite imagery. By using geological and land form maps, information on the type of soil and source can be obtained. Regarding the soil texture, inference can be made through the use of geological and drainage systems. Vegetation maps and land form maps derived from the Landsat imagery provide the information on the water régime in the context of Nepal's mountains. Mostly, southern aspects are drier than the northern aspects. Thus it it well to grow different types of vegetation in these areas. Slope maps can be prepared through the use of topographic maps. Thus information regarding the type of land and the soil's boundaries are delineated by overlaying and comparing them.

There are features visible on remotely sensed images that are related to soil. These include, as mentioned above, topographic form, stream drainage pattern, land form boundaries, land use and vegetation characteristics. Thus Landsat scenes can be studied using standard photo interpretation technique in a systematic analysis of these visible pattern elements. Landsat data can be studied for soil and land resource inventories.

Landsat color composite imagery provides a synoptic view, multispectral and multi-temporal capabilities and is near-orthographic. The synoptic view is possible because about 3.5 million hectares of earth surface can be examined on each scene, and all objects have the same sun angle and energy reflected by objects in the scene. Thus objects can be compared across the entire scene. The multispectral capability permits establishment of a unique system for vegetation- and soil-related objects. The temporal capabilities extend throughout the year. The near orthographic features mean that the map scale is nearly true, so that ancillary map data can be overlain with very little distortion.

Thus Remote Sensing technology offers numerous advantages over the traditional method for conducting soil surveys or agricultural surveys. Advantages include potential capabilities for accelerated surveys, capability of repetitive coverage which can define seasonal and long-term changes and the inexpensive cost as compared to other forms of survey for monitoring purposes from space.

Need

Nepal, practically a mountainous country, is situated between China and India, and comprises an area of 147,181 sq.km. with three distinct physiographic regions:

— The high mountain region covers mostly the snow-capped Himalayas and represents 35 percent of the total area of the country.

This region contains 5 percent in agricultural land, 25 percent in forest, 14 percent under grazing, 40 percent with snow, rock and water, where settlement is only 0.2 percent.

— The hill region extends from Siwaliks and Mahabharat to the lower foot of the Himalayas and covers 42% of the total country. This region contains 21% in agriculture, forest with 43%, grazing land 14%, snow and rocks 2% and 0.8% under settlement, while water bodies cover 15 percent.

— The Tarai region is the southern part of the country and it comprises 23% of the country. This region has 42% devoted to agriculture, 42% to forest, 4% with grazing land, 1% in settlement, with 11% under bodies of water.

90 percent of the total population of 1.6 millions of Nepal are engaged in agriculture. Agriculture contributes 66 percent of G.N.P. and thus constitutes the bulk of the economy of the country. Land is a vital resource to Nepal and it supplies the growing population with food, fiber, fuel wood and construction materials. Thus a knowledge of the basic resource situation is required for sound management and planning at all levels. Resource inventories and base line studies provide these important data for planning and management.

Reconnaissance surveys do not provide the information on soil series concerned with the range of characteristics upon which the soil is classified. These surveys, usually for general purposes, help to determine resource potentials and also to identify problems. This type of surveys leads to more detailed surveys for large area planning.

Taxonomic units (soil series) cannot be identified on Landsat images and these terms are familiar to soil scientists only. Therefore, in order to make non-soil-scientists understand soil characteristics, it is required to make descriptive terms (generic) rather than taxonomic units so that land managers can make suitable choices to put their land into proper use.

Nepal, a very rugged country with limited resources and communication system, offers a great problem to carry out soil and agriculture or other surveys through the conventional and traditional survey technique. The conventional survey method is not only expensive and time-consuming but requires lots of trained manpower, which developing countries like Nepal cannot afford. Realising the importance and the role played by Remote Sensing Technology, HMG/Nepal established a Nepal National

Remote Sensing Center with the modest assistance of U.S.A.I.D. in 1981. The main objective of this Center is to:

1. Provide Remote Sensing data in the form of maps, photographic and statistical data to various HMG Agencies engaged in managing the natural resources of the country.

2. Provide training to various HMG staffs and agencies.

3. Create a data bank for natural resource information.

4. Establish relationships with various regional and international Remote Sensing Agencies.

In order to achieve these objectives the Center has different laboratories, such as:

a) *Photographic Laboratories* which can process both color and black and white.

b) *Cartography Laboratory* where both color and black/white line maps can be produced.

c) *Interpretation Laboratory* containing different types of Stereoscope, Zoom transferscope, color-addition viewer, diazo machine, planimeters, pentographs, reflecting projectors, etc.

d) *Computer Laboratory* equipped with one Micro computer, capable of image processing and G.I.S. Since the storing capacity of this system is small, it therefore cannot be worked on an operational level. The ERDAS software system is being used for analysing and G.I.S.

e) *Documentation* has around 400 books of various reports on Remote Sensing, natural resources as well as maps and imageries.

f) *Class room* can take 20 students at a time, and training is provided to 15 to 20 students every year for one month. Besides this, a seminar for two or three days is also conducted by the center every year.

In addition to these facilities, the center has professionals from different disciplines such as Hydrology, Meteorology, Soil, Agriculture, Forestry, Geology, Photo Technician, and Cartographer to carry out the survey, tracing and research works.

In its brief life, the center has conducted various pilot studies on natural resources through the use of remote sensing techniques. Different types of thematic maps, based on natural watershed boundaries such as land use/cover, geology, drainage, deforestation, climatology, soil, forest type, and soil, etc., were prepared through the use of Landsat imagery and with ancillary data. Most of them are prepared by manual interpretation. These maps are verified and modified through the field visit. It is found that Landsat imagery is a good basis for small survey work. Remote sensing technology offers numerous advantages over traditional survey work. Advantages can be cited such as potential abilities for accelerated survey, capabilities to achieve a synoptic view under uniform lighting conditions, capability of repetitive coverage which can define seasonal and long-term changes.

A Case Study

Bagmati watershed was the pilot project undertaken by the center, where integrated studies on drainage, geology, climatology, land use/ cover, forest type, sub-watershed basin with drainage water, ecological and soil maps were prepared, in order to initiate watershed management in this watershed. Analysis of these maps through overlaying and matrix through G.I.S. is on the way by using the microcomputer, newly acquired by the center, to investigate the hypothesis of land planning. A number of thematic maps that were produced for Bagmati watershed by the Center are included here as an example.

Conclusions

The importance of remote sensing data with other auxiliary information and the use of computers for natural resource management provide evidence of its usefulness. But there are use restraints now because data is unavailable at an economical price for a developing country like Nepal. Therefore considering its potential use and the benefit that can be derived, requires that for problems such as in-depth training in remote sensing, demonstration projects be conducted to convince decision makers to understand its importance, and availability of data at an economical price be provided through international assistance so that a developing country like Nepal can benefit by improving the decision-making process in managing the fragile ecosystem of Nepal's mountains.

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REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS FOR MONITORING THE ENVIRONMENT AND COMBATING DESERTIFICATION

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Abstract

The Global Environment Monitoring System (GEMS), a Programme Activity Centre of the United Nations Environment Programme (UNEP), promotes the use of remote sensing techniques for environmental monitoring. It encourages the use of data from earth resources technology satellites, complemented by data from systematic reconnaissance flights using light aircraft, and the appropriate field work. To accommodate this approach and yet be able to engage in effective monitoring, a computerized data base known as the Global Resource Information Data Base (GRID) has been established within the UN Environment Programme. GRID utilizes ARC-INFO software and NASA's ELAS software, and has two main operating centres, GRID-Control in Nairobi and GRID-Processor in Geneva. The global data base permits rapid assessment of large areas and so provides a diagnosis of trends unhealthy for the environment. More detailed monitoring can be done, in a cost-effective manner, using satellite and aircraft techniques. The necessary field work provides the final details and permits planning and remedial action. The techniques

of remote sensing also permit users to monitor the effectiveness of the actions taken. The geographic information system (GIS) technology in GRID provides for rapid analysis of the monitoring data. This in turn is a basis for an early warning system capable of revealing the onset of the adverse conditions of desertification, brought about by drought, deforestation, soil degradation or other causes.

On an individual project, or national basis, this technology can also be applied using the smaller systems based on micro-computers. Such systems are being introduced into developing countries in Africa by UNEP/GEMS and through proposed cooperation between World Bank, UNDP and the Regional Centre for Services in Surveying, Mapping and Remote Sensing. These systems are capable of analysing data from earth resources technology satellites and of operating a geographical information system suitable for regional development, planning, management, and monitoring. Present plans call for the diffusion of the technology throughout Africa in the next decade.

Introduction

The use of satellite technology is now commonplace and one whole generation has grown up with space-systems constantly available. Global communication by telephone, television, telex, radio and facsimile transmission using satellites is well established. The monitoring and forecasting of weather using satellite data is a routine matter and earth resources technology satellites have been producing information about the earth since 1972.

1972 was also the year of the United Nations Conference on the Human Environment held in Stockholm, which adopted twenty-six principles. One of these stated: "Science and Technology, as part of their contribution to economic and social development, must be applied to the identification, avoidance and control of environmental risks and the solution of environmental problems and for the common good of mankind." (GEMS, 1982) This brief was taken up in 1974 by the Global Environment Monitoring System (GEMS), which working through the other United Nations agencies, addresses five key areas identified by the Stockholm conference. These five areas are climate, long-range transport of air pollutants, renewable resources, the oceans and human health.

Climate, renewable resources and the oceans may be conveniently grouped together as natural resources and as such are all suitable for monitoring by earth resources satellites. In the GEMS programme the need to understand the functional inter-relationships between the elements of a given environment has emphasized the requirement for gathering and processing large quantities of information over large areas. The combination of satellite and computer technology has made this possible.

Satellite Remote Sensing Systems and GEMS philosophy

Present earth resources satellite systems can produce data over large areas and are capable of doing so on a regular repetitive basis. The flow of data from these systems is immense and the task of analysing it is daunting. To date only a relatively small proportion of the data gathered by the U.S. satellite Landsat has been utilized, and there is no agency yet responsible for routine inspection of the data for signs of environmental change, damage or human impact on environment. On an individual basis, country by country and project by project, such examination is done to a limited extent, and significant work has been sponsored by UNEP, which reports that about 20% of the world's desert and semi-arid zones has now been assessed using satellite remote sensing technology. The task of gathering data about the environment and especially about desertification is overwhelming.

Conventional data sources such as maps, reports and national statistics do not provide the necessary information in an appropriate form. Data from these sources are valuable and should not be discarded, but, in order to be useful they must relate to each other. The ability to compare and contrast data sets to detect change is an essential part of the task of environment monitoring. Whilst this is possible using large numbers of field workers and ground survey crews and a vast amount of computer power, GEMS considers the task is more reasonable if monitoring is based on aerial survey data and suitably selected ground surveys. Even the efficiency of remote sensing at this level produces an unmanageable amount of data.

The use of data from the earth resources satellite Landsat makes the system more efficient, and, with suitable aircraft data, sub-samples and appropriate ground surveys, this approach produces a data volume which can be managed within large data systems. However, at this level the volume immediately becomes unmanageable if data are entered in a time sequence to permit monitoring. If data from meteorological satellites are used, the time series data are manageable, and nested sub-samples based on earth resources satellites, aircraft data and ground survey are able to provide the necessary detail.

This approach can be adapted to various situations and by appropriate activity at each level it is possible to monitor phenomena at any scale. As with all studies based on sample data, the balance between sample size and the standard error of the estimate must be weighed against the cost and time required to gather data and process it. Satellite systems presently available produce data with ground resolutions in the range 20 km. (Meteosat) to 10 m. (SPOT-1, panchromatic). The difference is three orders of magnitude on a linear scale and for area studies is six orders of magnitude. Thus, a single Meteosat picture element (pixel) of 20 km. × 20 km. requires 1,000 × 1,000 or 1 million pixels of SPOT-1 multispectral data to cover the same area with 20 m. resolution data and 4 million pixels for SPOT-1 panchromatic data with 10 m. resolution.

GEMS

The Global Environment Monitoring System (GEMS) is a collective effort of the world community to acquire, through monitoring, the data that are needed for the rational management of the environment. This responsibility was given to the United Nations Environment Programme following the recommendations of the UN conference on the Human Environment held in Stockholm in 1972. Consequently, in late 1974 UNEP moved into the field of monitoring in a deliberate and systematic manner by establishing at its Nairobi Headquarters a Programme Activity Centre (PAC) for GEMS. The role given to this centre by governments is to coordinate the disparate international monitoring activities that are conducted throughout the world, particularly within the United Nations system, and to advise the Environment Fund of UNEP on how best to support and stimulate the initiation of new activities or the expansion of ongoing ones through the allocation of financial resources.

In developing GEMS networks, great care is taken to ensure that the data produced are of the highest quality that it is possible to maintain. Throughout the work of GEMS the emphasis is and always has been on data quality rather than quantity. Without excluding the utilization of existing monitoring stations, and in many cases starting from them, monitoring networks have been established, the main output of which is comparable data — an output that can only be obtained from the repeated rounds of inter-calibration that are built into all the activities coordinated by the GEMS Programme Activity Centre.

GEMS' concern with the renewable resources of arid and semi-arid ecosystems involves two very closely related monitoring fields: rangelands and desertification. Here, the operational basis advocated by GEMS is in each case the Ecological Monitoring Unit approach developed during the last 15 years for use in the arid lands of tropical Africa. In its broadest sense this means monitoring the life support capacities and the productivity of land — including climate, soils, plants and animals, as well as man and his activities — with the ultimate aim of ensuring optimum utilization of the natural resource base. Basically, this involves repeated multi-stage sampling from three data acquisition levels: space, air and ground.

As with all systems, the benefits and the problems of satellite data are very closely related. The GEMS approach permits great flexibility in the design of a monitoring system and notes that data rates from meteorological satellites are low enough to permit monitoring with a relatively short time interval, however the data do not provide detail. More succinctly stated: the meteorological satellites provide data with a good temporal but poor spatial resolution. Conversely, earth resources satellites such as Landsat and SPOT provide data with good spatial but low temporal resolution. The problem is simply the handling of huge volumes of data, and the balance between spatial, temporal and spectral resolution must result in data volumes within the handling capacity of the system.

For desertification studies this means that weather satellites such as Meteosat yield data with a coarse resolution (c. 20 km.) which have a half-hour time interval; thus studies of cloud patterns, and movement, provide a basis for estimating rainfall on an hourly basis. Where there are no clouds the systems view the earth's surface. The spectral resolution is such that an index of vegetation can be calculated. This reveals the location of vegetation with active chlorophyll, and the absence of it. Thus desert boundaries can be located within 20 km. Seasonal and annual fluctuations in the desert boundary can therefore be mapped, and if this is done using the data from the NOAA-7 satellite with resolution at the one-kilometer level or the 5-kilometer level, more precise boundaries can be drawn using this improved resolution. These data, however, are only available twice each day and the angle of view is not always optimal, so data are good about seven days in ten. The analysis of such data has been refined and developed by Tucker (1979; Tucker *et al.*, 1985; Justice *et al.*, 1985), who has published continental and global summaries of vegetation with monthly and more frequent time intervals. Tucker's analyses provide a valuable continental overview of vegetation status and show seasonal shifts in vegetation conditions. This is exemplified by a series of monthly data summaries for Africa, which clearly show the major deserts of the continent and the associated arid lands.

From such a data set, norms for seasonal boundaries may be deduced and comparison to seasonal norms will rapidly reveal anomalous conditions. Once such anomalies are detected a more detailed inspection of the area may be made using earth resources technology satellites, such as Landsat or SPOT. At this level the effective ground resolution is in the range 80 m.-10 m. At these resolution levels desertification studies can include data which relate to sand movement corridors, rock outcrops, major physical features and the vegetation/soils/man interaction over the area.

If these studies indicate that greater detail is required, aircraft data can be gathered over specific target areas. This may be conventional survey photography or it may be the informal 35 mm. photography used in the systematic reconnaissance flight (SRF). Such a flight, gathering a one-percent sample of the area flown in the form of vertical, colour 35 mm. aerial photographs at scales in the range 1:7,500 to 1:20,000, yields data amenable to detailed analysis. The photo-sample can be analysed in the laboratory for percentage of various categories of ground cover, the characteristics of settlement and the presence and numbers, or absence, of livestock. Individual crop types can be identified and the data necessary for a detailed development plan can be gathered.

Satellites gather data on a pixel basis and the images generated are therefore in a grid format. Comparison of satellite images requires that images be accurately overlain so that changes seen are not spurious and generated only by the system. Once this is done, an area shown to be anomalous immediately generates questions about other factors. Soil type, rock type, terrain type, vegetation type, land cover, land use and agro-ecological zones are all useful information in understanding the changes shown, and if stored in a geographical information system (GIS) they can be readily and rapidly retrieved.

This logical sequence of events requires a data flow from satellite remote sensing systems, a commitment to deploy aircraft and field teams as necessary and a GIS with all pertinent background data, and the capacity to analyse relationships between the measured properties stored as background data. Interrogations of the system, prompted by anomalies detected by satellite data analysis should lead to an improved understanding of the relationships between variables in areas of desert or in areas susceptible to desertification. From this improved understanding should come the ability to combat the problem, alleviate it or at least draw attention to the nature of the problem encountered, such a result being entirely compatible with the GEMS brief.

GRID

The Global Resource Information Data base (GRID) is a new initiative of the United Nations Environment Programme (UNEP), and an element of the Global Environment Monitoring System (GEMS). The pilot phase of the project was approved by the Executive Director of UNEP in September 1984, formalised as a UNEP Internal Project in March 1985, and presented to the UNEP Governing Council in May 1985.

GRID grew out of the need to coordinate within a common geographic reference system the numerous environmental data sets that have been collected and continue to be collected by GEMS, other UNEP programmes and UN Specialized Agencies, and to provide a capability to access and analyse the data for environmental and resource assessments. Additionally, the data are made available in georeferenced form to the global, regional and national environmental research communities and to responsible resource management officials.

The pilot phase of GRID is currently due to end on 31 December 1987. This phase of GRID originated as a cooperative project between the GEMS Programme Activity Centre of UNEP and the National Aeronautics and Space Administration (NASA) of the USA. It grew out of common interest of the two organisations. UNEP is mandated to monitor and assess the state of the global environment on a continuing basis; NASA is one of the principle organisations involved in studying the long-term changes in processes that affect life on the Earth. From this beginning other nations and organisations have been brought into the venture so that GRID has become a truly international cooperative effort.

The aims of this pilot phase are:

— to develop geographic information system (GIS) methodologies and procedures for constructing and manipulating global environmental data sets for the purpose of conducting environmental assessments. (The continent of Africa has been selected as the case study for this objective);

— to demonstrate that GIS technology as applied within GRID is an effective tool which combines global and national data sets for resource management and planning applications at the national level. (The countries for these demonstrations are China, Ethiopia, Indonesia, Kenya, Panama, Peru, Senegal, Sudan, Thailand and Uganda);

— to establish the framework for cooperation and data exchange within international and intergovernmental organisations which deal with environment-related matters, such as FAO, WHO, WMO, ICSU, ILCA, IUCN, etc.;

— to provide training opportunities in GIS and resource data management technologies employed by GRID to the scientists and resource managers from participating developing countries.

In order to conduct the pilot phase, two computer processing centers have been established within UNEP: GRID-Control at UNEP headquarters in Nairobi, Kenya; and GRID-Processor in Geneva, Switzerland. The NASA Earth Resources Laboratory in Mississippi, USA, is the principal supporting NASA centre providing both tecnical support and engineering expertise to the project.

GRID will initially give priority to data processing required for the construction of the data base for Africa. At present this includes land and water boundaries, political boundaries and elevation data. The FAO/UNESCO 1:5M scale soils map of Africa, the 1:2M scale vegetation map and White's UNESCO/AETFAT map, a series of meteorological values (e.g., rain-days, anomalies, etc.), locations of endangered species and protected areas have all been entered into GRID. The vegetation index images derived from NOAA AVHRR data for four seasons for Africa, with 4 km. resolution for calendar year 1984 have also been entered.

As the number of inputs to GRID increases, so will the power of the analyses, and the information which the system can return to the user will increase also. The value of this is that it increases the data available to the researcher, manager and planner. When sufficient data are available, it becomes possible to test hypotheses and reduce the speculation to ordered scientific understanding. This does not eliminate the interaction between man and his environment but rather permits a more carefully controlled view of it.

Desertification

A recent study (Olsson, 1985) entitled *An Integrated Study of Desertification: Applications of Remote Sensing, GIS and Spatial Models* *in Semi-Arid Sudan* concludes: "It has not been possible to find a consistent trend of a degrading landscape. The conditions vary with the climatic conditions. An area with appropriate land-use in a year with adequate rainfall may suffer from crop failure and show signs of over-exploitation another year." (Olsson, 1985, p. 147) This type of conclusion is of great importance. The massive desertification represented by the dust bowl developments in the southern USA in the 1930's resulted from this type of climatic control of vegetation. Land which was apparently good grassland was settled and cultivated. It yielded good cereal crops. However, when the drought cycle came, the land, without the vegetation cover, was vulnerable to wind erosion. As the drought deepened, the topsoil was blown away, and a potentially productive region was destroyed. Similar cycles of events have occurred in Australia (Graetz, 1983). In Africa the proportion of the continent available for arable agriculture will be increasingly exploited by the growth of populations. These lands should not be lost to production through oversight, or inadequate control. The errors have been made before, but the availability of satellite data, GIS and the cost efficient Systematic Reconnaissance Flight should together provide the necessary information for the control of desertification or its avoidance.

Developing Countries

The majority of the world's thirty poorest countries are located on the African continent. The Regional Centre for Services in Surveying, Mapping and Remote Sensing serves a twenty-country area designated as East and Southern Africa, and within this group eleven countries appear on the UN list of the world's thirty poorest countries. For these countries development of natural resources is the only way to improve the level of human existence. This improvement requires investment in development projects and that investment requires feasibility and pre-investment studies.

Such studies require data. Currently available data are often compiled on mismatched bases, outdated, not mapped or otherwise not available in optimum format. Realizing this, the World Bank, a major investor in development projects, and UNDP, a major funding agency for the implementation of development programmes, have jointly proposed that the management and analysis of natural resources data be given greater priority. The RCSSMRS has for some nine years been offering courses in remote sensing and has provided support to users in both project design and implementation. The result of most studies has been an analysis of natural resources, usually in map form. For development purposes, change in the natural resource base needs to be understood. So too does the functioning of ecological regions, especially those which operate as independent spatial systems, such as the territory occupied by a given group of nomadic pastoralists.

The RCSSMRS proposes to devote its next five-year development phase to the integration of GIS and satellite remote sensing data. On a project basis the results of the analysis of satellite remote sensing data will be entered into a GIS. Thus the map product can be amended, updated and revised as new data become available. The difference between the new map and the old, a map of change, can be readily prepared if both new and old data sets are entered into a GIS. Such a system offering interactive data management is ideally suited to project areas, development areas or even national data systems for small countries.

World Bank and UNDP regard GIS and satellite data analysis as useful management tools for natural resources development projects, and as data banks for monitoring change in the natural resource base, or environmental quality. Accordingly, GIS systems based on readily available micro-computers will be introduced to the region through a series of training programmes and seminars held at the RCSSMRS with the support and collaboration of the World Bank and UNDP. Those trained will be expected to return to their home country/agency/project and operate GIS systems there. This concept does not require the massive data base, GRID, but sub-sets from it would be valuable to the users of the micro-computer based systems. Equally the data bases built up by the individuals in projects and in national development planning will be of interest to UNEP/GEMS and if compatible with GRID may be entered into it.

The availability of robust, relatively low-cost computers capable of supporting this activity and the availability of satellite remote sensing data from which natural resources data can be extracted make this co-ordinated approach by UNEP, World Bank and RCSSMRS a viable proposition. Individual projects can be monitored with relative ease and data analysed to determine anomalies in environmental conditions. The supporting technology of Systematic Reconnaissance Flight and ground survey provides all that is required to investigate anomalies visible in the data and to determine if they are benign or malignant. This alone is of great value to most of the countries in the East and Southern African region served by RCSSMRS.

Discussion

The GEMS philosophy of using remote sensing techniques from various types of satellite and aircraft offers an efficient, cost-effective approach to natural resources monitoring, mapping and assessment. The philosophy provides for the most efficient use of available ground crews and their equipment. The results of all types of analysis including ground studies can be entered into a micro-computer based GIS for ease of management, storage and retrieval. With appropriate interfaces so that data from GRID can be written onto diskettes for use in the micro-computer based GIS and data sets from the micro-computer GIS's can be read back into GRID, all components of the system become mutually supportive, interactive and of maximum effectiveness.

Not only does the manager or planner have regional data available to him for monitoring and recording development and environment related data on a geographical base, he also has a powerful analytical tool. With this system it is possible to analyse patterns of interaction amongst variables and to define functional regions for ecological purposes, environmental purposes or monitoring purposes as well as planning purposes.

Good development planning attempts to suit projects to the available resources, and to fit them into appropriate locations or areas. Semi-arid areas in which there is a risk of desertification need to be managed on a holistic basis. Administrative fragmentation of such a zone would usually not be in the interests of good management of a fragile environment.

Suitable analyses of this type will provide for the identification of core areas which always provide water and forage for livestock. Such areas become refugia for wildlife and livestock in times of drought. Conversely, analyses should also pinpoint the areas of high risk, where fragile environments are known to be particularly sensitive to drought and become centres from which drought spreads. Monitoring these areas, and associated features such as the extent of lakes, swamps or rivers, the indices of biomass and other such items, should provide an early warning of the onset of unfavourable conditions. These unfavourable conditions may include drought, famine, soil erosion, destruction of vegetation canopy, irreversible conversion of land from forest to agriculture or from agriculture to residential use. All these conditions can be considered contributors to desertification. Remote sensing systems coupled with GIS seem to offer a means of monitoring this, and when warning signs can be detected and fully understood it will be possible to avoid the serious consequences of loss of potentially productive agricultural land.

Conclusions

— Appropriate use of data from satellite and aircraft remote sensing systems can make field work more efficient and provide effective monitoring of desertification.

— The data flow from satellites has to be considered carefully in terms of the analytical needs and the capacity of the system available. It is necessary to determine the appropriate balance between temporal, spatial and spectral resolution to meet the defined objective.

— GEMS methodology includes the use of satellite and aircraft remote sensing, together with appropriate field work, and recognizes the great advantage of managing such data in a GIS.

— GRID is the basis on which GEMS hopes to build a global monitoring capability, with links to national and project level natural resources and environmental data-gathering activity.

— With the support of the World Bank, UNDP and RCSSMRS, UNEP hopes to implement an interface between GRID and micro-computers so that information can be written from GRID to a diskette form suitable for micro-computer use and so that data from micro-computer systems can be read into GRID. Training for the east and southern Africa region, in order to implement this, may be undertaken by RCSSMRS with World Bank and UNDP support.

— The combination of earth resources technology satellite data and GIS systems provides a powerful system for monitoring environmental parameters. Judicious application of this technology should greatly assist in the detection of desertification, the monitoring of it and, hopefully, in combating it especially in developing countries where natural resources are scarce.

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REMOTE SENSING AND THE LAND USE SECTOR

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The Global Perspective

Land use studies are directed towards the major objective of the optimum utilisation of the land resources for sustainable use by man. The management of the earth's natural resources — land, water, forests, soils, etc. — for man's benefit is of primary concern.

The production of enough food to feed the world's population and to provide the other basic amenities to enable the peoples of the developing world to achieve a reasonable living standard is a worthy goal.

The reasons attributed to the problems of the world's hungry and starving people are (a) poor management of the natural resources, (b) soil degradation, (c) large increase in population, (d) shifting cultivation and the reduction of the fallow-period cycle due to population pressure, (e) deforestation, (f) silting of lakes, reservoirs and lowlands, (g) erosion, salination, (h) natural and man-made disasters, etc.

The solutions offered to overcome these problems are: control of population; increasing the crop yields by utilising scientific farming methods and newly developed high-yielding varieties of grains; bringing new land under cultivation; increasing the cropping intensity of lands presently under cultivation; better management of the natural resources, etc. It has even been stated that in some parts of the world the land area presently under crop cultivation should actually be reduced to allow re-forestation of areas suffering erosion and soil degradation.

On the other hand, it is stated that the global production of food is far in excess of the needs of the world's present population. It is even stated that the capability to produce food on the lands presently farmed is sufficient to meet the food requirements of the world's population. That is, if we look at the world as a whole, there is no scarcity of food, excess food produced in vast quantities is destroyed to maintain world price stability and in some countries farmers are encouraged to reduce food production. While these measures continue, one sees great attempts to provide funds to help those in famine-stricken areas. It is stated that really the inability of the poorest peoples to purchase food is what causes this imbalance, that they do not have the means to purchase food for survival, that what is required is to provide them with the means to enable them to do so. In real-worldly terms, this amounts to providing employment to these people. Unfortunately, the governments in the developing world do not have the capacity (mainly capital) to create mass industrialisation, which is highly capital-intensive and competitive. At the same time the poorest peoples are exerting pressure on lands that are not ideal for cropping. Therefore, new agricultural development programmes of low capital investment and high employment generation potential are resorted to by the developing countries. This is the dilemma, of which Land Use Planning and implementation of sound land use policies attempt to seek solutions.

Land Use Planning aims to optimise the use of presently cultivated lands by diversification of crops, increasing yields per hectare, or by increasing the cropping intensity by adopting multiple cropping techniques which produce two or three crops annually where perhaps only one crop was cultivated before, or by bringing new lands under cultivation. Both these strategies are resorted to in most countries. Other needs for land, such as for housing, recreation, conservation, industry, etc., have also to be considered and planned for carefully.

Optimising Land Use

Optimising of Land Use involves the use of the natural resources in a sustained manner with a reasonably equitable distribution of the benefits. In doing so we must simultaneously control degradation of the natural resources and even go to the extent of conserving and, if possible, improving these resources and the quality of the eco-system. These objectives provide areas of conflict and competitive use of land. Hence the need for careful planning and implementation of sound policies. In order to do these things we need data of sufficient quality, intensity and timeliness. We also need mechanisms — legal, administrative, political and organisational — to implement such planned policies.

Data Requirement for Land Use Planning — Remote Sensing

For planning the optimum utilisation of any resource, data is the basic requirement. Questions such as what? where? how much? etc. have to be answered. It is not easy to provide answers to these and similar questions, and to provide timely answers. When the phenomena one has to report on are of a highly dynamic nature, the task becomes even more difficult.

The data requirements need specifying in detail, depending on the nature and scope of the planning exercise. The specifications will include data themes or types to be inventoried, the area of territory to be covered, the intensity of data, etc. For example, reconnaissance/regional/broad overview type of information is required first to enable the resource scientists to pick out the more feasible areas for development. Small-scale mapping would be sufficient at this stage. There would be subsequent intensification of data on larger and larger scales covering specific (perhaps smaller) areas. At this stage a more detailed resource inventory with new and larger numbers of planning parameters would be required. The raw data has to be processed and presented in a mode which is meaningful to the planner.

Taking a common mapping example, we would first map the broad area in which we expect to go into development projects. This mapping would be on a small or medium scale showing the physical characteristics (e.g., topography) of the land and what is appearing on the surface. All cultural features also would be shown. After this preliminary stage of reconnaissance, one merely leaves out the areas that are definitely not to be brought under development — e.g., natural forests to suit a forestry policy or non-arable areas, etc. Then one can overlay climate, rainfall, ground water, soils information, etc., if already available or gathered on a generalised/broad basis.

The next stage is to go in for a more detailed inventory mapping of the areas selected for possible development. Here the mapping is more detailed in intensity of data acquisition as well as in the number of data themes required. Better data on soils, infrastructure, population, present land use, hydrology, geology, close contours, etc., would be included.

The data now enables a reasonably detailed level of planning to be performed. The areas suitable for specific development techniques (irrigation versus highland cropping, forestry, infrastructure, settlements, hydro-power and even the selection of broad crop types, etc., are now earmarked as feasible. This systematic zooming-down process is performed as a logical procedure and eliminates unnecessary expenditure and time loss in the data acquisition procedure. The techniques to be utilised in this procedure of systematically intensifying the data requirements are selected after study of the resources available, time frames required for acquisition and based on technical analysis.

Land Use Development into New Areas

The data now provides information on the spread and types of existing land use and also the possibilities of optimising the existing land use, depending on the government policies and the needs of the people. An overlay of parameters such as present land use, soils, hydrology, climate and rainfall, topography, etc., enables the evolving of a land capability and land development plan. Further data requirements may be imposed at this stage for specific areas of interest. This procedure is continued from the macro to the micro stage where individual farm lots and the infrastructure and support facilities for such farms are planned for. At the same time, location of dams for irrigation/hydropower, roads, settlements, etc., are planned. Specialised surveys for construction sites, etc., are now undertaken.

Land Use Optimisation in Settled Areas

Studies in intensively settled areas undergo a process of data gathering and presentation in a somewhat different form. Here we are looking at occupied lands. The spatial characteristics of land use are now very complex, and the data acquisition would be on a detailed (large) scale, except that the parameters may be mostly common with the earlier example. Here again the information on land tenure problems is required. As is common in Sri Lanka's Southwestern belt in the Wet Zone, the land is fully occupied and the area of land held by each farmer is becoming smaller due to population pressure, and serious problems of land ownership prevail. This has caused serious obstacles to optimising land use and good productivity. It is most important in such instances to introduce proper land ownership procedures together with land consolidation measures. If such measures are not taken promptly, the productivity of land drops drastically even to the extent of causing severe degradation of the lands due to over-burden, erosion, hazardous uses or neglect.

The solutions to such problems require state intervention, in the form of legislation, title registration procedures, introduction of cadastre systems, introduction of land consolidation and soil conservation measures and the organisational and social systems to support such beneficial measures. The techniques required for data acquisition in such congested areas are different from those used in new unoccupied areas.

The evolving of such Land Use Planning and Implementation measures is undoubtedly a multi-disciplinary and multi-institutional process that requires excellent management and support of the people through education and communication. The coordination of such multidisciplinary activities appears to be a most difficult task, especially in the developing countries. A combination of political will, political stability, social awareness and acceptance, combined with multidisciplinary collaboration and good management is the only way in which beneficial results can be achieved.

Land Use and Remote Sensing

The data acquisition procedures for Land Use Management itself require a multi-disciplinary approach. All available information on themes covering historical, sociological, cultural aspects, etc., is brought together to evolve a preliminary political decision. Simultaneously, available information on physical, topographical, climate, hydrology, soils, etc., is brought together. The data gap for each stage of decision making or planning is now identified. At each stage the decisions have to be arrived at on the technologies to be utilised for data acquisition. Broadly speaking, the methodologies to be utilised for acquisition of physical data are multi-level in nature. They are:

— Ground Surveys.

— Airborne data acquisition.

— Satellite Remote Sensing.

The latter two techniques fall within the scope of Remote Sensing. Comparison between ground surveys and remote sensing technologies involve parameters such as cost, completion time, accuracy, intensity of detail required, type of data required, etc. Generally, ground surveys are more costly and time-consuming and are resorted to for sampling ground-truthing, field completion and for very detailed surveys. However, they are essentially utilised when demanded by the type of data required, accuracy specifications, and mainly when the intensity of detail required is high or in tree covered areas. Satellite Remote Sensing is resorted to when the area is unmapped and when broad, low-intensity data is required. This technology is also ideal for monitoring of changes or monitoring the progress or effects of a large development project. For example, denudation of forests, water distribution and progress of cropping in homogeneous areas, etc., can be monitored on a timely basis. Aerial photography, air photo interpretation and photogrammetry appear to be the best fully operational tools for data acquisition in most countries. This method, together with complementary ground surveys, appears to give answers to most of the data gap issues. Other airborne scanning systems, such as multispectral scanning, radar, infra-red and thermal scanning, have special applications. Use of air photography in colour, infrared (colour or B/W), etc., is also resorted to in special cases. The techniques utilised in ground surveying too have undergone vast improvements recently. Use of Electromagnetic Distance Measurement, Electronic Angle Measuring techniques and Satellite Doppler positioning systems, together with digital data recording devices used in the field, processed in computers linked with digital mapping systems, have revolutionised their applications on a cost-effective and timely basis. The latter remain as the best, and perhaps only tool, for engineering type of applications and for cadastre purposes.

Satellite Remote Sensing technology is advancing even more, providing better spatial, perhaps better spectral resolution as well as stereo capability for estimating topography variations.

However, problems of compatibility, continuity and commercialisation policies have yet to be resolved before satellite remote sensing becomes acceptable to the developing countries as a fully operational tool for data acquisition and as a complement to other data sources.

THE USE OF REMOTELY SENSED DATA IN GEOGRAPHIC INFORMATION SYSTEMS FOR HYDROLOGIC STUDIES IN DEVELOPING COUNTRIES

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ABSTRACT

A variety of Earth-observing sensors on board orbiting satellites that are presently operating or are planned will assure continued data availability to developing countries. Interpretations of these data have the potential to derive large amounts of hydrologic and other information on a worldwide basis. Incorporation of the interpretation information into geographic information systems (GIS) offers advantages in efficient handling of the map and tabular information. This approach will permit the remotely sensed interpretations to be merged with traditional resource information and formatted and output as thematic spatial and tabular summaries for use by resource managers and decisionmakers.

Potential uses of Landsat and Advanced Very High Resolution Radiometer (AVHRR) satellite sensor data are shown for the region adjacent to the Jonglei Canal in southern Sudan. The advantage of using low-resolution AVHRR data in a time-series analysis to monitor flooding is described. The derivation of hydrologic and other resource interpretations for combatting desertification by sand encroachment is illustrated for an area in central Sudan. Procedures for using a GIS for estimating soil erosion and the resultant soil degradation are described. The procedures

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use soil and land cover data within a hydrologic network. The use of remotely sensed data input to a GIS for estimating irrigation water and energy demands is described.

Introduction

Image data from remote-sensing satellites have been available to developing countries since the launch of the first Landsat satellite in 1972. Multiple images that have been acquired for most areas of the world can be used in a variety of resource-mapping programs. For example, in the Republic of Senegal, reconnaissance maps, including hydrogeology, soils, vegetation, land use, and water-table elevations, were prepared for the entire country at 1:500,000 scale. These products demonstrate the advantages of having synoptic data with the spatial detail of Landsat multispectral scanner (MSS) imagery (Stancioff and others, 1986).

A common approach for preparing a Landsat data base for surveys is to include wet-season and dry-season images to enhance interpretations for mapping vegetation and soils. Minimum-Sun-elevation angle images benefit geologic investigations; peak surface-water area is advantageous for hydrologic investigations. Other specific data may be required as determined by the theme to be mapped and the interpretation model used for deriving that theme. Unfortunately, the Landsat archive of images covering developing countries often lacks a sufficient diversity of data to use for specific interpretations. Secondly, costs of data and processing and limitations in available foreign currency for developing countries often restrict the selection and numbers of scenes so the image data base for interpretation is not optimized for all interpretations. However, it is generally accepted that for large-area mapping, Landsat or other similar satellite data provide the best available image base.

Multispectral data having different spectral signatures and scene feature contrasts offer the interpreter an opportunity to enhance tones, textures, and patterns as interpretation variables for themes of interest. The interpreter's knowledge of the landscape and interpretation models can be used to derive information from multispectral data. The interpreter's ability to conceptualize the landscape and to define interpretation models to relate the three-dimensional landscape to the two-dimensional spectral data is the key to the utilization of the remotely sensed image. Moore

(1982) presented approaches for linking interpretation models to remotely sensed images and demonstrated how interpretation clues could be used to derive ground-water information. Moore (1980) illustrated a physical model for the interaction of light and water and modeled the effects of increasing turbidity of the water as viewed by a remote-sensing system. Interpretation models and the field knowledge of the interpreter are key factors for successfully using the space imagery in resource mapping.

Monitoring, in contrast to resource mapping, requires sequential time-series data. As an example, assessing the change in apparent turbidity of a stream after a rainfall requires that data are available both before and after the rainfall event. Opportunities to use remotely sensed data to gather information where repetitive observations are required have not been generally available to the developing countries, especially if they have relied solely on Landsat data.

In the future, data availability should improve with advances in the design of satellites and data relay systems and with the increased number of satellite systems planned by many countries. Watkins and others (1985) summarized historic, existing, and planned satellite systems. The spectral sensitivities span the range from visible through microwave wavelengths. Nominal ground resolutions from 10 m to many kilometers are proposed for these future satellites. The satellites will provide low-resolution data useful for repetitive monitoring as well as higher resolution data for resource mapping.

Satellite operations are planned by agencies of the United States, the Union of Soviet Socialist Republics, India, China, the European Space Agency, Germany, France, Japan, Brazil, and the Netherlands (jointly with Indonesia). In addition, commercial ventures including the present program of EOSAT of the United States and proposed programs of Eastman Kodak Company and Fairchild Leasecraft, can provide a continuum of data. This level of activity provides reasonable assurances that satellite remotely sensed data collection will continue and that there may even be an increase in availability of remotely sensed data to the developing world.

Continued data availability tied to programs that train developing-country resource scientists and managers, plus programs that financially support data purchases will provide a mechanism of creating an information explosion to the planners and managers of developing countries. To use the information beneficially, integrated resource inventories, well-structured monitoring programs, and efficient methods of information management must be established.

Various literature compilations describe hydrologic applications of remote sensing. A comprehensive document by Deutsch and others (1979) includes sections on the various applications in hydrology, mainly using data from land-resources satellites. Summaries of the use of low-resolution Advanced Very High Resolution Radiometer (AVHRR) data from meteorologic satellites were presented by Matson and Parmenter-Holt (1985). They summarized applications in continental snow-cover mapping, river-basin snow mapping, regional soil-moisture analysis, and other uses requiring large-area repetitive coverage. They pointed out that inherent within many hydrologic applications is the fact that the remote-sensing data must meet time-series information needs.

Technology transfer to developing countries and infrastructure development by their governments must occur to derive, integrate, analyze, distribute, and effectively use the information. For the presentation of this paper, it is assumed that developing countries have the need, desire, and prioritization to acquire resources information for programs of planning, development, and monitoring. It is further assumed that international organizations and donor countries will continue to transfer technology and will provide the remotely sensed data in useful formats and with appropriate timing for use in critical country programs.

This paper suggests that a variety of sensors may be required to derive hydrologic information and that often data from these sensors must be merged with other information types to develop an understanding of hydrologic resources and the most effective uses of these resources. A variety of case studies illustrates specific points.

Preparation of the Data Base

Image Mapping

A variety of remotely sensed data are and will be available in the future for interpretation. These data will be at different scales, map projections, and geometric qualities and will yield a variety of disparate resource interpretation maps. Hydrologic information interpreted from the remotely sensed data will probably require merger with other spatial data for use in country programs. Cartographic base maps that have an acceptable level of accuracy are needed so that interpretations can be merged with other map information and used in country programs.

Satellite images have been used not only to derive resource information through interpretation, but also have been used to create cartographically acceptable base maps on which to compile other information. The United States, through the U.S. Geological Survey, has initiated an experimental program to use the Landsat multispectral scanner (MSS) data and Thematic Mapper (TM) data to construct these base maps. The maps range in scale from 1:100,000 with TM data, through 1:250,000 with MSS data, to 1:3,000,000 with AVHRR data. An MSS image map (original scale of 1:250,000 for a 1° by 2° block) is illustrated in Figure 1. An image map prepared from AVHRR data of a polar-orbiting meteorologic satellite is presented in Figure 2.

Image maps have many uses. First, they provide a cartographic base upon which other data can be compiled. Because many data will be partially derived through image interpretation, land features in the image map can be visually correlated to other images for transfer of the resulting map information. In addition, if the image map shows the spectral detail necessary for interpretation of the theme of interest, it can be used directly for the interpretation. Since many copies of base maps are usually printed, a number of resource interpreters can use the same images. The image map also presents a landscape view such that even those unfamiliar with image interpretation can gain an understanding of the landscape by viewing the map; the same conceptual understanding is difficult to visualize in standard planimetric maps.

Hydrologic Mapping

Multispectral data can be used to produce a color composite image by displaying three bands, or can be used in digital analysis. If digital counts (or image tones) are the key to interpretation, pixels that correspond to the multispectral characteristics of the features of interest can be categorized into classes and statistics can be created. These techniques are often effective in land cover mapping by which spectral properties discriminate the classes. Surface water, which has a distinctive signature in the reflected infrared spectral region, can be effectively mapped using digital classification. Digital classification is not effective when land and water features are not spectrally unique. When this is the case, they may (or may not) be separated by evaluating image texture, pattern, location, and association.

Digital classification is of limited use in developing countries since facilities are not commonly available to conduct the computer analysis.

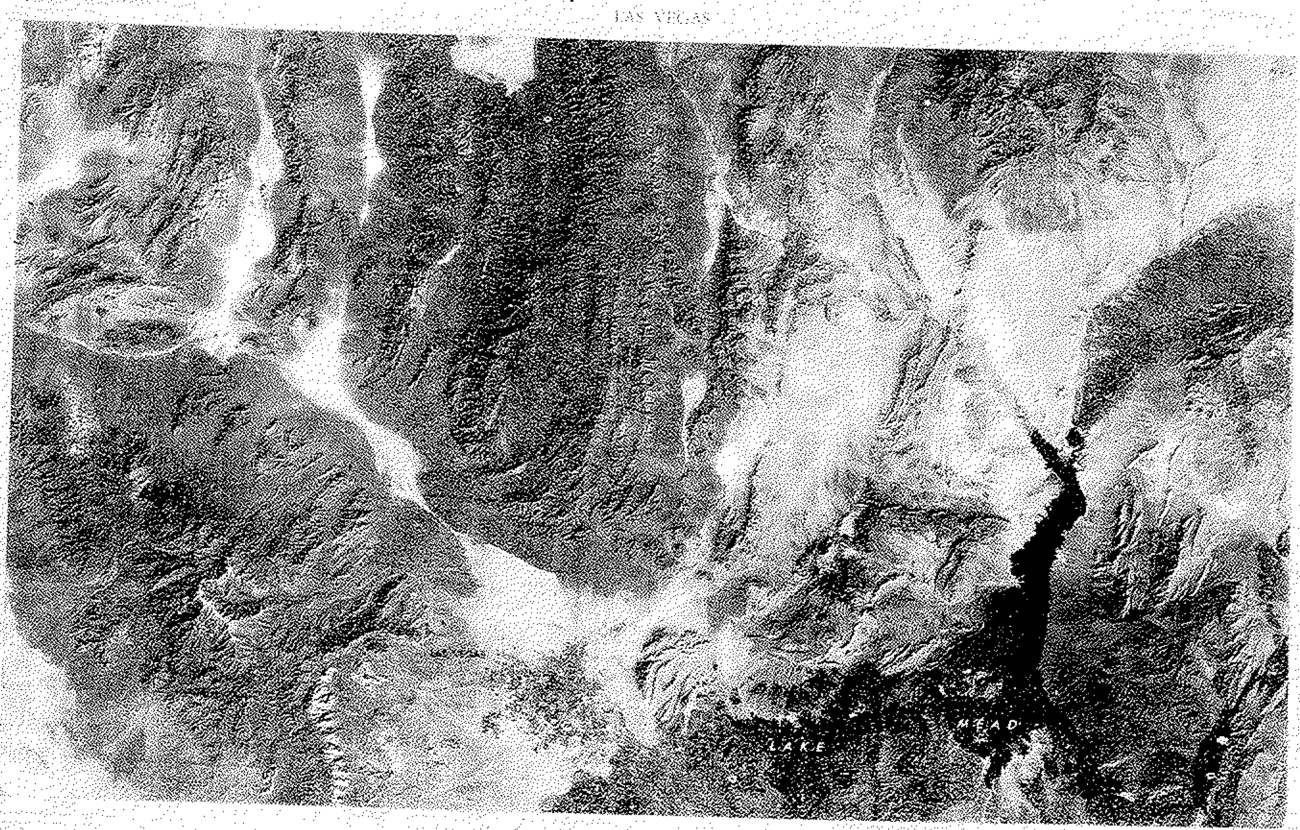


Fig. 1. Black and white reproduction of a digitally mosaicked and enhanced color image map of the Las Vegas, Nevada, USA, 10 by 20

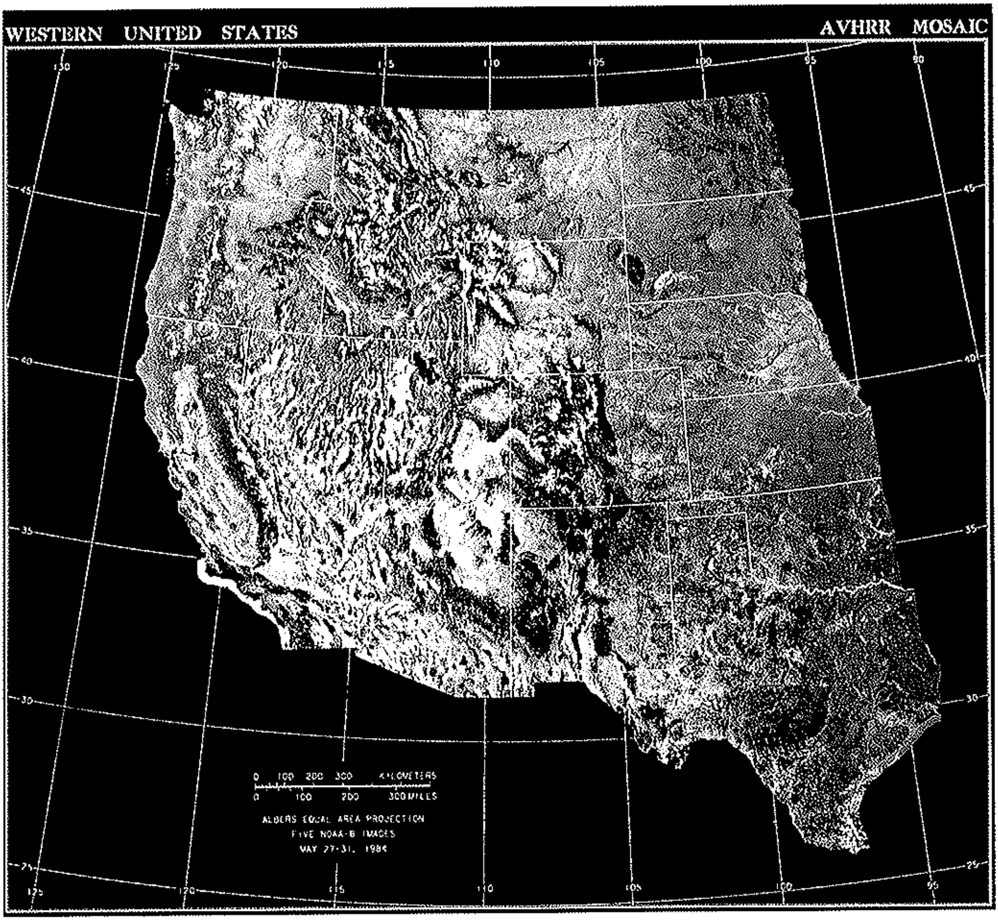


FIG. 2. Reproduction of a digitally mosaicked and enhanced color image map of the western portion of the United States. State boundaries digitally embedded in the image are from a digital map series produced by the U.S. Geological Survey. The spectral AVHRR data are from the NOAA-8 polar-orbiting satellite. Portions of five images were used to prepare the mosaic. The mosiac can be displayed to scales of 1:3,000,000 or smaller.

A recommendation is that developing countries should train resource scientists in the art of visual image interpretation and should provide high-quality images for their mapping programs. Improved resolution of planned satellites will facilitate more effective data for visual interpretation. Scales of 1:250,000 for Landsat MSS and 1:100,000 for Landsat TM images will normally allow an interpretation framework to be implemented that results in maps having sufficient detail in resource information for those scales and maps that are of adequate cartographic accuracy for natural resource mapping programs. When enlarging scanner data, the level of image detail does not increase; the image feature just gets larger. Therefore, preparing the MSS or TM image at larger scales does not normally allow for more detail in the final mapping. With the 10-m data available from the SPOT satellite, images for interpretation at 1:50,000 scale should be available. This scale fits many resource mapping needs of developing countries.

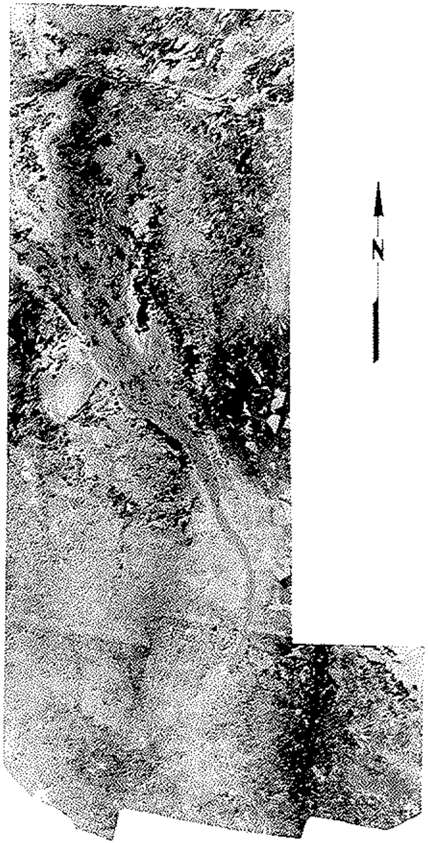
Using a typical soil survey at the soil series level, Wehde (1982) estimated spatial accuracy of the measured polygon at different cell sizes. The reader is referred to his paper for estimating the impact of cell size (or instantaneous field-of-view, IFOV) on mapping accuracies. As a variety of data sources become available, selection of appropriate data will require that analyses of spectral content and of spatial detail must be conducted. Wehde's approach for spatial detail should be considered.

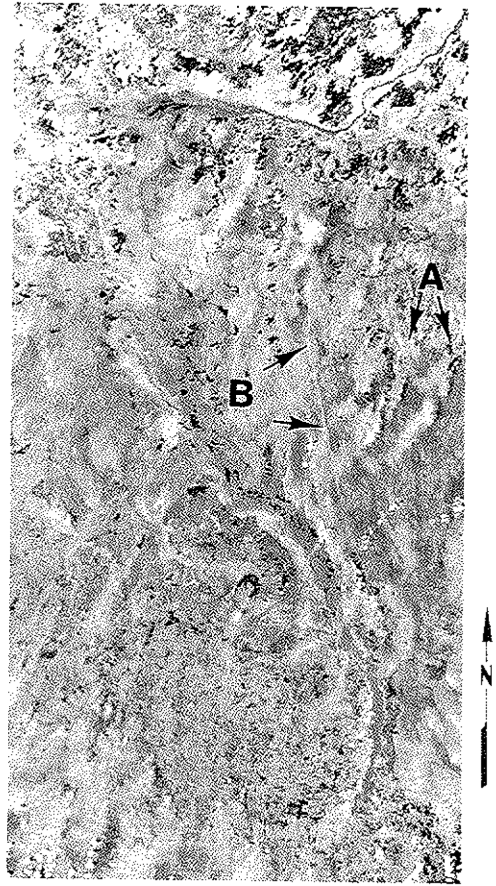
Tucker and others (1985) demonstrated that continental mapping of land cover could be effectively accomplished for Africa. He used a model of sequential spectral assessments of the continent from AVHRR data, which captured the vegetation phenology and seasonality over an 11-month period. The opportunity to synoptically assess the vegetation dynamics with time-series data is a unique capability offered by satellites.

Moore and others (1978) demonstrated that Landsat MSS data could be effectively used to map surface drainage, soils, surficial geology, and vegetation at 1:500,000 scale for a 168,000 km^2 study area surrounding the potential site for the Jonglei Canal in southern Sudan. Fourteen Landsat scenes were required to construct the uncontrolled mosaic (Figure 3). The 220-km Jonglei Canal was to be constructed from the villages of Jonglei to Malakal. The canal would transport up to one third of the water which would normally flow into the Sudd and which would otherwise be lost through evapotranspiration. Detailed engineering maps were available along the proposed canal route but no reliable maps were available for the surrounding area. A critical need existed for such basic information as a surface drainage map and for complex maps of soils and surficial geology. The project, including field truthing was conducted in only 18 months. The use of Landsat data, aerial reconnaissance, and field data collection proved to be a cost- and time-effective method to obtain the required information.

In the Jonglei Canal region, rangeland vegetation is burned at the end of the rainy season. Controlled burning commences when the vegetation dries enough to maintain fires. This rate of drying is determined by landscape position and drainage. The internal drainage characteristics of the soils are an indication of soil texture. Therefore, timing of the burning provided information on soil texture and internal drainage. Figure 4 is a color composite of AVHRR (1-km IFOV) data, which has the potential of daily acquisition by each of two polar-orbiting satellites. Note that active burns can be easily interpreted from the image. The arrows at A are coarse-textured remnant terraces that have dried sufficiently to allow burning. The soil and vegetation disturbance from constructing the Jonglei Canal is indicated at B on the image. Time-series observations from low-resolution meteorological satellites are effective for observing rapid changes associated with surface wetness for this and many other areas. A combination of high-resolution and low-resolution data, each having its associated costs, should be used for interpretation and mapping to realize economies afforded by each type of data. Data such as from Landsat can be used to prepare the georeferenced base map and to interpret and delineate polygons of interest. The time-series low-resolution data such as AVHRR may assist in describing characteristics of the resources within the polygons.

Time-series data are often required to assess change in a resource. For example, a time sequence of AVHRR images of eastern South Dakota show an increase in surface water area from April 7, 1986, to May 4, 1986 (Figure 5). The surface water accumulated during this period from rapid melting of winter snow and from above-average rainfall. Many lakes increased in size and other lakes were visible on the May image but could not be detected on the April image. Eight counties in the east-central portion of the image were declared disaster areas because farmers could not plant their crops and assure crop maturation before freezing in the fall. The May 30, 1984, image shows the area of surface water that is normally present. Low-resolution (1-km IFOV) data were used rather than higher resolution Landsat or SPOT data because (1) during the months of April and May, cloud cover resulted in no usable SPOT or





Kilometers
0 90 185

FIG. 3. Uncontrolled mosaic of Landsat MSS data used for interpretation and mapping the area around the Jonglei Canal of southern Sudan. The imaged area is about 168,000 km^2. The Sudd is the swamp depicted in red tones going north to south. The darkened burn patterns of various sizes and shapes were clues to image interpretation. The

FIG. 4. A color composite of an AVHRR image covering approximately the same area as the Landsat MSS mosaic in figure 3. This image of the southern Sudan was taken near the end of the rainy season. The burns noted by « A » are on coarse-textured soils of remnant river

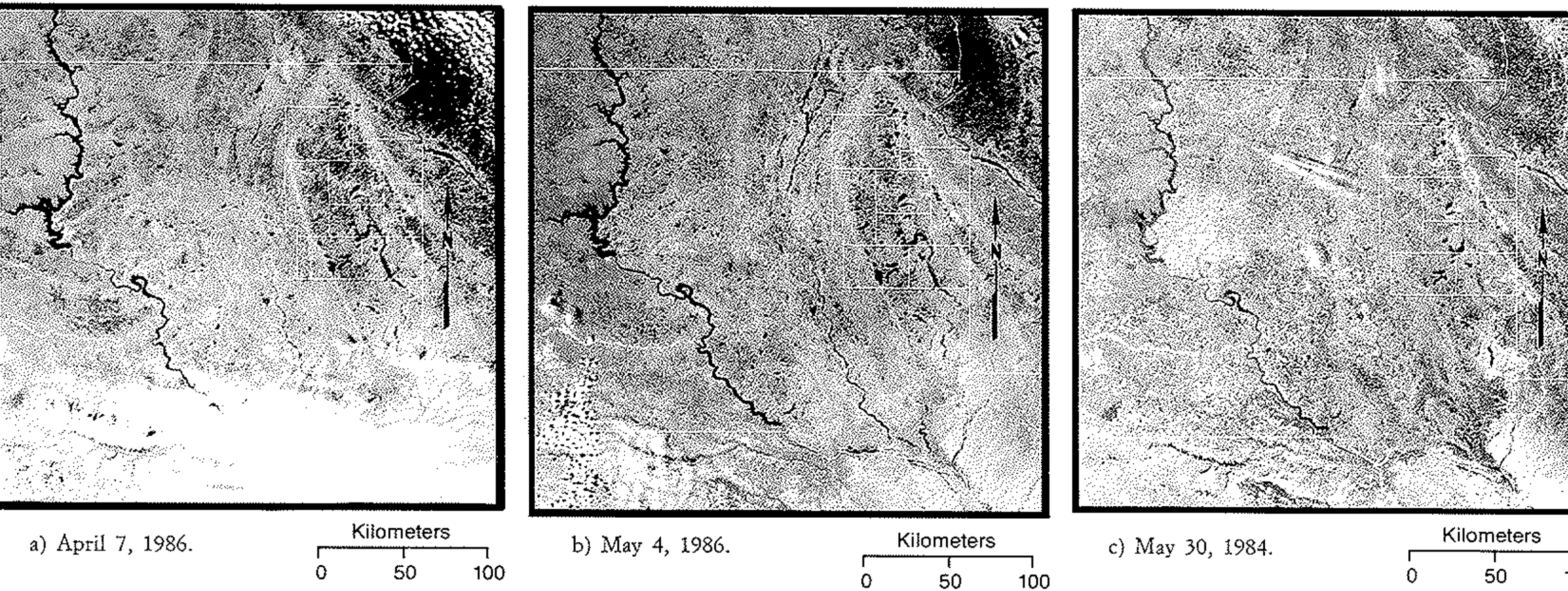


FIG. 5. A sequence of AVHRR images of eastern South Dakota showing the excess surface water caused by abnormal snowmelt runoff and high rainfall. Note the increase of surface water from April 7 (5a) to May 4 (5b). The May 30, 1984 image, (5c) illustrates the normal spring appearance of the lakes. County and state boundary lines are from a digital map series maintained by the U.S. Geological Survey.

Landsat data, and (2) only a small portion of a single image was required to provide coverage of the entire study area with AVHRR data. Since the purpose of the analysis was to synoptically assess inundation of farmland and not to measure the area of inundation, the AVHRR data were suitable. If an accurate measure of inundation area were required, the AVHRR data would not be of sufficient resolution. However, the analysis described using AVHRR data was completed with a fraction of the costs when compared to doing a similar analysis with Landsat data.

Integrated Surveys

A single example demonstrates the requirement for multidisciplinary information to study and manage the environment. Figure 6 is a Landsat MSS scene of an area north of Khartoum, Sudan. A desert corridor is shown in the northeast portion of the scene. The environmental problem is to locate these desert corridors and to reduce sand migrating from the Sahara Desert south into the Sahelian zone. One mechanism to reduce sand migration is to establish a shield by introducing a vertical barrier, such as a vegetation shelterbelt.

The location of the corridor, identification of regions of shifting sand, evaluation of the effects from the sands on agricultural land, and estimation of the area of impacted agricultural land can all be interpreted from the image. In this low precipitation zone, establishing a vegetation shelterbelt would require irrigation. No surface water is within a reasonable distance of the proposed shield; thus, ground water would have to be located and developed. The topographic high identified as a natural highland barrier in the image has a radial drainage pattern in which the drainage channels disappear at its edges. Accumulations of stored ground water near these highland edges could possibly yield sufficient amounts of water for irrigation. Targeting areas to be field surveyed for availability of ground water can be accomplished using interpretations of the Landsat image.

Monitoring

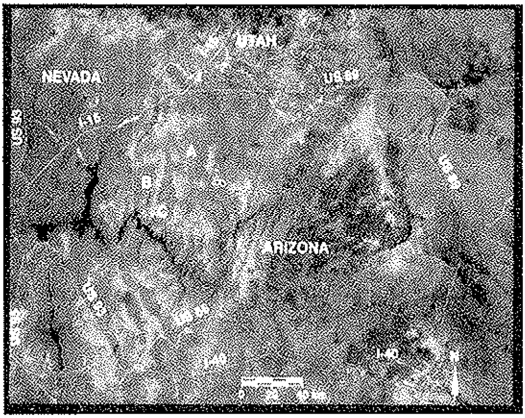
Hydrology, especially surface water hydrology, is dynamic. There are many requirements for monitoring changes in occurrence, amount, and quality. The Bureau of Reclamation of the United States operationally uses Landsat and aircraft multispectral scanner images to monitor water turbidity. Verdin (1984) reports that regression techniques that used remotely sensed data to estimate Secchi disk depth (water turbidity) and chlorophyll 'a' concentrations, were successfully developed. The most appropriate use of the techniques is to spatially extrapolate from point measurements collected at the time of overpass of the remote sensor. However, after atmospheric correction, date-to-date variations in water turbidity were assessed using Landsat data where no point samples were available. Results have been satisfactory to meet information needs.

Where vegetation cover is required in distributed models of watershed hydrology, satellites can provide the time-sequential data necessary to monitor and measure the vegetation changes. Miller and Moore (1983) demonstrated that time-sequence data were useful for locating and monitoring the growth of annual herbaceous vegetation in the desert Southwest of the United States. The AVHRR images in Figure 7 show changes in a computed value of greenness over the period from April 7 to April 29. Figure 8 shows changes in the grenness values at three sites in this area throughout the season. These greenness values are related to the amount of standing green biomass. The changes in vegetation cover can be used to predict evapotranspiration, soil erosion, and rainfall interception. Sequential monitoring of large areas can be cost effective and conducted using the AVHRR data.

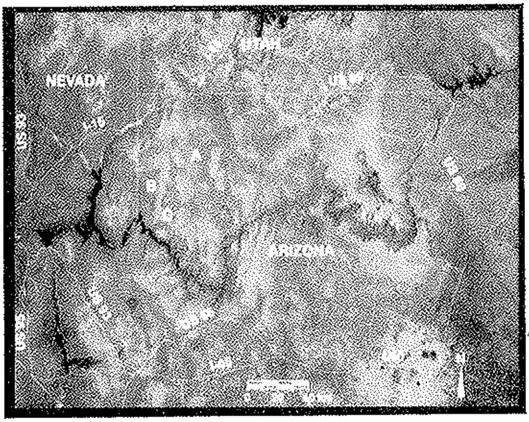
McGinnis and others (1985) used a combination of Landsat and AVHRR data to compare the hydrologic state of the Lake Chad Basin in central Africa during normal years with that of the recent drought. The surface area of the lake decreased to one-fourth of its normal size during the drought. The Landsat data archive is often the best available documentation of surface features, at least those which can be interpreted from the data. Without these archived data, the sequential comparisons would not have been possible. The investigators combined the Landsat detailed view with weekly observations using the AVHRR imagery. Interpretations of AVHRR data from 1982-1984 showed that vegetation in the northern basin effectively disappeared.

These examples demonstrate that a combination of different types of satellite data should be considered for programs in surface water hydrology. Developing countries are encouraged to define the actual level of detail and accuracy of information required in their mapping and monitoring. Often satellite data offer the only economical method of assessing dynamic changes.

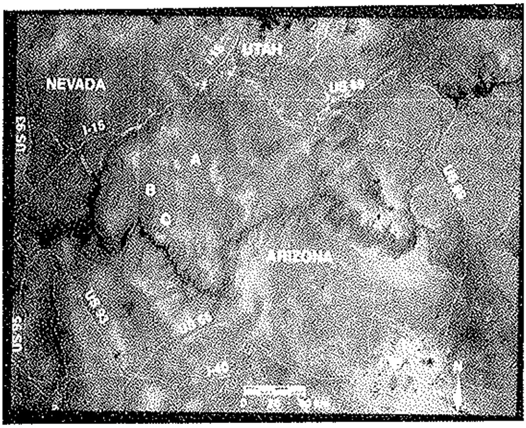
FIG. 6. A Landsat scene of an area north of Khartoum, Sudan, which graphically illustrates a desert corridor where sand from the Sahara Desert is moving south onto agricultural land and causing desertification. (Illustration courtesy of Remote Sensing Institute, South Dakota State University).



a) April 7, 1982.



b) April 20, 1982.



c) April 29, 1982.

FIG. 7. Normalized difference (greenness) images of northwestern Arizona and surrounding area as computed from AVHRR data. Lighter tones indicate higher levels of greenness. Roads and state boundaries are embedded in the image for locational purposes.

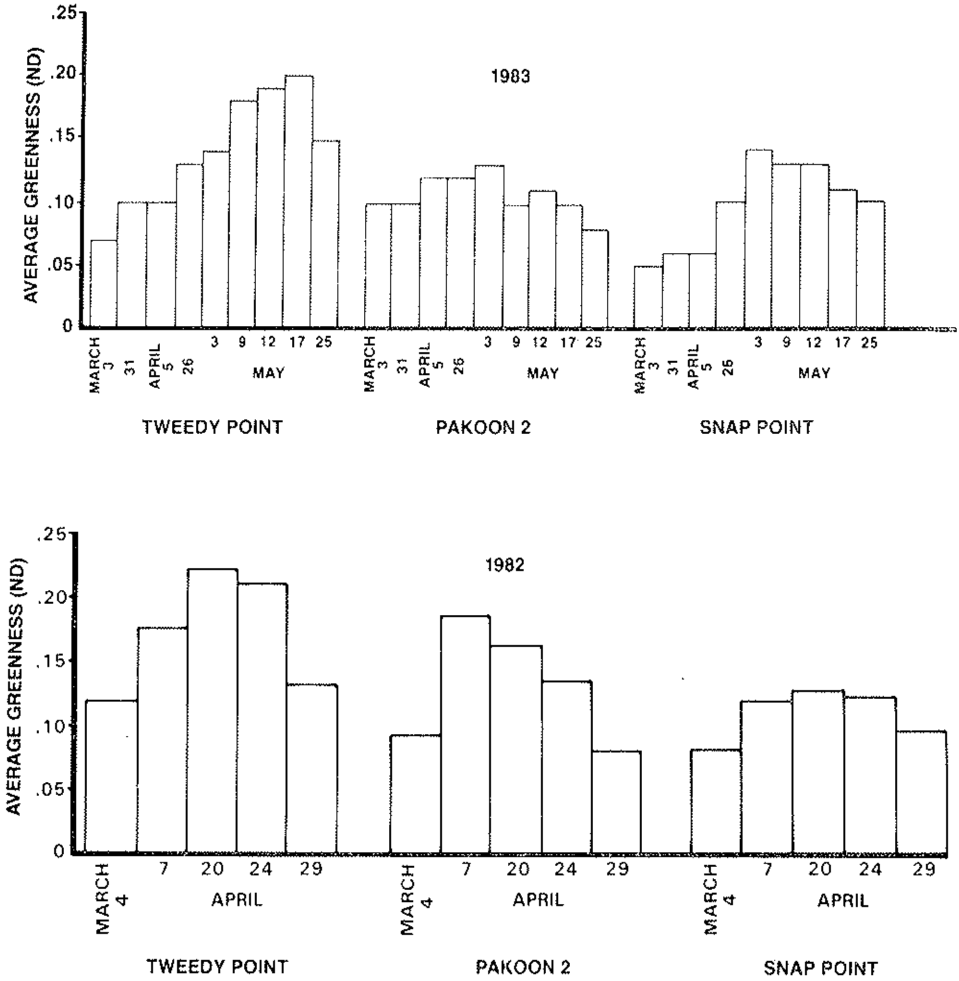


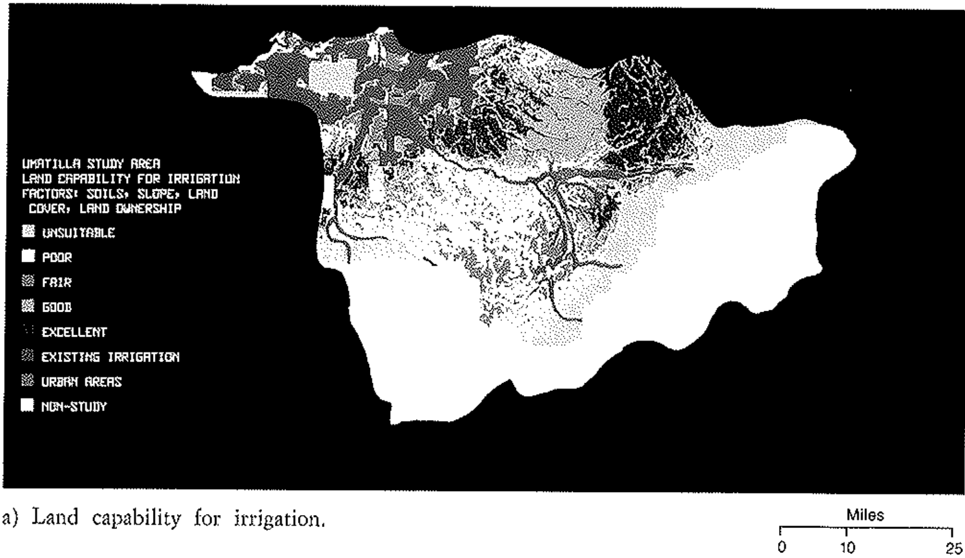
FIG. 8. Computed greenness values from the AVHRR images presented in Figure 7. Each value or bar is an average of six 1-km pixels at each of three selected ground sites. Note that Pakoon 2 reached peak greenness earlier than Tweedy Point or Snap Point. Also, Tweedy Point reached a higher level of greenness than the other sites.

Geographic Information System Approaches

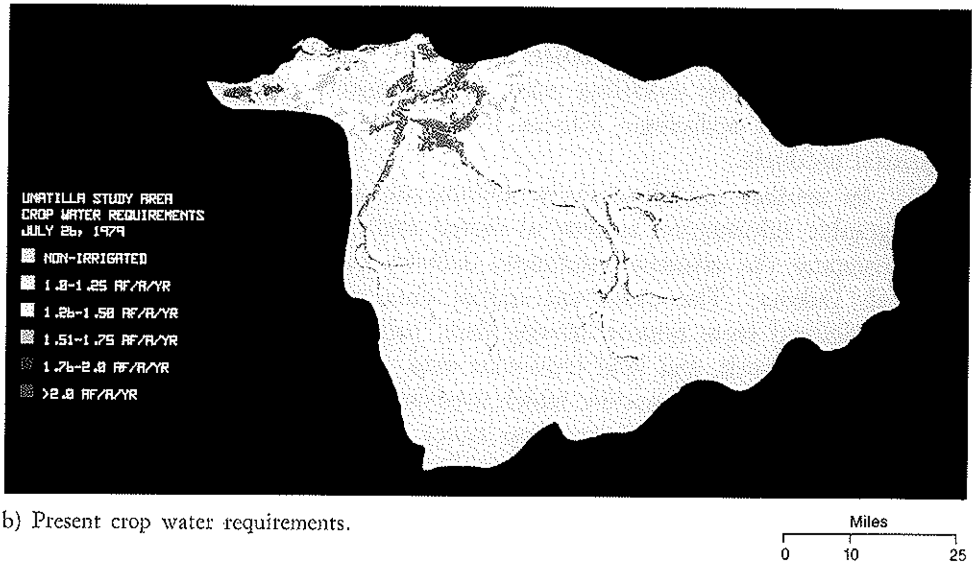
Present satellite remote-sensing systems measure reflectance of the land surface. Longer wavelength microwave energy penetrates dry materials, but data from land remote sensing imaging systems in the microwave regions are not available to developing countries. Often, the hydrologic parameter to be measured cannot be directly measured from surface reflectance but must be inferred or modeled with measurements of surface features. A geographic information system can be used to merge multiple categories of input data, to model and make inferences from the available data, and to format the output information.

Loveland and Johnson (1981) demonstrated that multiple spatial categories of information had to be merged and used with a consumptive water use model to estimate both irrigation water requirements and energy requirements for pumpage in the Umatilla Basin, Oregon. By estimating the potential increase in irrigated cropland, they also predicted the potential increased demand for irrigation water and energy requirements. The U.S. Army Corps of Engineers wanted to predict the growing electrical energy demands necessary for pumping the irrigation water. The data layers required to implement the model were land cover, crop type, pumping plant locations, slope, elevation, soil irrigation potential, and land ownership. The project demonstrated that the hydrology information could only be derived by modeling using data categories that are not normally thought of as hydrologic information. Figure 9 illustrates two of the spatial products.

In another modeling study, Eidenshink and Wehde (1981) used a geographic information system to merge multiple categories of data and to compute the estimated sediment delivery to Lake Herman in central South Dakota. The combined spatial data categories, many of which were derived from remote sensing data, included soil, slope, land cover, drainage network, and land treatment data. The model was based on the Universal Soil Loss Equation, which uses factors of rainfall, soil erodability, slope length, slope gradient, crop cover and management, and erosion controls, together with distances to the drainage network and distances along the drains to the point of sediment deposit. Spatial analysis procedures were used to create distance ranges and then appropriate weights were computed for eroding surfaces. The procedure is complex but geographic analysis of the multiple data categories leads to the data integration and analysis. Figure 10 illustrates some of the resource data categories.

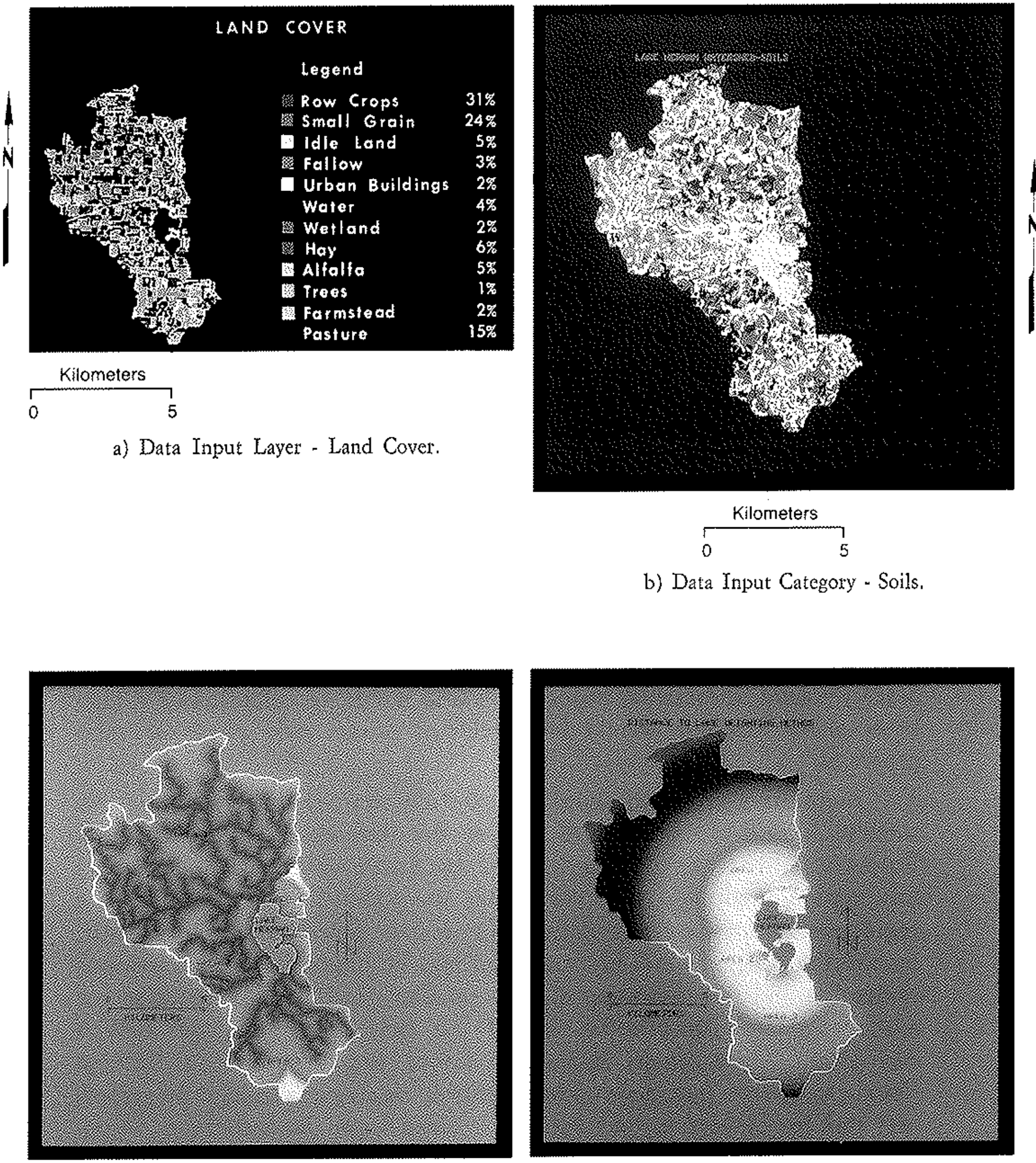


a) Land capability for irrigation.



b) Present crop water requirements.

FIG. 9. Example output images from a modeling study of existing and potential energy requirements for irrigation water in the Umatilla Basin, Oregon.



a) Data Input Layer - Land Cover.

b) Data Input Category - Soils.

c) Spatial Computation - Distances to Streams.

d) Spatial Computation - Distances to Lake.

FIG. 10. Input data categories used for modeling sediment delivery to Lake Herman, central South Dakota.

Summary

Many countries have plans for launching and operating remote-sensing satellites. The development of additional Earth-observing satellite programs should improve data coverage for developing countries. If funding to purchase the data and technology transfer to these countries is continued, an explosion of hydrologic information may result. The developing countries must have the desire and capability to effectively use this information in their critical resource assessment and monitoring programs.

Mapping applications are often limited by system resolution. Improved satellite resolutions such as the present 10-m SPOT and 30-m Landsat TM data are sufficient for most resource inventory and environmental monitoring. Where very detailed resource information is required, countries are encouraged to use aerial photographs rather than satellite images. The satellite images provide synoptic, small-scale views of large areas. Visual interpretation procedures and satellite resolution should permit maps at scales as large as 1:50,000.

The countries can use satellite images to prepare comprehensive base maps and compile resources information. The countries must also look toward establishing efficient information system capabilities to merge, store, analyze, and use the multiple layers of geographic information. Since resource information needed in a GIS would be compiled on a map base, image mapping should be conducted at an early phase of their programs.

Monitoring programs should be carefully defined so that appropriate satellite images are utilized to acquire the time-sequential information. Resource technicians should understand that low-resolution data may supply information needs and that these data are potentially available. If the requirements for level of detail and spatial precision are unrealistic, monitoring programs will be costly and may be impractical. A continuous evaluation and understanding of new satellite capabilities is required for appropriate and cost-efficient use of the technology. Regional centers such as the Africa centers in Nairobi, Kenya, and Ouagadougou, Burkina Faso, can assure that developing countries receive technology awareness and transfer to optimize advantages received from the techniques. Continued support of these regional centers is encouraged.

Developing countries typically have inadequate resource data from which to prepare development plans. Remote sensing will continue to be an effective tool for these countries.

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REMOTE SENSING OF THE WATERS AND LANDS VIA MICROWAVE RADIOMETRY (THE PRINCIPLES OF METHOD, PROBLEMS FEASIBLE FOR SOLVING, ECONOMIC USE)

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SUMMARY. The bases of the method of microwave radiometry are briefly explained. An analysis is given of the state of the studies in this field. The comparative estimates of the sensitivity of the radiation to the variations of the parameters of the waters, soils, and vegetation are presented. The feasibility of the variations of the water surface temperature and mineralization determination, soil moisture, shallow water tables, and green mass of vegetation sensing by means of microwave radiometry is shown. Examples of the economic use of this method in agriculture, hydrometeorology, for the purposes of land reclamation and the control of the state of the environment are given. The perspective areas of the microwave radiometry development and use are shown.

1. WHAT IS MICROWAVE RADIOMETRY?

Physical principles, wavelength range, scale of the intensity of radiation.

Microwave radiometry is one of the radiophysical methods used for remote sensing of the environment. It is based on receiving the natural electromagnetic radiation of the objects in the wavelength range of millimeter, centimeter, and decimeter wavelengths [1-4].

The main investigations of the water and land surfaces usually take place in the range of 1.5-2 to 20-30 cm. For example, the author and his colleagues conducted their investigations, as a rule, in the range of 2.25 to 30 cm [4-8, 12-14, 18-22]. The spectral dependence of the ratio "signal + noise/signal", given in a schematic way in Fig. 1, explains this peculiarity. The "signal" is the intensity of radiation from a water surface, and the "noise" is the intensity of the emission from the atmosphere and space. It is seen that the radiation of the system "space-atmosphere-surface" is considerably influenced by the atmosphere at the wavelengths λ shorter than 2-3 cm and is affected by the galaxy radiation at wavelengths longer than 30 cm.

The measure of the intensity of radiation at microwaves is a brightness temperature T_B, which is a product of emissivity $\varkappa$ and thermodynamic temperature T_e within the effectively emitting layer (skin-depth) of the object. The brightness temperature is measured in Kelvins (K). Within the above mentioned wavelength range for T_e = 10-30°C, the metal surface is characterized by minimum brightness temperature (about 0 K); this surface is followed by the water surface (about 90-110 K), very moist ground surface (about 160-180 K), and a very dry one (about 250-270 K) (Fig. 2).

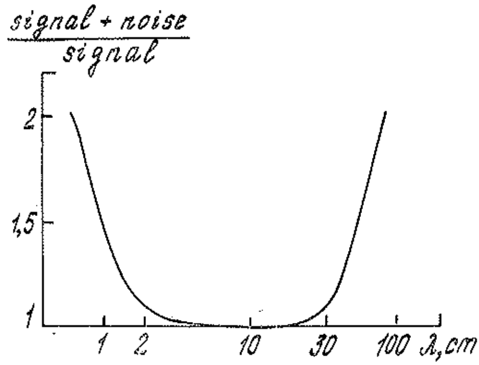

Fig. 1. Approximate character of a spectral dependence of "signal + noise/signal" ratio where "signal" is the intensity of water surface radiation, "noise" is the intensity of atmospheric and cosmic (space) radiation, reflected by a water surface.

The sources of information.

The sources of information in microwave radiometry are:

— the data of temporal and spatial measurements of the contrasts in microwave radiation for certain types of polarization at the fixed wavelengths λ and angles of observation Θ, and the data of contrasts in the degree of polarization at given wavelengths and angles of observation;

— the peculiarities in a spectrum of intensity of radiation for certain types of polarization at fixed angles of observation and the peculiarities in a spectrum of the degree of polarization (coefficient of polarization) at fixed angles of observation;

— the peculiarities in the angular dependences of the characteristics of radiation at certain wavelengths.

It is necessary to recognize the methods based on the analysis of the contrast and spectral peculiarities of radiation for $0 \leq \Theta \leq 50°$ to be the mostly worked out and practically used by now for studying the waters and grounds.

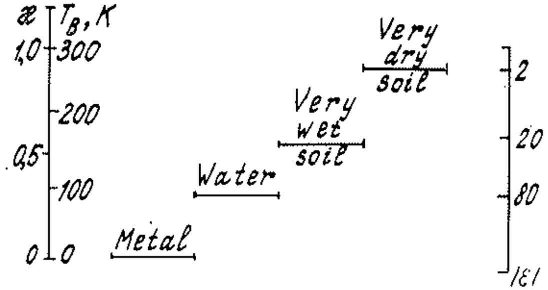

Fig. 2. Scales of dielectric permittivity modulus / ε /, emissivity ϰ, and intensity of radiation (brightness temperature T_B) values and approximate values of these data for metal, water surfaces, very wet and very dry soil (Schematic representation).

2. The state of investigations.

Theoretical investigations of the sensitivity of the radiation to the variations of physico-chemical parameters and geometric characteristics of water and ground surfaces.

It is shown theoretically that the main parameters that affect the radiation are:

— the dielectric properties of the medium (including a conductivity) that are dependent mainly on the moisture content of the object, its temperature, the types and quantity of dissolved matter (degree of mineralization or, in particular cases, salinity);

— the peculiarities of a vertical profile of temperature within an effectively emitting layer that varies from some parts of λ for a water medium to some wavelengths for a dry ground;

— the peculiarities of a geometrical structure of the surface (the presence of large and small compared with wavelength undulations);

— the presence of the transition layers (between an atmosphere and the media) in a view of the foamy patches on a water surface and the vegetation on the ground surface.

Summarizing the state of the theoretical investigations, it should be pointed out that:

— radiophysical models of the water and ground media that describe more or less adequately the influence of practically all of the mentioned parameters were worked out;

— the problems studied in the most complete way are: the dependence of the characteristics of radiation on a water surface, temperature and concentration of NaCl in aqueous solutions, on the characteristics of large and small undulations and their combination, on the moisture content in soils and some biometric parameters of vegetation;

— the problems studied less completely are: the models of radiation of a mixture of salts in aqueous solutions, the description of the dependence of the characteristics of radiation on the parameters of foam on a water surface, on the granulometric characteristics and a vertical structure of soil, on the forms of water in a soil, its salinity, on the content of humus etc.

That is why, in order to understand many of the problems mentioned, there were conducted the representative experimental investigations in the laboratories, from aircraft, and from satellites in the USSR [1, 3-8, 12-14, 18-21], USA [9-11, 15, 16], Switzerland [2], Italy [17] and some other countries.

Experimental investigations in laboratory conditions, at pools, fields, from aircraft and satellites.

The data presented in Tables 1 and 2 give an idea of the experiments conducted by the author and his colleagues at the Institute of Radio-engineering and Electronics of the Academy of Sciences of the USSR.

TABLE 1 - *Experiments over the water:*

1a. The conditions for conducting the measurements.

1	At the laboratories
2	At the pools
3	At a coastal location
4	From aircraft
5	From satellites

1b. The band of microwave spectrum.

The wavelength range, λ, cm	(0.8-2,25 - (8.5-30)

1c. The physical parameters.

1	Wind speed, V, m/s	0-25
2	Temperature, T, °C	0-30
3	Salinity, S, ppt (g/l)	0-400
4	Types of salts	NaCl, Na_2SO_4, $MgCl_2$, $MgSO_4$ sea water
5	Types of acids	HCl, H_2SO_4
6	Liquid water content in clouds, W, kg/m²,	0-I

TABLE 2 - *Experiments over the ground surface.*

2a. The conditions for conducting the measurements.

1	At the laboratories
2	From stationary platforms
3	From mobile platforms
4	From aircraft
5	From satellites

2b. The band of microwave spectrum.

The wavelength range, λ, cm	(0.8-2.25) - (8.5-30)

2c. The parameters of soils.

1	Free water content, ρ_w, g/cm^3	0- 0.5
2	Dry soil density, ρ_d, g/cm^3	0.8- 1.75
3	Temperature, T, °C	0-50
4	Salinity, S, ppt (g/l)	0-60
5	Types of soil	sand, clay, silt, etc.
6	Climatic zones	from arid to humid

2d. The parameters of vegetation.

1	Green mass (biomass) content, Q, c/ha	0-500
2	Types of crops	grass, wheat, barley, corn, cotton

The theoretical and experimental investigations described above gave trustworthy information on the sensitivity of the characteristics of radiation to variations of the parameters of the waters and the ground surfaces.

3. The basic "radiation vs geophysical parameters" dependences.

The sensitivity of the intensity of radiation to variations of the water surface parameters — temperature, mineralization, water surface state.

The results of investigations and generalizations allow to conclude:

— for fresh water the dependence of T_B from T is practically linear in the wavelength range 5-10 cm; the sensitivity of T_B to T variations is about 0.4-0.55 K/°C for $0 \leq \Theta \leq 30°$ (Fig. 3a);

— an increase of salinity leads to a decrease of T_B vs T dependence at decimeter wavelengths, and for $S \geqslant 30\text{-}40$ ppt the sign of this dependence is becoming negative (Fig. 3b);

— the T_B is sensitive to S variations mainly at decimeter wavelengths; the value of sensitivity is about −(0.8-1.0) K/ppt for $0 \leqslant S < 40$ ppt and is about −(0.1-0.2) K/ppt for the greater values of salinity (Fig. 3c);

— the sensitivity of T_B to T and S variations is weakly affected by a water surface state;

— the sensitivity of T_B to the wind speed variations (first of all due to the influence of foam) for $0 \leq \Theta \leq 30°$ is about 1 K/m s^{-1} at the centimeter wavelengths and decreases for greater λ;

— all of the above mentioned salts are characterized by the similar to NaCl dependences of T_B from T, S, and λ;

— the sensitivity of T_B to the variations of H_2SO_4 and HCl concentration is 3 to 5 times greater than to NaCl concentration (Fig. 4).

The sensitivity of the intensity of radiation to variations of ground surface parameters: soil moisture content, dry soil density, temperature, and salinity. The screening effect of vegetation.

The results of investigations and generalizations allow to conclude that:

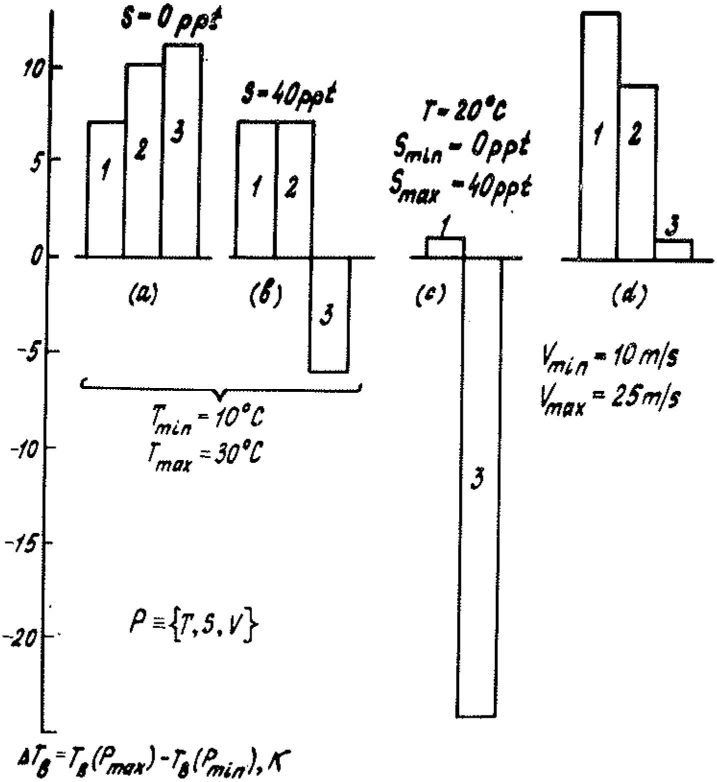

FIG. 3. Comparative estimates of the intensity of water surface radiation variations at the wavelengths of 1-2 cm (1), 5-8 cm (2), and 20-30 cm (3) under the variations of a water surface temperature (a), (b), salinity (c), and near surface wind speed (d).

— the characteristics of ground surface radiation are dependent mainly on a volumetric content of free water in a soil ρ_w (this water can move in pores — to flow down due to gravitation, to rise in capillaries); the sensitivity of T_B to ρ_w variations is not less than -200 K/g $\cdot$ cm^{-3}, to ρ_d variations is not greater than -20 K/g $\cdot$ cm^{-3}; these estimates are almost independent of the wavelength and a type of a soil (Fig. 5 a,b);

— the influence of day-to-night temperature variations on T_B decreases for longer wavelengths (Fig. 5c); at decimeter wavelengths the sensitivity $\Delta T_B/\Delta T_o$ does not exceed 0.1 K/°C;

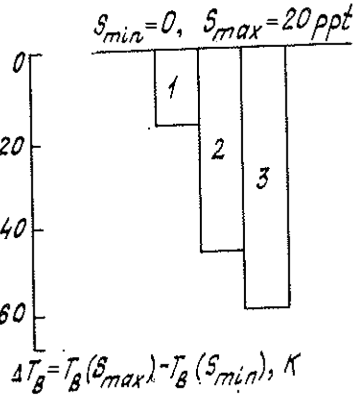

FIG. 4. Comparative estimates of the variations of microwave radiation from water surface at 30 cm wavelength for $\theta = 0°$, T = 25°C under the variations of concentration of NaCl (1), H_2SO_4 (2), and HCl (3) in a range from 0 to 20 ppt.

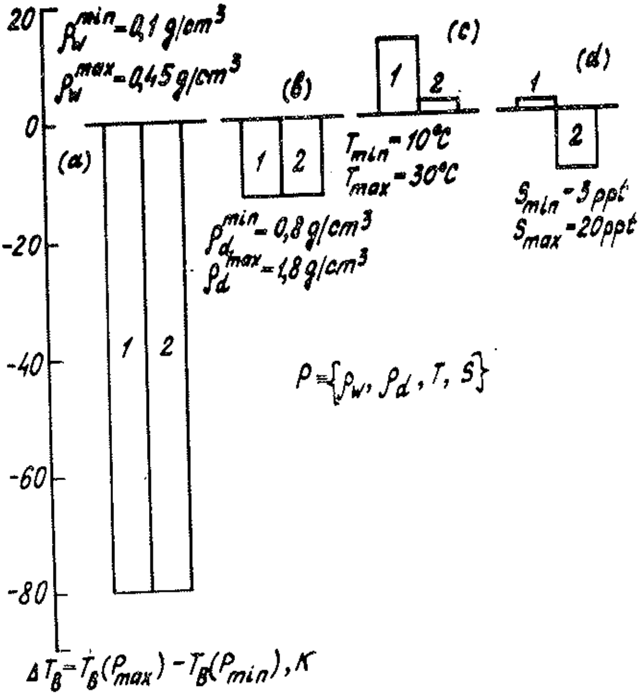

FIG. 5. Comparative estimates of the variations of microwave radiation from ground surface at centimeter (1) and decimeter (2) wavelengths for $\theta = 0°$ under variations of volumetric content of free water (a), dry soil density (b), temperature (c), and salinity (d).

— T_B is sensitive to salinity at the decimeter wavelengths for a very wet soil; the value of sensitivity is about $-(0.7\text{-}0.8)$ K/ppt for $10 \leq S \leq 60$ ppt (Fig. 5d);

— for a steady moisture profile the T_B at decimeter wavelengths is sensitive to the shallow water tables (subsoil water levels) H_{SWL} for $0 \leq H_{SWL} \leq 3\text{-}4$ m in arid areas and for $0 \leq H_{SWL} \leq 1\text{-}1.5$ m in humid areas (Fig. 6);

— the sensitivity of T_B of the system "vegetation-soil" to moisture content variations increases for longer wavelengths; the sensitivity to a green mass of vegetation is characterized by a maximum at a certain wavelength that is dependent on a biomass; the crops of the narrow-leaf types, such as wheat, barley, grass, are practically transparent for the electromagnetic waves of a decimeter band and semitransparent at the centimeter wavelengths; the wide-leaf crops, like corn and cotton-plant, are semitransparent at decimeter wavelengths and practically screen the radiation from the soil at centimeter wavelengths (Fig. 7).

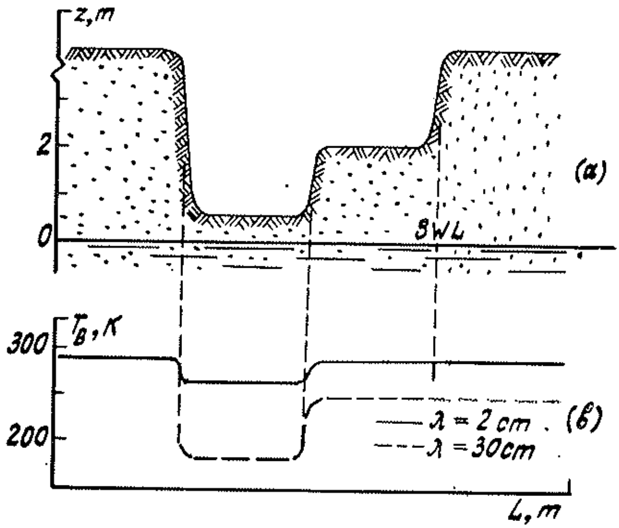

FIG. 6. On the dependence of intensity of radiation from ground surface (b) at centimeter and decimeter wavelengths on the depth of shallow water tables (a).

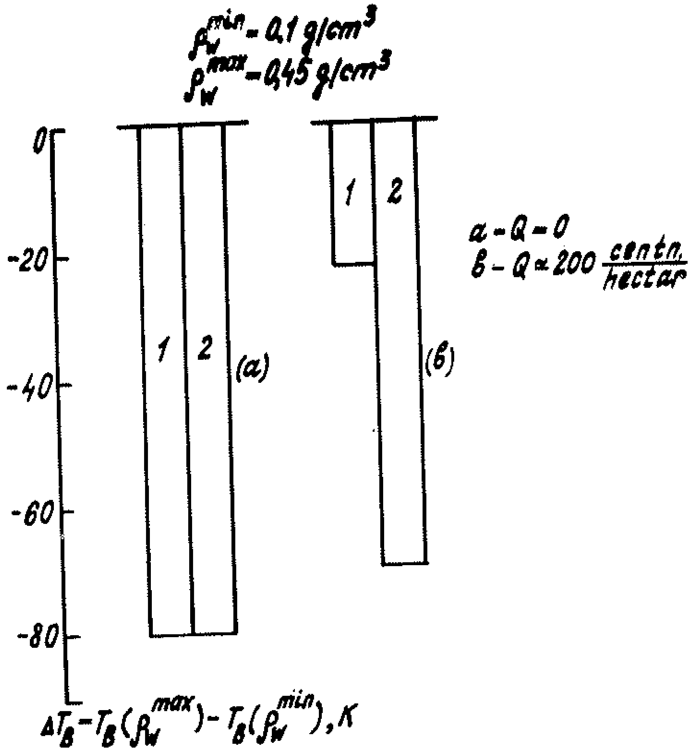

FIG. 7. Comparative estimates of the variations of microwave radiation from ground surface at centimeter (1) and decimeter (2) wavelengths for open soil (a) and under the presence of vegetation (b).

4. THE ACCURACY ESTIMATES OF GEOPHYSICAL PARAMETER DETERMINATION BY MEANS OF MICROWAVE RADIOMETRY.

Water surface temperature and salinity determination.

There were worked out the one-channel and the two-channel methods of the variations of T and S parameter determination (the application of a certain method is dependent on the range of these parameters and on the expected state of a water surface) [5-8]. The methods were metrologically tested by the services of the State Committee of Hydrometeorology. The results of these tests are as follows:

— the threshold of sensitivity is about 0.2 ppt for HCl and 2 ppt for NaCl;

— the range of measured salinity data of the natural waters is from the threshold to about 400 ppt;

— with a probability of 0.95 the errors of salinity determination are about 2 ppt for $2 \leq S < 60$ ppt, 6 ppt for $60 \leq S < 150$ ppt, and 12 ppt for $150 \leq S < 400$ ppt;

— with a probability of 0.95 the error of water surface temperature determination does not exceed 2°C for $0 \leq T \leq 35$°C.

The noted characteristics can be realized for $0 \leq V \leq 12$ m/s and $0 \leq W \leq 0.5$ kg/m^2.

The almost similar accuracy data for $0 \leq S \leq 40$ ppt are given in [9-11].

The results of a comparison of the retrieved radiometric data of the temperature and salinity with the sea truth data are presented in Figs. 8 and 9.

Soil moisture content and shallow water table determination.

There were worked out the one-channel and the two-channel methods of soil moisture content and shallow water table determination (the application of a certain method is dependent on *a priori* information about a moisture profile, the biometric parameters of vegetation, on the date of watering) [12, 14, 18-21]. The methods were metrologically tested by the services of the Ministry of Land Reclamation and Water Management and the State Committee of Hydrometeorology. The results of these tests are as follows:

— by means of microwave radiometry there can be determined the data of volumetric free water content in the upper soil layer of about 20 to 30 cm thick; the error of a moisture content determination is almost independent of the type of soil, of the value of a dry soil density and with a probability of 0.9 is equal to about 0.04 g/cm^3 for open ground and to about 0,08-0.1 g/cm^3 for a ground surface covered with vegetation, the biomass of which does not exceed 200 c/ha;

— with a probability of 0.9 there can be determined 3 to 5 gradations of H_{SWL} down to the depth of 1.5-3.5 m (the lowest level of sensing is dependent on a type of soil-climatic zone) under the conditions of a quasi-stationary moisture profile (that is, 2 to 5 days after watering) and a presence of vegetation the biomass of which does not exceed 200 c/ha;

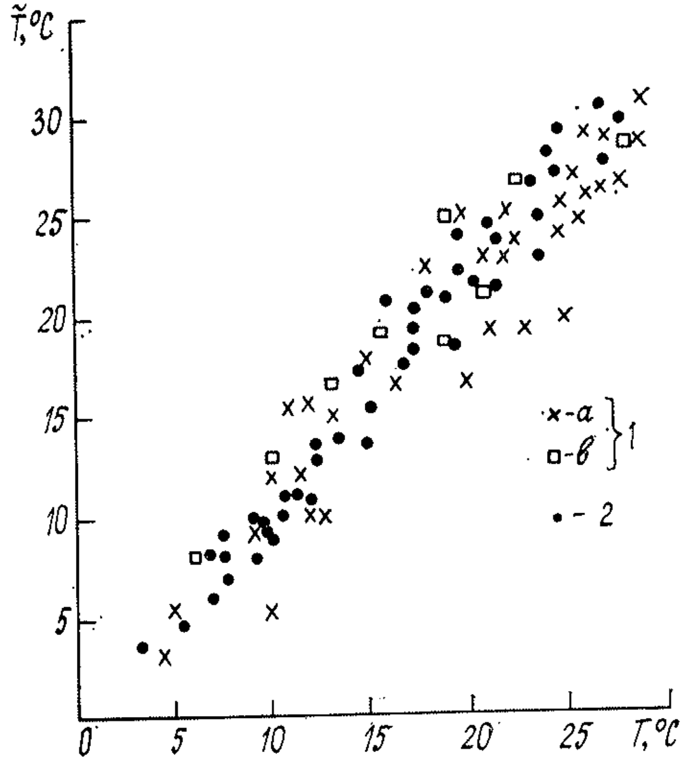

FIG. 8. Comparison of the retrieved radiometric data of water temperature with the data of contact measurements. (1) radiometric measurements from satellites, (2) radiometric measurements from aircraft.

also under the mentioned conditions the total water content in a layer from the surface to the water table can be determined.

The results of a comparison of the retrieved radiometric data of a moisture content and a shallow water table with the ground truth data are presented in Figs. 10 and 11. The data given in Fig. 11 illustrate the effect of vegetation on the accuracy of a soil moisture determination.

The author's conclusion on the main effect of a volumetric content of free water on the characteristics of microwave radiation of the ground surface differs very much from the results presented, for example, in 15, 16, where the relationships are established between the intensity of radiation and a relative (weight percent) soil moisture which included

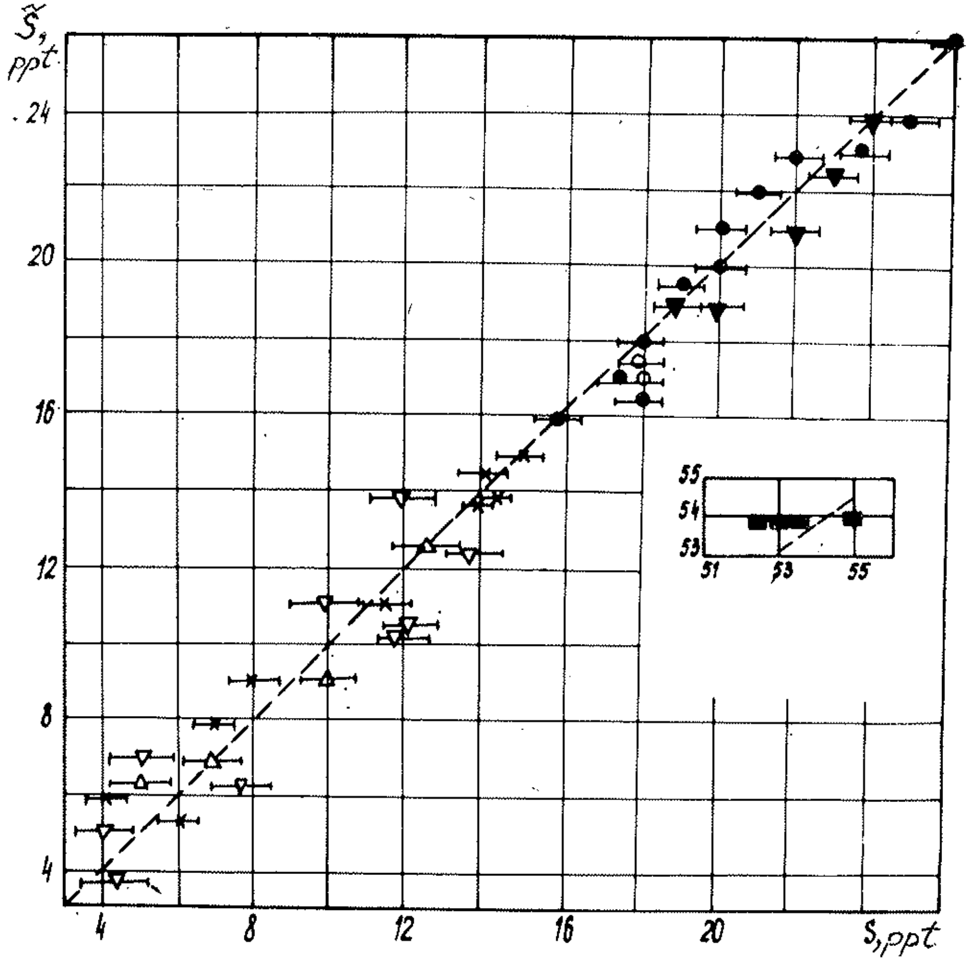

FIG. 9. Comparison of the retrieved radiometric data of water surface salinity with the data of contact measurements.

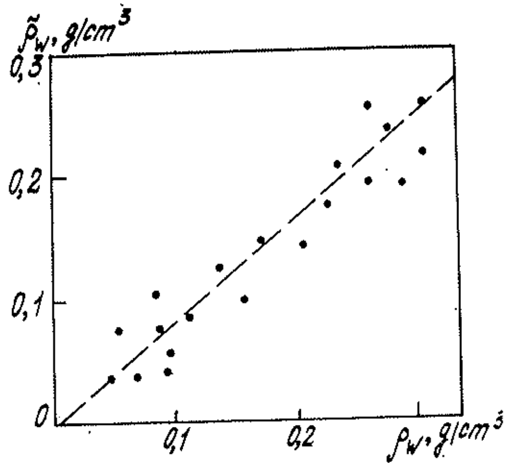

FIG. 10. Comparison of the retrieved radiometric data of volumetric content of free water with the data of ground truth measurements in an upper soil layer of 20 cm thick.

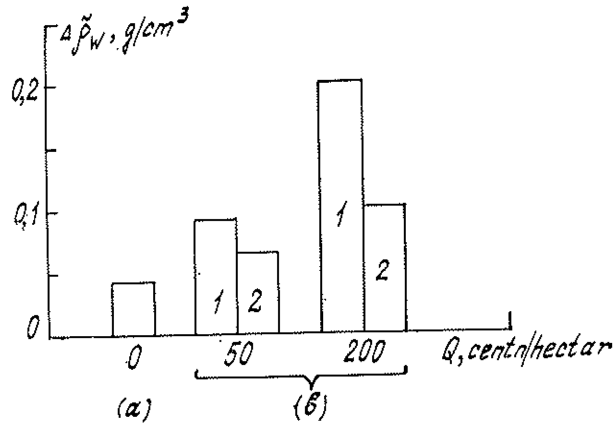

FIG. 11. The influence of vegetation on the accuracy of soil moisture content determination: (1) no information about biomass of vegetation, (2) the biomass is known with a relative error of about 30%.

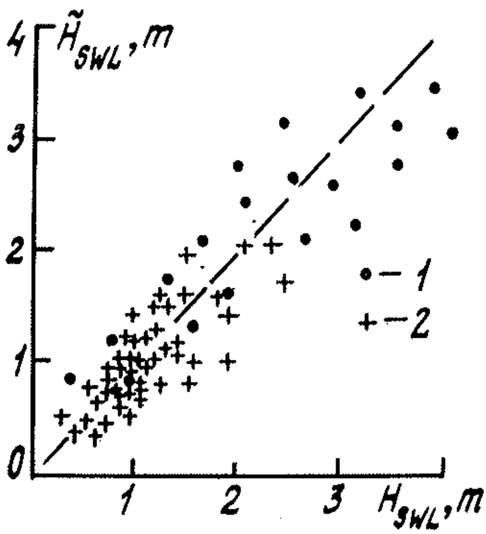

FIG. 12. Comparison of the retrieved radiometric data of the depth of shallow water tables with the data of ground truth measurements for the arid zones (1) and the humid areas (2).

adsorbed as well as free water content divided by a dry weight of samples or by a field capacity. As shown by the author, the accuracy of the soil moisture estimates expressed as weight percent is dependent on a type of soil and on its density [14].

The above-water biomass of vegetation determination.

For the conditions when a vegetation is stretched by the very wet soil or by the water surface, the method of microwave radiometry can be used for determination of the above-surface biomass of vegetation with an error that does not exceed 20%. The typical examples of such crops are rice and cane (rush). The data presented in Fig. 13 illustrate the results of a comparison between the retrieved radiometric and the ground truth data of a rice biomass.

It is worth emphasizing that neither clouds nor fog nor smoke nor conditions of illumination by the sun affect noticeably the accuracy of the above-mentioned parameter determination by means of microwave radiometry.

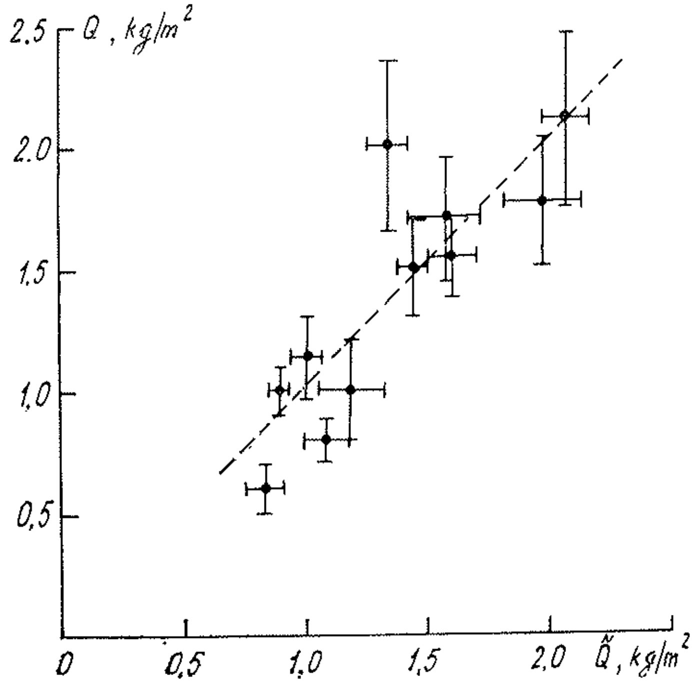

FIG. 13. Comparison of the retrieved radiometric data of the biomass of rice crop with the data of ground truth measurements.

5. THE PRACTICAL (ECONOMIC) USE OF THE WORKED OUT METHODS OF MICROWAVE RADIOMETRY.

The users of information.

The microwave radiometric methods of the water surface mineralization, soil moisture content, and shallow water table determination worked out at the Institute of Radioengineering and Electronics, Academy of Sciences, USSR, have been successfully tested for more than 10 years in the different soil-climatic zones of the USSR over the territory of 10 republics, among them RSFSR (Russian Federation), Ukraine, Moldavia, Estonia, Georgia, Turkmenia, Uzbekistan. The experiments were conducted over fields covering more than 7 million hectares. The results of these experiments revealed the interests of the agricultural organizations, the services of land reclamation and water management and the hydrometeorological organizations in using these methods for operational purposes.

Problems which can be solved. The areas of application.

The experience gained during scientific investigation and operational use has shown the possibility and the advisability of the application of these methods for solving the following problems.

— *Soil moisture sensing in agricultural fields* for determining the dates of sowing, filterization, estimating the rates and the dates of watering. The example of a soil moisture content map obtained by means of microwave radiometry is presented in Fig. 14.

— *The control of the quality of moistening* by the different types of water sprinklers. It is well seen in Fig. 15 that the quality of soil surface moistening by a central pivot of the "Fregat" type is much worse than by a conventional system of DDA-100 M type.

— *The control of the quality of ground surface planning* in fields with water feeding by furrows (in Middle Asia) and fields of rice crop. The example of the exposure of a field with low quality ground surface planning is presented in Fig. 16.

— *Shallow water table determination, exposure of the zones with destroyed drainage systems, marshy area monitoring.* The shallow water table is one of the main parameters required for undertaking the different land-reclamation measures. The information on this parameter that may be obtained operationally from aircraft over large areas of deserts, semi-deserts, steppes, and irrigated zones of hundreds of thousands and even millions of hectares, allows solving the problems of optimum water distribution and expenditure from the rivers, lakes, storage lakes; the problems of projecting the optimum canal tracks, and the drainage systems; the problems of determining and setting the scientifically-based régimes of watering or drainage for obtaining stable crops and maintenance of the land in a good state. The example of the exposure of zones with high levels of water tables is presented in Fig. 17.

— *The control of the state of hydrotechnical works* (canals, dams, dikes, etc.) for the exposure of the zones of canal seepage. See example in Fig. 18.

— *The biomass of rice and cane determination* for the harvest of rice

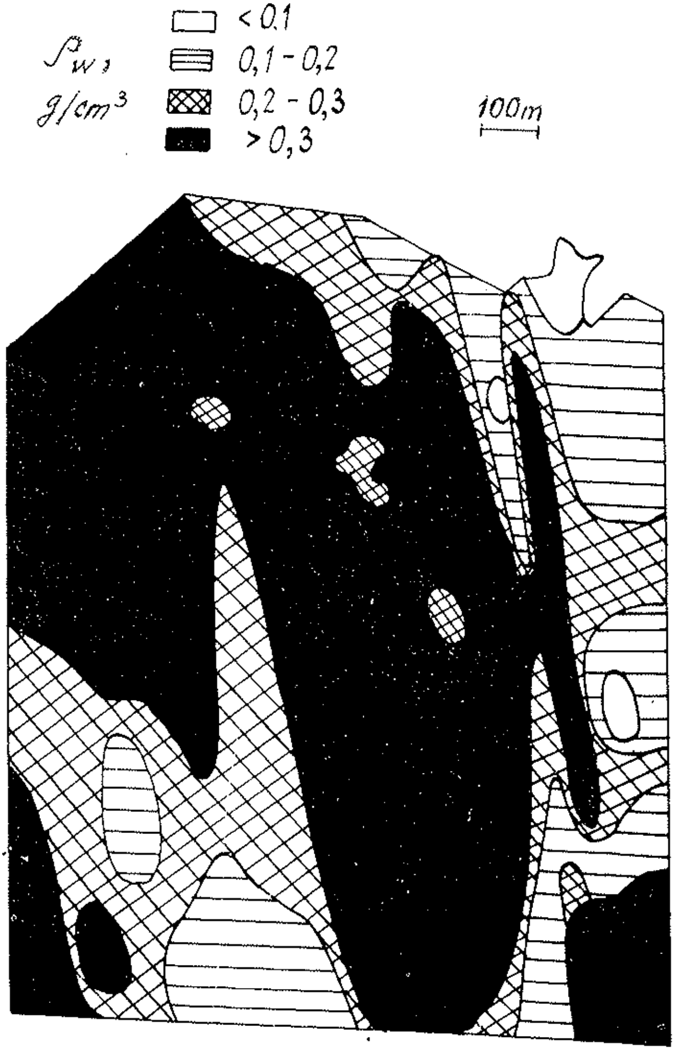

FIG. 14. Map of retrieved radiometric data of soil moisture content.

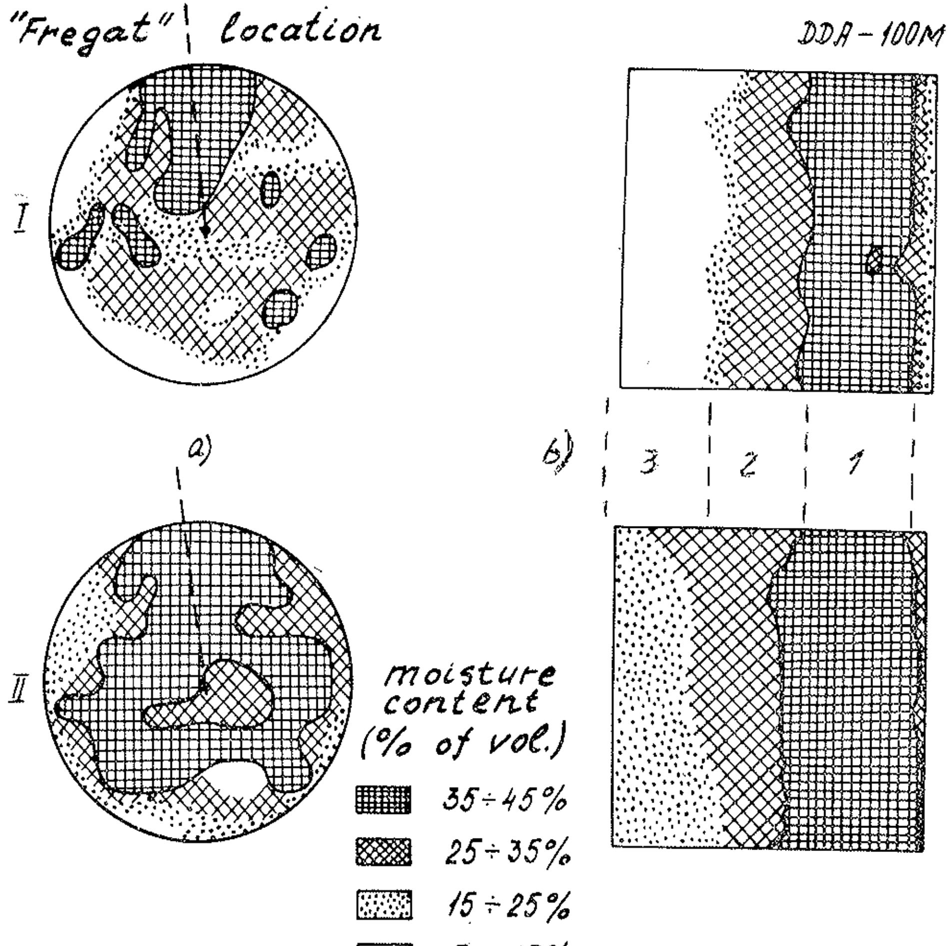

FIG. 15. Moisture content distribution within the area "Fregat" type (a) and "DDA-IOOM" type (b) of water sprinkler operation obtained by radiometric sets at 2.25-cm (I) and 18-cm (II) wavelengths. Watering: (1) on the day of measurements, (2) one day before, (3) two days before.

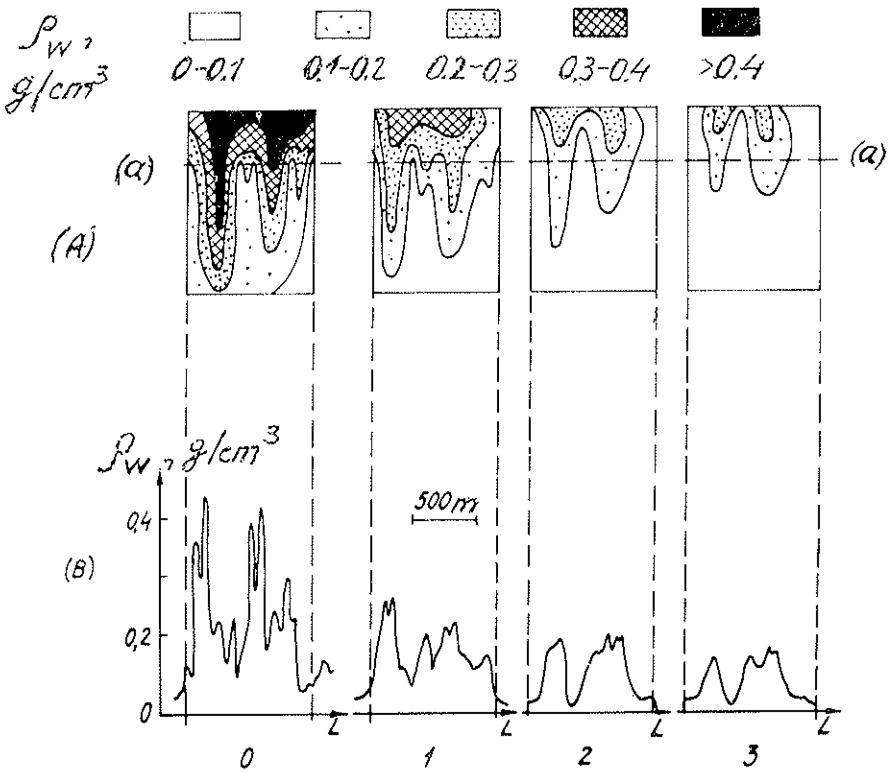

FIG. 16. Spatial-temporal soil moisture content monitoring that reveals the defects in ground surface planning at the fields with water feeding by furrows (A), and (B) retrieved radiometric moisture content data variations along the aircraft track (a). (0) day of water feeding, (1-3) days after water feeding.

crop forecasting and obtaining the degree of flood-lands overgrowth with cane for forecasting the spatial dimensions of high water in spring during snow melting. The example of the retrieved biomass of rice data is presented in Fig. 19.

— *The control of the degree of inland waters and coastal zones of water salting, freshening, contaminating* due to the river outflow, industrial and urban waste flow. The example of the salinity data in a coastal zone is presented in Fig. 20.

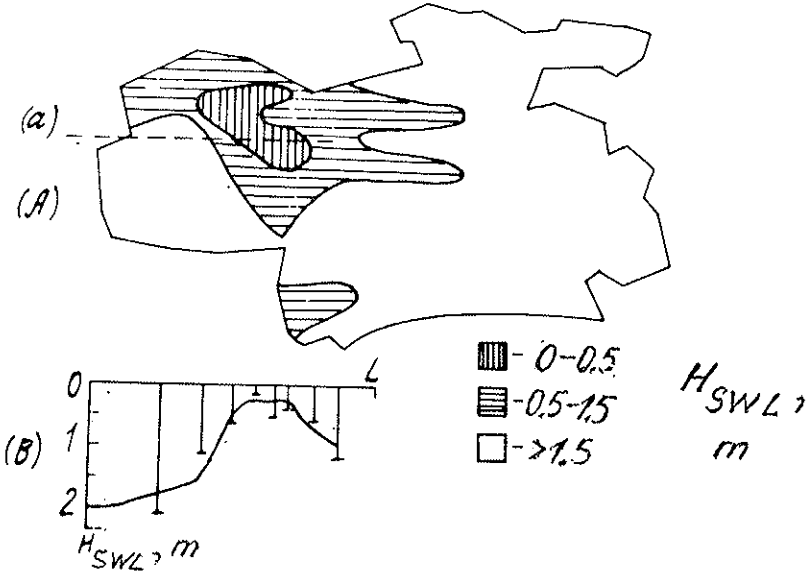

FIG. 17. Retrieved radiometric data of shallow water tables on an area of about 2000 hectares (A) and the results of a comparison (B) between radiometric (solid line) and ground truth data (vertical lines) of the depths of shallow water tables along the aircraft track (a).

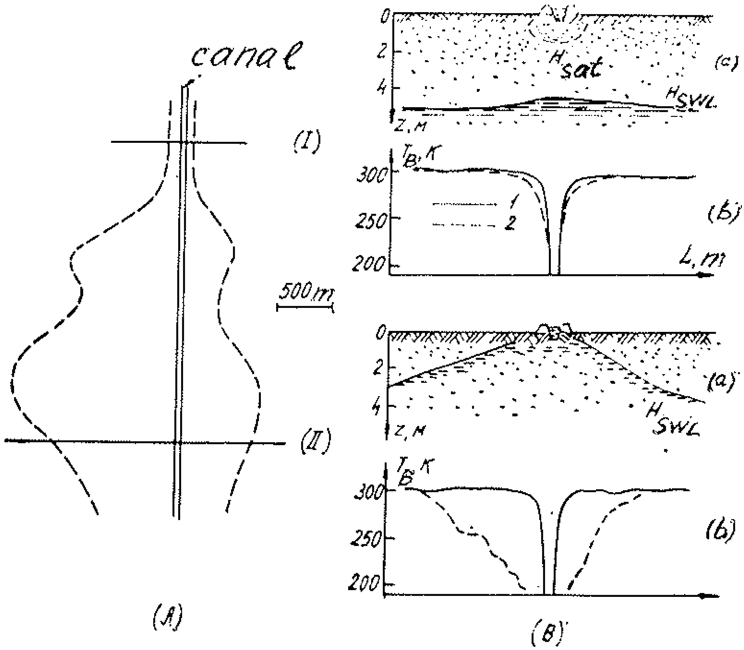

FIG. 18. Schematic map of a seepage zone (A) detected by means of microwave radiometry and examples of shallow water tables H_{SWL} and the depths of highly moistened soil layers (in a state of saturation) H_{sat} variations (a) as well as intensity of radiation (brightness temperature) variations (b) at the wavelengths of 2.25 cm (1) and 30 cm (2) along the aircraft tracks (I) and (II).

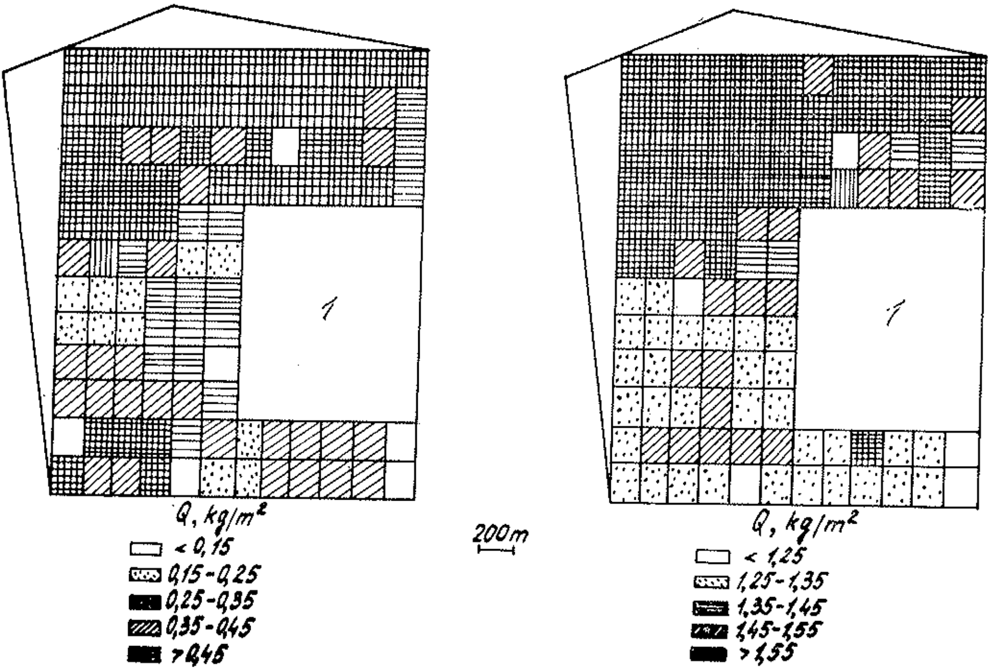

FIG. 19. Maps of a biomass of rice crop at the different stages of vegetation obtained by means of microwave radiometry, (1) other than rice crops.

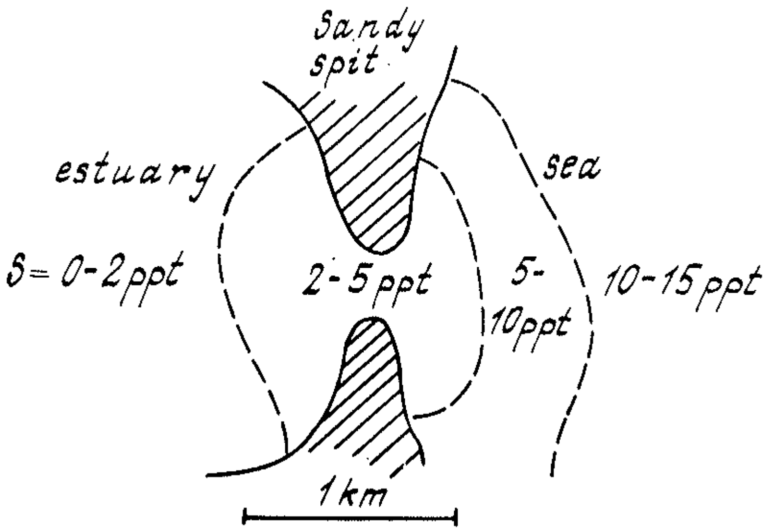

FIG. 20. Water surface salinity data obtained by means of microwave radiometry.

The local, regional, and global monitoring by means of passive microwave remote sensing. The platforms for sensors.

The methods described may be used on the local, regional, or global scale that is dependent on certain scientific and practical requirements. (See Table 3) [18].

The services of microwave remote sensing for soil moisture. Technical means. Indices of effectiveness.

The operational experiments described resulted in the organization of operational services for soil moisture sensing by means of microwave radiometry. That was done for the first time in the USSR and in the world. They were organized by the above mentioned ministries in Ukraine, Moldavia, North and South Caucasus, in some Volga regions, etc. [19-21]. The services solve many of the problems pointed out in Table 3.

The basis of technical means is a set of three radiometers that operate at the wavelengths of 2.25, 18, and 30 cm [22]. The beam width of antennas is about 30°. Nadiral orientation is used for all the antennas. This provides a spatial resolution about 70% of a carrier altitude.

The most effective type of carrier was shown to be a small biplane of ANTONOV-2 (AN-2) type already used for a long time in agriculture. This aircraft can solve about 90% of all the problems of the services of agriculture, land reclamation and water management, hydrometeorology.

There were revealed the next indices of effectiveness of the operational services of remote sensing for soil moisture:

— the productivity of mapping with a spatial resolution of 100 m (the area of pixel is about 1 hectare) that is required for the interest of separate farms is about 1000 hectares per hour; the cost price is about 10-20 kopeck per hectare;

— the productivity of mapping with a spatial resolution of 1 km that is required for regional or republic departments is about 10,000 ha/hour; the cost price is about 1-2 kop/ha;

— the farms receive the information in 5-10 hours after the flights; regional and republic departments in 1-3 days after the flights;

— the economic profit from the operation of these services is about 1 to 4 rubles per hectare.

TABLE 3 - *Possible use of the methods of microwave radiometry worked out.*

Nos.	Scales, problems, objects	Required spatial resolution	Type of platform
1	2	3	4
1	*Local scale problems* — soil moisture content determination in lands belonging to farms and in separate fields — obtaining estimates of the quality of watering and moistening in general — obtaining data on the state of canals, drainage systems — studying the characteristics of water régime (elements of water balance) in the dynamics of the moistening and drying of the soil at different depths — the exposure of zones with a high shallow water level — the control of a biomass of rice crop inside separate fields — the monitoring of mineralization of water in rivers and small reservoirs	50-200 m	— mobile platform, — small aircraft of ANTONOV-2 (AN-2) type
2	*Regional scale problems* — soil moisture content and storage of productive water determination in large farms, regions, certain geographical zones — the dynamics of soil moisture monitoring in the middle and large water basins — land-reclamation state determination, exposure of zones with high levels of shallow water tables — mapping of biomass of rice and cane crops — the monitoring of mineralization of water in large lakes, storage lakes, coastal zones of seas	200 m - 2 km	— small aircraft of AN-2 or AN-28 type
3	*Global scale problems* — mapping the rain precipitation over the land — monitoring the snow melting process — estimating the elements of water and thermal balance (régime) in the continents — the exposure of the direction and the intensity of some of the global processes in the continents (for example, expansion of the desert areas bogging up the territory, etc.)	2 - 50 km	— aircraft of AN-30 type, — satellites

Here is an example that illustrates the high economic effect of the operation of one of these services. Only during a springtime in 1986 there was a saving of about 500 million cubic metres of water in Uzbekistan by the use of operational maps of soil moisture content and the determination of norms of watering in a territory of about 2 million hectares. The radiometric data of moisture content were obtained for four days [23].

6. The Perspective areas for development and use of the microwave radiometry method.

It is shown that the microwave radiometry method is a perspective for development and use in the following areas:

— ground surface monitoring during freezing and thawing; detection of snow melting zones;

— detection of saline zones; obtaining the estimates of hydrological regime of dry and drying salt lakes;

— determination of salinity of soils;

— obtaining the information on potential productivity of lands by getting the radiometric estimates of such a parameter as "radiation index of dryness" that characterizes the relationship between heat and moisture content in the soils of different natural zones;

— determination of the condition of stress in plant [17] that characterizes the initial stage of plant fading.

At the end of my presentation I want to say: the specialists in remote sensing know that these methods can serve both welfare and warfare. Let our meeting become a dedication to the welfare.

Auguro buona fortuna e pace in tutto il mondo.

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REMOTE SENSING APPLIED TO NON-RENEWABLE NATURAL RESOURCES

THE USE OF SATELLITE IMAGERY IN BOLIVIA

C. BROCKMANN
Bolivia

Introduction

When the National Aeronautics and Space Administration (NASA) of the United States received approval for the Earth Resources Observations Systems program in 1968, NASA began making bilateral agreements with other countries (Mexico and Brazil), to test sensors on aircraft over their national territory.

These agreements provided data for training local scientists in the use and evaluation of the satellite data on these countries and helped to generate interest in remotely sensed data among the scientists of neighboring regions.

In 1971 Bolivia was one of several Latin American nations that submitted proposals to test and evaluate data from ERTS 1 (now known as Landsat) when it was launched in 1972.

At that time Bolivia, an area of 1.1 million km^2 had aerial photography of less than half of the national territory. The Instituto Geográfico Militar, Bolivia's National Topographic Agency, had undertaken to supply topographic maps at scales of 1:50,000 and 1:250,000. Good map coverage had been completed for most of the western part (Altiplano), but the mountainous regions (Cordillera Oriental) of the eastern cordillera and the low land of the Amazon basin were not yet surveyed. Best estimates at that time were that it would take at least 25 years more to complete the effect if aerial photography could be obtained without too much delay.

In other words, Bolivia in 1972 did not have a good topographic map or thematic maps.

The government of Bolivia in 1973 recognized an acute need for better information on resources in the national territory, and became interested in the satellite program. It decided that a national experimental program should be formed and managed by GEOBOL under the Ministerio de Minas y Metalurgia, with the participation of other government agencies having responsibilities for national resources.

In July 1972, more than 360 principal investigators from the world involved in the EROS program learned that ERTS 1 had successfully reached orbit and that all systems were functioning normally, but not until November of that year did GEOBOL obtain the first image of Bolivia.

From that time on, however, the data, in the form of black and white transparencies, continued to arrive in La Paz by mail; because of the limitations of tape recorders and other demands on the capabilities of the satellite, data collection over Bolivia was extremely sporadic. Another constraint was that the weather did not cooperate and clouds covered part of the scenes. Finally after 4 years, Bolivia had a complete set of cloud-free imagery, due to the excellent cooperation of the Instituto de Pesquisas of Brazil. This ground station has a range for reception of satellite data covering 70% of Latin America that includes all of Bolivia.

The early work done in Bolivia on the analysis of Landsat data was described in short, informal reports presented at NASA's Earth Resources Program review conferences. These conferences helped build the confidence of the interpreters and stimulated them to explore new avenues of research. It was truly an exciting period in the development of the technology applications.

Applications

Perhaps one of the most important results is related to the spectral studies of the Salar de Uyuni in the southwestern part of Bolivia, using Landsat computer tape analysis, an interactive computer analysis system, and Larsys software.

In standard images, the vast salt surface is so bright, similar to snow and clouds, that films and CCT's of the visible bands of the images are saturated. In the near-infrared bands, however, some patterns, probably related to water distribution and difference in relative depth, were noted. Computer analysis indicates that at least three different types of salt and nine patterns are related to water covers of varying depths. Field work confirmed this relationship, and sampling of brine and salt revealed the presence of very high potassium and lithium concentrations. Subsequent sampling by the Servicio Geológico de Bolivia (1976), U.S. Geological Survey (1976), ORSTOM (1976-1980), Gulf Research (1977-1978) and others, showed that the most abundant concentrations were located in the southeastern quadrant of the salar and near the mouth of the Río Grande de Lípez, which flows into the salar from the south. Because lithium is important in the manufacture of alkaline storage batteries and is a major constituent in fusion reactors, this deposit is the largest salt flat in the world (9000 km^2) and perhaps the richest in lithium, with more than 5.5 million tons. According to the latest news of the Ministerio de Minas y Metalurgia, the annual income could be over U.S.$ 110 million.

In the Empexa salt flat, where the spectral rationing bands and multispectral analysis were made, it was possible to identify three different surfaces. These, after being correlated with the field work, were found to coincide with salt crust, and surfaces of gypsum and calcium carbonate.

The eventual availability of images covering the entire national territory of Bolivia finally resulted in the compilation of a semi-controlled image mosaic and preparation of a new geological map.

In 1978 the first Bolivian Geological map was completed (scale 1:1,000,000), based on the compilation of the existing information in GEOBOL and the National Oil Company; in areas without geological information the multistage system was followed, that is to say, photogeologic interpretation was made using aerial photography, transcription to Landsat image, scale 1:250,000, and finally reduction to scale 1:1,000,000.

This new map, believed to be the most complete geologic map ever produced in Bolivia, is an excellent base for future mineral and energy exploration in the nation.

In 1976 an agreement was signed between GEOBOL and the British Geological Survey to map the Precambrian area in the eastern part of Bolivia. In this project 16 Landsat images were used, enlarged to a scale of 1:200,000 in infrared format, and this was the only base for mapping.

In these projects many new and significant mineral occurrences have been found such as gold concentrated in quartz veins, pegmatites with columbite-tantalite, beryl, cassiterite. There are very important concentrations of uranium, thorium, rare elements, niobium and phosphate rock.

Another project was the Metallogenic Map of the Bolivian Andes, which consists of three units: a Landsat image mosaic showing the prominent linear features; a second map on the same basis that shows all the mines of the region by name and type; and a third map showing type and relative size according to production with isothermal lines and contours based on the Mohorovic discontinuity (i.e., the top of the Nazca Plate). These maps are fundamental data bases for planning new exploration strategies.

Analysis of lineaments in the tropical lowlands of the Amazon basin (Beni region) also suggests the presence of structural patterns, that had not been recognized here before. The control of river drainage and the location of major meanderings indicate that some structural controls are related with buried anticlines of interest in petroleum exploration. Lineaments appear to control the shape of some of the lakes in this region and may reflect major fault zones in the basement structure.

Finally, in the same area there have been found and mapped many paleochannels, related with the actual Rio Beni. At the present time the main gold production comes from the Araras region (Madera River) and eventually from the paleochannels of the Rio Beni.

Geographic Information System

Bolivia, like many other developing countries in the world, has a tremendous need for basic, up-to-date, and readily available information about its natural resources, to provide planners and decision makers with the required information.

The system is an invaluable tool for a broad range of applications throughout the different phases of a development project, such as its planning and preparation, monitoring, and evaluation.

In addition, the system would be useful not only for more effective and efficient storage, management, analysis and retrieval of information, but it can become the basis for an integrated inter-institutional communications network.

Essentially, the Geographic Information System (GIS) was designed for the entire territory of Bolivia, and the development and implementation of this system for the Oruro Department. A simplified schematic configuration of the Bolivian GIS is illustrated in Figure A, and the natural resources, environmental and socio-economic elements of geocoded plane data base are shown in Figure B.

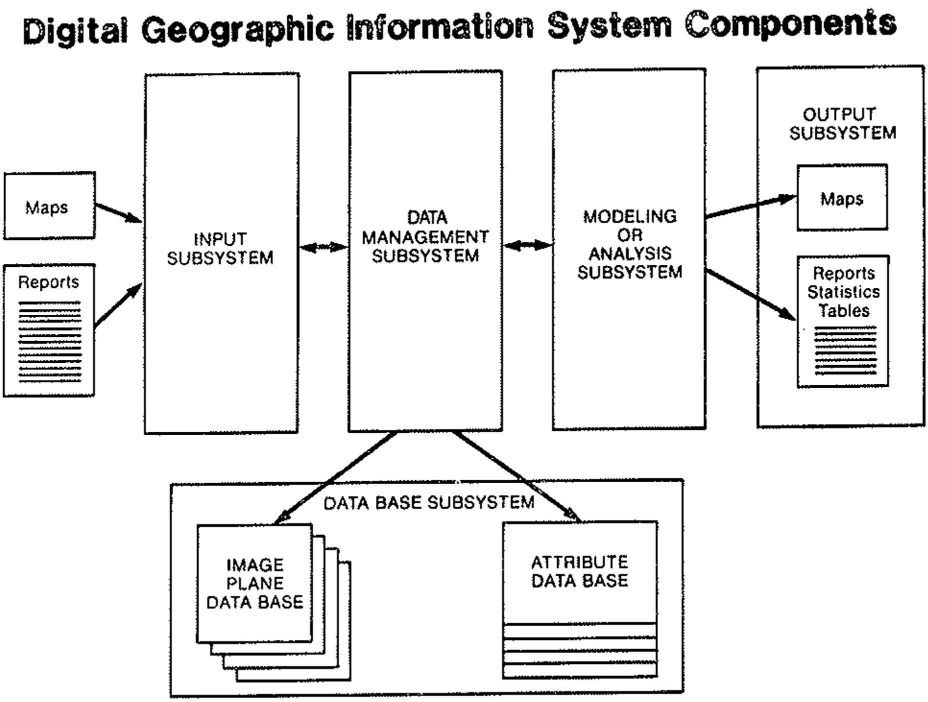

FIG. A.

The most significant achievements derived from this project include:

— The design of a digital geographic information system of national scope.

— A thorough investigation was possible to define the optimum resource map projection for Bolivia, i.e., the Albers conical equal-area projection.

— Development of hierarchical classification schemes (legends) for the various thematic elements, (classification coding).

— Development and implementation of an addressing scheme for storing geo-referenced data in a digital image format.

— Development of a method for storing large quantities of data for natural resource inventories and environmental data that allows managers, planners and decision makers to obtain useful information in an interactive mode at national, regional and local levels.

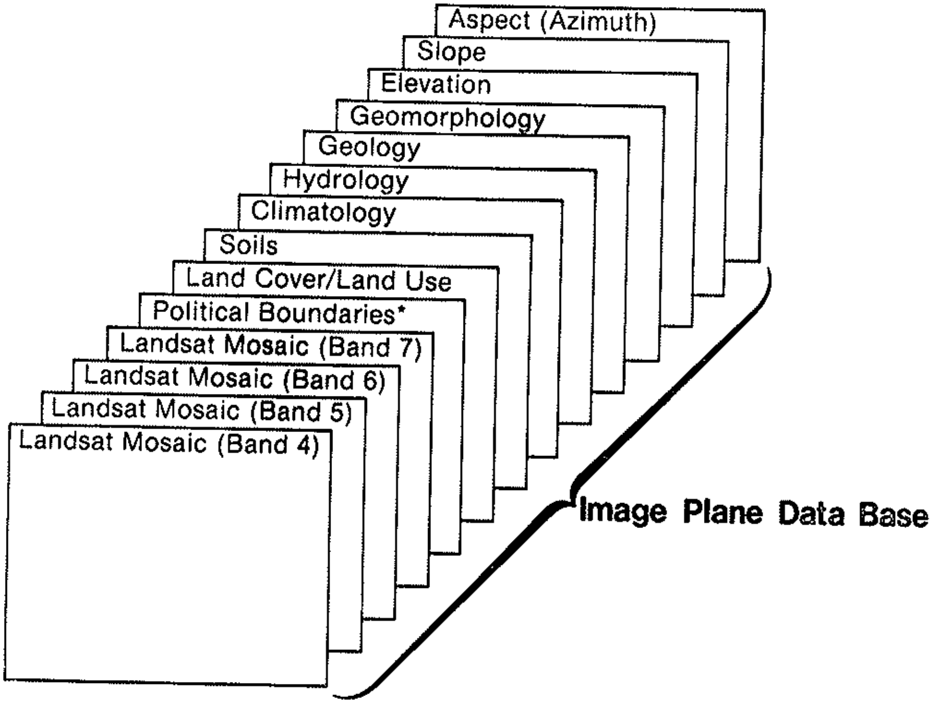

FIG. B.

* The Political Boundaries element includes the departmental, provincial, and contour boundaries of Oruro, Bolivia. It also contains the Socio-Economic variables.

— GIS provides the capability to store, manage, analyze and update effectively the country's natural resources, environmental and socioeconomic data.

— Creation of a digital Landsat MSS mosaic of the Oruro Department complete (seven images) with a quantitative planimetric accuracy assessment (RMS 126m).

— Development of computer programs for the conversion of topographic maps into digital terrain models (DTM).

— Definition of procedures to determine quantitatively the mapping and tabulation errors resulting from digitization of resource maps.

— Determination of an appropriate "cell-aggregation" method for the Landsat MSS mosaic data.

Land Cover and Land Use

In 1978 the first "Land Cover and Land Use Map of Bolivia" was published by ERST/GEOBOL on a scale of 1:1,000,000. The country was classified into eight categories at level I; i.e., pastures, forests, cultivated areas, swamps, water bodies, deserts, permanent snow and ice and cultural features, suitable for preparation maps on a scale of 1:4,000,000.

The introduction of the parameter "Altitude above sea level" defining level II, allows to prepare maps at a scale 1:2,000,000; the "humidity" and "characteristics of each category" correspond to level III of information enabling the preparation of inventories and maps on scales of 1:1,000,000 to 1:250,000.

Integrated Surveys

The Bolivian Landsat Program using Integrated Surveys (Geology, Geomorphology, Edifology and Geography/vegetation, etc.) using 65 Landsat images, has the Land Complex Maps of Bolivia on scales of 1:1,000,000 and 1:250,000, Soil maps at sub-order level with their corresponding taxonomic and Soil Capacity classification, Terrain Type maps, Vegetation and Land Use maps, on a scale of 1:250,000, which, due to economic reasons, could be published on a scale of 1:500,000 with an explanatory note.

Planning Transportation Routes and Other Civil Works

The broad perspective provided by satellite images and their spectral characteristics has helped in selecting transportation routes in Bolivia.

The first was the route of a gasline more than 500 km long, from Santa Cruz southeastward to the Brazilian border, to provide energy for the industrial centers of São Paulo State and southern Brazil. Several proposed routes were plotted on Landsat imagery, and the positive and negative aspects of the routes were found to be affected by outcrops, drainage, river flooding, swamps and related construction problems.

In 1981 the Italian company SNAM Progetti carried out the basic study of the preliminary route from Santa Cruz (Bolivia) to São Paulo (Brazil), which coincides with one of the selected alternatives in the Landsat image.

A second case was in the planning of a railroad spur from Santa Cruz to Trinidad (Tropic area). The land is relatively flat with heavy tropical vegetation terrain cut by meandering branches of the upper tributaries of the Rio Grande, a tributary of the Amazon River. The flooding and erosion by these meandering streams were avoided. A route was well protected for a long time and river crossings were kept to a minimum. In this project Landsat images with IR black and white and panchromatic aerial photographs have been used.

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REMOTE SENSING APPLIED TO NON-RENEWABLE RESOURCES - FOSSIL FUELS

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Une série d'analyses ne fait pas une synthèse
TEILHARD DE CHARDIN

INTRODUCTION

For at least six hundred years scientists have been making analyses and through further analysis have attempted to synthesize the results of much painstaking work. Notwithstanding these efforts, it is generally true that man's discoveries have not been made directly through synthesis but more often by what appears to be chance. In fact, these apparent happenstance occurrences owe their appearance to the aggregation of accumulated knowledge in the collective consciousness of science. It might be added that it is not a plethora of data which necessarily yields a useful conclusion but rather it is the proper arrangement of that information which provides the catalyst for synthesis, discovery and change.

For centuries we have had few means of collecting, viewing, interpreting, storing and manipulating data. In the earth sciences this has been particularly true and our discoveries have been serendipitous and few. With the advent of earth viewing space systems and computers we have a much enhanced ability to go from hypothesis to synthesis.

Aerial photography came into use as a remote sensing exploration tool in the 1920's. It and other remote sensing systems continue to be used as analytical tools and we shall discuss this analytical aspect further. Similarly, the computer, because of its speed and its capacity for information storage, has been used as an analytical adjunct to exploration work, particularly in the acquisition and processing of seismic reflection data. But have remote sensing and the computer added to our ability to synthesize? Space borne imaging platforms view large areas of the earth's surface simultaneously. When studying these synoptic views we can, if we are conscious of the existing ground data, manipulate, and integrate, much of this information with the assistance of computers, and so by deduction better understand the context of the many occurrences of fossil fuels which may heretofore have been treated parochially. With this approach we can begin to fashion more realistic postulates and models for the exploration of fossil fuels.

This paper will describe some of the analytical aspects of remote sensing and its use in exploration, and although we wish to emphasize that remote sensing is, if used analytically, merely one of many tools used in exploration, nevertheless we also wish to show that remote sensing and computers used in concert permit the user to synthesize tremendous amounts of data that it was previously impossible to integrate. This combined ability of remote sensing as an analytical tool and as a means of synthesis is its claim to fame and offers enormous potential for scientific advance and the discovery of additional sources of fossil fuels.

It is obvious that this academy is aware of the interest, if not the potential, of remote sensing or we would not be here; but it is also possible that some skepticism may exist because initially satellite remote sensing was poorly used as applied to the geological sciences. Slipshod studies were made, expensive and erroneous analytical methods were applied and unmerited claims were made. Much good, simple, straightforward geologic work has been conducted using remote sensing methods, including aerial photos, satellite imagery, radar and other systems; nevertheless, the mineral and oil industry has been generally disappointed by the results of those who promoted an alchemical approach to satellite remote sensing. A few technicians sold expensive surveys in which they promised that by the "transmutation" of spectral signatures they could "produce" oil fields and mineral deposits. Still others described remote sensing as a panacea. Employing it as a "tabula rasa" they plotted "anomalies" and the intersection of lineaments without concern for lithology, geologic time or existing descriptive work, and thus gave this technique a bad name. Such shoddy work continues and is at the basis of the views expressed by A. P. Miall in "Principles of Sedimentary Basin Analysis" (1984) in which he says in part: "One new mapping technique that has generated some interest recently is the use of satellite imagery to locate subtle structures in a search for giant oil and gas fields. The results are singularly unconvincing. Vague tonal changes and disconnected lineaments are apparent, but in most cases these bear little or no relationship to the fields. It seems unlikely that such images will ever be of more than passing interest for basin mapping purposes,...".

Our concern in this paper will be to prove that remote sensing can be used to find new sources of fossil fuels *per se*, but that remote sensing, artfully and carefully used in conjunction with other analytical methods, provides the means to view the world in a new and more critical way, which will allow for up-to-date syntheses, new exploration hypotheses, new models, and new discoveries.

Purpose

Our purpose, then, is to show how remote sensing can make a *contribution* to the search and discovery of fossil fuels in the Third World. We must not consider the present low prices of fossil fuels as a deterrent in our search, but rather remember that these prices are not any more related to true supply now than they were in 1973, when the prices were raised. It is this very situation which must convince us to assist the Third World in locating and developing their own supplies so that entire populations are not at the mercy of a few countries or companies.

Method

To understand how remote sensing can be used for exploration purposes we will first discuss the characteristics of fossil fuel accumulation, the geologic setting of sedimentary basins, their location, extent, and potential as well as conventional exploration methods. Finally, we will try to give some examples of applicable remote sensing techniques, examples from the recent literature and the work of scientists throughout the world.

Characteristics of Fossil Fuel Accumulation

Oil and Gas

Oil and gas accumulations are mixtures of hydrocarbon compounds which are found primarily in sedimentary rocks. Until recently it was thought that these compounds were formed from chemically and physically altered organic material. Recent work suggests that at least some hydrocarbons may be derived from primary methane. There is no question that through geological (tectonic) processes hydrocarbons migrate into permeable and porous lithic reservoirs, from which they can be extracted by drilling or mining (oil shales). Just as the origins of oil and gas are still being debated and may include organic and inorganic sources, so too, oil and gas are being found in a greater spectrum of reservoirs including not only sedimentary sequences but porous volcanic rocks known as tuffs and metamorphic and igneous rocks. A hydrocarbon reservoir is defined as the type of rock or lithology and its geometric configuration. These distinctive features are known as "traps" and are generally found in the major sedimentary basins of the world.

Since 1960 more and more oil and gas have been found offshore in the extensions of continental sedimentary basins. These regions are as yet only partially explored and may ultimately contain between 40-50% of the earth's reserves. They are, nevertheless, of little or no interest to those of us who are using present remote sensing techniques. Nevertheless, large areas of source rocks with potential remain to be explored within the Third World continental boundaries. The sedimentary basins with the highest potential for oil and gas are those where great thicknesses of sediments have accumulated. Reservoir depths can vary from near-surface to over 9 km. The average reservoir depth is about 1.5 km, but this figure will change as deeper producing horizons are tapped due to the decline in production from shallow reservoirs. The greatest accumulation of oil and gas took place during the Mesozoic ± 100 Ma ago when major tectonic activity took place and the supercontinent known as Gondwana broke up to form Africa, South America, and India. At this same time, less important tectonic activity occurred along the Persian Gulf rift zone, creating continental subsidence and the accumulation of organic rich sediments. This sedimentation occurred during a tropical period, which was the reason for the increase in organic materials. A subsequent decrease in tectonic activity in the Persian Gulf and the Gulf of Mexico protected the giant oil fields in these areas.

Coal, Lignite and Peat

Although these three sources of energy have dissimilar characteristics, their mode of formation or origin and occurrence is the same. These three sources of energy are all the products of decayed plants which have been either slightly compacted (peat), indurated (lignite and bituminous coal), or metamorphosed (anthracite coal). These materials are classified by type (by the difference in the kinds of plant materials they contain), by rank (differences in the degree of physical and chemical change they have undergone, which can also be referred to as metamorphism) and by grade (the range of impurities they contain). Generally, we use the term *bituminous* for normal coals. Peat, lignite or brown coal and bituminous coal form a part of a characteristic sedimentary phenomenon called a cyclothem. This refers to the rhythmic and repetitive occurrence in sediments of these sources of energy. This point is important because a typical sedimentary sequence formed in a deltaic basinal environment will consist of a succession of repetitive coal measures. Thus, the discovery of one bed or measure of peat, lignite or coal usually implies the existence of others stratigraphically higher or lower. These sources of energy originate in a variety of geographical settings, including deltas, lagoons and estuaries. The rhythmic or repetitious nature of these deposits is due to a number of causes, including the fluctuation of sea levels, but more often to the slow formation of basinal depressions which occur along the continental margins. Coal formation is accentuated in deltaic regions where rivers provide the ecological conditions required for vegetative accumulation and the volumes of sediment needed to perpetuate basinal development. Most coals and associated combustible materials are of the Carboniferous age (320-285 ma.), when climatic conditions and evolutionary trends combined to create an enormous expansion of the vegetal kingdom. Such conditions exist today in tropical regions, which tend to be more favorable to coal formation, but also in other climatic regions, including sub-polar regions where organic matter accumulates in bogs due to the downward (basinal) pressure exerted by the weight of ice sheets. Many of the Permian (285-225 ma.) coal measures in the southern hemisphere formed, after the late Carboniferous ice age, in limnic bogs, at between latitudes of 50°s and 70°s. Large areas of Africa, South and Central America have potential for coal, lignite and peat and some countries, such as Colombia, have major reserves of coal. Other areas, as in Senegal, in West Africa, are the site of intensive exploration due to recent discoveries of near-surface lignite (brown coal).

Conventional Exploration Methods

Effective exploration for energy resources attempts to syncretize data acquired by many techniques. Seldom is a discovery attributable to one exploration method. In addition, new technologies have never resulted in quantum or even important leaps in discoveries. New technologies have added significantly to reserves, but these usually have had a "waiting period" before such benefits could be clearly measured. Although coal exploration is somewhat less complicated, it employs the same basic methods used in oil and gas exploration.

Surficial or Seep Prospecting and Surface Mapping

Coal, in its various forms, and oil have been explored for, mined or collected at the surface for thousands of years. Surface geologic mapping as a means of defining subsurface rocks and their relative position with the object of finding coal did not begin until the early eighteenth century, and similar mapping for oil and gas did not begin much before 1900.

Core Drilling Exploration Methods

Core drilling is a relatively old (circa 1900) and simple exploration tool. By comparing the core chips from an exploratory drill hole to those of a successful hole, an effective system of exploration was developed by analogy. Core samples made it possible to identify lithologic, paleontologic, stratigraphic and structural controls. Core drilling methods continue in use in both hydrocarbon and coal exploration and reached this peak in the 60's with the optimal application of microfossil analysis.

Geophysical Well Logging (Subsurface instrumentation)

In the 1930's, subsurface exploration methods were much improved by the invention and application of mechanical and electrical methods of bore hole analysis. Instruments lowered into the drill hole on a wire line were used to measure the physical properties of the rocks. These instruments measured the change in the lithology, porosity, permeability, and the degree of saturation of the rocks by gas, oil and water. These exploration tools have, over the last 50 years, reached an extreme degree of complexity and to this day continue to furnish a great deal to most exploration programs.

Geophysical Exploration by Surface or Aerial Methods

Although these exploration methods predate well logging, they did not come into widespread use until the late 30's and 40's. Because these systems gather large quantities of three-dimensional information over extensive areas, the interpretation of such data was time-consuming and therefore expensive. The development of the analog and digital computers increased the speed of collecting and analyzing such data.

The most important system of this kind developed in the 1950's and 1960's is seismic reflection. This system, employed on and offshore, delineates the interface between rocks and/or sediments with different physical and chemical characteristics which therefore reflect sound in different ways. Continuous sonic profiling also provides information on the geometric aspects of the rock or sediment interfaces, thus permitting the mapping of non-visible subsurface structures such as domes, faults and fractures.

Gravimetric and magnetometric surveys were introduced in the 30's and 40's. Gravity and magnetic methods are useful in determining the configuration of the subsedimentary basinal rocks which typically are crystalline and usually are referred to as basement rocks. Magnetic and gravity surveys also permit the mapping of folded sedimentary belts and often can be used to define faults and other rock discontinuities as well as subtle structures not obvious at the surface.

Geochemical and Geobotanical Prospecting

Geochemistry is used to measure the quantity of organic matter in rocks and sediments or the surface emission of certain gases or trace elements associated with oil, gas or coal deposits. Geochemical surveys help to identify potential source rocks and to measure the level of thermal maturity of the source rocks with respect to the potential generation of oil and gas. Another geochemical tool developed in the 60's measures the radiometric response of rocks. Airborne and ground radiometers measure the gamma ray intensity emitted by the surface rocks from sources of uranium, thorium or potassium. The concentration or absense of radioactive elements can provide information concerning the lithology of a region or its mode of origin, and so, by inference, its potential as a source for oil, gas or coal.

Geobotany has been used primarily in the Soviet Union as a means of measuring the effects of hydrocarbon or methane gas leaks on surface vegetation. Abnormal leakage of such gases produces change in vegetative patterns at the surface. It is possible that certain species are affected by such leaks and thus are either stronger, weaker, fewer or more numerous, depending on a number of other variables. Geobotanists attempt to map these variants and provide information to petroleum geologists showing the anomalous vegetated areas. These analyses require the combined knowledge of botanists, geologists, geochemists, plant physiologists, foresters and soil scientists, among others.

Remote Sensing Exploration for Fossil Fuels

Remote sensing techniques used in exploration for fossil fuels include: aerial photography, airborne radar and satellite sensors including active sensors such as radar (Seasat satellite), Landsat scanners and Return Beam Vidicon cameras and Spot satellite scanners.

Aerial photography is considered a remote sensing exploration tool. Notwithstanding this rather exotic appellation, it is the most basic and most often employed exploration tool of the geologist with the possible exception of the pick and hammer. Before we describe the more recent remote sensing techniques, we should review the role of aerial photography in exploration for fossil fuels. We should also make the distinction between aerial photography, which is acquired by airplanes, and space-acquired photography. The distinction is one of scale rather than type. Aerial photos are seldom produced at scales less than 1:125,000 and are typically acquired at scales of 1:60,000, 1:50,000 and 1:40,000. These scales are used for conventional reconnaissance mapping, whereas larger scales, such as 1:20,000 and 1:10,000 and larger are used for detailed mapping or for outlining coal deposits in complex structural terrains. Of course, the greatest advantage of aerial photos is that they provide a three-dimensional view of the terrain when viewed through a simple stereoscope. This ability to see the relief of the area of interest greatly facilitates the plotting of outcrops and the mapping of discontinuous lithologic units as well as making it relatively easy to understand the causes of these discontinuities and the geometry of the rock units. One disadvantage of aerial photos is that only the central point in each photo is in its correct geographical position; all other points are displaced, particularly in terrains of variable relief, due to distortion inherent in all lens systems. Another disadvantage of aerial photos is their small size and therefore limited areal coverage, in comparison, for example, with satellite photos. A further disadvantage is that aerial surveys are costly and coverage may be discontinuous due to weather conditions.

Interpretation Factors

Gray tones on black and white aerial photos, whether panchromatic or infrared, are related to the reflectivity of visible outcrops. Quartzite, granite, some limestones, and felsic igneous rocks reflect a high percentage of the incident light and so have light tones; shales, massive limestones and slate have darker tones; basalt flows or other ultrabasic rocks and many metamorphic rocks absorb most of the incident light and appear very dark. Tonal contrast and textural appearance depend on climatic, soil and vegetation conditions as well as the reflective signature of the rock units themselves and shadows cast by objects. Interpretation factors considered by geologists using aerial photos include photographic tone as described above; color, which is especially useful in arid areas and used to detect vegetative stress; texture, which is a composite of tone and other natural aspects familiar to the interpreter, such as topographic or drainage texture; pattern, which is distinguishable by the spatial arrangement of lithologic, topographic or vegetative features, which in turn are attributable to such features as faults, joints, dikes, bedding, etc. Other significant, but secondary, interpretable factors distinguishable on aerial photos are the size and shape of features, the combination of recognition elements, and the interrelation of associated features.

Type of Information Derived from Aerial Photos

In exploring for oil, gas and coal, the geologist using aerial photos must determine the distribution of rock units, including overburden or surficial deposits, and define the geometry of geologic structures. Vegetation, soil wetness, direction of rock units, and a myriad of other means, both qualitative and quantitative, are used in deriving information from aerial photos. By interpretation we attempt to derive the following types of information:

— The lithologic character of the rock
    sedimentary-bedded

igneous - homogeneous or flow-like
metamorphic - combination of above

— Structure or geometric relationships

Flat lying beds	
Dipping beds	Thickness Slope
Folds	
Faults	
Joints	
Cleavage/Foliation	Slope Direction
Unconformities	
Topography	

— Vegetation Characteristics

— Drainage Characteristics

In regional photo analysis, particularly for petroleum and gas exploration, a worthwhile approach is to prepare a small-scale photographic mosaic and to interpret the geology by identifying the associated geomorphic features. Such an approach is hierarchical and distinguishes between 1st order features: continents and ocean basins, 2nd order or constructional land forms, including plains, plateaus, block, folded, dome, volcanic and complex mountains, and 3rd order features which are destructional. Third order features are either erosional, such as valleys; residual, such as hills or buttes; or depositional, such as deltas. All these forms relate to the activity of either streams, glaciers, waves, or wind. Each can be further classified as to its stage of development. A meandering valley thus represents the old age part of the geomorphic cycle, whereas a deeply incised "V" shaped valley represents the youthful part of the cycle.

If this mass of data seems mind boggling, we should do well to remember that it is only a partial list of the possible ways aerial photos can be used . It does not include the use of colour photography or multispectral photography, both of which systems provide additional masses of information to an interpreter trained in the use of these techniques.

Radar Imaging Systems

Since the 1950's side-looking radar images have been acquired from aircraft (SLAR). Commercial use of this technique has been available since about 1965. Radar systems send out their own signals and record the returning response as opposed to recording only incoming radiation. The latter systems are known as passive, whereas radar is considered an active remote sensing system very much akin to the systems used by bats and dolphins or the camera taking pictures with a flash. The obvious advantage of radar systems is that by providing their own source of radiation they make all-weather and day-and-night operations possible. In addition, radar systems can be controlled to send and receive signals at a variety of angles. This provides a means of defining features in relatively flat regions by using a low angle source of energy. Conversely, a high angle source of illumination can be used in rough terrains, or can be "aimed" to accentuate certain subtle features which may have significance in exploration and which would otherwise not be available.

Side looking-airborne radar (SLAR) has a typical spatial resolution of 10 to 40 m. Satellite synthetic aperture radar (Seasat, SIR-A and SIR-B) has provided imagery with 80 meter resolution.

The advantages of radar coverage in heavily vegetated, high altitude, poorly mapped and cloud covered areas are significant. Most of Brazil, Venezuela, Colombia and Indonesia, as well as other parts of the Third World have been flown by radar. The disadvantages are that aircraft coverage is expensive and that as of today satellite radar coverage is only partial.

Satellite Multispectral Imaging Systems

General

When the subject of this paper was considered, it was assumed that the audience would be most interested in hearing about the potential for fossil fuel exploration by means of satellite-borne multispectral systems that are presently in common use. These systems include Landsat with 80 meter resolution, Landsat Thematic Mapper with 30 meter resolution and SPOT with 10 meter resolution. Although the cost of such imagery has risen markedly since 1972 (from about $200.00 to about $3,000.00 for the most useful products), nevertheless the advantages of such images still far outweigh the costs, especially in poorly mapped areas. It has been shown over the last 14 years that conventional photo interpretive techniques can be applied to Landsat imagery with positive results (Lang *et al.*, 1985; Colwell *et al.*, in Manual of Remote Sensing, 1983). Such surveys have been funded by USAID (Senegal, Mali, Zaire, etc.), the World Bank (Madagascar) in Third World countries. Nevertheless, such simple surveys have seldom been tested. Highly sophisticated analyses have been conducted by the oil industry, but few results have been published. These analyses have become more and more dependent on two important but not essential analytical approaches. The first is digital image processing. Digital image processing is used to improve the interpretability of an image for a particular reason. The second technique involves the integration of various levels of geologically related information by means of computers; so that for example, topographic information is super-imposed on geological information, on which is added geobotanical data or Landsat-derived lineament analysis or geochemical data. This combination of data sets or "data stacking" has proved to be very effective and is used by every major oil company, but it is also very expensive and labour intensive. Furthermore, and in the final analysis, both conventional and sophisticated approaches still require the services of a highly trained, eclectic interpreter.

Rather than describe multispectral satellite imagery analysis in detail, I have chosen to discuss a number of test cases. These test cases include: conventional photoanalytical surveys using ancillary data, including other remote sensing systems and field work, and non-conventional surveys using digitized data and computer enhancement of various remotely sensed data as well as computer manipulation and compositing of other data sets.

Test Cases

NASA/Geosat Test Case (A sophisticated computer-aided analysis)

In October, 1984, NASA and the Geosat Committee published the results of a number of test case studies in mineral and hydrocarbon exploration. The Geosat Committee is composed of a number of corporate representatives interested in the application of modern remote sensing techniques to exploration. The test sites include a temperate vegetated area in folded mountains at Lost River, West Virginia, a semi-arid area at Patrick Draw, Wyoming, in a relatively simple geologic environment but in somewhat complex topography, and a deep, complex oil "play" in a sparsely vegetated and relatively flat area of the Permian Basin.

In each case a very thorough analysis was made using the following methods and criteria:

1. Climate
2. Physiography
3. Surface Geology
   — structures
   — stratigraphy
4. Subsurface geology
   — Reservoir Stratigraphy
5. Production
   — location
   — statistics
6. Vegetation
   — collection of data in the field
   — cover estimates
   — species diversity
   — vegetation stress (stunting or dechlorophilization)
7. Soils
   — organic geochemistry
   — soil gas chemistry
   — soil elemental geochemistry
   — soil carbon and oxygen isotope geochemistry
8. Multispectral Remote Sensing
   — Systems
      · Landsat MSS (4 bands) (multidate)
      · aircraft NS-001 thematic mapper simulator (8 bands)
      · Bendix (M^2S) (11 band) photography
      · color photography
   — Evaluation methods and criteria
      · geologic interpretation of multidate Landsat data
      · spectral characteristics of cover types
      · spectral characteristics of soil/rock types
      · lineament analysis
      · tonal/textural analysis

9. Radar analysis (Seasat)
10. Luminescence studies (Fraunhoffer Line Discriminator)

The conclusions from these test case studies are as follows:

1. *Direct detection of hydrocarbons* - In spite of a very expensive, high level scientific effort, no direct relationship could be made between anomalous tones, either pedologic or vegetative, which would permit one to conclude that surface anomalies at the 3 sites represent the effects of hydrocarbon seepage.

2. *Stratigraphic (lithologic) Mapping* - Thematic mapper (simulated) interpretation was shown to produce better geologic maps than previously existed in Wyoming, less so in Texas, and when related to vegetation mapping in the Lost River test area, this method improved the geologic maps available.

3. *Structural Mapping* - Detection of joints, faults and folds is clearly excellent and previously unmapped structures were found in all 3 test sites.

4. *Lineament Mapping* - Linear features are directly related to structural features in all 3 test sites and when mapped for their density per given area they show a direct relationship to the gas field at Lost River. Such a direct correlation cannot be made at Patrick Draw or the West Texas site, but lineament analysis is correlated to major oil-bearing structures in a general fashion and helped to localize search areas within the basins. Such lineament analysis also helped to refine locations of areas with potential for enhanced fracture porosity.

5. *Spectral Analysis* - It was the general conclusion of the NASA/Geosat test case studies that "Analysis of field and laboratory spectral data and image spectral data . . . demonstrates that in mixed soil/rock/vegetation terrain this goal (identity of surface materials) is not accomplished. Mixing several spectral components in the scanner-acquired radiance data typically precludes unique identification of materials".

U.S.G.S. - Spanish Test Case

Dr. Larry Rowan of the Geophysics Branch of the United States Geological Survey is presently completing the analysis of a Thematic

Mapper test case survey in Spain. Although this study was made on a tin-bearing province in western Spain, it nevertheless exemplifies the use and potential of spectral discrimination of rock types by remote sensing systems, and has obvious implications for fossil fuel exploration.

The area in question is a tin-producing region in a Paleozoic sedimentary terrain which has been intruded by Hercynian Granites. These granites are clearly visible on the "principal components" enhanced version of the TM imagery used for this work. The granites often have associated tin deposits, therefore a search for buried granite intrusions was the objective of this study. The typical granite apophyses are surrounded by metamorphosed haloes. These rock types are identified as hornfelses. It is clear that a buried granite might well have a surficial halo of hornfels. Typically the spectral signature of hornfels is different from that of the granite and surrounding slates. Therefore, the identification of this unique spectral signature should point to buried granite masses. This in turn should provide the geologist with potential tin targets near the surface.

This study clearly concludes that rock discrimination by spectral signature analysis is possible in semi-arid areas and so applicable to fuel exploration.

Oil Exploration in the Michigan Basin

Paleozoic rocks of the oil-producing Michigan Basin are overlain by about 200 meters of Quaternary overburden. It can be readily concluded that such thicknesses of overburden would preclude the interpretation of linear features and other structures in the underlying productive Paleozoic rocks.

Landsat analysis of this area (Drake and Vincent, 1975) by Geospectra Corporation defined a northeast-southwest trending lineament corresponding to one side of a similar trending graben correlated to the Lake Saginaw depression. The study by Geospectra of Landsat computer-processed images in combination with seismic data and other available published information confirmed the discovery of a subsurface structure favorable for hydrocarbon accumulation to a depth of 3500 meters. Drilling located gas in this structure, and additional analysis of enhanced Landsat imagery of the Michigan Basin has been used by Geospectra to identify several previously unknown areas of favorable structures.

Other Recent Fuel Exploration Efforts

Other authors, including Maurin and Riguidel (1978) of TOTAL Paris, used Landsat digitally enhanced imagery to assist in mapping a Tunisian oil field. Their enhancement technique helped to refine structural information in a folded and faulted system of Mesozoic rocks.

Bedzhiev and Natapov (1985) used Soviet acquired space imagery to map deep seated tectonic features in northwestern Siberia and related these to potential reservoirs.

Halbouty (1980) studied 15 giant oil fields throughout the world and noted that if Landsat data had been available before their discovery at least 13 of these fields could have been located with the help of Landsat imagery and at lower cost.

Taranik and Trautwein (1976) and Taranik (1978) describe the methods of computer processing of Landsat data for geologic applications and the integration of geological remote sensing techniques in subsurface analysis for fossil fuel exploration.

The U.S.G.S. (Ray, 1984) has through its National Mapping Program continued research in satellite image mapping and processing. Recent work in Kenya, Tunisia and the Western Sahara has produced superlative enhanced Landsat TM imagery and Mosaics. Mosaics are of great importance in the analysis of large basins and their structure. This program is also reconstituting geometrically corrected and enhanced data from TM and Spot in a quadrangle format.

Ishanov *et al.* (1985) found that satellite remote sensing techniques were very useful in evaluating the prospects of oil or gas in Tadzhikistan and that space imagery could be used in overthrust geologic terrains in which subsurface structures could be interpreted by inference.

Harold Lang *et al.* (1985) conducted a workshop including 43 geologists from government, industry and academia to discuss basin development problems in Wyoming and other areas and to determine the application and usefulness of remote sensing to such problems. During this workshop, Dr. F. Berger, Exxon Production, concluded that interpretation of Landsat MSS, TM, radar, and aerial photos had been successfully used to locate geologic discontinuities associated with oil and gas accumulation.

Other significant results of this workshop include the recognition of previously unreported thrust faults, identification of an increase in thickness of an oil producing sandstone and the determination and location and stratigraphic distribution of several rock types. These results were confirmed by unpublished and proprietary geologic mapping and geophysical data.

Stancioff, A. (1982) in a report for Billiton of Canada showed that by combining conventional Landsat Imagery (MSS), R.B.V. photography, magnetic, gravity and topographic data with geologic maps, small structurally controlled oil and gas traps could be identified in the Carboniferous Basin of New Brunswick.

Coal Exploration Using Remote Sensing

Coal Exploration is a much less complex problem than the search for oil and gas simply because coal is deposited in strictly confined horizons and is, unlike oil and gas, "immobile" even when disturbed by tectonic activity. Therefore, once a coal horizon or bed is located, it can usually be traced in all directions for long distances. Another parameter which in a sense simplifies this search is that coal exploration is typically conducted near the surface and not at great depth.

Coal exploration is usually conducted using topographic maps with aerial photos. Once a coal bed has been identified its lateral extension is traced on the topographic maps by referring to the aerial photos (usually colour). Because of its colour, coal is easily identified on aerial photos. Although it is difficult to see on 80 m resolution Landsat images, TM and Spot provide much more useful imagery for coal identification. As in oil and gas exploration, structural controls, including discontinuities, are important in the location of coal resources and in this context satellite sensors are extremely useful in establishing the structural relationships within coal hosting basins. Thermal imagery is sometimes used to locate areas where coal has burned at the surface and so provides a unique and easily identifiable signature.

Remote Sensing for Fossil Fuels in Senegal — A Conventional Survey

In 1986 the Remote Sensing Institute of South Dakota State University completed a multidisciplinary mapping effort of Senegal. This project provided the Senegalese Government with maps of the geology, hydrology, vegetation, land use, soils, land capability and other resources of Senegal.

The maps produced were at 1:500,000 scale and were to be used as planning documents by the Government. No specific work was done to locate fossil fuel sources. Nevertheless, the survey suggested a number of areas of fossil fuel potential.

Before discussing the results of the work done, it might be worthwhile to point out the methodology used in conducting this survey.

Methodology

The methodology used in this survey is relatively simple and consisted of the following steps:

A. Choosing the best available imagery as a base for interpretation.

B. Conducting a rapid literature review to understand the basic geological and hydrological aspects of the country.

C. Conducting a rapid interpretation of the major lithological and structural entities of the country at a scale of 1:1,000,000 on individual images and on a black-and-white mosaic at the same scale.

D. Comparing initial interpretation results to available maps to verify the ability to identify known rock units as well as faults, fractures, and folds, and correcting the initial interpretation and redefining the approach if necessary.

E. Making short field trips to establish spectral characteristics of the land surface and the relationship of various morphological features.

F. Interpreting the geomorphology and geology of Senegal at a scale of 1:250,000 using available maps and aerial photographs. Completing first order interpretation, beginning with the least complex areas. Using all available imagery, including RBV and multidate (multiseason, multiyear) imagery. The interpretation is conducted by placing the Landsat imagery on a light table and overlaying a clear acetate or frosted transparent material (mylar), on which definable units or features are drawn. Once interpretation is complete on one image (for example, a color composite), comparison is made by using either a color image of a different date or by using a black-and-white image of the same or different date. Better results are also achieved by using RBV imagery or aerial photographs. Usually transparencies of topographic maps (if available) at the same scale are used to locate the features interpreted as they relate to roads or towns. Sometimes roads and towns are preplotted on the interpretation sheets; however, these tend to be distracting. Available geologic or other maps are also used in order to maintain consistency and assist the interpreter where the lithologic units are masked by thick vegetation (as in Casamance) or by brush fires (as is often the case in Senegal). Generally, dry season imagery is used for hydrogeologic interpretation. Preparation of a first legend follows this step.

G. Preparing field work by choosing areas or specific points on the Landsat interpretation where disagreement exists with published results. Defining anomalous areas which may not have been previously noted for verification. Choosing areas or points which are difficult to interpret. Preparing final traverse maps to cross the maximum number of anomalies, geologic or hydrologic boundaries or other distinguishable features.

H. Conducting field work to verify the above.

I. Correcting interpretations to agree with the field-collected data and preparing the second order legend.

J. Conducting aerial overflights to better understand the relationships between ground and interpreted features.

K. Making final corrections to interpretations.

L. Transferring interpretations to base maps and assuring unit continuity between Landsat images.

M. Preparing final legend and defining unit relationships, (i.e., age, geometry, etc.).

N. Correcting and coloring base maps to assure coherent relationships, refining legend by means of this step.

O. Scribing and/or drafting the final map for publication.

P. Preparing additional maps based on interpretation of results (e.g., tectonic, fuel and mineral potential, water availability, water degradation, etc.).

Results

The work conducted in Senegal from 1983 to 1986 resulted in the production of the following:

a. A hydrogeologic map in colour at 1:500,000
b. A hydrologic map in black and white at 1:500,000
c. A tectonic map at 1:1,000,000
d. A hydrocarbon and mineral potential map at 1:1,000,000

Conclusions relative to fossil fuel sources in Senegal are as follows:

1. *Oil and Gas*

Oil and gas sources are generally restricted to the western portion of Senegal and its offshore continental shelf extension. It would be foolish to hazard any guesses concerning the offshore and coastal areas without the benefit of data accumulated by the oil companies that have worked in Senegal. On the other hand, reports of oil seeps are numerous in Senegal, especially in the area between Bambey and Joal on the Petite Côte. Gas was found in the Cap Vert area and is known to occur offshore. An excellent summary of the oil and gas potential of Senegal can be found in a recent issue of *The Oil and Gas Journal*, (Dumestre, 1985). In this article, M. Dumestre divides Senegal into two basinal zones, one north of Dakar, the other south. Both appear to have potential. Salt domes and associated diapiric sediments were drilled, and the presence of 600 million to 1 billion barrels of heavy crude oil was confirmed in Oligocene, Eocene and Paleocene carbonates. Furthermore, light oil is found in Paleocene and Maestrichtian sediments of predominantly arenaceous character. Gas/condensate was found but not evaluated in other Tertiary and Cretaceous reservoirs within the same structure. M. Dumestre also notes the potential for hydrocarbons in the northern offshore and onshore areas of the country and in Paleozoic sedimentary sections, hitherto not considered as having much potential and only recently identified by the interpretation of gravity, magnetic and seismic data. Based on available gravity and magnetic data, we believe that hydrocarbon accumulations should be found on the west limb of a faulted Paleozoic trough that extends from approximately Pointe Serene in the south to Tidem and Ross-Bethio in the north. Other possible targets in Paleozoic sediments of Silurian age occur in the Loumbol-Diourbel axis and the Barkedji-Boulel axis. Both these zones are underlaid by block-faulted rocks represented by negative gravity anomalies.

The areas considered to have high potential for oil and gas (as well as for salt and sulfur) are outlined and numbered "17" on the project's mineral potential map. A small 20 by 30 km basin occurring southwest of Tambacounda is considered to have some potential for gas production. Another area of potential for gas and possible oil is the western flank of the deep faulted synclinal depression which extends from Rosso to Tivaouane.

Without the benefit of seismic records, no further comments can be made concerning the potential for oil and gas either at the above sites or in the more promising offshore areas of Senegal.

2. *Lignite and Coal*

Since 1984, the Government of Senegal has begun the evaluation of lignite deposits in the central Groundnut Basin of Senegal. Specifically, two test borings have been made by a drilling company under the aegis of the Department of Mines and Geology, and results should be forthcoming. In 1981, Dr. C. Bliss, Office of Energy, USAID, reviewed the work on lignite in Senegal. In his report, Dr. Bliss shows that most of the oil and gas wildcats drilled in Senegal penetrated a number of lignite seams of varying age and thickness. Drilled and hand-dug water wells have also found lignite. The *Plan Minéral* (1985) has summarized this data and produced a map and cross-sections showing that lignite occurs in the Oligo-Miocene (at lesser depth) in the Sine Saloum and Casamance regions.

These deposits vary in thickness as does their quality (B.T.U. content), and no evaluation of bulk samples has been made. Some samples were seen by project staff from the uppermost levels of a drill hole at Tieneba, which show carbonaceous material mixed with a high percentage of sand and clay.

3. *Recent Corroborative Work*

Recent work in Senegal (A. Sow personal communications, 1986) confirms some of the interpretations. In April a contract was signed by an unspecified American oil company to explore the aforementioned down-faulted Paleozoic sequence in the region of Louga. In addition, lignite deposits were found in the region south of Nioro du Rip and eastward toward Kolda as postulated from the integrated Landsat/Geophysical analysis.

4. *Costs*

The cost of remote sensing surveys varies with the area studied, the number and quality of remote sensing materials used, the availability of other information, the degree of enhancement and digital analysis and computer manipulation, and the amount of supporting field work. An advantageous approach to Third World fossil fuel exploration is a multi-resource survey approach. Such surveys are needed, and each separate study supports and improves the results of the other. The Senegalese survey just mentioned cost \$2,000,000 and included much training, equipment and material purchasing. Although not complete by any means, it has been considered a success by USAID, the funding agency, by the World Bank and by the UNDP. This survey cost \$10.00 a square kilometer for the four disciplines covered. For geology alone the cost was less than \$2.00 km^2. The time required to conduct such a survey would be less than 2 years. It must be remembered that this survey employed a minimal amount of computer enhancement techniques. Such techniques are still being developed, and the data integration computer systems are also in the development stage. Perhaps the best enhancement techniques are presently available at the Jet Propulsion Laboratory in California, at various oil companies, at the EROS Data Center in South Dakota and at Geospectra Corporation in Michigan. One of the best geologic integration systems has been recently developed by the Ontario Geological Survey and is called GEOSIS. (Geoscience Spatial Information System).

Conclusion

Geologic Remote Sensing for fossil fuel exploration has become routine in developed nations of both east and west. Numerous test cases have shown its utility. Recent work clearly shows that the combination of remotely sensed data from various sensors with information derived from other sources (seismic, magnetic, etc.), can provide a wealth of useful material to the exploration geologist. This work has also shown that remote sensing systems cannot be used alone. Furthermore, it has become apparent that visual (manual) interpretation can be an effective low-cost method of interpretation. It is just as evident (in areas which have been under study for many years and for which a great deal of data is available), that computer aided data enhancement, manipulation and integration will play a more and more important if costly role.

It is hoped that this exposé on remote sensing will have been of some use to this audience, and that they will not feel intimidated by the myriad ways that science has developed. It is sometimes painful to keep up with the changes that technology imposes on us but we must not fall into the bad habits described by Edith Nesbitt in the Magic City, in which she says "And there's a dreadful law here — it was made by mistake, but there it is — that if anyone asks for machinery they have to have it and keep on using it." Rather let us become involved in what technology has to offer for the betterment of mankind. To paraphrase Milton: we should not let remote sensing technology "become a fugitive and cloistered virtue, unexercised and unbreathed, that never sallies out and sees her adversary."

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SATELLITE REMOTE SENSING APPLIED TO CLIMATOLOGY

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I. Introduction

Climatology is, of all the environmental sciences, one of the most demanding in terms of its data requirements. Because of its concern with mean conditions, and deviations therefrom, over relatively long periods of time, climatology calls for standards of data homogeneity and continuity which can be particularly difficult to satisfy. During the Twentieth Century climatological science has developed many facets, some distinguished by scale (principally as macro-, meso-, and microclimatology), some by area of focus (e.g., surface climatology, climatology of the free atmosphere, and climatologies of other planetary atmospheres), and some by topic or theme (e.g., agroclimatology, bioclimatology, historical climatology, etc.).

Recognising that the theme of this Symposium is "Remote Sensing and its Impact on Developing Countries", our attention will be directed towards mainstream macro-climatology of the surface of the Earth and the troposphere (which contains all those weather systems which directly affect the surface of the Earth), with special emphasis, at least by way of illustration, on the application and potential of remote sensing for Third World regions. Although surface-based remote sensing can be used for atmospheric monitoring (e.g., weather radar, and acoustic sounding), it is the weather satellite which affords by far the best opportunities for the sustained monitoring which climatology demands. Therefore this paper concentrates on climatology from satellites.

II. Satellite Climatology

Satellite climatology is the study of climate, climate parameters, and atmospheric systems that contribute significantly to regional climates and their differentiation, based primarily on data from Earth-orbiting satellites. As such, it is a new area of atmospheric science, still in the early stages of growth and development. The scene for satellite climatology was set by the launch of the first specialized weather satellite, Tiros I, in 1960. The first comprehensive text on this theme was published 14 years later (Barrett, 1974). However, even now it is a young discipline, whose coverage of global climates is both partial and fragmentary. The chief reasons for its slow growth and development are:

1. Climatology, as we have seen already, demands long runs of homogeneous data to meet the requirements and satisfy the conditions of statistics. Weather satellite data still fall significantly short of the 30-35 years required for the confident evaluation of climatic norms. Frequent changes of satellite platforms, orbital patterns, and sensor systems have resulted in much problematic variety and inhomogeneity in the basic satellite data sets.

2. Methods of satellite data preprocessing, processing, and analysis have developed greatly since the earliest years of satellite remote sensing of the atmosphere. Consequently, not only have the basic data varied and changed since 1960 but so too have the archived products that have been derived therefrom.

3. Major national and coordinated international programs in satellite climatology have been few and far between, and their results characteristically limited with respect to space, time, and elements considered.

However, there is no doubt that satellite climatology has already increased dramatically our knowledge and understanding of the atmosphere of planet Earth, particularly with reference to its more remote and inaccessible regions. It seems certain that satellite climatology will go on increasing in importance, both as a pure science and as an applied science through a growing influence on climate-related problem solving, not least in the Developing Countries of the world. Indeed, if it is true — as many believe — that conventional (*in situ*) supplies of climatic data are actually declining, and will continue their decline in the foreseeable future, satellite climatology is destined to fulfill an increasingly significant role in relation to its scientific parent.

III. Factors Affecting the Use of Satellite Data in Atmospheric Science

Barrett and Martin (1981) listed a number of reasons why satellites are so vital to modern atmospheric science, followed by a similar number of reasons why the use of satellites in climatology and meteorology is often difficult or problematic. These opportunities and problems may be summarized as follows:

Positive attributes of satellite data:

1. Satellite systems can provide complete data coverage of the entire globe, or large parts thereof.

2. Satellite data can be spatially continuous (imagery) or relatively regularly distributed (soundings) across the area(s) of interest.

3. Single sensors or sensing systems can provide homogeneous data sets over very wide areas.

4. Some (geostationary) satellites provide data with a very high temporal frequency (half-hourly data are commonplace).

5. Satellites afford new views of the atmosphere, monitoring it from above rather than within. For example, integration of parameters (e.g., radiation fluxes) along lines, over areas, or through volumes of the atmosphere can be obtained readily.

6. Data from satellites, being remotely sensed, usually have physical meanings different from, but complementary to, those of *in situ* data.

7. Satellite data can be obtained even for broad areas in or near real time, and are commensurate with automatic data-reception handling, and analysis computer systems.

Neutral or negative attributes of satellite data:

1. Data from satellites are rarely for synoptic reporting hours, presenting problems of assimilation into conventional data sets.

2. Elaborate transformation procedures may be needed to convert satellite measurements (antennae temperatures) into observed radiances, and thereafter into evaluations of climatologically useful parameters. Related algorithm development has been very patchy.

3. The user is distant from the data source and may have little or no influence on sensor system design and operation.

4. The types and resolutions of available data are often less than optimal for many classes of potential users.

5. Information extraction can be difficult and/or inefficient because, not uncommonly, the content of the data of interest to a particular user is only a tiny fraction of the total.

6. Archiving of data until the present has left much to be desired and most satellite data runs are much too short for classical climatological research.

7. Operational inertia affecting the adoption of new procedures for data analysis and application can be very strong.

These general attributes of weather satellite data comprise the framework within which the steadily developing picture of satellite climatology is set.

IV. Satellite Evaluations of Key Climatic Variables

Radiation, Energy and Temperature

Unless dealing with the Earth/atmosphere system as a (global) whole, it is useful to distinguish between *radiation* and *energy* budgets. Radiation budgets, which only involve energy interchanges in the plane of the vertical, differ from place to place. Thus some areas are *sources* and others *sinks* of radiational energy. Energy budgets, which must be balanced climatically so that energy inputs and outputs are equal, involve also energy storages, imports or exports of energy in the plane of the horizontal.

The net radiation balance (*RNEA*) of any region or column of the atmosphere depends on three quantities, namely:

(1) The solar irradiance (I_o) at the top of the Earth's atmosphere;

(2) The planetary albedo (A), which governs shortwave (reflected) energy losses (H_r) to space; and

(3) Longwave (reradiated) energy losses to space (H_L).

Satellites are helping to evaluate the solar constant more accurately than was possible before, and to monitor its short-term temporal variations and its influence on absorbed solar radiation (H_a). They are also providing more direct, complete and continuous observations of (2) and (3) than were possible in presatellite days (see Vonder Haar and Suomi, 1971). One finding of special significance is that the mean global albedo is considerably less than previously thought: presatellite estimates decreased from 50% (Dines) in 1917 to 35% (London) in 1957. Today a value of 30% is widely accepted as the most appropriate (Henderson-Sellers and Hughes, 1982).

Of progressively more direct interest to Developing Countries, more detailed and repetitive evaluations of components of the Earth/atmosphere radiation budget have begun to reveal that:

1. Significant variations may occur from year to year in global averages. For example, it appears that the annual average albedo for the entire globe may vary by as much as 2% or 3%.

2. Latitudinal contrasts of some components are more strongly marked than was previously believed. For example, it is now clear that solar radiation reflected from the tropics is much less than earlier estimates (24% compared with immediately pre-satellite estimates of 34%).

3. Longitudinal variations are found in the net inputs to the global budget, some of which are related to land/sea distributions, but others to air mass and circulation patterns.

4. Considerable diurnal fluctuations also occur. Recently data from geostationary satellites have been invoked in radiation and energy budget climatology for the first time, permitting the embroidery of much finer temporal detail onto these patterns than polar orbiting satellites allow. Research with Meteosat data has suggested that both albedo and outgoing longwave flux vary markedly through the day, but these variations differ from one type of surface to another (Saunders and Hunt, 1980).

5. Local climates can be typified by their own radiation budget and cloud characteristics, as exemplified by Figure 1.

6. Radiational aspects of significant fluctuations of regional climates, e.g., drought episodes in the Sahel, are now amenable to evaluation and analysis even if conventional data are very sparse.

Current efforts are being made to intercompare data sets from different satellites and sensors so that they might be used more interchangeably and in more broadly complementary ways than hitherto (Henderson-Sellers, 1984).

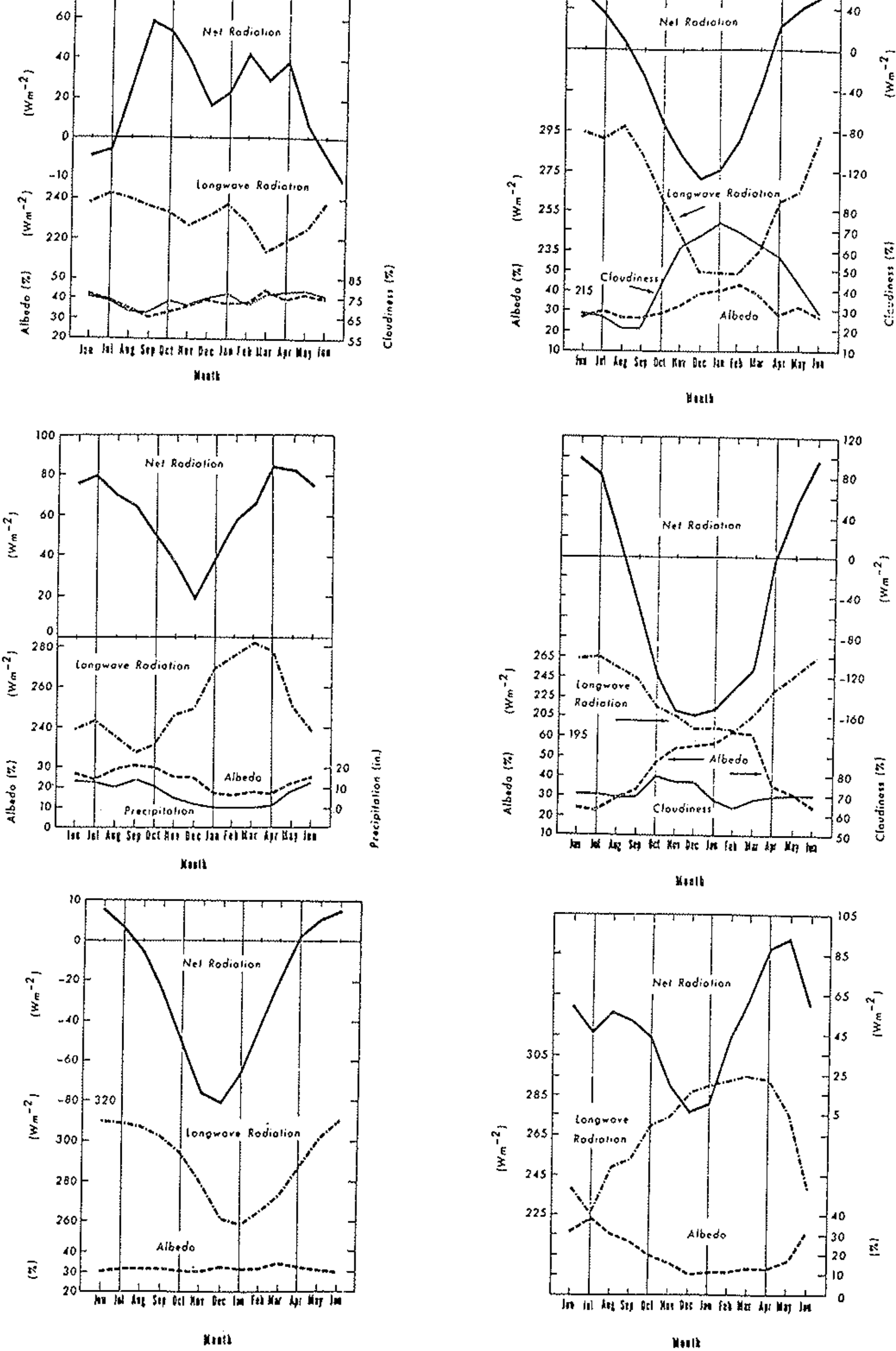


FIG. 1. The annual variation of the Earth-atmosphere system radiation budget and cloudiness for an equatorial location (equator, 67.5°W - Sao Gabriel, Brazil), (top left); a subtropical continental location 40°N, 55°E - Aidin, USSR), (top right); an equatorial monsoon location (10°N, 107.5°E - Saigon, Vietnam), (middle left); a midlatitude continental location (52.5°N, 82.5°E - Barnaul, USSR), (middle right); a tropical continental location (25°N,

Putting the radiation budget findings into the broader context of energy budget climatology, bigger problems are encountered, for here energy movements in both atmosphere and ocean are involved, as well as subsurface and atmospheric storages, and these cannot yet be evaluated from satellite evidence alone. However, it is possible to make *quantitative* assessments of some of the fluxes (e.g., nonlatent energy) from the results of radiation budget studies and *qualitative* assessments of other processes (e.g., the need for higher estimates of total energy to be exported from the tropics) following on from the satellite radiation findings. The future is certain to provide an increasingly kaleidoscopic view of atmospheric radiation and energy distributions and interrelationships. As atmospheric energy is the fuel for atmospheric motion, which is itself the driver of many significant secular variations of climate, the place of such studies in the very forefront of satellite climatology is firmly assured.

Great progress has been made also in the monitoring of the upper atmosphere using data from satellite sounding systems, from which vertical profiles of temperatures can be retrieved. Apart from the insight these data provide into the inner workings of the layers of the upper atmosphere, it is hoped they will also help resolve some of the outstanding questions of global weather and climate, not least in relation to climate forecasting. Prominent among these are questions concerning the directions and degrees of vertical interactions in the atmosphere: for example, do weather and climate develop dominantly from the top down or from the bottom up? The answers may lie in the middle atmosphere. It is now clear that some frictionally driven waves propagate to such levels, but key events such as sudden warmings of the stratosphere seem to have their origins outside rather than inside the atmosphere of the Earth. Meanwhile, exciting progress has been made with the derivation of various global-scale climatological products including day and night surface (skin of the Earth) temperatures, and monthly and interannual differences using sounding data from the multispectral HIRS2/MSU instruments (see Plates 1 and 2, Chahine, personal communication).

At lower levels concerted efforts are now being made to use cloud top temperature data to generate much-needed global climatologies of clouds classified according to their heights above the ground. For Earth-surface applications of climatology in support of agriculture, fishing, and other industries, there is quickening interest in the use of satellite-derived sea-surface, air, vegetation canopy, and ground temperatures, and thermal

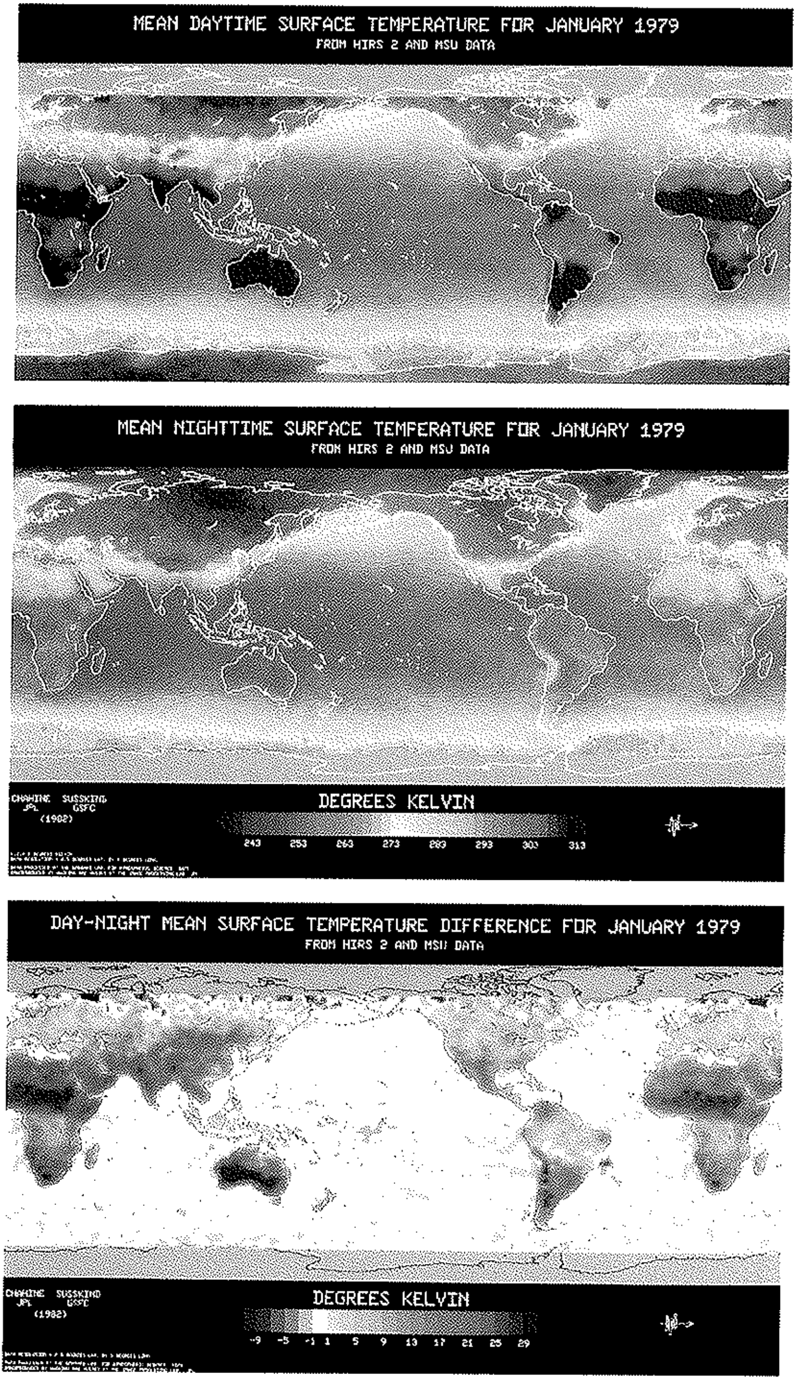
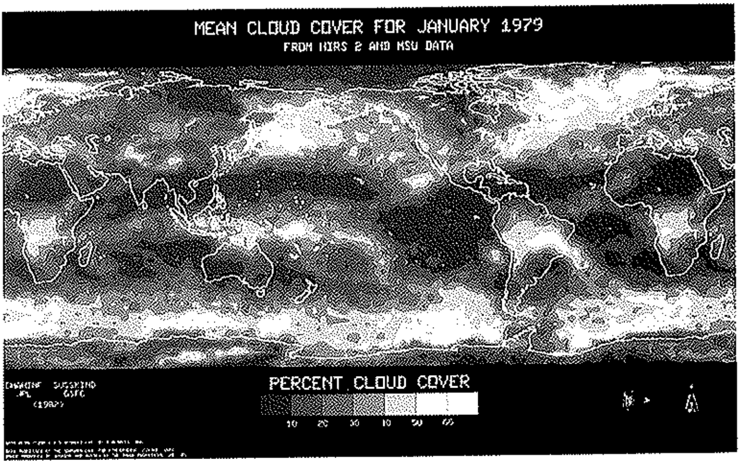
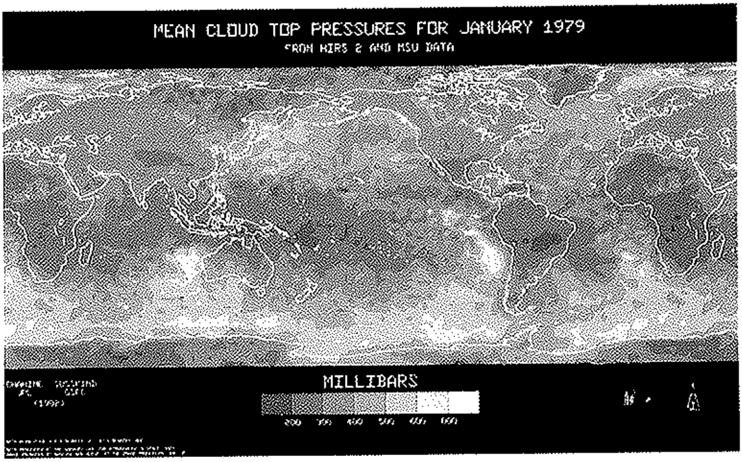


PLATE 1. Day-night surface temperature products for January 1979, showing Day (top); Night (middle); an Day-night differences (bottom). These were the first global maps shown of the Earth's monthly mean ski surface temperature for day and night, and day-night temperature difference. The day and night maps ar in very good agreement with ship and buoy measurements and show general ocean surface temperature feature such as the Gulf Stream, the Kuroshio Current and the local temperature minimum in the eastern tropica Pacific Ocean. The day-night temperature differences over land clearly distinguish between arid and vegetate areas and may indicate soil moisture anomalies. The map at the bottom shows the monthly average of th differences betwen day and night temperature. This difference map provides striking contrasts between ocean and continents to any Earth observer. The white area on this map indicates day-night temperature difference in the range ± 1K. This small difference indicates areas of high heat capacity and large degree of homo geneity. These areas are « oceans »; the other areas with larger day-night temperature differences are « con





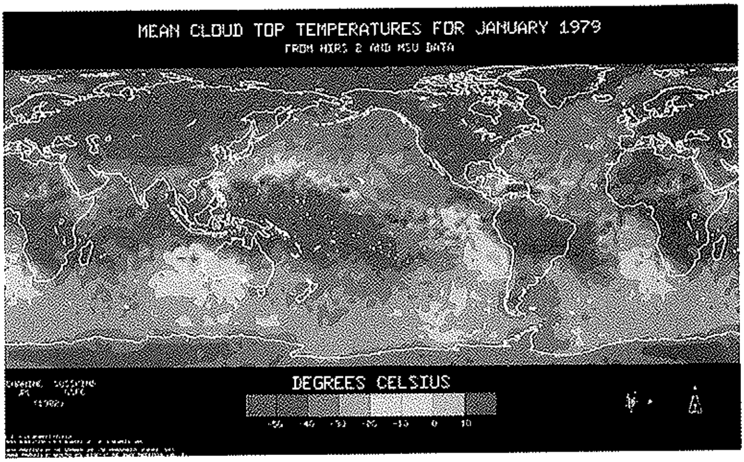


PLATE 2. Mean monthly cloud cover for January 1979, showing cloud amount (top); cloud height (middle); and cloud top temperature (bottom). Monthly mean fractional cloud cover, cloud top pressure, and cloud top temperature for January 1979 derived primarily from two HIRS 2 channels in the 15 micrometer region in combination with additional HIRS 2 and MSU channels used to correct for the effects of atmospheric absorption and atmospheric and surface temperature. The major features such as the Intertropical Convergence Zone, the storm tracks in the North Atlantic and North Pacific Oceans, the transfer of clouds from the central tropic Pacific to the North American continent and the Siberian high are readily observed in the cloud cover map. The cloud top pressure and cloud top temperature map indicate extensive areas of predominantly stratus cloud cover off the west coast of the southern hemisphere continents as well as the high cold clouds in the

inertia, though the latter three pose particular problems yet to be satisfactorily solved (Barrett and Hamilton, 1981).

Winds, Air Flows, and Circulations

In contrast to radiation and energy budgeting, the assessment of winds, air flows, and circulation patterns from satellite evidence is much more difficult and the results more sporadic.

The earliest worthwhile efforts to estimate wind speeds from satellite visible and infrared imagery were linked with hurricane forecasting. By the late 1960s regular estimates were being made of sustained maximum wind speeds, and the results have led to the present scheme for the assessment and forecasting of hurricane intensities as developed by Dvorak (1975) (see Fig. 2). However, it is far from certain that this scheme (developed primarily for storms over or near North America) is fully applicable in other hurricane-affected areas. Climatological intercomparisons are needed to clarify this issue, especially in eastern and southern Asia, the South Pacific, and east Africa and the South Indian Ocean.

With the advent of geostationary satellites the task of deducing wind speed and direction from visible and infrared images has been greatly eased. Both interactive and fully objective schemes have been developed to facilitate the establishment of *cloud motion vectors* from successive pairs of triplets of such imagery. The results have been used in satellite-only research studies and are being fed routinely into the data pools from which upper-level charts are prepared, both for forecasting and subsequent climatological mapping purposes. The satellite wind data relate dominantly to the 900 mb and 300 mb levels, for example some five hundred wind retrievals per day are obtained from computer analysis of infrared images from the Meteosat-2 satellite, including many over the African continent itself. Such satellite winds seem reasonably commensurate with those from radiosonde ascents, although it is difficult to compare the two types of data very definitively because of the very different areas to which they refer. It is also difficult to assess their significance in wind and air flow climatologies because of the way in which they are interwoven with the *in situ* observations.

Satellite observations processed for air flow (streamline) analyses would seem to have most to offer in the tropics, where conventional data are particularly sparse and winds are less geostrophic than in higher latitudes. It was shown first by Fujita *et al.* (1969) that geostationary

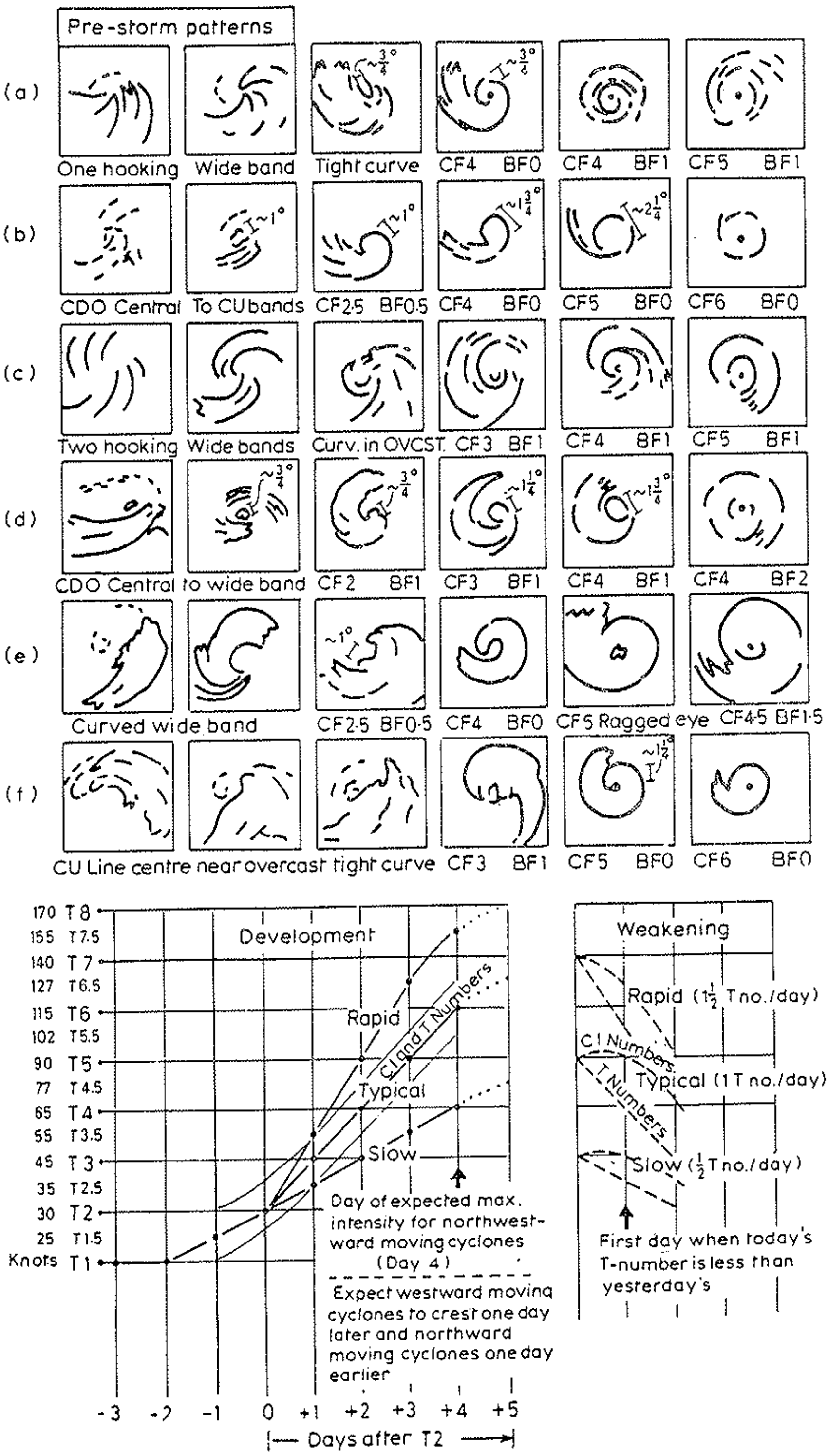


FIG. 2. Classification of tropical storms and tropical cyclones from weather satellite image evidence (top), and T-nos. versus expected wind speeds (bottom). (From Dvorak, 1977).

satellite data can be processed to yield a variety of wind, air flow, and circulation parameters once cloud motion vectors have been evaluated. They include not only wind speed and direction but also relative and absolute vorticity and horizontal divergence. The same study showed the value of satellite data for the recognition of new weather structures not identified prior to the satellite data analyses. Unfortunately, such approaches have not been applied routinely, and dynamic climatology has yet to benefit from them.

Perhaps of greatest direct interest to climatologists have been the satellite-based studies of the distributions and tracks of organized weather systems of significance to both general circulation and regional climatologies. Studies of hurricanes, easterly waves and squall lines (e.g., over West Africa), and the Inter-Tropical Cloud Band (ITCB) have been of special value to Developing Countries in tropical and sub-tropical zones. Every important tropical storm or cyclone anywhere in the world since 1966 has been identified in, or tracked through, satellite imagery. Yet again, global climatologies of intense revolving, tropical storms have still to be updated to include this information.

Clouds, Precipitation, and Atmospheric Water Vapour

Since clouds figure so prominently in weather satellite images, it is to be expected that cloud climatologies will have figured significantly in the growth of satellite climatology. However, it seems fair to remark that more attention has been paid to the development of cloud climatology *techniques* than to the systematic compilation of their results, especially at scales of value to individual countries or sub-continental regions.

In the 1960s the dominant approach to cloud type and cloud cover mapping was based on the satellite nephanalysis, a simplified, schematic representation of the clouds evident in any satellite image. However, by the late 1960s the need for more objective approaches was already pressing, in view of the rapidly growing supplies and archives of cloud imagery. The first objective technique yielded multiple exposure averages from the exposure of a single photographic plate to a number of mapped ESSA (Environmental Sciences Services Administration) satellite images for selected numbers of successive days. This was an inexpensive and successful method in that its results revealed a number of previously unrecognized cloud structures, e.g., the split ITCB (Inter-Tropical Cloud Band) of the eastern equatorial Pacific. This method was quickly superseded by a computer-based technique based on a mesoscale archive of polar-orbiting satellite imagery, comprising a 512^2 data matrix for each hemisphere. This yielded perhaps the most comprehensive satellite climatology of clouds to date. By saving the daily values month by month through the period from 1967 to 1970, results could be presented in ten-class cloud amount frequency distributions for each unit area in the array, and in a wide range of maps on both polar sterographic and Mercator projections for total cloud cover as well as a number of subordinate cloud cover categories. More recently attempts have been made to reduce the common problems of underestimation of cloud amount at the low end of the okta scale, and overestimation at the high end of the scale, by bispectral histogram approaches in which cloud brightnesses in the visible are plotted against those in the infrared. Such techniques not only aid in differentiating between cloud and background brightness but also in differentiating various types of cloud. Further efforts to develop objective cloud type recognition procedures have used multispectral data from sensor systems on Nimbus and NOAA satellites, not visible, or visible and infrared, data alone. Multispectral techniques are much more demanding of computer time, so more research is needed before such approaches could be countenanced for very wide-scale climatological applications (Henderson-Sellers and Hughes, 1982). Plate 2 illustrates cloud and cloud-related products produced in sequence with the contents of Plate 1.

Whereas cloudiness is clearly evident in most weather satellite images, rainfall is not. Yet rainfall is such a vital and highly variable climatological element — and is so inadequately measured on the ground — that much effort has been expended in the search for suitable ways to assess and monitor rainfall from satellites (Barrett and Martin, 1981). Several aspects of rainfall hydrometeorology are now amenable to analysis using satellite data alone or, more commonly, satellite data are used as supplements to conventional (gauge and/or radar) measurements. Satellite data can aid in:

1. Mapping the boundaries of areas likely to be affected by rain;
2. Mapping rainfall totals accumulated through unit periods of time;
3. Assessing extreme (intense) rainfall events;
4. Assessing the climatology of rainfall distributions; and
5. Forecasting rainfall, especially in areas open to systems from relatively poorly observed regions.

During the first decade of satellite meteorology, the satellite was viewed generally as an *alternative* to the ground observing station for local environmental information. However, during the second decade, the two have been viewed more as complementary. The ground station (e.g., raingauge, streamgauge, etc.) has the advantage of being able to provide quantitative data through time but represents rainfall variations only at a single (point) location; the satellite has the advantage of being able to provide really complete information but only for separated points in time.

Most satellite data relate only indirectly to rainfall as measured on the ground. Therefore, the practice has grown to use satellite data to fill gaps in the conventional data network, evaluating those remote sensing data by reference to the units and values of the *in situ* observations. Methods of improved rainfall monitoring by satellite include the following:

1. *Cloud-indexing methods.* Satellite cloud images are ascribed indices relating to cloud cover and the probability and intensity of associated rain. Different methods have been used to calibrate the indices to give final rainfall estimates. Such techniques are in widespread use for a variety of applications over land, e.g., in support of irrigation design in Indonesia, water resource evaluation and management in Oman, desert locust control in Northwest Africa, and general environmental assessment in tropical Africa and the Caribbean (see Fig. 3).

2. *Rainfall climatology methods.* The basis of the most significant of this group of methods is the relationship between climatologically averaged rainfall and the long-term average contribution made to it by numbers of key types of synoptic weather systems (e.g., mobile mid latitude lows in China). Climatology thus dictates the amount of rain deemed likely to be carried by a significant cloud system. Use of this method has been limited to support of general crop-information services.

3. *Life-history methods.* These are based on the twin premises that, at least in some areas, the most significant rains fall from convective clouds and that these clouds can be distinguished from others in satellite images. Models of cloud development are incorporated to allow for changes in rainfall intensities at different stages in the life cycles of individual clouds. Such methods have been widely used to assess rainfall climatologies in parts of the tropics and subtropics and their life-saving potential has been demonstrated through operational support of flash-flood forecasting in the United States.

Fig. 3a (right): The BIAS Global Regression, as development for the AgRISTARS Program. In comparison with earlier versions the major change is an extension to cover a wider range of climatic regions.

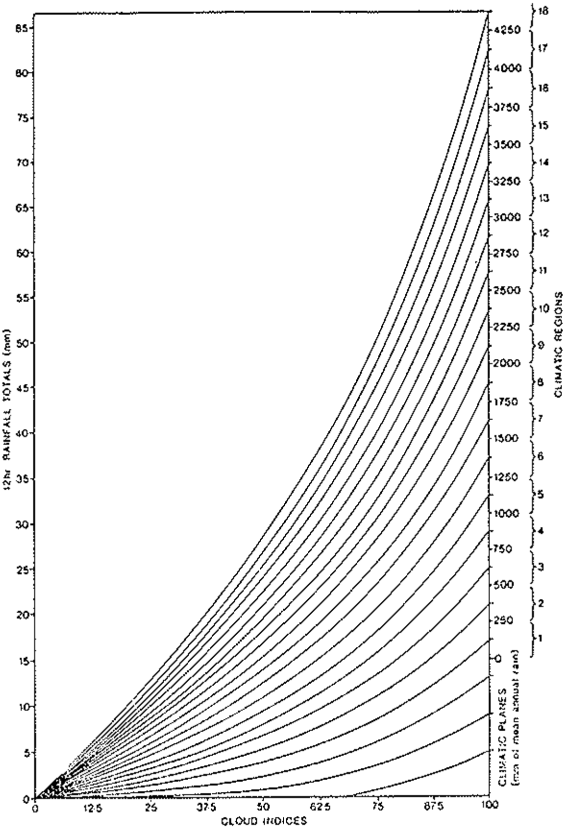
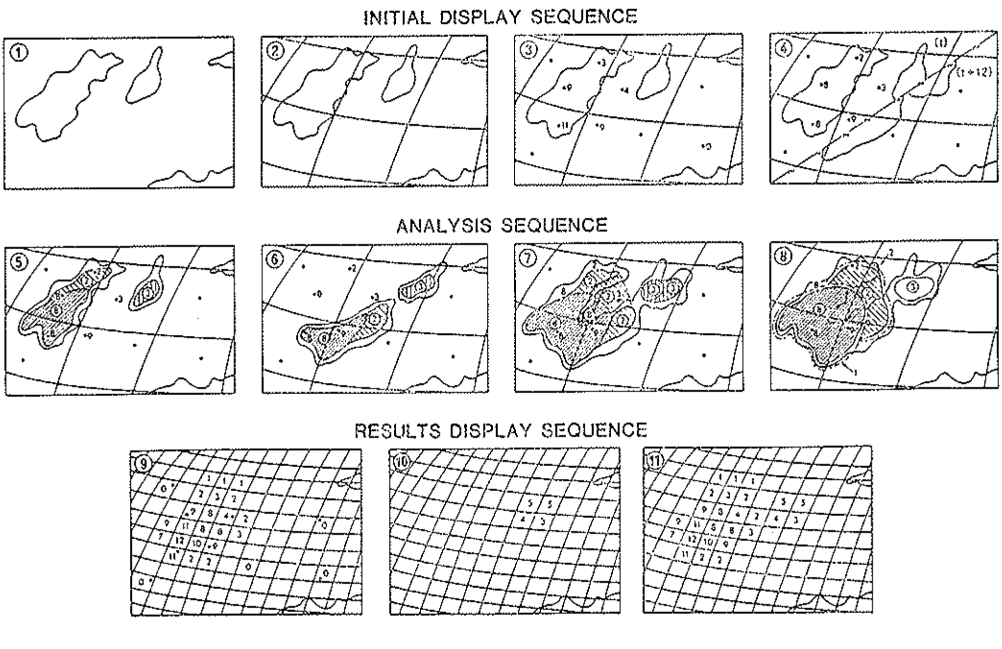


Fig. 3b (below): Steps in the BIAS interactive technique. In the *Initial Display Sequence* the analyst acquaints himself with the synoptic situation, and the main features of the cloud and rainfall fields. In the *Analysis Sequence* he identifies and maps cloud features, in relation to ground truth. In the *Results Display Sequence* he chcks and approves (or disapproves) the analysed rainfall fields.



4. *Bispectral methods.* Here visible and infrared images are analyzed together objectively to map extents and distributions of precipitation. Rainfall is then scaled according to some form of ground truth (gauge and/or radar data). The central assumption is that heaviest precipitation falls from clouds that are both *bright* and *cold.* These are now being actively developed for operational (regular) use over Africa based on imagery from Meteosat as Plate 3 illustrates (see Barrett and D'Souza, 1986). For this scheme an objective distinction is made between rain clouds (cold and bright) and non-rain clouds, so that daily rain area maps can be computed. These are aggregated over desired periods (e.g., 10, 30, 90 days and one year), and multiplied by a mean rainfall per rain day statistic derived from climatology to provide maps of estimated rainfall. This method can be applied at the full resolution of the satellite imagery, and is being implemented in FAO at reduced resolution for crop yield assessment over Africa.

5. *Cloud model methods.* These are essentially research techniques, being developed in human-machine modes in the search for more elegant formulations of relationships between clouds and rainfall. At present these methods are typified by a high degree of rigour but also by very complex algorithms, and hold promise for the future rather than applicability for the present.

6. *Passive microwave methods.* Radiometers on recent Nimbus satellites have measured naturally emitted radiation from the Earth and its atmosphere. Some data (e.g., from sensors observing at 19.35 and 37.9 GHz) have been processed successfully to yield mesoscale rainfall intensity distributions over sea areas. An atlas of maritime rainfall has been published by NASA based on work by Rao and Theon (1977). Over land, background radiation is much stronger and the problems of identifying and quantifying rainfall are much more severe. However, some promising progress is now being made in such areas (Spencer, 1984).

7. *Active microwave methods.* These may become available in the future if tests of planned satellite-borne radar systems prove a success, for example, on the Tropical Rainfall Monitoring Mission (TRMM) planned for the late 1980s.

Methods for rainfall monitoring by satellites were intensively researched during the early 1980s, especially through the U.S. AgRISTARS and Climate programs. Although there are good grounds to believe that a multi-

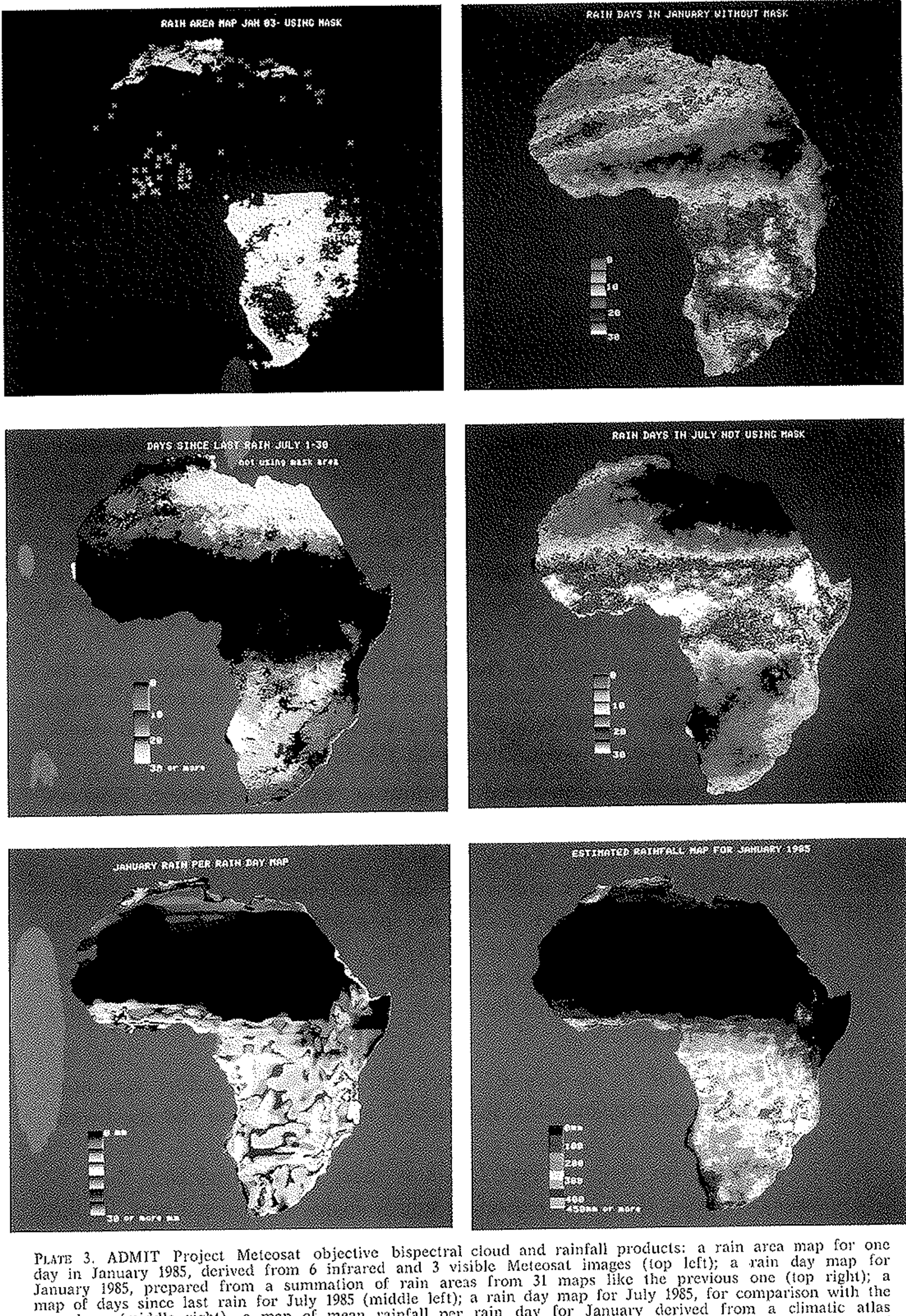


PLATE 3. ADMIT Project Meteosat objective bispectral cloud and rainfall products: a rain area map for one day in January 1985, derived from 6 infrared and 3 visible Meteosat images (top left); a rain day map for January 1985, prepared from a summation of rain areas from 31 maps like the previous one (top right); a map of days since last rain for July 1985 (middle left); a rain day map for July 1985, for comparison with the one above (middle right); a map of mean rainfall per rain day for January derived from a climatic atlas (bottom left), which, when multiplied by the appropriate satellite rain day map (top right), gives a map of estimated rainfall for January 1985 (bottom right).

spectral approach (involving visible, infrared, and passive microwave data) might be the best in the medium-term future, at present different approaches seem best for different regions. Over land, geostationary techniques (3, 4, and 5 above) are applicable in low to middle latitudes, whereas polar-orbiting techniques (1 and 2 above) are necessary in middle to high latitudes, and elsewhere if geostationary data are unavailable. Results from land and sea areas have yet to be combined into broad regional or global satellite-improved rainfall inventories. Some interesting but rather restricted tests have been undertaken to demonstrate the high potential at least some of these techniques must have for applied climatological purposes in poorly-instrumented areas. These have included the following:

1. Pest monitoring and control, particularly the Desert locust (*Schistocerca gregaria*) in conjunction with the Desert Locust Commission in Northwest Africa (Barrett, 1979), and the East African Armyworm (*Spodoptera exempta*) in conjunction with the UK's Tropical Development and Research Institute, and the Kenyan Agricultural Research Institute (Garland, 1985).

2. Global and regional crop prediction, under the auspices of the U.S. AgRISTARS (Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing), and the provisions of the new Netherlands Trust Fund project in conjunction with FAO.

3. Regional environmental monitoring, e.g., the western Sahelian study sponsored by the EEC, and involving laboratories and institutes in a number of Western European countries.

4. Water resources assessment and monitoring, e.g., recent studies in the Sultanate of Oman under the sponsorship and direction of the Public Authority for Water Resources (e.g., Barrett, Hamilton & Power, 1986). Results have demonstrated the viability of the evaluation of rainfall from extreme events for pixels, grid squares of selected size, and catchment basins.

It may well be in such directions that satellite climatology has most to offer Developing Countries in practical ways, at least in the short-term future.

Finally, for the mid-term future it must be reported that there is increased hope that useful satellite climatologies of water vapor in the atmosphere may soon emerge from operations of sensors such as the water-vapor absorption waveband (6-6.7 μm) sensor on the Meteosat series of satellites (although these only cover the middle and upper troposphere over African and European regions), and the Tiros Operational Vertical Sounder, which gives very generalized profiles of water vapor in the lower and middle tropospheres.

Synoptic and Regional Climatologies

It has already been remarked in passing that satellite evidence has been used in support of a number of synoptic system studies. Therefore it is sufficient at this juncture to summarise the satellite contributions which have been of most interest to the climatologist. Most of these studies have been undertaken by manual analyses of hard-copy data, and have therefore cost little. Data sets such as the NOAA 35 mm films archive of mapped daily Mercator and polar stereographic mosaics are particularly suitable for broad-area, long-term studies (back to at least 1970):

1. The recognition of new types of weather systems and structures, e.g., the Intra-Tropical Cloud Band, Burst Bands of the equatorial eastern Pacific, Northwest Australian Cloud Bands, and mesoscale vortices.

2. A fuller appreciation of some previously recognized families of weather systems, e.g., tropical wave disturbances (easterly waves and "inverted V" systems).

3. The extension and completion of the life cycles of many weather systems, including some as widely studied previously as midlatitude frontal lows.

4. More complete mapping of the distribution and tracks of most families of synoptic and subsynoptic scale weather systems and structures, especially in the more remote regions, e.g., tropical cyclones, and midlatitude lows and their attendant fronts over the Southern Ocean and Antarctic coastal waters.

It is somewhat surprising, in the light of all that has been accomplished in satellite climatology, that relatively little effort has been expended in the development of integrated regional climatologies based on satellite data. Most regional studies to date have been concerned with individual climatic elements (e.g., cloud cover) or single types of weather systems (e.g., frontal lows). The challenge remains to develop new methods of analyzing and presenting satellite data to fill out the dynamic climatologies of many major world regions, through the development of techniques designed to bridge the gap between the mean distributions so commonplace in conventional climatology and the richness of spatial and temporal detail evident in much satellite imagery.

Other Climatic Phenomena and Characteristics

The comprehensive and complementary view of the Earth and its atmosphere from space is opening up new opportunities to assess both atmospheric phenomena and surface features of significance to the atmosphere that were previously inimical to global survey. One example of an atmospheric phenomenon that can now be monitored on a much wider scale than before is *lightning.* Analyses of infrared images from the U.S. Department of Defense Meteorological Satellite Program (DMSP) satellites have shown that lightning flashes can be identified and locations plotted. Another example is *Saharan dust*, whose outbreaks have been analyzed using geostationary satellite data. An example of a surface feature now amenable to quasi-global mapping is *ice and snow.* For example, routine snow-cover maps are now prepared by the U.S. National Oceanic and Atmospheric Administration, and a ten-year summary was prepared by Matson (1977), covering the period from 1966-1976 in North America and Eurasia. The pontential in this respect of passive microwave imagery has been amply demonstrated through analyses of SMMR data from Nimbus-7, but for a relatively short period of time.

A related possibility of considerable significance for the future is that, as satellite data sets of these and many other parameters and phenomena become longer and, it is hoped, more homogeneous through extended periods of time, they will support an increasing number of studies of *climatic change.* It was shown by Allison (1972) that visible imagery of the Pacific Ocean can be processed to reveal quasi-cycle variations of cloud cover with periodicities of some four to five years, and that these correlated rather well with sea-surface temperature anomalies. More studies of this kind are required. Unfortunately, the scale of the associated data-processing problem is such that only central funding is likely to be sufficient to permit such work to be successfully completed. It is hoped that efforts such as the World Climate Program will take such matters on board.

Another related matter that satellites should help to elucidate in the future concerns the nature and degree of *atmospheric teleconnections*, long-distance interrelated events and situations, especially where these are anomalous. It already has become possible, with the aid of satellite information on the central Pacific, to propose a chain of cause-and-effect relationships between Amazonia and Sri Lanka to explain the long-established but obscure fact that the best predictors of the date of the burst of the South Asian summer monsoon is the level and trend of atmospheric pressure over South America. Many more predictively useful interrelations between different regions and different types of atmospheric and related surface activity (e.g., the El Niño, see Ramage, 1975) are to be expected as satellite-based research into climatic change and its variable pattern from region to region becomes more advanced. The benefits of those ultimate types of applied climatology — long-range (monthly, seasonal, annual, or longer-term) weather and climate forecasting — are potentially of critical significance to the world community.

V. International Programmes: Recent Progress and Future Needs

International exchange of data and cooperation in scientific and operational programmes are probably better-established and more extensive in the atmospheric sciences than in most other fields of environmental monitoring and research. In satellite climatology two programmes of particular potential interest to Developing Countries have been initiated recently.

1. The International Satellite Land Surface Climatology (ISLSCP) Project, a wide-ranging scheme to further the detection and quantitative assessment of climate and other impacts using satellite-derived information. Concerned with matters as broad and diverse as monitoring and modelling for global, mesoscale, and high-resolution applications, numerous projects and proposed regional experiments are planned. However, the great range and variety of this rather amorphous project may render it less effective than more modest, controllable, and focussed schemes might be WCP, 1985a).

2. The World Climate Research Programme, in particular the initiation of efforts to compile Global Large-scale Precipitation Data Sets from geostationary satellites (WCP, 1985b). As a beginning, a ten-year activity is planned, beginning in 1987, covering the collection of cloud statistics from satellites for 250 km grid boxes, plus supporting *in situ* data from both land and oceanic regions.

However, much remains to be done if satellite climatology is to contribute significantly to problem-identification and problem-solving in the less-favoured areas of the world. Chief of the requirements at present would seem to be:

1. Better provision for complete satellite data archives, the basic resource from which satellite climatologies must be constructed.

2. Much increased provision for algorithm development, especially for scales and in areas of potential value for operational applications in Developing Countries.

3. More specific and serious attention to the requirement of land surface climatology when planning and designing new satellite systems and sensors for the future, e.g., the proposed Polar Platforms of the Columbus Project.

4. A conscious policy of continuity in sensor operation and management so as to meet the needs of climatology for both homogeneous and relatively long-term data sets.

Only in these ways will the piecemeal progress of the past yield to properly planned and structured advances in the future.

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USE OF METEOROLOGICAL SATELLITE DATA IN BANGLADESH

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INTRODUCTION

Bangladesh is situated in the northeastern corner of the South Asian sub-continent with the Bay of Bengal in the South, and India on the West, North and East, and Burma on the South-East. The geographical boundaries are between 20°35′ and 26°45′ North latitude and between 88°03′ and 92°25′ East longitude. The country falls into the hertland of the Monsoon Region with average annual rainfall of about 100 inches a year and varying between 50″-200″ in various regions. About 80% of the rainfall occurs in the months of June to September. The months of November to February are very dry. The country is traversed by three of the world's major river systems, namely the Ganges, the Brahmaputra and the Meghna. The country has an area of little over 55,000 square miles and with a present population of about 100 million is one of the most densely populated regions of the world.

The peculiar geography of Bangladesh brings not only the life-giving monsoons, but also catastrophic ravages of tropical cyclones, nor-westers, tornadoes and floods. The Bay of Bengal is an ideal breeding ground for tropical cyclones. Table I gives a list of Tropical Cyclones that have affected Bangladesh since 1960, with maximum wind speed, storm surge height and casualty figures given wherever available. We find that 32 severe tropical cyclones hit Bangladesh during the last 25 years. Table II gives the area inundated in recent times by major floods. An exact estimate of the damage due to natural calamities in economic terms is not available. However, a good guess could be several hundred million dollars per year on the average.

Bangladesh was quick in realising the potential of space technology in tackling the problems of natural disasters, and an Automatic Picture Transmission (APT) station was established in 1968. At that time there was no infra-red sensor on the satellite and we used to get one picture a day from the ESSA series of satellites during the day time. The satellite technology improved rapidly, and with the launching of TIROS-N series of satellites in 1978 our system needed to be updated.

The United States Agency for International Development came to our assistance in updating our receiving and analysing capability of space imagery. Under the Agro-Climatic Environmental Monitoring Project (AC/EMP) the agency, with technical support from NASA and NOAA, provided us with an integrated advanced system for receiving both low and high resolution imagery from NOAA and GMS satellites and computer equipment capable of analysing not only NOAA and GMS satellite data but also Landsat data.

The system consists of the Ground Station, Alden and Muirhead recorders, two VAX-11/750 computers, one TRS-80 computer, two I^2S image processors, disc drives/tape drives, plotters/printers, a digitizing table, matrix film recorder, optronics scanner, wing lynch film processor, several terminals, a number of peripherals and interface equipment.

A number of Data Collection Platforms (DCP's) on land and one in the coastal area have been installed. The land-based DCP's transmit real time data on atmospheric pressure, air temperature, humidity, rainfall, wind direction and speed, water temperature and water level and solar radiation. The DCP data are collected via the orbiting NOAA satellites up to a maximum of eight times a day on real time basis by SPARRSO Ground Station and processed by the processing equipment. These data have largely augmented the existing network of meteorological and hydrological data collection capability in the country.

Necessary software, though not complete, has been procured. For example, real time low and high resolution GMS and NOAA satellite data ingest programmes, programmes to overlay latitude/longitude and political boundaries on images, DCP conversion programme, programmes to create computer compatible tapes from raw data, to output high resolution HRPT data, to print the product on Muirhead recorder/Facsimile paper, to analyse AVHRR data, to compute TIROS Vegetation Index, to obtain sea surface temperature, to classify Landsat scenes, etc. Facilities also exist for extracting

TABLE I - *Cyclones affecting Bangladesh since 1960.*

Date	Max. wind speed in miles/hr.	Storms surge ht. (in ft.)	Deaths
9 Oct. 1960	100	10	3,000
30 Oct. 1960	130	15-20	5,149
9 May 1961	90	8-10	11,466
30 May 1961	90	20-29	—
28 May 1963	125	14-17	11,520
11 Apr. 1964	—	—	196
11 May 1965	100	12	19,279
31 May 1965	—	20-25	—
14 Dec. 1965	130	15-20	873
1 Oct. 1966	90	15-30	850
11 Oct. 1967	—	6-28	—
24 Oct. 1967	—	5-25	—
10 May 1968	—	9-15	—
17 Apr. 1969	—	—	75
10 Oct. 1969	—	8-24	—
7 May 1970	—	10-16	—
23 Oct. 1970	—	—	300
12 Nov. 1970	140	20-30	5,00,000
8 May 1971	—	8-14	—
30 Sept. 1971	—	8-14	—
6 Nov. 1971	—	8-18	—
18 Nov. 1973	60	8-13	—
9 Dec. 1973	75	5-15	183
15 Aug. 1974	60	5-22	—
28 Nov. 1974	100	7-16	a few
21 Oct. 1976	65	8-16	—
13 May 1977	75	—	—
10 Dec. 1981	60	6	02
15 Oct. 1983	60	—	—
9 Nov. 1983	75	—	—
3 June 1984	55	—	—
25 May 1985	95	10-15	11,069

TABLE II - *Area flooded and estimated losses.*

Year	Flooded Area sq. miles	Total value of losses in 1969 prices in million taka
1954	14,200	1,200
1955	15,000	1,290
1956	13,700	2,180
1962	14,400	1,020
1963	13,600	83
1964	12,000	246
1965	11,000	45
1966	12,900	544
1967	9,900	90
1968	14,400 (two floods)	1,645
1969	14,000	330
1970	14,800	1,380
1974	25,000	10,000
1984	10,000	—

information on the upper atmosphere regarding water vapour content, temperature, ozone content, etc., as a function of altitude at 15 different levels from the Tiros Operational Vertical Sounder (TOVS) data of NOAA satellites. Under the ACEM Project, training has been provided to SPARRSO scientists on hardware, software and applications. Some in-country training on satellite data interpretation has also been provided.

The system is capable of monitoring weather data with the help of GMS satellites every three hours and in addition with NOAA satellites 4 more times a day. The system is most useful in the case of tropical cyclones which are formed in deep seas where no data is available otherwise. No tropical cyclone escapes our attention because of this system. We can detect the cyclone at the time of its formation in the Bay, monitor its movement and estimate the maximum sustained wind speed from the size and degree of organisation of the cloud by the D'vorak method. Two separate models, one for the Atlantic and another for the Pacific Ocean, for the estimation of maximum wind speeds in cyclones from satellite data have been prepared by D'vorak. One may naturally ask whether either of these models, and if so whether the Atlantic or the Pacific model, could be used for the Bay of Bengal. An independent statistical model for determining maximum sustained wind speeds in the Bay of Bengal cyclones has been prepared and it has been found that this does not differ significantly either from the Pacific or the Atlantic model. The difference is within the limits of error in the models. The results are shown in Table V. It is seen that the Bay of Bengal model resembles the Pacific model for weaker cyclones but resembles the Atlantic model for stronger cyclones. Thus the D'vorak model can be applied for estimating the maximum wind speeds in the cyclones of the Bay of Bengal.

Present generation of NOAA satellites have 5 AVHRR channels and 27 channels of the TIROS Operational Vertical Sounder (TOVS). The TOVS has three instruments, the High Resolution Infrared Radiation Sounder (HIRS-2), the Stratospheric Sounding Unit (SSU) and the Microwave Sounding Unit (MSU). The characteristics of these instruments are given below (Table III and IV). With the help of these instruments it is possible to obtain surface emissivity and temperatures, total precipitable water, stability index, total ozone content, thermodynamic profile and temperature sounding and geopotential height as a function of altitude at fifteen different levels. The facility which SPARRSO has developed to analyse data from TOVS will certainly improve our understanding of severe storms and tropical cyclones. It may be possible to predict the onset and withdrawal of monsoons with TOVS data.

TABLE III - *TIROS-N AVHRR Channel Characteristics.*

Channel	Resolution at Subpoint	Wavelength (μm)	Primary Use
1.	1 Km	0.55-0.90	Daytime Cloud and Surface Mapping
2.	1 Km	0.725-1.10	Surface Water Delineation
3.	1 Km	3.55-3.93	SST, Night-time Cloud Mapping
4.	1 Km	10.5-11.5	SST, Day/Night Cloud Mapping
5.	1 Km	11.5-12.5	SST

TABLE IV - *Characteristics of TOV Sounding Channels.*

HIRS Channel Number (High Resolution Infrared Radiation Sounder)	Central Wavelength (μm)
1	15.00
2	14.70
3	14.50
4	14.20
5	14.00
6	13.70
7	13.40
8	11.10
9	9.70
10	8.30
11	7.30
12	6.70
13	4.57
14	4.52
15	4.46
16	4.40
17	4.24
18	4.00
19	3.70
20	0.70
MSU (Micro-wave Sounding Unit)	Frequency (GH)
1	53.31
2	53.73
3	54.96
4	57.95
SSU (Stratispheric Sounding Unit)	Wavelength (μm)
1	15.00
2	15.00
3	15.00

Role of Weather Satellites in Cyclone Warning

Weather is a global phenomenon, and to know the initial state of the weather at a particular time, accurate observations on worldwide scale are needed.

The distribution of surface observations is heavily biased towards well populated land regions. Commercial shipping does provide some observations over the oceans. But as the ships avoid cyclones and bad weather, most vital data on cyclones are left out. High in the atmosphere, balloons can rise up to a maximum height of 20 miles only. Thus the vast expanse of the atmosphere and the oceans remained unexplored before the coming of the space age. With the advent of the space age, rockets began to gather data at different heights of the atmosphere, and satellites can survey the earth's weather from a point well above the earth's surface. The advantages of space meteorology over the conventional methods are as follows:

(1) Spatial continuity: The observations are horizontally continuous; this eliminates interpolation and thus the ambiguity often present in synoptic charts.

(2) Provides information on a synoptic scale with virtually no time lag.

(3) Visual Integration: Permits integrated visualization of weather systems in a way readily acceptable to the human mind.

(4) Independence of Communication Systems: Provides large scale weather information even if normal systems of communications have broken down.

Thus the superior quality of Space Meteorology is unquestionable. But this does not make the traditional synoptic meteorology obsolete. It rather supplements the new system. Improvements and innovations of the old system are continually taking place.

Bangladesh does not have either rocket or satellite facilities of its own, but with the help of ground stations we can receive weather data from weather satellites launched by advanced countries.

With the help of equipment provided by US AID and NASA, both low and high resolution data from US NOAA-6 and NOAA-9 and Japanese GMS-3 satellites are received. The GMS satellites transmit data normally every three hours. However, as Bangladesh is at the corner of the picture, resolution of GMS for Bangladesh is not so good. NOAA-9 satellite transmits good quality both low and high resolution data twice daily. Two previous NOAA-7 and NOAA-8 satellites are not functioning now and in their place an older satellite NOAA-6 is working though it does not give very high quality data. NOAA is launching its next satellite NOAA-10 sometime during this year. An automatic grid, i.e., latitude and longitude, can be fitted in the picture with the help of the present equipment. Because of this equipment, no cyclone in the Bay of Bengal can escape our notice. We can detect the cyclones, analyse their intensity, determine their position and track their motion. From the degree of organization of the cloud patterns and their sizes, we can deduce the maximum wind speeds in cyclones.

Bay of Bengal Cyclones

Because of the funnel-shaped coast, Bangladesh very often becomes the landing ground of cyclones formed in the Bay of Bengal. The Bay of Bengal cyclones also move towards the eastern coast of India, towards Burma and occasionally into Sri Lanka. But they cause the most damage when they come into Bangladesh. This is because of the low, flat terrain, high density of population and poorly built houses here. Most of the damages occur in the coastal districts of Khulna, Patuakhali, Barisal, Noakhali and Chittagong and the off-shore islands like Bhola, Hatiya, Sandip, Monpura, Kutubdia and the newly formed chars.

Of all the terrible cyclones that hit Bangladesh, perhaps the most deadly one was of 12 November, 1970, which is still fresh in our memory. Officially the death figure due to this cyclone was 500,000, but in reality it could be more. Nearly 90% of the marine fishermen suffered heavy losses. It is estimated that some 46,000 inland fishermen operating in the cyclone-affected region lost their lives. Some 9,000 fishing boats were destroyed during the cyclone. The damage to properly and crops was colossal. The estimated maximum wind speed of the 1970 cyclone was about 140 miles/hr. and the maximum storm surge height was about 30 ft. The cyclone occurred during the high-tide period and hence this great surge height. The cyclone of 25 May 1985 also caused considerable damage.

Though records of cyclonic storms affecting Bangladesh in the past are available, they may not give the full story as the recording device was not so efficient in the past. It is only after the advent of weather satellites that no storm can escape our notice. There is the record in

Ain-E-Akbari of a great storm of 1584 which affected the district of Barisal. There is the record of another great storm of October 1876 which affected the coastal districts of Barisal, Noakhali and Chittagong. The storm surge due to this cyclone was estimated to be about 40 ft. About 200,000 people died during this storm; but perhaps more people died from after-effects of the storm, such as epidemic and famine. No relief reached them for months. Considering the low population at that time, a death figure of 200,000 was tremendous. The great cyclone of 1919 also deserves mention. It originated in the Pacific about 4,000 miles away and it took some twenty days to reach the coast of Bangladesh. Records show that from 1918 to 1985, 174 severe cyclones (wind speed more than 54 miles/hr.) were formed in the Bay of Bengal. Their monthly distribution of occurrence is shown below:

January	*February*	*March*	*April*	*May*	*June*
1	1	1	9	32	6
July	*August*	*September*	*October*	*November*	*December*
8	4	14	31	47	20

It is apparent from the above figures that severe cyclones occur mostly during pre- (April-May) and post- (September-December) monsoon periods and they are the ones which cause most destruction. Of these cyclones, all did not come towards Bangladesh. The cyclones that affected Bangladesh since 1960 are shown in Table I with official casualty figures, storm surge heights and wind speeds whenever available.

Classification

Cyclones in the South Asian sub-continent are presently classified according to their intensity, and the following nomenclature is in use:

Depression: Winds up to 38 miles/hr.

Cyclonic Storm: Winds from 39-54 miles/hr.

Severe Cyclonic Storm: Winds from 55-73 miles/hr.

Severe Cyclonic Storm of Hurricane Intensity: Winds above 73 miles/hr.

SATELLITE FREQUENCIES AND CHANNELS

Satellite Type	Transmitting Frequency in MHZ	Down converted Frequency in MHZ	Transmission Channels/Bands
GMS (High)	1687.20	122.20	IR/VIS
GMS (Low)	1691.00	126.00	IR/VIS
HRPT/AVHRR			
(High Res)			
NOAA-6,8	1698.00	128.00	*5 Channels*
NOAA-7,9	1707.00	137.00	1. Reflected VIS Solar 2. Reflected Near IR Solar 3. Emitted Thermal IR Reflected Solar IR 4. Emitted Thermal IR 5. Emitted Thermal IR
APT (Low Resolution)			
NOAA-6,8	137.50	——	IR/VIS
NOAA-7,9	137.62	——	IR/VIS
METEOR	137.15	——	VIS
METEOR	137.30	——	VIS

It has been observed from satellite pictures that a mature cyclone has a well organized cloud pattern. It is possible to deduce the wind speeds in cyclones from the size and degree of organization of the cloud pattern. Accordingly, the cyclones have been divided into four categories. Category 1 stands for the least intense cyclone, whereas category 4 stands for the most intense ones.

Category 1: Pattern centre is apparent and cloud pattern is quite organized. A wide break and a long tail may be present. No eye is visible and the wind speed ranges from 30-50 miles/hr.

Category 2: Pattern centre is apparent and cloud pattern is quite organized. A wide break and a long tail may be present. No eye is visible and the wind speed ranges from 40-80 miles/hr.

Category 3: Eye is usually visible but ragged and irregular in shape. The cloud is compact and tends to be circular. Wind speed ranges from 50-125 miles/hr.

Category 4: Eye is prominent and circular; cloud pattern is almost circular and smooth. Wind speed ranges from 80-200 miles/hr.

Further refined classification from categories T 1 to T 8, also called Current Intensity Number (C.I.), at intervals of ½ an integral number has been made. Central pressure of the cyclone, corresponding C.I. number and wind speeds in the Pacific, the Atlantic and the Bay of Bengal are shown in Table V.

In meteorology, pressure is measured in units of millibar (mb). Normal atmospheric pressure comes out to be the weight of a length of a column of mercury equal to 76 cm. In terms of millibar, this comes out to be 1013 mb. This varies from season to season and from ocean to ocean. In the Bay of Bengal near the Bangladesh coast, during pre-monsoon months, normal atmospheric pressure is little more than 1000 mb; in the

TABLE V - *Comparison of Mean Sea Level Pressure Corresponding to Different Maximum Wind Speeds (MWS) among Atlantic, Pacific and Bay of Bengal.*

C.I. Number	MWS (Knots)	MSLP (mb) (Atlantic)	MSLP (mb) (Pacific)	MSLP (mb) (Bay of Bengal)
1.5	25	1010	1004	1000
2	30	1007	1001	998
2.5	35	1003	997	997
3	40	998	992	995
3.5	50	993	987	992
4	60	988	982	989
4.5	72	979	973	983
5	85	970	964	975
5.5	97	960	954	965
6	110	948	942	949
6.5	122	934	928	937

monsoon months this is around 1000 mb, and in winter this could be around 1015 mb. A drop in the atmospheric pressure from the local seasonal normal is an indication of the formation of a low pressure which may or may not develop into a tropical cyclone depending on surrounding environmental factors. The magnitude of the drop in the atmospheric pressure from its value before the start of the disturbance gives an indication of the maximum wind speed the cyclone is going to possess. Table V shows the relation between Mean Sea Level Pressure and the maximum wind speed for different oceans.

During the May 25, 1985 cyclone, the Ocean Buoy transmitted a pressure drop of 19 mb in the evening of 24 November, which corresponds to a pressure of 980 mb, giving a MWS of 70 knots (78 miles/hr). Maximum wind speed can also be calculated using Fletcher's formula, and this gives MWS of 80 miles/hr for a pressure drop of 19 mb. Actual wind speed when the cyclone struck the land areas was higher as the cyclone was further intensified as it moved towards the coast. The Meteorological Department recorded a maximum wind speed of 95 miles/hr at Chittagong at 4:20 a.m., 90 miles/hr at Sandip at 3 a.m. and 65 miles/hr at Cox's Bazar at 2.30 a.m. in the morning of May 25, 1985.

Features

The most individual feature of a cyclone is its "eye", usually found in severe cyclones. The eye can be seen in the satellite pictures clearly in the case of strong cyclones. The eye is small and almost circular, and coincides with the area of lowest pressure having a diameter ranging from 5-30 miles. The eye is warmer than the rest of the storm. The more violent is the storm, the warmer is the eye. The winds are very light in the eye, usually not more than 15-20 miles/hr, and rain is practically absent. In contrast, the strongest wind and the heaviest rain occur just outside this central eye.

The wind speed gradually diminishes as one goes away from the region of strongest wind. The main core of the cyclone is circular or nearly circular, having a diameter ranging from 100-500 miles. The main cyclone is often accompanied by a long tail having more than one band, the whole thing making a spiral structure and looking like an inverted comma. The tail may extend up to a few hundred miles. The tail usually crosses the land well before the main core of the cyclone, and as a result the sky is overcast with cloud, and rain often sets in before the onset of a cyclone.

Such symptoms can serve as a warning for the possible approach of a cyclone.

The May 1985 cyclone did not have an eye at any stage. At times it was showing a multicentred structure. Without the presence of an eye, the cyclone fell in category 2 with a T number 4.5, this gave an estimated maximum wind speed of about 80 miles/hr. In its mature stage the main cyclone had a central overcast cloud extending over 300 miles in dimension with a core of about 100 miles. It had also few tail bands of clouds extending over several hundred miles. When the cyclone struck the Chittagong coast, observations showed that it had an intensity of T = 5 with wind speed of 95 miles/hr.

The Track of the Cyclone and Storm Surges

The cyclones in their initial stages move at a rate of 5-10 miles/hr. In their final stages they may move at a rate of 15-20 miles/hr or even up to 30 miles/hr. Cyclones formed in the Bay of Bengal usually move northwesterly in the beginning and then curve eastwards. But this pattern is not uniform as can be seen from the tracks of various cyclones. The cyclone usually decays after crossing the land. Cyclones are accompanied by heavy rains and swell of the sea, called "storm surges". If the cyclone occurs during high tide, then the storm surge is reinforced considerably. The maximum value of storm surge can be as high as 40 ft in the Bay of Bengal. Most of the damage is done by the deadly wall of water associated with cyclones which cause colossal death and destruction. The storm surges associated with various cyclones that have struck Bangladesh since 1960 are shown in Table I.

The May 1985 cyclone was initially moving northwesterly with a speed of about 5 miles/hr, then turned northeastward and finally, making a double hump, moved north-northeasterly and crossed the Chittagong coast in the early morning hours of 25 May, 1985. The positions of the cyclone, as determined from satellite pictures for various dates and times with the corresponding estimated wind speeds, are shown in table VI.
During its final stage it possibly moved at a rate of 15-20 miles per hour. There was a pass of NOAA-9 satellite at 0230 hrs in the early morning of 25 May. The picture at this time shows how the cyclone engulfed the whole eastern coast of Bangladesh.

A model estimation of storm surge heights corresponding to various wind speeds as prepared by SPARRSO is shown in table VII. From the

TABLE VI - *Position of the May 1985 Cyclone Corresponding to Various Dates and Times as determined from Satellite Pictures.*

Date	Time	Lat.	Long.	Estimated wind speed, miles/hr
22.5.85	1430	16°	88°.5	40
23.5.85	0725	17°	88°	55
23.5.85	1408	17°.5	88°.5	60
24.5.85	0815	19°	89°.5	70
24.5.85	1358	19°.5	90°.5	80
25.5.85	0230	22°.5	91°.5	—
25.5.85	0800	23°.5	92°.5	Dissipated

table we see that the maximum storm surge height corresponding to a wind speed of 80 miles/hr is 15 ft. The observed storm surge height did not exceed this value.

The cyclone in its course affected the whole eastern coast of Bangladesh, starting from St. Martin's Island, up to Patuakhali. There was a reported storm surge of 5 ft at St. Martin's Island and some 10-12 ft surge at Urir Char north of Sandip, where it did the maximum damage. Similar surge was reported in the newly formed chars in the southern part of Noakhali district.

All the satellite pictures taken by SPARRSO during the storm period, i.e. 22-25 May 1985, were promptly supplied to the Meteorological Department for use in forecast of the storm. During 23-24 May pictures were taken during both day and night.

Determination of the Cyclone Track

The precise forces responsible for the motion of tropical cyclones are not understood clearly, and hence determination of the path of the cyclone in advance is one of the most difficult tasks in meteorology.

The classical methods for forecasting cyclone tracks are judicious consideration of the climatology of cyclones, persistence of motion and some steering current of the upper atmosphere. Tropical cyclones often show different preferred paths at different times of the year. Hence,

TABLE VII - *Relationship between Pressure Drop, Wind Speed and Surge Height.*

Pressure Drop (mb)	Wind Speed (miles/hr)	Surge Height in ft (maximum value)
10	40	3.87
12	47	5.71
14	54	7.48
16	60	9.18
18	67	10.81
20	72	12.38
22	77	13.88
24	82	15.31
26	87	16.68
28	91	17.98
30	94	19.21
32	98	20.38
34	101	21.48
36	104	22.51
38	106	23.48
40	109	24.38
42	111	25.21
44	113	25.98
46	115	26.68
48	117	27.31
50	119	27.88
52	121	28.38
54	123	28.81
56	125	29.18
60	129	29.70
62	131	29.88
64	133	29.98
66	136	30.01

climatology of cyclones provides some good guess for considerations on which to base the initial forecast. However, as there are a large number of exceptions, forecasts based on climatology alone cannot be entirely relied upon.

Persistence of motion assumes that the integrated effect of all forces which have caused the tropical cyclone to move during some past period will continue in the future. However, the technique fails when recurvature takes place and some cyclones may depict recurvature more than once.

In cyclone forecasting, it is often assumed that cyclone follows the direction of upper atmosphere current at 200 or 300 mb. SPARRSO, in collaboration with Dhaka University, has undertaken an investigation into the problem, and it has been found that there seems to be a steering current for every cyclone, but the level differs from cyclone to cyclone and there does not seem to be any relation with intensity of the cyclone. Moreover, the upper atmospheric current is as variable as the track of the cyclone and hence it is difficult to find out the exact steering current.

Recently various statistical and numerical dynamical methods have also been introduced for the forecast of cyclone paths. The track of the cyclone can be monitored from satellite pictures.

Protection Against Cyclones

What can be done to protect ourselves from the cyclones? A cyclone is a natural phenomenon like an earthquake or a volcanic eruption. We have to learn to live with it. Experiments are being conducted in the United States to reduce the intensity of cyclones and we are watching these experiments with great interest. But until cyclones are controlled, we have to strengthen the cyclone warning system and adopt protective and relief measures to minimize their onslaught. Strongly built houses have to be constructed high above the sea level to serve as emergency shelter places. People from the low lying areas in the coastal region can be evacuated into these shelters in the event of a cyclonic hit. Coastal embankments have to be made to protect life and property from the onslaught of storm surges. Plantation of trees along the coastal area can also diminish the fury of the storm surge.

Besides taking up an elaborate programme for the construction of coastal shelters, embankment and afforestation, Bangladesh today has a very comprehensive and elaborate Cyclone Preparedness Programme operated by the Bangladesh Red Cross Society. It has a membership of about 20,000 devoted volunteers spread over 2,043 wards of 195 Unions of the coastal belt of Bangladesh. In each ward the trained volunteers do the needful in the event of a cyclone. Each ward is provided with a transistor radio, a megaphone-cum-siren, a signal torch light and first aid kits. Almost each Upazila is provided with a wireless set which keeps direct communication with Dhaka. The Red Cross volunteers are responsible for the following:

(1) Spreading warnings against approaching cyclones reported by radio, surveying damages caused by cyclones and reporting them to the Union Headquarters.

(2) The arrangement of shelters for people, possibly also for cattle and for the security of other property.

(3) The rescue of survivors still in danger.

(4) First-aid to the wounded and post-cyclone sanitary measures.

(5) Distribution of food and clothing to the needy.

The Red Cross volunteers go into action in the event of a cyclone disaster. This has been amply demonstrated during the last few cyclonic storms that struck Bangladesh. The whole Government machinery, including the Army, the Navy, the Air Force and the relevant agencies, are put into operation in the event of a cyclonic disaster.

Cyclone Warning Signals

There is a system of signal numbers for warning the port authorities of the danger of an impending cyclone. The same signal numbers are also applicable to the public in general. There are ten signals in use for the seaports. Explanations of the signals are as follows:

1) *Distant Cautionary Signal Number One*: This signal number means that a depression has formed in some part of the Bay of Bengal and the concerned port is not threatened by it, but a ship leaving the port is likely to experience bad weather on its way due to this.

2) *Distant Warning Signal Number Two*: This means that a cyclonic storm has been formed with a sustained wind speed of 40 miles/hr. or more, and the port is not threatened, but the ship leaving the port is likely to get bad weather on its way.

3) *Local Cautionary Signal Number Three*: This means that the port is threatened by squally weather.

4) *Local Warning Signal Number Four*: This signal number means that the port is threatened by a storm, but it does not appear that the danger is yet sufficiently great to justify extreme measures of precaution.

5) *Danger Signal Number Five*: This means that the port will experience severe weather from a storm of slight or moderate intensity that is expected to cross the coast to the *south of the port.*

6) *Danger Signal Number Six*: This means that the port will experience severe weather from a storm of slight or moderate intensity, that is expected to cross to the *north of the port.*

7) *Danger Signal Number Seven*: This means that the port will experience severe weather from a storm of slight or moderate intensity, that is expected to cross over or near to the port. The above three signals 5, 6 and 7 are advised to be hoisted when a cyclonic storm is expected to have sustained wind speed of 39 miles/hr. or more but less than 55 miles/hr.

8) *Great Danger Signal Number Eight*: This means that the port is threatened by severe weather from a storm of great intensity that is expected to cross the coast to the south of the port.

9) *Great Danger Signal Number Nine*: This means that the port will experience severe weather from a storm of great intensity that is expected to cross the coast to the north of the port.

10) *Great Danger Signal Number Ten*: The port will experience severe weather from a storm of great intensity that is expected to cross the coast over or near the port.

Thus we see that Signals number 5, 6 and 7 are similar; the difference is due to the direction of the storm. The same is true for signals number 8, 9 and 10.

During the 25 May 1985 storm, as the storm was expected to cross the coast between Chittagong and Cox's Bazar, great danger signals number 8 and 9 were hoisted at Chittagong and Cox's Bazar respectively.

Signals for River ports

Besides these signal numbers, a set of four signal numbers are used for the river ports as described below:

1) Cautionary Signal Number 1 means that the area is threatened by squally weather, the river crafts should move with caution but navigation may not be stopped.

2) Warning Signal Number 2 means that the area may face wind due to depression with wind speed less that 39 miles/hr. or a norwester. When this signal is hoisted, small river crafts should take shelter.

3) Danger Signal Number 3 means that the area is threatened by a cyclonic storm with sustained wind speed between 39 miles and 54 miles/hr.

4) Great Danger Signal Number 4 means that the area is threatened by a cyclonic storm with wind speed greater than 54 miles/hr.

When river port Danger Signal Numbers 3 and 4 are hoisted, all the river crafts should take shelter.

Future Programme of Agroclimatic Monitoring

The system provided by US-AID has been termed Agroclimatic/Environmental Monitoring Project (ACEMP) because of its use for agrometeorological purposes in addition to routine meteorological use.

The current and potential uses of the system are the following:

1. Conducting studies of monsoon clouds over Bangladesh for a better understanding of rainfall, flood, and drought.

2. Determining the structure, dynamics, intensity and movement of storms and storm surges.

3. Conducting studies on cropping patterns and cropping intensity and developing identification keys for major crops.

4. Preparing estimates of the acreage and yields of principal crops, including the extent of damage by natural disasters.

5. Determining of crop calenders.

6. Development of planning strategies for flood prone areas and delineating areas prone to inundation.

7. Conducting follow-up studies of land accretion in the Bay of Bengal.

8. Conducting forest resource inventories.

9. Mapping and monitoring coastal afforestation.

Agrometeorological Use of Weather Satellites

The daily wide area coverage provided by the NOAA satellites have advantages in monitoring the agricultural crop cycle and the wetness/dryness of the soil due to rainfall and irrigation. The day/night coverage of the same areas allows the investigator to observe the temperature differences or thermal inertia of the earth's surface. The multispectral channel of the AVHRR allows the routine measurement of the greenness of vegetation or the vegetation index as described in the following section. Natural resource satellites like Landsat can be used for vegetation measurements at higher resolutions but the weekly or biweekly data is not always available to the investigator on a timely basis to be practical for a current season crop monitoring programme. This restriction on access to data need not apply to countries which operate their own ground stations. For a country like Bangladesh, a single pass of the weather satellite provides a complete image of the country so that statistics on vegetation growth can be readily obtained. In comparison, complete coverage of Bangladesh by Landsat takes 16 days. Individual Landsat MSS frames can only be taken every 8 days using both Landsat 4 and 5 data. These satellite data can be used for change detection studies including forestry, coastal accretion/erosion, river course changes and land use.

Multidate vegetation index calculation and analysis

The satellite study of vegetation began with the launching of ERTS 1 (Landsat 1). Investigators have developed techniques to convert the information from the four MSS bands to a single parameter in various mathematical combinations for measurements of the vegetation characteristics. This single parameter has been termed the vegetation index (VI). Perry and Lautenschlager (1984) have reviewed the literatures on vegetation indices and given references to about four dozens of vegetation indices. However, the most commonly used one is the normalized vegetation index (NVI), which is defined as the following combination of the Landsat MSS.

$$\mathrm{NVI} = \frac{\mathrm{MSS\ 7} - \mathrm{MSS\ 5}}{\mathrm{MSS\ 7} + \mathrm{MSS\ 5}}$$

It is known that bare soil reflectance for MSS 7 and 5 are close to each other (the earlier being a bit higher), while for vegetation it is widely apart (MSS 7 reflectance is much higher than MSS 5 reflectance). For water MSS 7 reflectance is lower than that for MSS 5. Consequently the difference (MSS 7 − MSS 5) is much higher for vegetation than for soil or other features, thus providing distinct signature for vegetation.

The AVHRR sensors are so designed that channels 1 and 2 are similar to band 7 of MSS and are suitable for mapping the surface features including vegetations. For AVHRR channels 1 and 2, the VI has the following expression:

$$NVI = \frac{\text{Channel 2} - \text{Channel 1}}{\text{Channel 2} + \text{Channel 1}}$$

Using the above algorithm, a computer programme for calculation of normalized vegetation index (NVI) with a suitable enhancement scheme

$$(SNVI = (\frac{\text{Channel 2} - \text{Channel 1}}{\text{Channel 2} + \text{Channel 1}} \times 100 + 100))$$

has been developed and implemented in the I^2S image processing system/VAX 11/750 computer of SPARRSO. A suitable colour table has also been developed for easier and meaningful visual representation of the results. The vegetation index represents the green biomass intensity, health and vigour of the vegetation. The NVI values depend on the percent coverage of the vegetation, height of the plants, colour of the leaves or stages of the crops. The NVI values limit from −1 to +1, depending on the nature of the surface and intensity of vegetation. Values equal to or less than zero represent water. Values higher than zero represent different vegetation intensity, depending on the magnitudes of the values. The higher the NVI, the higher the green biomass intensity.

Table VIII provides the techniques of interpretation of the digital NVI counts for agricultural/agrophysical analysis.

As mentioned earlier, the major crop during March is the winter rice. Thus, except for the Dhaka forest areas, the vegetation is the boro rice. Most intensive and uniform boro is found to be in the Ariol Bil of the Dhaka district. A comparison of this image with that from the AVHRR shows that the values obtained from these sensors have approximately the same level of magnitude for the uniformly cropped areas. For sparsely vegetated areas, the vegetation index values obtained from AVHRR differ from those of MSS due to large difference of pixel

TABLE VIII

NVI Values	*Colour*	*Features*
0.0	blue/magenta	Water (also may be cloud, cloud shadow for values near to zero).
0.0-0.1	red	Bare soil with insignificant vegetation coverage
0.1-0.2	dark yellow	Vegetation with lower percentage of coverage/early stage of crops.
0.2-0.3	dark green	Vegetation with low percentage of coverage/matured crops wtih yellow leaves, etc.
0.3-0.4	bright green	Medium intensity of vegetation/ medium healthy crops.
0.4-0.5 0.5-0.6	dark sky bright sky	High vegetation, healthy crops, dense forests, etc.
0.6-0.7	light pink	Very dense and healthy forest.

resolutions of these two sensors: AVHRR pixel size = 1.1 km sq and MSS pixel size = 80 m sq. Because of very low ground resolution of AVHRR, there is need to be careful for estimation of crop using these data.

It has been seen that for the state of Nebraska in the U.S.A. the crop area measurements by AVHRR have been corrected using correction formulas developed from samples of area measurements from AVHRR and MSS. This method is known as the double sampling technique. Investigations of development of such a crop area estimation scheme for Bangladesh from AVHRR and MSS data will be performed under future programmes of SPARRSO.

Mapping of Thermal Inertia (TI)/Soil Moisture Index

The thermal inertia of soil may be considered as the index of soil moisture content. The moist soil has high thermal inertia, due to which it heats slowly by day and also cools slowly during the night. Thus the difference of maximum and minimum temperatures (T_{max} - T_{min}) is relatively low. On the contrary, the dry soil has low thermal inertia and, unlike moist soil it heats rapidly in the day and cools rapidly in the night, resulting in high maximum and minimum temperature difference. Thus, T_{max} -

T_{min} is a relative measure of the thermal inertia and is expressed as

$$\text{Relative thermal inertia (RTI)} = \frac{1}{T_{max} - T_{min}}$$

The RTI or $T_{max} - T_{min}$ provides a relative measurement of soil moisture.

The NOAA-9 passes are such that they approximately coincide with the times of temperature extremes. This made the thermal channels of NOAA-9 AVHRR suitable for calculating the day maximum and night minimum temperatures. These day and night temperatures are used to calculate the difference ($T_{max} - T_{min}$).

Conclusion

Thus the facilities developed at SPARRSO for the reception and analysis of meteorological satellite data are very useful not only for monitoring daily weather and tropical cyclones but they can also be used very profitably in various application activities such as land use, crop pattern, crop intensity, crop damage, crop yield and crop calender, land accretion, forest inventory, coastal afforestation, etc. Developing countries like Bangladesh can profit immensely from this technology, which provides most valuable information not only about the weather but also about agriculture, land accretion, forestry, etc.

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REMOTE SENSING AND ITS IMPACT ON DEVELOPING COUNTRIES' RAINFALL, TEMPERATURE AND SOIL MOISTURE

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GENERAL

Need for Improved Technology

One of the important findings of the global 2000 study is that enormous growth in the world's population will occur by the year 2000, while world food production will increase at an average annual rate of about 2.2%. The projections indicate that most of the increase in food production will come from more intensive use of yield-enhancing, energy-intensive inputs and technologies (Global 2000, 1980).

Dr. Norman Borlaug, Nobel Laureate, who had much to do with bringing about the "Green Revolution", commented on the world food supply situation. "We are running out of land," Borlaug says. "I mean good agricultural land. Ninety-eight percent of the total tonnage of food comes from the land. Only 2% comes from the ocean and the inland waters, and those percentages are not likely to change very much in the next several decades. So we've got to make the land produce much more by improved technology." (Jourdain, 1982).

The relatively poor performance of agriculture in the developing world cannot be blamed entirely on shortages of land, rainfall, fertilizers, and other inputs because those variables cannot explain wide differences in agricultural productivity among many individual countries. Historical experience in the Western world and in various developing countries demonstrates that if technical knowledge can be made available to countries in appropriate forms and combinations, and if it can be shown that the use of these inputs is profitable, agricultural production can be greatly increased under widely varying conditions of soil, climate and topography. (Carter *et al.*, 1975).

It is well to keep in mind that the economy of the western world is tied not only to that of other developed nations but also to that of developing nations. These countries not only serve as markets for our agricultural products and manufactured goods, but they, in turn, provide a very high percentage of the world's strategic metals and petroleum products. For these developing nations the importance of remote sensing technology is in the detection, characterization and management of renewable and non-renewable resources. Management of agricultural and rangeland resources can be greatly augmented by periodic data on the location and amount of rainfall. Most of the world's cultivated land depends on natural rainfall.

Rainfall Distribution and Effectiveness

For many decades scientists have made attempts to relate the various factors which determine aridity, or whether precipitation is adequate for growing crops. One of the earliest, and possibly least successful, classifications was based on rainfall alone (Worcester *et al.*, 1978). The Sahara was excluded southward to the 250 mm isohyet and the southern margin of the semi-arid area was placed at the 400 mm isohyet. These oversimplifications ignore the parameters of temperature and evapotranspiration as related to the effectiveness of precipitation. This important link was proposed by Penck in 1910 in defining the boundary of drylands where evaporation exceeds precipitation (Walton, 1969).

The significance of temperature was recognized by Koppen in 1918 (Walton, 1969). De Martonne (1926) utilized temperature and rainfall data to produce an aridity index. In 1942 the aridity index was further modified to account for seasonal distribution.

Thornthwaite (1948) proposed a precipitation-effectiveness index or P/E ratio. The index is calculated for each month (P being precipitation and E evaporation), summed for the year and multiplied by 10. The P/E limit for the semi-arid margin is 20, and 40 for the arid margin.

Meigs (1953) applied Thornthwaite's index for determination of the earth's arid regions. He further refined the groupings into regions with similar seasonal distribution of precipitation and temperatures for the coldest and warmest months. Semi-arid, arid and extremely arid zones were identified.

Applying the criteria of Meigs, there are 21,243,000 square kilometers of semi-arid land, 21,803,000 square kilometers of arid and 5,812,000 square kilometers of extremely arid land in the world, or approximately 33% of the earth's land surfaces excluding cold, arid regions (Dregne, 1976).

Although these approaches appeared reasonable, they were still simplistic in considering only climate. Many significant factors were overlooked (Worcester *et al.*, 1978). Such factors as soil type and texture, soil moisture holding capacity, wind velocity, relative humidity, vegetation cover and land use are also significant although difficult to accommodate with simple equations.

The National Oceanic and Atmospheric Administration Environmental Data Service in the U.S. computes a weekly Crop Moisture Index (CMI) for agricultural regions. The Index is a measure of the amount of moisture available for crop growth and takes into account rainfall and evapotranspiration. The Index is an average condition applying to large areas and requires that adjustments must be made in specific areas for precipitation received and soil moisture holding capacity. The CMI has value for large areas but does not take into account soil factors or local variability of precipitation.

It is obvious from the above that inhabitants of arid and semi-arid regions can benefit from technology that provides data on rainfall distribution and amount only if resource information is available concerning productivity and characteristics of soils.

Rainfall and Soil Moisture in the Sahel

Precipitation Characteristics of the Sahel

The African Sahel, the sub-Saharan strip stretching from Sudan to the Atlantic between about 14 degrees and 18 degrees north latitude, is an area typical of those experiencing irregularities in rainfall occurrences and amounts. There are approximately 20 million subsistence farmers and pastoral herdsmen who inhabit this savanna.

The most dynamic element that dominates the welfare of the inhabitants of the Sahel is the occurrence of rainfall. Rainfall on the one hand is the lifeblood of the Sahel, but its variability and inconsistency in its patterns of occurrence are responsible, at least in part, for most of the ecologic and sociologic ills of the region.

The average annual rainfall in this area ranges from about 100 mm to 750 mm. The adjacent agricultural areas to the south of the Sahel, with rainfall amounts up to 1000 mm, also may experience shortages of moisture during certain seasons of the year or during certain years.

Desert systems and their fringe areas are more variable in climate than any other ecosystem. Rainfall can vary five or tenfold from one year to the next, and it is this extreme variation that makes the land so vulnerable (Mosaic, 1977). The rainfall of the sub-Sahara region results from monsoons which sweep up from the Atlantic. When the monsoon is weak, the result is a dry year, and a succession of these produces a major drought.

Unlike the steadier precipitation of temperate regions, rainfall in arid and semi-arid lands often comes in violent bursts, often resulting in considerable runoff and erosion. Therefore, precipitation measured in rain-gauges may not be at all representative of soil moisture. Also, rain-gauges are so scattered in the region that they cannot be considered to be representative of rainfall for any particular area.

An excellent initiative to gather meaningful weather data related to desertification was undertaken at Dakar, Senegal, by the Agence pour la Sécurité de la Navigation Aérienne (ASECNA) at Dakar, Senegal, which began in 1972 using ESSA and NOAA satellite imagery to track disturbances during the Global Atmospheric Research Program of the Atlantic Tropical Experiment in the summer of 1974 (Mosaic, 1977).

Their results make it clear that further cooperative action of the west and central African countries to make wider use of such data (already received by several meteorological services in the area) could materially improve forecasting of the displacement of the major rainstorms.

Reconnaissance Soil Survey Requirements Related to Soil Moisture

The soils of the Sahel range from sand dunes to deep productive soils of the river valleys. Entisols, consisting largely of sand dunes and shallow to deep gravelly soils, are by far the most extensive soils in the semi-arid and arid regions of Africa. The most productive agricultural soils of the continent are irrigated Entisols in the river valleys, and the poorest are Entisols of the mountain massifs and mobile dunes of the

Sahara. Alfisols are the dominant soils in the Sudanian Zone south of the Sahara and in the semi-arid fringe of southern Africa. Alfisols are the soils of the savannas; Aridisols, Vertisols, Inceptisols, and, rarely, Oxisols are the soils in the other vegetative zones of the Sahel.

Worcester and Dalsted (1978), have shown that specific short- and long-term indicators of soil and vegetation conditions are associated with soils as responsive indicators of environmental conditions. The Entisols are fragile soils which exhibit rapid response to ecological changes. Soils of intermediate response to environmental hazards such as overgrazing or salinization are the Aridisols. As soils become more weathered and more fully developed, such as the Alfisols and the Vertisols, they have higher moisture-holding capacities and are more resistant to drought. As one progresses from Entisols through increasingly well developed soils — Aridisols, Inceptisols, Alfisols, Vertisols and Oxisols — the resistance to drought increases.

The productivity of the various soils of the Sahel provides the basis for determining optimum land use and is the basis for concentrating analyses of remote sensing monitoring efforts. It is for this reason that a soil survey on at least a reconnaissance level should precede studies of soil moisture distribution and utilization. Soil moisture is an important factor in the mapping of soils and their taxonomic classification.

Locating Productive (High Moisture-Holding Capacity) Soils in the Senegal Kaffrine Area

The Government of Senegal is involved in the implementation of a five-year plan for the management and optimal utilization of Senegal's natural and human resources. The Remote Sensing Institute (RSI) of South Dakota State University (SDSU) has only recently completed maps and a report on the natural resources of Senegal, using satellite imagery and ground checking procedures (RSI-SDSU, USAID, Senegal, 1986). In conjunction with this project, a pilot area in the economically important Groundnut Basin of Senegal was selected by Cisse *et al.* (1984), to demonstrate the utility of a Geographic Information System (GIS) for natural resources management. A soils map, land use map, forest and pasture reserves map, and administrative boundary map served as inputs to the GIS. Tabular data which were used included agricultural production statistics, demographic data, soil capability and suitability information, crop use intensity information, and crop management data.

DeVries (1985) reports that linking the soils data with the GIS resulted in a number of useful thematic maps, including soil capability class, soil slope, water erosion hazard, soil drainage, root restriction limitation, and suitability for various crops. It can readily be recognized that many of these thematic interpretations are directly or indirectly related to the moisture-holding capacity of the soils. Interpretation of the land-use data resulted in maps showing agricultural lands and grazing lands. An appropriate land-use map was derived from an interpretation of the composited soils and land-use data sets. Estimates for total yield for peanuts and millet and per capita production in the pilot area were made by combining the agricultural production statistical data, the demographic data, the crop management data, the crop use intensity information and the land use within administrative units areal tabulation data. Figure 1 shows a map of soil capability classes for the Kaffrine area which, even without other supporting interpretations, would be useful in conjunction with rainfall data for estimating potential crop yields.

Remote Sensing for Estimating Rainfall and Soil Moisture

Agrometeorological Needs and Remote Sensing Development

Since the earliest days of images from satellites, meteorologists have been interested in cloud patterns and the possibility of relating satellite imagery to cloud parameters in terms of quantitative amounts of precipitation. As the result of a decade or more of development, meteorological satellite observations now provide the capability for the direct estimation of precipitation and the measurement of cloud coverage and type (a major factor in the amount of energy available for evapotranspiration), and permit direct estimation of soil moisture levels through various models and with other inputs.

Mathematical models used to predict the yield of a crop require the best available meteorological information throughout the growing season. Precipitation is one of the most important, and its distribution within the growing season may be even more influential than the total amount.

The amount of water stored in the soil profile is extremely important in agricultural management. Soil moisture is essential for seed germination and for the growth and development of agricultural crops. A knowledge of soil moisture present in the profile is also important for partitioning rainfall and irrigation water into runoff, infiltration and redistribution,

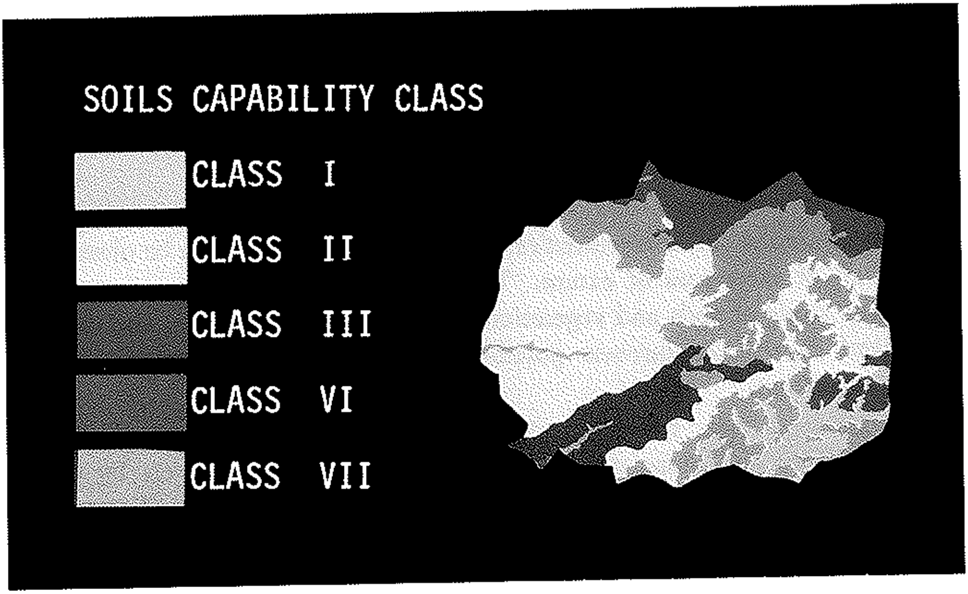

FIG. 1. Soil capability classes for Kaffrine, Senegal area.

drainage, and storage. (Myers *et al.*, 1983). Soil moisture influences the development of insects that spend part of their life in the soil; soil moisture also influences soil-borne plant pathogens. In addition, soil moisture affects soil erosion and evapotranspiration, and it is a critical input in models used in irrigation management and yield prediction.

These kinds of data are not normally available on a routine basis, particularly in developing countries. Operational satellites now provide rapid, continuous global coverage and are potential sources of the required information. Meteorological data that are derivable from environmental satellite observations include precipitation, temperatures, albedo, soil moisture and others. These kinds of information are useful for crop yield and hydrologic models, for determining water requirements for irrigation, for producing vegetation index products, for predicting and assessing drought, for predicting insect infestations, and for numerous other purposes.

There are a number of established procedures for estimating soil moisture, including point sampling methods, bookkeeping methods and others. Point sampling methods are laborious and difficult to extrapolate to entire fields or other large areas, and bookkeeping methods require assumptions concerning runoff, deep percolation, and evapotranspiration.

Several spectral regions have been investigated to determine the feasibility of using remote sensing for soil moisture detection. All of the reflective, thermal, microwave, and gamma spectral regions have distinctive characteristics and advantages and require rigorous evaluation for soil moisture detection.

Remote sensing offers a regional view of soil moisture conditions. Areas of similar soil characteristics, called soil associations, can be observed over all of their area of extent. The temporal aspect of remote sensing permits study of soils and vegetation as they change with time, and multispectral capabilities increase possibilities of unique signatures for soils and vegetation.

In some soils soil color changes markedly with moisture content. Between dry and moist conditions colors commonly are darker by one-half to three steps in value and may change from $-\frac{1}{2}$ to $+2$ steps in chroma.

Skylab investigations showed that wavelengths greater than 2.1 µm were required to reliably distinguish spectrally between wet and dry base surfaces. Also, thermal data provided a better estimate of soil moisture than data from reflective bands (Moore *et al.*, 1975).

In the 4.0 to 5.0 µm wavelength region, thermal emission generated as a result of various soil, water, and plant characteristics adds a vital dimension to reflective radiation phenomena, the two being generally non-redundant. Thermal inertia, which considers the dynamics of temperature phenomena, is a powerful tool due to its indirect indication of soil and plant moisture conditions.

Thermal techniques have the potential to infer soil moisture variations beneath a vegetation canopy by sensing the crop canopy since temperatures are directly related to variations in plant transpiration. Experiments indicate that surface temperature differences of up to 3 degrees Centigrade can be produced by subsurface moisture differences occurring at depths of 10 cm or more. Thermal techniques for estimating soil moisture are extremely useful since plants sample a volume of soil which may extend to their rooting depths (Heilman *et al.*, 1978).

In the microwave region of 0.1 to 30.0 cm, microwave emission occurs and is influenced by variations in emissivity and, to some extent, by surface ad subsurface conditions. Microwave frequencies offer a good possibility for evaluating soil moisture by virtue of the large difference in dielectric constant between moist and dry soil conditions. The dielectric constant of water at microwave frequencies is large (as high as 80), whereas that of dry soil is typically less than 5.

Microwave has some distinct advantages over other shorter wavelength sensors, including the ability to penetrate clouds and some precipitation and to view a scene by day or night independent of sunlight.

Passive gamma radiation measurements are recognized as having potential value for evaluation of mean areal soil moisture but are not included in this paper because of limited development.

Table 1 shows the electromagnetic properties and wavelength intervals for various remote sensing systems.

TABLE 1 - *Electromagnetic Properties for Soil Moisture Sensing.*

Wavelength Region	Property Observed
Reflected visible and infrared 0.3-3.0 μm	Reflectance/index of refraction
Thermal infrared 10-12.5 μm	Temperature
Active microwave 1-50 cm	Backscatter coefficient/dielectric properties
Passive microwave 1-50 cm	Microwave emission/dielectric properties and temperature

The remote sensing procedure most applicable to developing countries at this time is that of thermal infrared technology. The thermal inertia feature makes it possible to obtain indications of the presence of moisture for a number of days after precipitation occurs, and the technology is now available.

The Role of Meteorological Satellites in Agricultural Remote Sensing

Methods have been developed for obtaining both geostationary and polar-orbiter data. The geostationary spacecraft, which provide observations of North and South America at 30-min intervals are the primary source of precipitation data for these regions. However, for those areas where geostationary satellite data are not available, techniques using polar-orbiter data alone are used. Visible and infrared observations are the principal data sources.

There are two basic types of precipitation-estimation techniques:

cloud history and cloud indexing (Yates *et al.*, 1984). Cloud history works best where geostationary satellite data are available. The frequent looks from geostationary satellites allow the life cycle of a cloud to be followed and precipitation estimates to be computed for each stage of the cloud's development. In contrast, cloud indexing is the principal method where only polar-orbiter satellite data are available. Only two pictures a day can be obtained from one polar-orbiting satellite. Cloud indexing involves characterizing a cloud by an index number according to its appearance in imagery and then using a look-up table or regression equation to estimate the precipitation from the cloud.

NOAA Satellites for Estimating Soil Moisture and Plant Condition

The current U.S. polar-orbiting satellites are named simply NOAA-1, NOAA-2, etc., as successive satellites in the series are launched. The thermal sensors aboard NOAA satellites can provide data for moisture detection. Two of the four daily observations of the NOAA satellites are at good times for daily temperature extremes. One pass is in early morning (0230 local time) near the expected time of minimum temperature, and the other is in the afternoon (1430 local time) near expected maximum temperature.

All surfaces exposed to the atmospheric temperature variation and the variation of solar illumination will cycle in temperature with an amplitude depending on the atmospheric and solar effects and the thermal inertia of the surface. By sensing the temperature at maximum and minimum during a period of calm weather, the relative thermal inertias of the surface sensed can be determined. One of the main factors involved in thermal inertia is soil moisture content. The greater the moisture content the greater the thermal inertia and the smaller the diurnal variation in temperature.

Thermal infrared imagery obtained at night on bare soils provides temperature patterns that are interpretable in relation to moisture to a depth of 5 to 10 cm. Also, thermal infrared sensing of vegetation canopies which nearly or totally cover the soil can be used to relate vegetation temperature to soil moisture status. (Heilman *et al.*, 1976, 1978, 1981).

The imager now flown on the polar-orbiting satellites is the advanced very-high-resolution radiometer (AVHRR). The AVHRR can be used for some of the same functions that the multispectral scanner (MSS) on

Landsat performs. Although the spatial resolution is less (approximately 1 km for the AVHRR instead of the 80 m for the MSS), the spectral coverage is wider and the swath width of the sensor, combined with the orbital altitude, allows a given spot on the Earth to be revisited twice a day — once during daylight hours and once at night.

Microwave data, although not yet routinely available, will eventually provide estimates of soil moisture under adverse weather conditions. In the polar-orbiting system, the near future changes that are planned (McElroy, 1985) for NOAA-K through -M include the addition of an advanced microwave sounding unit (AMSU)) that is proposed for joint development with the United Kingdom.

Data Requirements

Two important criteria in providing soil moisture information are timeliness, and adequacy of coverage. Many users, when asked about their requirements of these criteria, will reply that they need the information as accurate and as rapidly as possible, updated every few days. When one really presses the user, there are some important aspects that should be considered when developing data acquisition systems.

Most users like to be alerted to deviations from the expected or the normal as soon as possible. Initial announcements need not be extremely accurate, but the alert of a problem is important. This is especially true for crop conditions, low water supplies, changing temperatures and other potential problems that affect many users. Therefore, timeliness of information is more important initially than accuracy.

After the initial alert, refinement of a specific answer should begin. Users would generally tolerate a one-week delay in obtaining refinement. Users would already be looking at various options and would make final decisions when refined data is received.

Reflective wavelengths permit recording of spectral radiance which can be related to soil moisture only at the soil surface and for very short periods of time until the soil surface dries. Microwave wavelengths have increased soil and cloud penetration ability and, therefore, have potential for relating to profile soil moisture. However, microwave has limitations of depth of measurement to about 10 cm, and, of more importance, microwave imaging acquisition is not now routinely available over developing countries. Therefore, for the immediate future, thermal infrared, combined with reflective wavelength imagery, appears to be the better wavelength region to utilize.

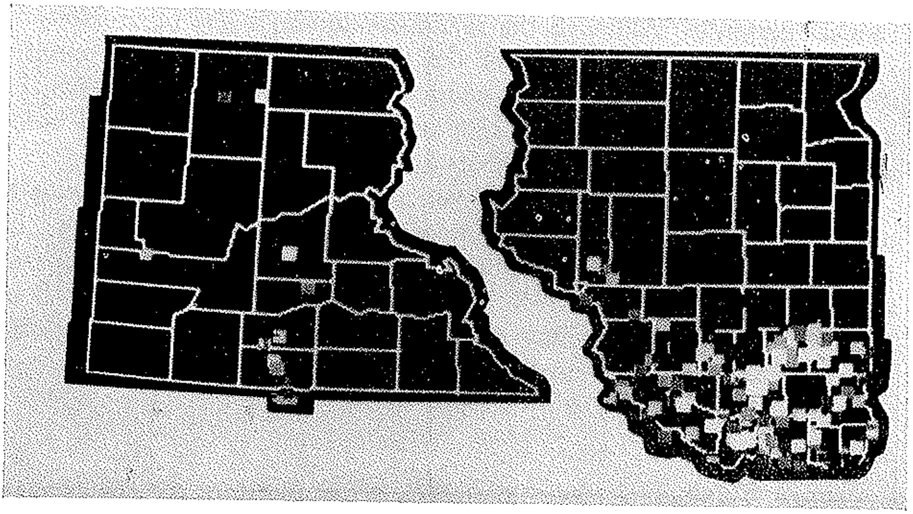

FIG. 2. Spatial display of South Dakota precipitation for the 24-hour period preceding the 22 July AVHRR overpass (original in color). The lightest toned squares represent rainfall amounts of greater than 4.4 cm. Progressively darker tones represent 0.6 cm increments to the darkest tone being a trace to 0.6 cm. The original color display contained eight definite levels. State and county boundaries identify geographic locations. The east and west portions of the state were displayed and photographed individually using a curved television screen and will, therefore, not register together. The approximate length of South Dakota is 650 km.

SOUTH DAKOTA RAINFALL DISTRIBUTION STUDIES

The South Dakota climate and crops are similar to those of many semi-arid developing countries. Therefore a South Dakota study site was selected for intensive soil moisture studies using visible, near-infrared and thermal infrared sensors, contained in the AVHRR instrument aboard the TIROS-N orbiting satellite (Moore *et al.*, 1983). A network of 1042 rain gauges was in place, established by the South Dakota Department of Water and Natural Resources. The gauges provided 24-hr rainfall measurements for the period June through September.

Average annual precipitation ranges from 350 mm in the west to 610 mm in the east. Principal crops are wheat, sorghum, corn, alfalfa and pasture in the east and small grains and rangeland in the west. The precipitation is typically frontal in the fall, winter and spring, and convective during the summer. Soils vary from warm, moist prairie (Udic Ustolls) in the southeast to cool, very dry plain (Aridic Borolls) in the northwest.

Data Sources

The AVHRR provided imagery for the project. The instrument was mounted in the TIROS-N near-polar, sun-synchronous orbiting satellite. The AVHRR provided coverage at about 0300 and 1500 LST. Spectral responses of the instrument were 0.55-0.90, 0.72-1.10, 3.55-3.93, and 10.5-11.5 μm. The instantaneous field of view (IFOV) at the nominal altitude of 833 km was approximately 1.1 km. Daily repeat coverage was available.

Data Processing and Map Registration

Daytime AVHRR data were acquired for two consecutive dates, 21 and 22 July 1979. The data were processed using the Interactive Digital Image Manipulation System (IDIMS) at the US Geological Survey's (USGS) Earth Resources Observation Systems (EROS) Data Center. Attempts were made to remove clouds and cloud shadows by training and executing a maximum likelihood classifier and creating a cloud mask image for each of the two dates. The two masks were combined with the image data to remove image regions where clouds were present in either of the two images. Rain gauge data were registered into the data base.

Rainfall occurred in southeastern South Dakota at 243 of the 1042 rain gauge sites during the 24 hours prior to the 22 July overpass. Figure 2 shows the general areas of rainfall, with light squares representing higher levels of precipitation. Maximum precipitation at any gauge site was 8.9 cm.

Fig. 3 shows AVHRR data of South Dakota before and after the rainfall. Spectral changes resulting from land use and vegetation contrasts are minimal in figure 3a which is an image of the 0.55-0.90 μm data. This wavelength band includes the chlorophyll absorption wavelengths and a portion of the infrared wavelength region of high vegetative infrared reflectance. Combining the wavelengths in a single band masks the effect of vegetative sensitivity to infrared reflected energy.

Fig. 3b includes data for the .725-1.10 μm region, a region of high infrared reflectance from vegetation. This wavelength interval is highly responsive to land use and vegetation contrasts.

Pixel by pixel subtraction of the spectral values of the 0.55-0.90 μm band (Fig. 3a) from the 0.725-1.1 μm band (Fig. 3b) created the difference image in Fig. 3c. The effects of spectral overlap (0.725-0.90 μm) are

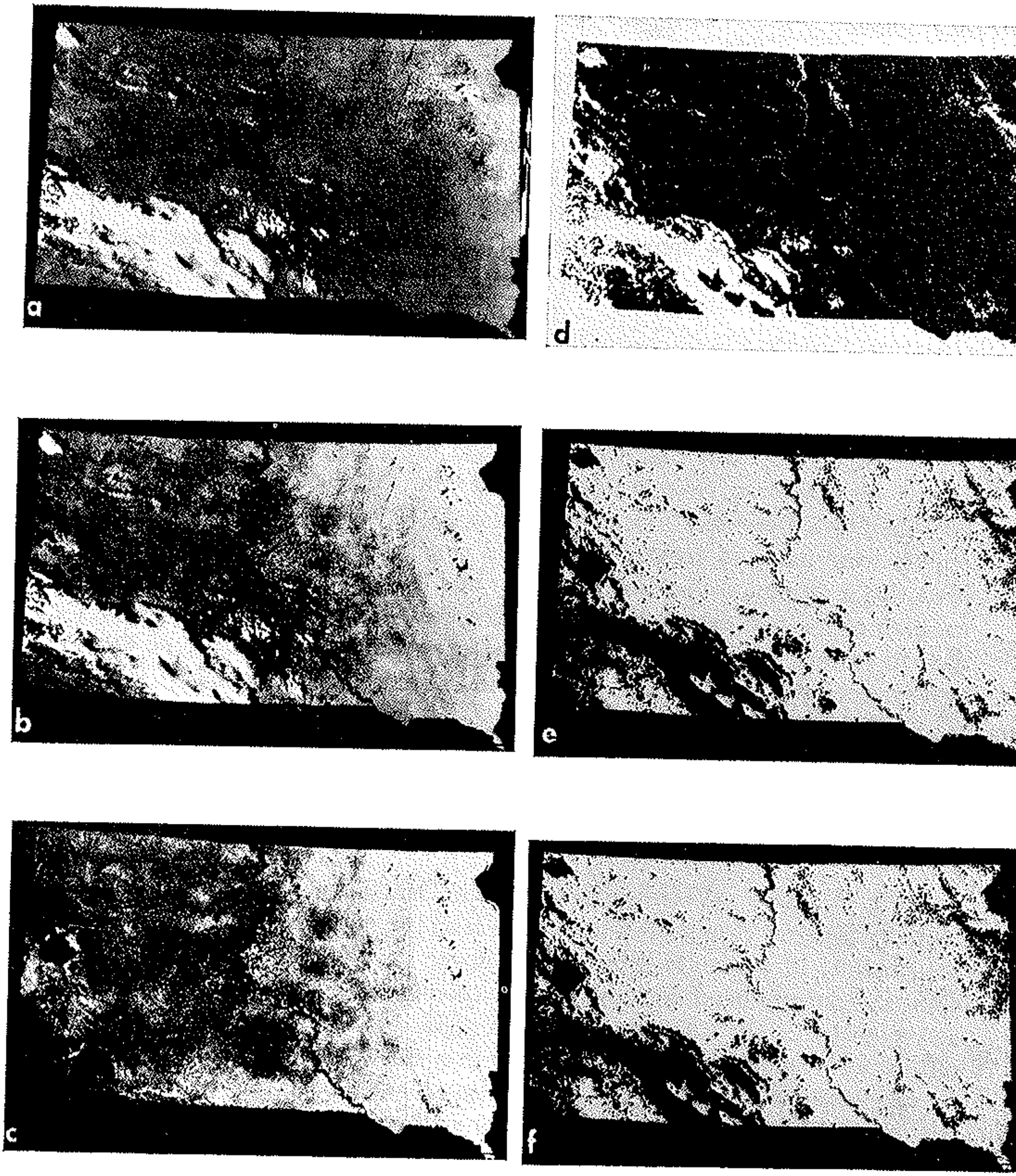

FIG. 3. AVHRR images of reflected solar data of South Dakota. 21 July was prior to the rainfall even displayed in Fig. 1 and 22 July after the event. The cloud mask in (d) shows cloud locations as ligh tones. Clouds are masked as dark in (e) and (f). (a) 21 July (0.55-0.90 μm). (b) 21 July (0.725-1.1 μm). (c) 22 July: difference image (b) - (a). (d) Cloud mask. (e) Difference image with mask, 22 Jul minus 21 July (0.55-0.90 μm). (f) Difference image with mask, 22 July minus 21 July (0.725-1.10 μm)

reduced, resulting in an image more representative of vegetative conditions. The eastern part of the state appears brighter in infrared reflectance than the western part, a contrast which accurately reflects the relative amount of rainfall and vegetative biomass in the two regions. Western South Dakota is largely range land while eastern South Dakota is predominantly row crops and alfalfa.

The pre-rainfall image was subtracted from the post-rainfall image as is shown in Figs. 3e, 3f and 4c. The method assumes that spectral change associated with the event is greater than the spectral change associated with other temporal variables (changes in plants, weather, sun angle, etc.). The reflective wavelengths would, of course, be influenced less by variables such as weather than the thermal IR wavelengths.

The difference images in Figs. 3e, 3f and 4c were prepared using both cloud and geographic masks. The masked regions are dark tones, areas of no change are medium tones; and a brighter appearance or cooler temperature in the second date as compared to the first date is light tones. The cloud mask in Fig. 3d was created by multispectral classification from both dates.

Figs. 3e and 3f indicate that the rainfall event documented in Fig. 2 did not cause a spectral change in the reflective portion of the spectrum. However, the thermal change in portions of Fig. 4c follows closely the rainfall distribution. The principal energy budget factor involved is the latent energy of evaporation. Statistical correlation studies involving temperature differences between the two dates indicated that the temperature change was not associated with changes in thermal inertia or transpiration.

The thermal infrared images of Figs. 4a and 4b which were associated with vegetation patterns in Fig. 3c have been cancelled in the difference image of Fig. 4c. Using time-series data to spectrally observe the same location for event detection decreases the complexity of interpretation by eliminating the need to model all the thermal variations for a single date to determine their actual physical causes. The only knowledge needed to interpret Fig. 4 is that wet surfaces are cooler than dry surfaces in midday. Light tones in the figure are cool, dark tones are warm. The area of rainfall is that identified by the letter A. An area in the northwest of the state also appears cool on the imagery. but not to the same extent as the area of rainfall occurrence.

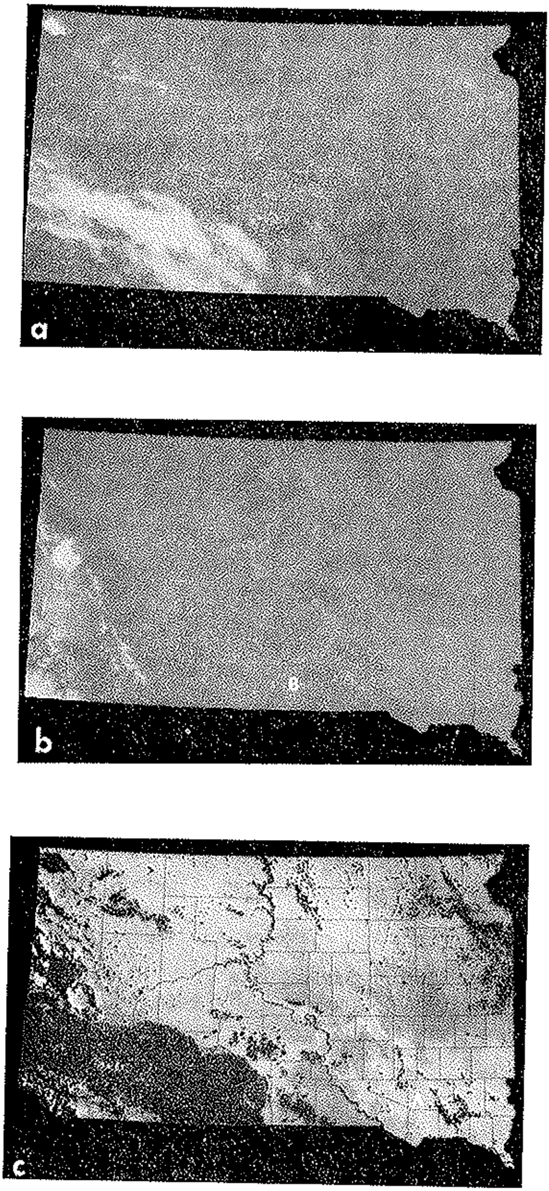

FIG. 4. AVHRR image of thermal infrared (10.5-11.5 μm) data of South Dakota. Points A in (c) and B in (b) denote rainfall locations as defined in Fig. 1. Light tones are cool. The difference image in (c) contains county boundaries for comparison with Fig. 1. (a) 21 July. (b) 22 July. (c) Difference image 22 July minus 21 July with cloud mask as dark.

Conclusions

The use of frequent multidate thermal infrared remote sensing imagery can improve the probability of rainfall event detection. Surface wetting by rainfall, in an otherwise dry region, changes the energy budget which is thermally detectable with existing remote sensing systems at least one day after the event. After the surface dries, thermal inertia and evapotranspiration remain sufficiently altered so that the increased moisture is detectable for an additional several days without interference of land use, terrain and soil factors.

A satellite with daily midday repeat coverage of every 4 or 5 days in regions with midday clear sky conditions would provide an effective system for rainfall monitoring. In regions where cloud cover would not permit that number of successful repeat observations, the use of cloud history or cloud indexing procedures would be appropriate. However, in regions where cloud cover is limiting, rainfall is likely to be sufficient so that soil moisture is not normally as limiting a factor in plant growth.

The 1 km resolution of the NOAA polar-orbiting satellites is adequate for regional applications. Other information such as estimates of green biomass can also be made using the reflected solar spectral intervals of the AVHRR instrument.

Effective conversion of rainfall data to useful soil moisture information and, in turn, to potential crop-land and range-land production depends on use of soil characterization and interpretations in a Geographic Information System.

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THE IMPACT OF REMOTE SENSING ON THE DEVELOPING COUNTRIES

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Progress in space technology has come about at the precise moment in history when the national economies of the developing countries are increasingly impoverished. The constant deterioration of the international monetary situation, the fluctuation of the exchange rates of the main reserve currencies and inflation all accent the imbalance in the world economic situation and continue to create difficulties for those countries' economies — difficulties which are reflected in all sectors and contribute to reducing the real value of their export revenues and their convertible currency reserves. The world now has a population of almost five billion, 75 percent in the developing countries. The remaining 25 percent hold more than 80 percent of the world's gross national product, consume about 75 percent of its energy and 95 percent of its technological resources.

Remote sensing activities in space are expensive, and direct, independent, active participation is generally beyond the reach of many developing countries; they have scant financial, material and human resources. Furthermore, the lack of highly skilled personnel and sophisticated technology, essential for those activities, substantially limits their possibilities of participation. The information obtained through remote sensing, when it is used in an arbitrary manner and without previous control or consent by the observed country, prejudices traditional security principles and violates the States' right to control the information collected about their respective territories.

We are of the view that, with regard to remote sensing activities, possible support and technical assistance from the developed countries to the developing countries should not in any way be expressed as a discriminatory business responding to political and economic interests and expressed in financial obstacles and hindrances and other measures incompatible with the developing countries' sovereignty.

More than two years ago, by decision of the United Nations General Assembly, the item on the drafting of principles on the legal consequences of remote sensing of the earth from space was included in the agenda of the Committee on the Peaceful Uses of Outer Space. In the course of the various meetings of the Committee and its two subsidiary bodies, working groups were formed to examine this item.

The Legal Sub-Committee, in particular, has analyzed working documents that contain draft principles proposed by different States. In the 25th Meeting of that Sub-Committee, a draft in this tenor was adopted as a compromise text. It was proposed by the delegation of Austria and supported by the majority of the delegations. It represents a step forward in the final elaboration of a draft and later a treatise on this topic.

This draft, although it is a document of conciliation among all the parties and an attempt to find consensus on the matter with a view to finally establishing needed principles, does not establish the precepts that would make the provision of prior information to the remote-sensed State compulsory and give the remote-sensed State priority of access to the data obtained about its territory. The establishment of these precepts would make it possible to regulate the possible transfer of primary or processed data and analyzed information to third countries, which is presently done without prior consultation with the remote-sensed State. It would guarantee that these activities follow the provisions of the principles of the United Nations Organization, respect the full and permanent sovereignty of all remote-sensed nations and States and not affect their economic or national security interests. The precepts that have been drafted do not include State control of non-governmental bodies that carry out remote sensing activities and the international responsibility deriving therefrom.

In the case of the Republic of Cuba, the results obtained through effective use of remote sensing technology respond, in the first place, to the gradual development of science and technology in our country since 1959. This development has responded to our needs and taken into account our real possibilities; it has made significant strides in many fields, among them the one we are concerned with here. Two main factors have influenced our development — begun in the 1970s — of remote sensing: the research done in the area of earth sciences and the possibilities provided by the cooperation offered with advantageous conditions of equality by the Intercosmos Program. These factors have contributed in great measure to the fact that such encouraging results have been achieved in a country where the natural resources are the heritage of the society as a whole.

In the main, preparation and analysis methods have been developed, based on analogical systems that yield satisfactory results without the complex and, of course, expensive technology that is beyond the reach of the developing countries. Major efforts have been devoted to training specialists, acquiring technological means, introducing technology from other countries and creating our own technology. Much attention has been given to the creation of interdisciplinary groups that can analyze and apply primary data in a comprehensive manner and make joint use of the installed technological capacity.

The space mission carried out by a Cuban researcher on September 18, 1980, as part of the Intercosmos Program was an event of enormous historical, scientific and technological significance. This space flight provided Cuban scientists with an exceptional opportunity and a challenge to their creative ability in a technologically complex field. The scientific program adopted was adapted to our reality and national interests, without losing sight of the indirect advantages linked to the possibilities of technological innovation. On the basis of more than 50 projects, a set of experiments of scientific and economic interest both to Cuba and to the rest of the countries participating in the program was identified. Many of these experiments were done during our cosmonaut-researcher's space mission and others have been carried out during later space flights. They cover a broad spectrum including remote sensing of natural resources, biology, medicine and meteorology. The remote sensing experiment was aimed at obtaining information from space on natural resources and the environment and included observation from space and measurements and research from the earth. Analysis of the data obtained has contributed to research on questions that are important to our scientific and economic development. At present, appropriate use has been made of remote sensing data in the study of natural resources and the environment.

There has been great interest in the methodological processing of primary information acquired through a subsystem of multiple sensors and the use of various photographic materials. This has made it possible to make comparisons in the entire visible, infrared region close to the electromagnetic spectrum.

Analogical processing of air and space information has been developed to solve various problems, both of a fundamental nature and as applied to research in different branches, especially those related to geology, geomorphology, oceanography, soils, agriculture, the study of landscapes, vegetation, protection of the environment and others. Methods for interpreting and mapping natural resources have also been developed.

The use of remote sensing methods in combination with geological, geophysical and surface geomorphological data has made it possible to detect the presence of circular alignments and structures, and extremely varied formation mechanisms and geneses that could be related to mineral deposits.

Information has been obtained on many elements and objects of the coastal zone, such as the boundaries of the waters, the sand beaches, sea karst zones, the study of sediments and biotopes.

Studies have been done on the soils, the distribution of taxa boundaries, and eroded soil, among others.

Remote sensing data have also been applied to agricultural studies and forestry economics; and interesting studies have been done on determining the use of the land and the dynamics of that use as well as on mapping plant formations and forests.

With regard to the environment, studies have been done on bay pollution and damage to crops and soil.

The progress achieved in little more than ten years in the field of remote sensing allows us to forecast a much more direct participation by this important technology in the country's socioeconomic development. For this, the peaceful use of outer space and cooperation among States are indispensable premises.

ECONOMIC, SOCIAL AND LEGAL ASPECTS OF REMOTE SENSING

SATELLITE REMOTE SENSING FOR DEVELOPING COUNTRIES

KARL-HEINZ SZEKIELDA *

Satellite imagery is already a routine tool in integrated mineral exploration programmes, and new techniques of interpretation offer improved geological discrimination, which is of value in locating buried ores. Several image analysis techniques are available. Although they are presently experimental, they show considerable promise for resources applications.

The extent to which foreign countries are utilizing LANDSAT data can be demonstrated in the statistics shown in Fig. 1.

In the coming years, many new products and services will be needed by users of remote sensing data. Some data users require access to satellite data in real-time or processing them in near real-time, with a trend in several developing countries to establish ground receiving and processing stations.

Capital costs for remote sensing programmes can be minimized by centralizing these programmes in regional institutions where developing countries and international organizations may use the available facilities under the concept of TCDC. This type of technical co-operation among countries within a region has the advantage of sharing the technology while lessening the financial burden of each participating partner. Remote sensing centres sponsored and developed for regional use are in existence in East and West Africa, and others have been established in Asia and Latin America with the technical assistance of UN/DTCD.

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LANDSAT DATA USERS

- More than 110 countries are participating in some form of remote sensing activity;
- More than 1,000 organizations worldwide are involved in remote sensing activities;
- More than 20 countries and/or international organizations have existing or proposed ground stations capable of receiving data;
- More than 30 countries are classified as having advanced remote sensing programmes; and
- More than 20 United Nations and other international assistance organizations are actively promoting the use of remote sensing data in developing countries or are using this technology in conjunction with existing projects.

FIG. 1. LANDSAT data users [ref. 1].

Satellite data receiving stations are variously designed as low-cost stations for low-resolution meteorological data reception ($ 5,000 - $ 100,000), for LANDSAT 1, 2, or 3, and high-resolution meteorological data reception ($ 1,000,000 to $ 5,000,000) and high data-rate reception of SPOT, LANDSAT-D, and high-resolution space-borne radar ($ 5,000,000 - $30,000,000) (see Fig. 2). Regarding the requirements of developing countries, the establishment of ground station facilities should be related to the expected level of applications of remotely sensed data. In the past, data have been available from external sources, but this may not always be the case. The delays in data products delivery which all users have experienced indicate the need for local sources of data acquisition.

Developing countries might consider an evolution of data processing capability in steps. The experience of several countries with visual analysis of photographic satellite products showed that they can produce surveys and inventories of natural resources which are a substantial increment to their national resource information. This first phase typically results in development of a small nucleus of specialists and facilities capable of complementing existing, traditional resource management staff deriving new inventories of national resources.

The next step from such a modest start would be the establishment of a national interministerial remote sensing group and integration of processing facilities. Training on digital processing is started at this stage usually outside the country. Facilities expenditures typically rise to the $ 100,000 level, and equipment maintenance becomes an important factor.

A third stage of development is the establishment of a national agency with digital facilities and often a satellite data receiving station. Very often a meteorological ground station has already been established and its data output is used by the remote sensing establishment. It is at this stage that new and unique benefits from remote sensing can be expected, while earlier stages can be expected to supplement and improve existing resource

FINANCIAL IMPLICATIONS OF THE USE OF SATELLITE REMOTE SENSING

- Low Cost Receiving Stations for Meteorological Data Reception
  US $5,000 – 100,000
- LANDSAT 1, 2 or 3 and High Resolution Meteorological Data
  US $1,000,000 – 5,000,000
- LANDSAT-D, SPOT and High Resolution Space-Borne Radar
  US $5,000,000 – 30,000,000

FIG. 2. Financial implication of the use of satellite remote sensing [ref. 2].

EVOLUTION OF DATA PROCESSING CAPABILITIES IN SEQUENTIAL STEPS

PHASE ONE
- Development of Nucleus Specialists
- Facilities Complementary to Existing Facilities

PHASE TWO
- Establishment of National Interministerial Remote Sensing Group
- Training on Digital Use of Data
- Facility Expenditure rise to US $100,000

PHASE THREE
- Establishment of National Agency with Digital Facilities
- Limited Capability to Receive Data Directly
- Enlarged User Community
- Facility Expenditure Rise to US $100,000 to 1,000,000

PHASE FOUR
- Fully evolved stage with staff equipment and institutional infrastructure
- Direct Data Acquisition and Processing Facilities
- Aircraft Capability—US $10 millions and above

FIG. 3. Evolution of data processing capabilities in sequential steps.

information sources. Typical investment levels are $ 100,000 to $ 1,000,000 and include some "simple" interactive digital capability.

The fourth stage can be considered as a fully evolved stage. There is an expectation that any level of remote sensing technology will produce *continuing* benefits, especially for resource exploration. However, it must be stressed that full benefits from application of remote sensing technology can only be derived most effectively from a fully evolved level of equipment, staff and institutional development. Such a capability includes direct data acquisition and data processing facilities. This requires a ground station ($ 1-5,000,000), an aircraft capability ($ 1,000,000 onward) and a substantial digital and photo-processing facility. Digital processing equipment should include image processing ($ 100,000 to $ 1,000,000), a data base management facility ($ 100,000 - $ 500,000), hard copy output devices such as high quality film writers ($ 80 - $ 300,000), digital map plotters ($ 20,000 to $ 150,000) and a high level applications software system ($ 50,000 onward) to operate this facility; a photo-processing facility would cost from $ 50,000 to $ 5,000,000.

With respect to the use of LANDSAT data, it has been shown that during 1979-1982 only five countries ordered more than fifty percent of the computer compatible tapes (CCT's), demonstrating that most developing countries were still not in a position to take advantage of relatively low-cost products for resources development. Similar conclusions can be drawn from the sale of CCT's of remote sensing countries and sales of data to countries interested in analysing their own territory. (See Fig. 4).

DATA SALES OF DATA TAPES FROM THE LANDSAT SYSTEM
(FROM: SZEKIELDA, 1986)

A: TOTAL SALE
B: SALE TO SENSED COUNTRIES

		1978	1979	1980	1981	1982
AFRICA						
	A	480	456	625	1,671	684
	B		5	4	24	51
MIDDLE EAST						
	A	263	188	281	746	168
	B		4	26	124	25
SOUTH AND EAST ASIA						
	A	227	345	1,081	1,641	654
	B		43	609	332	284
LATIN AMERICA						
	A	171	216	531	966	467
	B		63	356	326	117

FIG. 4. Data Sales of data tapes from the LANDSAT System [ref. 3].

As has been shown before, the establishment of a remote sensing programme for natural resources development may be implemented at various managerial, financial and technical levels. However, the main problem to overcome is still the lack of human resources and the adoption of new technology appropriate for the level of technical competence in a recipient country.

Typically, remote sensing projects are developed through technical and advisory assistance missions which lead in most cases to remote sensing projects. As the United Nations Development Programme (UNDP), the leading UN financing agency, is giving priority to training, many projects are dealing now with training as a major component, taking into account the need for developing human resources. Nevertheless, equipment and transfer of know-how through placement of consultants are still important factors of a technical assistance project (shown in Fig. 5).

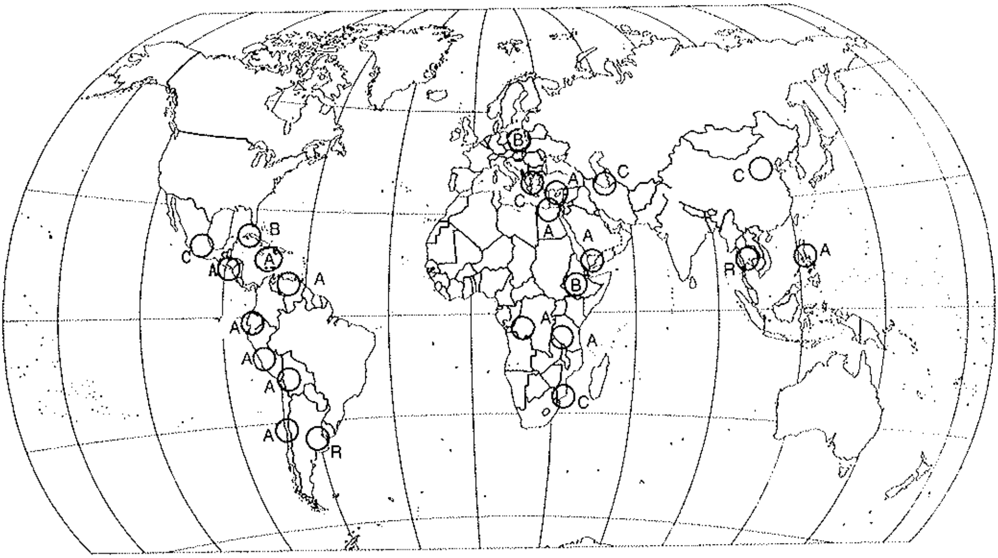
Under several programmes, training has been focussing on computer programmes for data handling, statistics and mathematics which are used in digital processing of remote sensing data. In some cases such efforts have been undertaken with course work at the university level. The training in its final approach has been dealing with specific application of remote sensing in different disciplines such as geology (for lineaments and other structure detection with satellites), cartography, hydrology, forestry and more generally in the inventory of natural resources.

In order to disseminate the know-how of the latest remote sensing technology to resource specialists in developing countries, and to assist developing countries in advanced planning for technology transfer, DTCD has prepared expert meetings with reports for wider distribution to developing countries. This is especially of importance with respect to the new microwave technology on spacecraft.

From the latest expert meeting the following outputs have been obtained: (a) over twenty remote sensing specialists trained in the use and integration of radar data into resources development programmes; (b) design of specific projects in the use of radars to be flown on future spacecraft; and (c) a book summarizing the main events of the meeting with guidance in the use of microwave sensors for future resources development.

In conclusion of the foregoing remarks, the following aspects for the transfer of remote sensing technology to developing countries should be considered in more general terms:

UNITED NATIONS ASSISTANCE
DEPARTMENT OF TECHNICAL CO-OPERATION FOR DEVELOPMENT



A: ASSISTANCE MISSION
B: CENTRES IN PREPARATION
C: OPERATIONAL CENTRES
R: REGIONAL PROGRAMME

FIG. 5. United Nations / DTCD technical assistance provided to Member States.

(a) Technology should be relevant and appropriate;

(b) The process of transfer should be a two-way traffic between developing and industrialized countries or within the framework of TCDC;

(c) The transfer should be through active involvement of the receiving party, which should be in a position to absorb the technology;

(d) The transfer should ultimately assist the country to be self-sufficient in the long run;

(e) The transfer should be on a "total" basis — i.e., transfer of operational, maintenance, modifications and engineering know-how.

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LA PERCEPCIÓN REMOTA EN EL PERÚ. ESTADO ACTUAL Y FUTURO

(text in Spanish)

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1. Aspectos Generales

El Perú posee un área de 1.28 millones de km^2 y su población sobrepasa los 18 millones de habitantes. Tanto su situación geográfica con respecto a los otros países latinoamericanos como la riqueza de sus recursos naturales y el mercado que le ofrecen la Zona Andina, EE.UU. y Europa, obligan a efectuar grandes esfuerzos a fin de obtener las mayores ventajas para su desarrollo económico.

Asímismo es un país con un potencial heterogéneo de recursos naturales y expuesto, casi cíclicamente, a riesgos climáticos y sismológicos que, en algunos casos, alcanzan la dimensión de desastres naturales. Por esta razón, la evolución socioeconómica del Perú ha mostrado, en diversos momentos de su historia y de acuerdo a coyunturas especiales, características propias de un país agrícola, pesquero, minero o energético, además de ser considerado un país con vasto futuro forestal, sin haberse definido periódica, se presentan fenómenos sismológicos, sequías y excesos de aún su real potencial ecosistémico global. Por otro lado, casi en forma lluvias con inundaciones y deslizamientos de masas terrestres superficiales que, muchas veces, provocan la pérdida de la producción agrícola, pecuaria y/o pesquera, la destrucción de la infraestructura de servicios sociales y de producción e, incluso, la lamentable desaparición de vidas humanas.

Dentro de este contexto, el Perú representa un país con una economía en desarrollo, que se caracteriza por la escasa disponibilidad financiera para el desarrollo de sus actividades económicas y una limitada capacidad tecnológica tanto para el manejo y procesamiento de sus recursos naturales como para la conservación de ecosistemas naturales y recuperación de territorios afectados por el deterioro ambiental.

Las tierras, las aguas y las condiciones climáticas generan una actividad agrícola dirigida al mercado interno de alimentos para la población y la producción de insumos para la actividad industrial. Los recursos mineros y energéticos fósiles, se orientan preferentemente al mercado externo y constituyen las actividades básicas para la generación de divisas, al igual que la actividad pesquera del mar pero con aportes de menor significado económico. La actividad forestal, a pesar del vasto potencial de la amazonía peruana, no alcanza aún la dimensión económica que le corresponde. La fauna, en determinado momento de la evolución económica del país, participó intensamente a través del guano de islas, pero en términos generales su incidencia es actualmente escasa, limitada al igual que la pesca en aguas continentales. El alto potencial hidroeléctrico nacional es de enorme importancia para el país, aunque su desarrollo es aún limitado.

El potencial de las tierras del país, de acuerdo a la clasificación según su capacidad de uso mayor, es el siguiente:

4'902,000	Ha.	Aptas para Cultivos en Limpio (3.81%)
2'707,000	Ha.	Aptas para Cultivos Permanentes (2.11%)
17'916,000	Ha.	Aptas para Pastos (13.94%)
48'696,000	Ha.	Aptas para Producción Forestal (37.89%)
54'300,560	Ha.	Tierras de Protección (42.25%)

De lo expuesto, se desprende que el Perú es un país eminentemente rico en tierras aptas para la producción forestal, distribuídas en su integridad en la región amazónica llamada a constituir, siempre que sea manejada racionalmente, la futura gran área poseedora de uno de los recursos renovables más productivos de la economía nacional. Una minoría de tierras apropiadas para fines agrícolas, cerca del 6% de la extensión territorial, constituye la máxima riqueza del país para la producción de alimentos.

Ocupan una posición intermedia las tierras que reúnen condiciones ecológicas para pastos (cerca del 14% de la extensión territorial), con el 60% de superficie localizada principalmente en las regiones altoandinas del país. Las tierras de pastizales altoandinos son las que presentan en forma dramática el problema de la desertificación, generado por el sobrepastoreo que ha conducido a un empobrecimiento del material vegetal, a la denudación del suelo y a la erosión acelerada. Los pastos naturales requieren de una atención continuada a fin de promover su real renovabilidad productiva y, por consiguiente, asegurar el sostenimiento de una ganadería económicamente rentable, principalmente de tipo lanar (ovinos y camélidos sudamericanos).

Finalmente, se dispone de una vasta extensión de Tierras de Protección (42.25%) que por sus características impropias no admiten, dentro de márgenes económicos, la actividad agropecuaria ni forestales de producción, pero presentan valor económico para actividades como la minera, suministro de energía, vida silvestre, pesca y recreación, así como atracciones paisajísticas y turísticas, entre otras. Estas últimas, en particular el turismo, suficientemente dotado de una infraestructura de facilidades, serían de gran beneficio general para la población del país y una fuente notable de ingresos para el Estado. Razonable es suponer que el Perú y aquellos países del mundo que disponen de una notable riqueza en escenarios naturales y arqueológicos están en condiciones, para fines del presente siglo, de desarrollar una de las industrias mayores fincada en el turismo.

2. Sistemas de Percepción Remota utilizados en el Perú

2.1 *Fotografía Aérea*

En el Perú se utiliza la fotografía aérea para múltiples propósitos y en sus diferentes productos, desde hace aproximadamente 30 años, tiempo en el cual, la fotografía se ha constituído en la herramienta más importante para la evaluación de recursos naturales y otros estudios vinculados al desarrollo. Paralelamente a esto se ha desarrollado la implementación de la infraestructura necesaria tanto en los aspectos de capacitación como en la adquisición de materiales y equipos, a fin de mantener una permanente operatividad de este sistema acorde con los nuevos adelantos. Es necesario mencionar que el territorio peruano se encuentra cubierto por fotografías aéreas en un 90% en diferentes escalas.

2.2 *Radar*

Los sistemas de Radar han sido también utilizados en el Perú lográndose excelentes resultados básicamente en los campos geológico y fisiográfico.

En el Perú han operado dos compañías extranjeras en la toma de las imágenes: Gruman Ecosystem Corporation, contratada por la Dirección General de Aerofotografías, en Julio de 1972 con el objeto de explorar mediante SLAR la región de la Selva Baja desde los 1°30′ hasta 7° de Latitud Sur aproximadamente. Dicha área ha sido cubierta por 25 mosaicos a escala 1:250,000.

Aero Service Corporation, contratada por la Dirección General de Aerofotografía y PETROPERU, en Mayo de 1973, con el objeto de explorar mediante SLAR toda la región de la Selva Baja a partir de los 7° hasta los 13° de Latitud Sur aproximadamente. Dicha área ha sido cubierta por 27 mosaicos a escala de 1:250,000.

La misma compañía también ha explorado, en contrato con la Dirección General de Aerofotografía y MINEROPERU, toda la Ceja de Selva y Valles Interandinos, lo que ha sido cubierto por 125 mosaicos a escala 1:100,000.

2.3 *Sistema LANDSAT*

Desde 1972, con el lanzamiento de los nuevos satélites, el Perú viene utilizando la información del satélite LANDSAT, la misma que es adquirida en un 20% de NASA y un 80% del INPE-Brasil. Se tiene también la infraestructura necesaria para su aplicación, habiéndose en los últimos años desarrollado los sistemas de clasificación digital, aspecto que ya se encuentra operativo en los organismos especializados, contándose como elementos de apoyo los laboratorios: Digital, Analógico, Fotográfico, especialmente diseñados como apoyo a las aplicaciones del sistema LANDSAT.

2.4 *Otros sistemas utilizados*

Se ha utilizado también las cámaras aéreas multiespectrales para el control estacional de cultivos pero se puede considerar que su uso no ha pasado de la fase experimental.

3. Aplicaciones Realizadas

Las aplicaciones de la Percepción Remota en el Perú se vienen incrementando día a día, en razón del desarrollo tecnológico y el conocimiento que sobre este punto toman las diferentes instituciones, las mismas que están realizando esfuerzos a fin de que la Percepción Remota se constituya en una herramienta efectiva para el Desarrollo Nacional. De acuerdo a lo mencionado se han realizado ya muchas aplicaciones en el Perú y se puede considerar que está totalmente operativa. Entre las principales aplicaciones tenemos las relacionadas con la Geología, que viene efectuando el Instituto Geológico y Minero del Perú, Catastro, por la Oficina Nacional de Catastro Rural, Forestales y Proyectos de ampliación de la frontera agrícola que desarrolla el Ministerio de Agricultura, así mismo las Universidades del país han incluído en sus programas cursos de Percepción Remota, y también muchas compañías privadas relacionadas con la minería y prospección petrolera están utilizando en forma cada vez más intensa los sistemas de Percepción Remota. Quizás donde más se halla profundizado el uso de la Percepción Remota es en lo que respecta a la Evaluación de los Recursos Naturales, campo en el cual la ONERN realiza una intensa actividad.

La Oficina Nacional de Evaluación de Recursos Naturales (ONERN) es el organismo público descentralizado del Sistema Nacional de Planificación, encargado de efectuar el inventario y la evaluación integrada de los recursos naturales del país, con fines fundamentalmente de desarrollo socio-económico. Asimismo, participa en la formulación de las políticas de uso y conservación de los recursos naturales y la de realizar estudios medio ambientales.

El Perú, desde finales de la década del 50, viene utilizando los sistemas convencionales de percepción remota, representada por fotografías aéreas, como documentos cartográficos de base interpretativa para la evaluación sistemática de los recursos naturales. A partir de la década del 70, con el lanzamiento de los satélites artificiales de observación terrestre y el uso de sistemas de plataformas portando sensores multiespectrales, el Perú ingresó al empleo intensivo de los sistemas de radar de vista lateral e imágenes de satélite.

Esto dió lugar al desarrollo progresivo de una infraestructura sólida y tecnificada tanto en su aspecto físico como la generación de un plantal de especialistas en la materia. El creciente desarrollo en la aplicación de esta tecnología está ligada estrechamente a la cooperación técnica internacional recibida por parte de la Agencia Internacional para el Desarrollo (AID) de los Estados Unidos de Norteamérica y de la Agencia Internacional para el Desarrollo del Canadá (CIDA). Con la ayuda mencionada y una sólida contraparte nacional ha sido posible lograr la infraestructura básica y necesaria para la transferencia al Perú de dicha tecnología de percepción remota, así como la de aperturar un nuevo horizonte de mayor eficiencia y precisión en la obtención de información cabal y más completa sobre los recursos naturales del país.

Desde 1962, fecha en la que ONERN inicia sus actividades en el campo del inventario y evaluación de los recursos naturales y del medio ambiente, ha logrado consolidar una fuente de información sistematizada, coherente e integrada que constituye una base sólida para los planes nacionales y regionales de desarrollo. Hasta el año 1984, ONERN ha inventariado y evaluado a nivel de reconocimiento 53 millones de hectáreas que representan el 41% del territorio nacional. De esta superficie, 17 millones corresponden a la Costa, 10 millones a la región de la Sierra y 26 millones a la Amazonía. A nivel de semidetalle y detallado preferentemente para los recursos suelo y forestal, la ONERN ha cubierto una superficie aproximada de 1,200,000 Ha., de las cuales 670,000 Ha. corresponden a la Selva Central. Por otro lado, ONERN ha realizado estudios de ordenamiento y protección ambiental en una superficie aproximada de un millón de hectáreas en la Costa, Sierra y Selva del país.

Otro rubro importante cubierto por ONERN son los trabajos globales y a nivel nacional, que corresponden a los estudios de los Lineamientos de Política de Conservación de los Recursos Naturales Renovables del Perú (1974), el Mapa Ecológico del Perú y Guía Explicativa (1976-1977), el Inventario Nacional de Aguas Superficiales (1980), el Mapa de Capacidad de Uso Mayor de las Tierras del Perú (1982), el Inventario Nacional del Uso Actual del Agua (1984) y el Inventario Regional de Aguas Superficiales del Sur del Perú (1984), encontrándose en la fase final de publicación el Mapa Planimétrico del Perú, confeccionado sobre la base de informaciones de Satélite a 1:250,000.

3.1 *Proyectos Específicos*

Se han desarrollado 4 proyectos principales que podemos considerar centrales, y sobre el resultado de ellos giran las diferentes aplicaciones; en los proyectos en mención se han tratado de cubrir los principales aspectos, tales como Estudios Forestales en Selva, Determinación de Usos de la Tierra en Sierra, Elaboración del Mapa del Perú y el proyecto de monitoreo medio ambiental, cuyo resumen se detalla a continuación.

3.1.1 *Estudio Forestal*

El presente informe reseña los procedimentos y resultados del estudio « Usos de los Sistemas de Percepción Remota para la Evaluación de la

Palmera Aguaje en la Selva Peruana », elaborado por la Oficina Nacional de Evaluación de Recursos Naturales (ONERN) en coordinación con el Instituto de Investigaciones Medioambientales de Michigan (ERIM) y con el financiamiento de la Agencia Internacional para el Desarrollo de los Estados Unidos (AID).

El referido estudio ha consistido, básicamente, en la utilización de la información suministrada por el satélite LANDSAT, para la identificación de las áreas pobladas con la palmera Mauritia, conocida en nuestro medio amazónico « aguaje » y otras asociaciones forestales existentes dentro del bosque húmedo tropical. Para la realización del presente estudio y sobre una superficie de 378,530 Ha. fueron seleccionadas dos áreas denominadas: Iquitos y Marañón.

Para el desarrollo del estudio en su parte interpretativa fueron utilizadas las técnicas de interpretación óptica manual y digital. La primera ha consistido en el análisis visual de las imágenes de las bandas 5 (0.6-07 μm) y 7 (0.8-1.1 μm), con la ayuda de equipos sencillos. La segunda ha consistido en el procesamiento automático, mediante computadores, de las cintas digitales, habiéndose empleado las técnicas avanzadas para discriminar espectralmente las áreas con aguaje y otras asociaciones forestales propias de nuestro trópico húmedo. Por este procedimiento automatizado se han identificado para el área de Iquitos poblaciones de « aguaje » además de cinco tipos de bosques. Para el área de Marañón se identificaron dos clases de « aguaje » en cuanto a su densidad así como cuatro tipos de bosques. Asimismo, para cada área de estudio se han confeccionado mapas adecuados con los resultados de las dos técnicas de interpretación empleadas. La cuantificación de las unidades clasificadas ha sido determinada por procedimientos automáticos. En la zona de Iquitos, con 311,970 Ha. evaluadas, fueron determinadas 65,540 Ha. (21.0%) de rodales puros de palmera aguaje y en la zona de Marañón, con 66,560 Ha. evaluadas, se identificaron un total de 22,620 Ha. (34.0%) de aguaje.

La información proveniente del Satélite LANDSAT representa una herramienta potencial para la realización de estudios forestales en nuestra vasta región amazónica. Este potencial aplicativo se centra en varios aspectos: el amplio escenario que muestra las imágenes del satélite, dándonos una visión sinóptica de las características terrestres sobre una superficie de 3,500,000 Ha. por imagen; escasa distorsión, permitiendo la elaboración de mosaicos; la observación dinámica de los objetivos o fenómenos naturales, es decir, los cambios que ocurren por el hecho de la repetividad del satélite al pasar por el mismo lugar cada 18 días; el registro de la información en cuatro partes diferentes del espectro electromagnético que, por consiguiente, permite incrementar notablemente el análisis y visión comparativa de los objetos o fenómenos naturales, y su rápida evaluación cuantitativa por medio de las cintas magnéticas digitalizadas.

Los resultados da la investigación efectuada indican que la interpretación manual u óptica de las imágenes LANDSAT, especialmente del canal MSS 7 (0.8-1.1 µm), permite la delimitación de las áreas pobladas por la palmera aguaje (Mauritia). Por otro lado, mediante esta interpretación, existe cierto impedimento en cuanto a la determinación de las líneas de contacto entre áreas de aguajes y otras unidades forestales donde prevalece la condición hidromórfica. En cuanto al procesamiento de las cintas digitales del satélite LANDSAT, proporciona una información mucho más precisa sobre la distribución de las zonas pobladas de dicha palmácea, por cuanto permite delimitar en forma profusa las áreas mencionadas así como el patrón entremezclado con otras unidades clasificadas, reflejando mas fehacientemente la característica heterogénea y compleja del ecosistema tropical amazónico.

Un aspecto a considerar en la utilización de las imágenes de satélite LANDSAT concierne a los efectos atmosféricos. En este sentido, aquellas imágenes que no presentan nubosidad principalmente ofrecen muy buenas condiciones tanto para los trabajos de interpretación óptica como automática. En cambio, la presencia de nubes dificulta mayormente los trabajos, en especial lo referente al procesamiento automático como a la producción de mapas temáticos de recursos naturales por estos procesamientos.

En referencia a la producción de mapas utilizando la capacidad de computadoras MIDAS, diseñadas por el ERIM para la elaboración de mapas temáticos a color y mediante la técnica denominada Multi-Element, se muestran con mucha claridad las diferentes unidades boscosas dentro de un molde abigarrado o de cromocidad heterogénea, difícil de lograr por los medios convencionales del grabado y pelado.

Dada la experiencia obtenida a través de este estudio, se recomienda, en complemento a los métodos tradicionales de fotografías aéreas convencionales, el empleo de las técnicas de percepción remota para la investigación sistemática de los recursos naturales del país a fin de obtener información rápida, más completa y precisa. La interpretación manual u óptica de las imágenes de satélite deben constituir un paso previo y necesario al procesamiento automático a fin de obtener resultados que reflejen la realidad de los fenómenos analizados. Finalmente, el procesamiento automático que involucra estas técnicas como la producción de mapas temáticos a color abre un campo expectante e insospechado en el suministro de información.

3.1.2 *Determinación de los usos de la tierra en Sierra*

El informe describe los procedimientos y analiza los resultados del estudio nominado « Determinación de los Usos de la Tierra Mediante la Percepción Remota », efectuado por la Oficina Nacional de Evaluación de Recursos Naturales (ONERN) en coordinación y con financiamiento de IBM del Perú S.A. que incluyó el apoyo técnico del Centro Científico de IBM de México.

El referido estudio ha consistido en la utilización de la información suministrada por el Satélite LANDSAT con el objeto de establecer una medida fehaciente de su valor práctico para los fines de identificación y cuantificación de los diferentes usos de la tierra. El área seleccionada para el presente estudio comprendió una superficie de 106,700 Ha. del valle del río Mantaro.

Para el desarrollo del estudio, fueron utilizadas las cintas digitales registradas por el Satélite LANDSAT, las mismas que fueron procesadas automáticamente mediante el empleo del sistema de procesamiento de datos del Centro Científico de IBM de México. Para tal efecto, se utilizó el sistema de computación que recibe el nombre de Earth Resources - Management II (ERMAN-II), el cual es una versión actualizada del desarrollado originalmente por la IBM para la Administración Nacional de la Aeronáutica y del Espacio (NASA) de los Estados Unidos, con el objeto de analizar la información obtenida mediante los satélites tecnológicos de recursos terrestres.

Mediante el procesamiento automático utilizado, fue posible identificar once clases de unidades que responden a 13 símbolos caracterológicos graficados en un Mapa de Caracteres. Los resultados obtenidos y que cuantifican los grupos de usos de la tierra generales identificados se resumen en: *70,227 Ha.* (65.8%) de terrenos de uso agrícola en su conjunto; *2,331 Ha.* (2.2%) de terrenos con vegetación natural; *449 Ha.* (0.4%) de tierras con cobertura arbórea; *20,863 Ha.* (19.6%) de tierras sin uso y/o improductivas y *12,830 Ha.* (12.0%) de tierras correspondientes a Otras Areas.

El análisis interpretativo de estos resultados revela una determinación dentro de márgenes aceptables de precisión de las tierras de uso agrícola en su conjunto, no acusando precisión en cuanto a la discriminación de tierras bajo riego y bajo el régimen de secano. No presenta una adecuada precisión la identificación de las tierras con vegetación natural y de las tierras con cobertura arbórea o de bosques. En cuanto a las tierras denominadas sin uso y/o improductivas así como de cauce de río y cuerpos de agua que se involucran en Otras Areas, su clasificación se encuentra a la infraestructura urbana. Esto permite reducir que la información que proporcionan las imágenes multiespectrales captadas por el Satélite LANDSAT sólo es útil para establecer unidades generales sobre el uso de la tierra y no siempre con suficiente precisión, debido fundamentalmente a su resolución de 80 metros. Asimismo, que se requiere de una mayor interacción entre el operador, la computadora y el examen del terreno, aspecto clave para proporcionar información adicional sobre base confiable. Por otro lado, se espera que la información a generarse en los futuros satélites LANDSAT de la década del 80 y un mayor grado de resolución de 30 metros permitirán una mejor y más precisa caracterización de las áreas agrícolas a nivel de cultivo así como de otras formas de la cobertura terrestre.

Dos mapas han sido preparados que se pueden obtener directamente del autor. El Mapa de Caracteres, a escala 1:100,000, representa la expresión gráfica en blanco y negro obtenida por el proceso de clasificación y muestra los 13 caracteres seleccionados para la clasificación. Complementariamente, se tiene el Mapa a Color a escala 1:100,000, obtenido mediante asignación de colores a los símbolos caracterológicos, seguido de procesos fotográficos y tricromáticos para su respectiva impresión.

Reconociendo la necesidad de adoptar una metodología rápida y eficiente para la identificación de los usos de la tierra, aspecto éste de suma importancia dentro del contexto de la racional explotación de los recursos naturales del país, se establece la recomendación de proseguir con este tipo de investigaciones para reducir los márgenes de error, esperándose mejores resultados con la utilización de la nueva información a generarse por la serie LANDSAT correspondiente a la década 1980. Asimismo, se recomienda a plazo corto la capacitación de científicos y especialistas nacionales en el análisis de la información obtenida a través de estas técnicas, considerándose ello como uno de los aspectos fundamentales para la asimilación de la referida tecnología y su adecuada aplicabilidad.

3.1.3 *Mapa del Perú*

La publicación del Mapa Planimétrico del Perú en hojas a escala de 1:250,000 representa una gran satisfacción para el Gobierno Peruano y sus instituciones, por cuanto es la conclusión de un gran esfuerzo plasmado en un valioso documento. Para su elaboración se ha empleado una moderna tecnología y una información cartográfica lograda desde el espacio la misma que da una visión real y actualizada de la configuración de nuestro territorio así como de sus aptitudes ecológicas, topográficas y demográficas. Asimismo la publicación del presente Mapa coloca al Perú a la vanguardia mundial de este tipo de trabajos por cuanto es el primer país que publica un Mapa de esta naturaleza sobre la totalidad del territorio.

El Mapa, que cubre la totalidad del territorio, consta de 95 hojas a escala 1:250,000, tiene el mismo formato de la Carta Nacional del Perú, o sea un grado y medio por un grado que representa una superficie aproximada de 1,768,000 Ha. La serie de Mapas han sido producidas a partir de los datos digitales del barredor multiespectral del satélite LANDSAT en un formato de cintas compatibles con computadoras (CCT) proporcionados por la Agencia Eros de la NASA, Estados Unidos, y por el Instituto de Pesquisas Espaciales del Brasil. Cada hoja del Mapa consiste en una composición en falso color de las bandas 4, 5 y 7 del barredor multiespectral de una sola escena o un mosaico constituído por un número comprendido entre dos y seis escenas de LANDSAT. Cada escena ha sido procesada por la computadora para maximizar la fidelidad geométrica e información radiométrica y minimizar diferencias visibles entre escenas adyacentes. Para el balance de los colores ha sido utilizado un algoritmo que apareja el color y reduce cualquier diferencia radiométrica entre las escenas empalmadas, aun así existen algunas diferencias mínimas de coloración que son producto de los cambios estacionales y/o de las diferencias atmosféricas. Para la composición a color representada en las hojas, se le ha asignado a la banda 5 del barredor multiespectral un color rojo en un alto porcentaje, dado que el color rojo tiene una mayor gama de matices perceptibles al ojo humano que otros colores, y por lo tanto es posible distinguir mejor los caracteres del terreno que se expresan en las hojas respectivas.

El Mapa ha sido corregido geométricamente para adecuarlo al sistema de proyección universal transversal mercator (UTM). El proceso utilizado compensa el movimiento del satélite, la curvatura y panorama de la tierra durante el proceso de barrido, las variaciones en la velocidad del espejo barredor, la desviación de altitud del satélite, y las diferencias entre las proyecciones espacio oblicuo mercator (SOM) y UTM. La corrección de los parámetros ha sido determinada combinando la posición del satélite, el reporte de la altura descrito en la CCT, y los puntos de control para lo cual han sido utilizados Mapas o, donde no existen Mapas, puntos de control identificables de las imágenes.

Cada hoja del Mapa lleva las anotaciones marginales, escritas en 4 idiomas: Castellano, Inglés, Portugués y Francés, las mismas que son compatibles en su totalidad con el formato que para estos casos utiliza el Instituto Panamericano de Historia y Geografía (IPGH), de tal manera que las anotaciones del Mapa sean similares a otros documentos que al mismo nivel se publican en Latinoamérica. Las anotaciones marginales incluyen: lugares poblados, límites tanto internacionales como departamentales, aeropuertos, carreteras pavimentadas y no pavimentadas, puntos de control horizontal, cotas comprobadas, centros mineros y puertos, asimismo se anotan las referencias cartográficas utilizadas para la precisión de las hojas, y cuadros con la ubicación de las hojas de la información básica empleada.

La selección de los rasgos toponímicos que se encuentran anotados dentro de las hojas ha sido efectuada de acuerdo a su importancia relativa, y la densidad de estos difiere entre las hojas en virtud de que existen algunas regiones en el país densamente pobladas y otras en las que hay muy pocas referencias; así mismo desde que la información existente en las hojas representa la realidad del terreno, se ha tratado de no recargar demasiado la toponimia de no « cubrir » la información disponible en las hojas.

El presente Mapa cubre el vacío de información cartográfica existente en el país y su publicación significa el contar por primera vez con información total del territorio peruano. En tal sentido su aplicación será amplia y generalizada a todos los sectores que requieran información cartográfica para proyectos de diferente índole; asimismo es un documento valioso para los investigadores y los educadores que deberán formar nuevas generaciones con una óptica geográfica diferente para el aprendizaje directo y práctico de la realidad geográfica nacional.

3.1.4 *Estudio de Monitoreo Medioambiental*

El informe describe los procedimientos y analiza los resultados del estudio denominado « Monitoreo Ambiental del Valle del Río », realizado por la Oficina Nacional de Evaluación de Recursos Naturales (ONERN), con financiamiento del Proyecto Especial Pichis Palcazú (PEPP).

El referido estudio se basa en una nueva metodología de vigilancia de impactos medioambientales utilizando la información suministrada por el satélite de Recursos Naturales LANDSAT, para la identificación de áreas de probables deterioros. Fue seleccionada para el presente estudio una superficie de 207,559.5 Ha. en el área denominada Puerto Bermúdez ubicada en el Valle del Pichis.

El procedimiento seguido en el desarrollo de la metodología se dividió en tres partes: la primera que consistió en la recopilación de información cartográfica, interpretación óptica manual de las Fotografías Aéreas e Imágenes de LANDSAT con ayuda de equipos sencillos y el procesamiento automático de las cintas digitales; la segunda etapa consistió en el reconocimiento de campo incluyendo los lugares muestreo y finalmente la tercera etapa que consistió en la revisión del Mapa digital y la elaboración del informe final.

Del procedimiento metodológico fue posible obtener un mapa, en el cual se identifican cinco clases diferentes de terreno las que responden a cinco símbolos graficados en el Mapa de carreteras. Los resultados obtenidos y que cuantifican las clases de terrenos se resumen en: 155,313.4 Ha. (75.0%) que corresponden a Bosque Primario; 11,948.8 Ha (5.7%) a terrenos cubiertos con Pastos Cultivados y Naturales; 31,336.5 Ha. (15.1%) a Bosques Secundarios; 583.0 Ha (0.2%) a Centros Poblados; 7,757.0 Ha (3.7%) a área de agua; y 620.8 Ha (0.3%) a área no clasificada.

Asimismo, se obtuvo en base al Mapa de caracteres en blanco y negro un Mapa a color a escala 1:100,000; mediante la asignación de color a los símbolos caracterológicos.

Dada la experiencia obtenida a través de este estudio, se recomienda continuar con el uso de la metodología propuesta a otras áreas del País que necesiten contar con información rápida y eficaz de los cambios que están ocurriendo en dichas áreas.

4. Cooperación Técnica Internacional

El desarrollo de la Percepción Remota en el Perú ha sido posible mediante los fondos asignados por el Gobierno Central a los proyectos de Percepción Remota y también por la ayuda Internacional, la misma que ha sido básicamente de las siguientes fuentes.

4.1 *Cooperación Canadiense (CIDA)*

El Perú tiene desde el año 1976 un proyecto de Cooperación con el Gobierno Canadiense para la transferencia de Tecnología en Percepción

Remota, bajo el cual el país ha podido adquirir la infraestructura básica para el desarrollo de la Percepción Remota, a través del proyecto PERCEP.

Proyecto PERCEP

El Proyecto « Utilización de Sistemas de Percepción Remota en la Evaluación de Recursos Naturales en Areas Piloto en el Perú », más conocido como Proyecto PERCEP, consiste en un Programa de Cooperación Técnica entre los Gobiernos del Canadá y el Perú. Su principal objetivo es el de contribuir al establecimiento de un Programa de Percepción Remota en el Perú para complementar los métodos convencionales de investigación que se llevan a cabo en el país, y también para resolver en parte la presente situación relacionada con el inventario y evaluación de recursos naturales, teniendo en cuenta la falta de información fotogramétrica en la cobertura total del país.

El Proyecto PERCEP terminó hace 2 años con su primera etapa, y en estos momentos están empezando la segunda etapa del Convenio.

La financiación del Proyecto PERCEP I, contó con una donación del Gobierno del Canadá a través de la Agencia Canadiense para el Desarrollo Internacional (ACDI) por Can. $ 634,500 y una contrapartida del Gobierno Peruano incluída en los presupuestos de ONERN e IGP por 13'340,000 soles peruanos.

En el Plan de Trabajo y Términos de Referencia, Acuerdo Subsidiario, se establecieron ciertas metas en una forma muy general. El cumplimiento de estas metas se basó en la ejecución de las siguientes actividades:

— Entrenamiento en el Canadá, utilizando las facilidades de la División de Aplicaciones del CCRS, de un grupo limitado de expertos peruanos, en el campo de la tecnología de percepción remota y basado en la preparación y ejecución de proyectos individuales de investigación y entrenamiento;

— Adquisición de productos estandard obtenidos con los Datos desde la serie de satélites LANDSAT, para poder conseguir un recubrimiento total del país con esta información; y

— Diseño y adquisición de varios componentes de un Laboratorio de Percepción Remota para que sea operado en el Perú.

Los resultados obtenidos en el Proyecto PERCEP I han sido satisfactorios y han sentado las bases para el desarrollo de la Percepción Remota en el Perú, por cuanto se ha adquirido la infraestructura tanto técnica como física que a continuación se resume:

4.1.1 *Capacitación de Personal.* - Se han capacitado en el Canadá a través de cursos cortos de entrenamiento (3-4 meses) 18 especialistas peruanos de los diferentes campos de los Recursos Naturales, Ciencias Físicas y Electrónica.

4.1.2 *Equipamiento.* - El Canadá ha donado al Perú en el marco del Proyecto PERCEP I el equipo necesario para la implementación de los siguientes laboratorios:

— *Laboratorio Analógico.* - Compuesto básicamente por un visor combinador de imágenes.

— *Laboratorio Fotográfico a color.* - Compuesto por una Ampliadora, Procesadora automática y Densitómetro así como los diferentes componentes periféricos para su utilización y también un lote de materiales fotográficos a color.

— *Laboratorio Digital.* - Compuesto de un Sistema Digital diseñado por la compañía DIPIX del Canadá, basado en un computador LCT-II con sus respectivos periféricos para el procesamiento de datos multiespectrales (Unidad de Cinta, Disco, Monitor a color, tableta digitadora, impresora gráfica etc.). Asimismo el soporte lógico necesario para la clasificación de los datos multiespectrales. También el Proyecto PERCEP-I ha donado al país equipo adicional consistente en maquinarias fotográficas, filtros y el apoyo técnico necesario para el funcionamiento de los laboratorios antes mencionados. Se ha logrado la implementación de una biblioteca especializada y la confección de un glosario de términos utilizados en Percepción Remota.

Finalmente es necesario mencionar que la transferencia de Tecnología Canadiense al Perú representa una de las formas más claras y directas de Cooperación Técnica, por cuanto el personal capacitado en el Canadá y el equipo donado por el Canadá está siendo utilizado en los proyectos de prioridad del Gobierno con fines de Desarrollo Nacional y cuyos resultados son realmente satisfactorios.

4.2 *Cooperación Norteamericana (AID)*

El Gobierno de los Estados Unidos a través del AID ha sido y es uno de los organismos que más colaboración prestan al desarrollo de la Percepción Remota en el Perú.

Desde hace aproximadamente 9 años en que el AID auspició en el

Perú las primeras aplicaciones de la Percepción Remota, tales como la evaluación del aguaje y las clasificaciones de Bosques que tuvieron resultados exitosos y marcaron el ingreso de ONERN en la utilización de los procesamientos digitales hasta la actualidad en que a través del proyecto « Planeamiento Ambiental e Identificación de los Recursos Naturales», se ha logrado instalar un Sistema de Información Geográfica que sitúa a la ONERN en posición de procesar gran cantidad de información, ubicándola en parámetros geográficos, la pone a disposición de los usuarios.

Durante los diferentes proyectos realizados con el AID se ha logrado entrenar 30 personas en Percepción Remota y Sistemas de Información Geográfica con la consiguiente transferencia tecnológica que esto implica.

El Sistema de Información Geográfica donado por el Gobierno de los Estados Unidos está compuesto básicamente de lo siguiente:

— CPU PDP 11/44
— 512 kb de memoria
— 2 Unidades de disco R 102-10.5 Mb
— Un impresor LA - 120
— Un multiplexor de 16 líneas (RS 232)
— 3 Unidades de disco RA - 80
— 2 Unidades de cinta TE - lb
— 2 Tableros digitalizadores opacos
— 1 Tablero digitalizador con luz
— 2 Terminales de video alfanuméricos
— 3 Terminales gráficos Tectronics
— 1 Sistema de video RAMTEC
— 1 Printer Plotter Versatec. 11 pulgadas

5. Futuro de la Percepción Remota en el Perú

El futuro de la Percepción Remota en el Perú es realmente expectante. De acuerdo a lo mencionado en el presente documento, el país tiene ya la infraestructura básica necesaria para la aplicación de los sistemas de Percepción Remota, y esta infraestructura la viene utilizando en los diferentes proyectos que realiza, algunos de los cuales se han resumido en este trabajo. De acuerdo también a lo expresado se tiene que el panorama que presenta el país en cuanto al conocimiento de sus Recursos Naturales es auspicioso por cuanto se está avanzando e integrando zonas anteriormente poco conocidas. Sin embargo es también cierto que, por la información cartográfica limitada con que cuenta el país, los estudios realizados han sido en su mayoría de tipo exploratorio, reconocimiento y en muy pocos casos semidetalle y detalle. En consecuencia el país ingresa en estos momentos a una etapa en la cual tendrá que dinamizar todos los medios disponibles a fin de completar la evaluación de los Recursos Naturales del país y en muchos casos hacerlos con un nivel de detalle que permita no solamente los asentamientos humanos y las colonizaciones sino ya la puesta en marcha de proyectos operativos de « Control Medioambiental », « Pronóstico de Cosechas », « Planeamiento y Urbanismo », « Aplicaciones Oceanográficas » etc., proyectos en los cuales la Percepción Remota debe ser una herramienta de singular importancia.

Felizmente, para consolidar lo expresado, los nuevos sistemas existentes, tales como el Thematic Mapping, SIR-B., Programa SPOT, etc., poseen las características adecuadas para complementar justamente la información que al país le falta y que se expresa en la unidad de los sistemas de Percepción Remota o sea la « Resolución », la misma que permitirá incursionar en campos en los cuales, debido al tamaño de los « pixels » de los anteriores sistemas, no se pudo ingresar en unos casos, y en otro se hizo solamente la primera parte del trabajo (Exploración). De todos modos el Perú no se ha descuidado y ha firmado convenios con el INPE del Brasil para comprar los datos del Mapeador Temático y también ha firmado una sub licencia con el Programa SPOT de Francia.

Asimismo, se está participando en el Proyecto SIR-B, como a continuación se resume.

5.1 *Participación Peruana en el Proyecto SIR-B* (Shuttle Imaging Radar-B).

Las ventajas de imágenes obtenidas por medio de técnicas de radar de vista lateral son, en el Perú, ya bastante conocidas. Estas se hacen principalmente ventajosas en áreas cubiertas por bosques así como aquellas que normalmente están cubiertas por nubes. Estos dos factores normalmente combinados, imposibilitan la toma ó dificultan la interpretación de las aerofotografías convencionales.

La posibilidad de obtener imágenes por medio de la técnica de radar de vista lateral es hoy en día posible de ser llevada a cabo desde satélites. Esto ha sido demostrado con el éxito de dos misiones: el Seasat SAR (Synthetic Aperture Radar) y el SIR-A (Shuttle Imaging Radar). A fines del presente año se llevará a cabo una tercera misión, el SIR-B, en la que a diferencia de las anteriores, habrá un proyecto de investigación con participación peruana. El proyecto está relacionado con el estudio de los posibles efectos nocivos que podrían tener irregularidades en la ionósfera en la calidad de las imágenes. Para esto se patrullará las condiciones ionosféricas por medio del radar de Jicamarca, así como por medio de experimentos de propagación (centelleo) a llevarse en Ancón y Huancayo a horas en que el transbordador espacial esté tomando imágenes de nuestro territorio. Aparte de determinar el posible deterioro que puedan sufrir estas imágenes por los fenómenos ionosféricos que ocurren frecuentemente en nuestras latitudes, el mayor beneficio que se obtendrá de este experimento es una mayor cobertura con imágenes de radar de nuestro país. Se están coordinando con las instituciones de desarrollo y proyectos nacionales para seleccionar los lugares a ser cubiertos por el satélite, con la idea de reducir la gran variedad de alternativas escogiendo zonas de interés relacionadas con nuestros proyectos de desarrollo.

FINALMENTE:

Cabe mencionar que, para que el Perú logre sus objetivos y pueda desarrollar e incrementar sus programas de Percepción Remota, va a ser necesario capacitar la mayor cantidad de técnicos que sea posible en las diferentes especialidades, así como la participación de mayor número de instituciones.

El futuro en cuanto a la Cooperación Técnica Internacional también es halagador, la transferencia de tecnología Canadá Perú va a continuar. En estos momentos se está iniciando el Proyecto PERCEP - II, el que ampliará notablemente la infraestructura que tiene el Perú en materia de Percepción Remota y eso permitirá estar en el « estado de arte » de la tecnología.

Finalmente quiero mencionar que existen otros proyectos que se están iniciando en el país, entre los cuales caben resaltar dos: « El Proyecto de Vigilancia Ecológica por medio de Percepción Remota », auspiciado por las Naciones Unidas y que tendrá una duración de 5 años, y el Proyecto « Planeamiento Ambiental e Identificación de los Recursos Naturales » auspiciado por el Gobierno de los Estados Unidos.

El Perú tendrá mucha actividad en los próximos años; los pasos que se han dado creo que son firmes y hacen mirar el futuro con optimismo, sin embargo dependerá del esfuerzo de sus instituciones y de sus técnicos, el mantener e incrementar el status logrado por cuanto recién estamos empezando.

REMOTE SENSING FOR DEVELOPING COUNTRIES

THE CASE FOR REGIONAL CENTRES

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ABSTRACT

Satellite remote sensing is uniquely able to provide regional, national and continental scale overviews of natural resources which permit the cost-efficient mapping and monitoring of such resources as forestry, soils, range-lands, agriculture, water and geology. The use of remote sensing to map natural resources leads to a sounder basis for planning, and produces new and innovative maps. In Africa, many countries are covered by about forty Landsat scenes or less; the typical receiving station gathers data for about 500 scenes. Thus there is great pressure towards regional collaboration in the construction and operation of a receiving station. The costs of centralised training, user support, data reproduction and enhancement are such that it is difficult for any but the largest countries to provide a full range of such services. As a result, a series of national centres linked to regional centres appears to be an efficient way of operating.

This is the structure emerging in the Eastern and Southern Africa regions. The Regional Centre for Services in Surveying, Mapping and Remote Sensing (RCSSMRS) provides training, user and project support services linked to national centres in the region. Since 1979 about 1,000 scientists from the East and Southern Africa Regions have attended courses at the RCSSMRS, and the courses have been oriented to user disciplines such as forestry, geology and agriculture.

Users of the services in remote sensing include the government

agencies of the region and international organizations. Collaboration between the member countries, international agencies and the donor community is good, Major projects to date include a soil mapping project in Zambia prior to implementing a World Bank financed agricultural scheme and a national map of forest cover for Tanzania. Various other projects include photo-maps for Swaziland, parts of Kenya, Tanzania, Uganda, Sudan and the whole of Lesotho. The Centre in Nairobi offers an effective service on a regional basis. The ready acceptance by countries in the region and support from donors suggests that it is meeting a real need. A continued demand for existing services and requests for additional services suggest that the regional centre concept is successful in Eastern and Southern Africa.

Introduction

The Regional Centre for Services in Surveying, Mapping and Remote Sensing (RCSSMRS) was established pursuant to the resolution of the first United Nations Regional Cartographic Conference in Africa, passed at its meeting in Nairobi, Kenya, in 1963. The recommendation of the meeting of experts on the joint centres for specialized services in surveying and mapping, held in Addis Ababa, Ethiopia, in June/July 1965, resulted in the establishment of the Regional Centre for Services in Surveying and Mapping, which began operating in Nairobi in 1975. In 1977, the centre began to develop remote sensing activity and by 1982 this was so firmly established that the Centre changed its name to the Regional Centre for Services in Surveying, Mapping and Remote Sensing (RCSSMRS). Now housed in new premises at Kasarani on the outskirts of Nairobi, the RCSSMRS has departments of geodesy, cartography, engineering and remote sensing, and offers training courses and technical services in these areas. The RCSSMRS is financed and governed by those states from the region which sign its charter, and presently this group includes Comoros, Kenya, Lesotho, Malawi, Somalia, Swaziland, Tanzania, Uganda and Zambia. Sudan is about to become a signatory member.

For these countries, and for many others in the Eastern and Southern Africa region, there is a critical need to invest in development projects in agriculture and natural resources. Many African countries have been hit by drought at least once since the midpoint of this century and, with existing population growth, the effects of drought become increasingly severe. The most recent droughts have resulted in major famines in Sudan, Ethiopia and the Sahelia region, as well as in Tanzania and other SADCC countries.

To combat these problems, agriculture must be expanded, and the infrastructure to support the movement of foodstuffs from the producing region to the markets and to the areas of food deficiency must be strengthened. For these developments to take place, the planners and investors require basic information such as maps of soil type, agro-ecological zones, crop suitability maps, maps of water resources, vegetation types, land use, land cover and revised maps showing major communications. The preparation of these maps from conventional survey photography and ground-survey techniques alone is both costly and time-consuming. Often existing information is inadequate for planning purposes, either because it is outdated or not prepared with a planning perspective or in map form.

The RCSSMRS in Nairobi attempts to provide support for agencies and countries in the Eastern and Southern Africa regions which are faced with the task of meeting these information needs. In remote sensing in particular, the support includes training courses, user services and project design and implementation support. Each of these areas of activity shows a continuing demand and offers services on a regional basis. Participation in these activities by individual countries is a function of existing facilities and national programmes. Zimbabwe has a well developed activity in remote sensing, making use of digital processing capability in the University and the Institute of Mining Research. Tanzania has optical image-analysis equipment in the Institute for Resource Analysis, and Sudan has a national remote sensing centre currently receiving direct assistance through an agreement with the RCSSMRS. Other countries in the region have developed remote sensing to varying levels. However, there is no operational receiving station for SPOT or Landsat 5. Thematic Mapper data in the region, and the Landsat-MSS receiving station near Pretoria has a coverage circle reaching only as far north as central Tanzania — not mentioning the fact that most of the African countries will not and cannot use information from that station.

Data Availability

For countries in the region to make effective use of satellite remote sensing techniques, data have to be available. The lack of receiving station coverage severely limits the opportunities for data gathering, and the pricing policies of both SPOT IMAGE and EOSAT corporations provide an alternative which is expensive and requires the use of foreign exchange. The Remote Sensing Department (RSD) of the RCSSMRS has an extensive library of Landsat MSS data for the service region, which was assembled before the present restrictions on data use and data reproduction were introduced.

Copies of materials in that collection are available for purchase from the RSD at prices ranging from 6 U.S. dollars to 75 U.S. dollars. This range includes photographic prints up to 90 cm × 90 cm and the smallest marketed product, a 35 mm colour transparency. Assistance with ordering is provided and users are able to consult a browse file of 1:1,000,000 scale prints of available data to ascertain cloud distribution in the image and its suitability for use *before* placing the order. This system has proved to be most effective, and browse files have been supplied to some countries in the region.

The service region of the RCSSMRS includes a total of 555 scene centres for the MSS data from Landsats 1, 2 and 3 and slightly less (approx. 485) for data from Landsats 4 and 5. For these scene centres, the RSD has a collection of more than 14,000 reproducibles, including at least one false colour composite (FCC) for each scene and more than twenty for certain scenes. This collection provides a suitable basis for each country to obtain an overview of its territory during a wet and a dry season. Some areas are consistently cloud-covered at the time of satellite over-pass, and no cloud free scenes are available. Other areas are so cloudy that no scenes with less than 30% cloud cover have ever been gathered. The Centre is also negotiating an agreement with SPOT IMAGE to act as an agent for the region.

The RCSSMRS therefore offers a data archive of MSS data for the region, a service not available elsewhere in Africa. Unfortunately, budget restrictions have resulted in this archive not being consistently up-dated. Trade-secret restrictions invoked by EOSAT Corporation since they assured commercial operation of the satellite in September 1985 have made this data archive activity difficult to continue. The policy adopted by the SPOT IMAGE of France has reinforced these difficulties and placed the open skies policy approved by the UN behind a formidable legal and cost barrier.

Availability of data now has two components, the first being the existence of data. If scenes have been gathered by NASA, NOAA, EOSAT or SPOT, their existence is recorded in a string of characters in a computerized library system. In general this system is not an adequate substitute for a browse file in which a copy of the image can be inspected. To the extent that the image exists and is catalogued, we have a theoretical availability in that the image may be purchased. The second component of availability is entirely controlled by cost. Prices currently quoted are such that the computer tapes comprising a single TM scene cost the same as employing a competent car driver for four years in Africa. If the tape is purchased by a government, using precious foreign exchange reserves, the use of the tape or the purchased photo-product is still restricted by the conditions of sale. It is difficult to reproduce the material for purposes other than those originally stated. Thus the cost-effective multiple use of data throughout agencies of a government of a developing country is negated. Regional Centres, acting as repositories of data archives and providing data reproduction services can, if not inhibited by restrictions of copyright or trade secrets, greatly assist in the development process. However, this assistance is reduced by the commercial marketing of their national resources data at prices which they cannot afford, once again making them ask support to acquire data about their own national resources from outside agencies.

When data are available without these restrictions, the RCSSMRS provides a product reproduction and enhancement service at subsidized prices. This has proved beneficial to users in the region and has assisted with several development projects. One solution to the problem of data availability is to have a functioning receiving station within the region, providing data on a regular basis to all countries within the receiving range of the station. Such a system would be of great benefit to the region but, with capital requirements estimated to be in excess of US$ 20 million and annual operating costs of the order of US$ 5 million each year, it seems unlikely that this will be done with funds from the countries of the region. Efforts and good will shown by EEC in this regard are very much appreciated.

There is, however, increasing use of data from the weather satellites for earth resources purposes. For agriculture and related activities the rainfall estimates derived from meteorological satellite data are particularly useful. When data from such a satellite are analysed for vegetation indices, or surface temperature, very useful information is obtained. The frequency with which this occurs means that changes in vegetation status in response to rainfall conditions can be monitored. Once again, the area for which the satellite gathers data far exceeds the boundaries of any single country in Africa. The need to understand broad regional movements of weather systems also indicates the wisdom of regional collaboration in establishing and operating a regional receiving station and data distribution centre.

The costs of establishing a receiving station for meteorological satellites are notably less than for earth resources technology satellites. Data from these satellites, when processed for vegetation and surface temperature studies, provide a valuable source of data for monitoring changes in crop growth conditions and therefore food and forage production. These items are of great interest to the agriculturalist and data from the meteorological satellites such as Meteosat and NOAA-7 can, when suitably processed, offer a valuable aid for crop yield prediction. The data from these satellites are presently free from the commercial restrictions now imposed on Landsat and SPOT data. They may offer an alternative to earth resources technology satellite data for monitoring and as such provide a valuable basis for regional assessments of food crop production. Once again the value of regional collaboration is evident.

Training

On a regional basis, there is a demand for short-term training in remote sensing which can support an on-going training programme. Since 1979 the RCSSMRS has offered a programme of courses as a means of transferring the technology to potential users. These courses have been held mainly in Nairobi. Courses have two formats, a short course usually of three weeks' duration, and extended courses. Extended courses consist of an initial period of study in Nairobi, during which the participants design a project for implementation in their own country.

They return to their employer, undertake the project and then return to Nairobi at the completion of the project, usually some 6-12 months later. The extended course concludes with a final review session in which the successes and failures of applying remote sensing in the project activity are compared and discussed.

Courses given are usually discipline-specific, and the regional basis of the RCSSMRS means that there are adequate numbers of professionals to make each course viable. The following list details some of the topics which have been covered in training courses held in Nairobi since 1979.

TRAINING COURSES HELD IN NAIROBI

Year	*Topic*
1979	Agriculture and Soils
	Hydrology
	Cartography and Surveying
	Forestry and Rangeland
1980	Agriculture and Land Use
	Mineral Exploration
	Teaching with Remote Sensing Data
	Transport Engineering
1981	Cartography and Map Revision
	Agriculture and Land Use
1982	Natural Resources [1]
	Teaching with Remote Sensing Data
	Geological Interpretation of Remotely Sensed Data
	Remote Sensing in Hydrology [1]
	Environmental Monitoring [3]
1983	Technical Basis of Remote Sensing [2]
	Cartography with Remotely Sensed Data [1]
	Teaching with Remotely Sensed Data
	Transportation Engineering and Materials Identification
	Geological Interpretation with Remotely Sensed Data [2]
	Remote Sensing and Rangeland [1]
	Remote Sensing to Assist in Increasing Food Production
1984	Energy, Forestry and Woodfuel Management (6 weeks)
	Geological Interpretation of Remotely Sensed Data
	Remote Sensing and Cartographic Requirements in Developing Countries.
1985	Remote Sensing for Agriculture
	Introductory Remote Sensing for Lake Basin Authority
	Earth Observation and Meteorology
	Agriculture Statistics
	Remote Sensing for Cartography
	Remote Sensing for Agro-Meteorology
	Remote Sensing for Highway Engineers
	Remote Sensing for Natural Resources

1986 SPOT Simulation Course
ESA follow-up Course
Oceanography and Remote Sensing [4]
Introductory Remote Sensing [2]
Remote Sensing for Lesotho

Because of the precise discipline focus of the courses and the fact that the participants are drawn from more than one country, there is a considerable interchange of opinion. Informed discussion on a comparative basis between representatives of different countries provides for useful re-examination of needs, problems and practices, and overall this is a very powerful advantage of a regional centre. In 1982 a questionnaire survey was sent out to persons who had participated in the training courses. The responses were summarized in Falconer and Odenyo (1984) as follows: A 32 point questionnaire was sent to 179 former participants in short training courses in 1982. Responses were received from 21 percent of the participants. The primary objectives of this questionnaire were to ascertain the use for which participants have utilized the information obtained in the training courses and what activities could be undertaken by the Facility to further promote the awareness and utilization of space-borne remote sensing techniques. Almost all of the respondents, 92 percent, thought the training course was good; and 54 percent have used Landsat data since attending a training course. Typical uses include: 1) revision of small scale maps, 2) location of seasonal river course changes where flood protection is necessary to develop irrigation sites, 3) vegetation mapping, 4) rangeland fire monitoring, 5) soil mapping, 6) land-use change detection, 7) flood extent mapping, 8) mineral exploration, and 9) land-cover type mapping.

All of the respondents, with the exception of one no response, believe Landsat data is a useful tool for resource analysis. Responses to the question "What in your opinion are the major difficulties limiting the use of Landsat data in East Africa?" were lengthy and informative. The recurring themes in these responses were 1) cost of imagery, and in particular, the need for foreign exchange, 2) lack of facilities and equip-

[1] Extended Training Courses.
[2] In French.
[3] One week of instruction was provided by the Facility as part of a ten-week workshop.
[4] Bilingual - English and French.

ment in their countries, 3) lack of awareness of the data or its applicability, 4) lack of trained personnel and 5) insufficient data resolution.

The former course participants were also asked to suggest services which the Facility might offer to promote the use of Landsat data in Eastern Africa. Suggestions for methods of technology transfer from persons who have been involved in the receiving end of the process are unique. Some of the more pragmatic suggestions included 1) visits by the Facility staff to organizations in the region to familiarize scientists and administrators with remote sensing techniques, 2) more Facility involvement with projects, 3) continuation of training programs in Facility offices, 4) active publicity, and 5) making Landsat data available with local currency.

The response to the extended training course format, introduced in 1982, has been excellent. The potential course participants are aware in advance that they will be required to formulate and implement a project of their own interest as an integral part of their training. Thus, they take the opportunity to clarify and arrange with their institutions prior to their participation in these courses. Their institutions are, therefore, involved in the course as institutions, rather than participants as individual members of their institutions. The institutions thus have a higher probability to obtain results from their project.

Clearly in these responses, the utility of Landsat data is appreciated. Implicit in the responses also is the regional nature of the program so that travel within and between countries and projects is seen as beneficial. Overall training seems to benefit from the centralization of teaching materials, staff and equipment in the Centre. If left to individual national programmes, it is doubtful if the majority would even approach the materials and resources available in the RCSSMRS. The centralization of teaching materials and equipment, together with the comprehensive image library, leads to an effective regional teaching programme which seems to meet with the participants' approval.

User Support and Projects

In the area of user support and projects, the reasoning implicit in the creation of the RCSSMRS has proved to be especially valid. The concept that the region would overall have sufficient demand for services, whereas each country would not, individually, generate enough demand to justify investment in a national service centre, seems to be particularly true for remote sensing. Users from around the region visit the Centre on a regular basis, searching the browse files and consulting staff, to determine how best to apply remote sensing to their particular problem. As a result of such enquiries, many people have used the equipment available in the Remote Sensing Department and produced sketch maps, overviews or analyses of natural resources in their chosen study region.

From these contacts and those developed during courses, the remote sensing staff have become involved in the design and execution of projects within the region. This has been beneficial because it has involved Tanzanian consultants who had completed courses in remote sensing in Nairobi, being used as staff members on courses given in Malawi and Kenya, and as advisors for projects in Swaziland. Similarly, we have had Ethiopian staff assisting with courses in Nairobi, and a Ugandan expert assisting with a soils project in Zambia.

Overall, this cross-fertilization is very beneficial to the region and is the point at which the regional concept begins to show its value. Specific project activities all drawing on the training capability of the RCSSMRS and the image library have resulted in some technical innovation and a series of useful map products. Several examples of project work are outlined here to illustrate the nature of project activities undertaken by RCSSMRS.

A forester from the Ministry of Natural Resources and Tourism in Tanzania has completed a vegetation map of Tanzania using Landsat imagery. This map consists of twelve primary classes, several subclasses and is at a scale of 1:2,000,000. A one-month field survey was conducted to review the imagery interpretation. Difficulties encountered with this study were the lack of single season and recent imagery. It was also determined that more field work at various stages of the imagery analysis would be desirable. Larger scale maps of individual provinces in Tanzania based on Landsat imagery are now under consideration. This was the first "country-wide look" for 25 years.

A reconnaissance soils map and an agricultural capability map were recently prepared by the soil survey unit of the Ministry of Agriculture, Government of Zambia for the Northwest Province of the country with assistance from the Department. This project was designed to evaluate Landsat imagery for this type of mapping. It incorporated Landsat images of different dates, some aerial photography, and field visits to identify the soils at preselected points and provide soil samples for laboratory analysis. This mapping effort was considered quite successful, and use of Landsat data for similar coverage for the whole country is now under preparation.

The Kenya Rangeland Ecological Monitoring Unit conducted a survey of the forests in Kenya and an evaluation of rates of forest depletion. This survey utilized Landsat imagery and equipment available at the Remote Sensing Department, historical aerial photography, overflights with light aircraft, some computer analysis of Landsat data, and ground surveys. Landsat false colour composite transparencies were projected onto the base maps at various scales using an overhead projector for forest delineations. This study mapped 270 forests with a total forest cover of 1,167,180 ha. or 2.35 percent of the country. The forests were divided into indigenous, plantations, and mangroves.

A member of the Forest Department of the Ministry of Agriculture and Irrigation in Sudan has compiled a forest resources inventory for Sudan, using RSD Landsat imagery and equipment. The intentions of this inventory were 1) to have an estimate of the growing forest stock, 2) to prepare an afforestation program and 3) to develop a national program for land use to conserve the natural resources. This initial inventory is the first step in a stratified sampling scheme using aerial photographs and field work to be implemented to quantify forest resources and refine the initial mapping.

The RSD has been active in several cartographic projects. These have included revising maps using Landsat data and using the images as part of a map product, an experimental map product. An experimental map at 1:250,000 consisting of a mosaic of Landsat images over-printed with cultural detail was produced jointly with the Survey of Kenya. The RSD has also worked with the U.K. Directorate of Overseas Surveys to produce similar sheets at 1:1,000,000 for Tanzania. Precision control points were collected with doppler positioning equipment to allow the Environmental Research Institute of Michigan (ERIM) to produce a map-corrected Landsat mosaic conforming to an existing 1:250,000 topographic map in Kenya and Tanzania. The RSD also produced a 1:250,000 photo map of Swaziland using a Landsat mosaic of the country produced by ERIM but reprocessing it in a simulated natural color and overlaying existing map data. These demonstration products have been extremely useful in providing potential users an awareness of possible space-borne remote sensing contributions to cartography.

The project activity listed does not emphasize sufficiently the regional nature of the staff resources applied and the cooperative, collaborative relationships entered into with the executing agency. Where possible, the remote sensing department prefers to work with the agencies and staff in designing and implementing project activity. This can include appropriate training for some members of staff and usually does include support with data selection reproduction and interpretation. This approach strengthens the agencies with which the RSD collaborates and serves to diffuse remote sensing technology into the region.

On a regional basis it is possible to encourage individual initiatives such as forest mapping in Kenya, Tanzania, Uganda, Sudan and Ethiopia. This can be drawn together into a coordinated evaluation of the forests of the region with a common legend and methodology so that a useful regional up-date of forest can be produced. Such coordination becomes much more critical when the study is of crop yield and there is a drought situation resulting in a famine. It is, however, an extension of the same technique and is independent of national borders. This concept of looking at a drought or famine region in its entirety is particularly well suited to regional centres, and a rapid assessment of such conditions which ignores national boundaries can lead to a realistic assessment of drought and famine regions. This in turn is the essential ingredient in programmes such as the SADCC Food Security programme where remote sensing inputs of both vegetation and weather from NOAA satellites can provide monitoring data three or more times each week. If this is supported by mapping of the natural resource base such as soil agro-ecological regions from the regional collection of Landsat data, suitably supported by field work, the result should be much more reliable than can be achieved by other methods.

Conclusion

The aerial coverage of satellite images, the area within range of a receiving station, and the regional nature of such natural disasters as drought, famine and flood all point to the desirability of a regional structure. The cost and effort required to establish a full national remote sensing programme in each country exceed the level of commitment usually found in natural resource agencies in this region. A dispersed system linked to a regional centre appears to offer a workable structure.

Ideally, the regional centre should be based on a receiving station complex, recording data and distributing the data products to the region. Increasingly the use of digital image processing is encountered in the region and the RCSSMRS has a role to play in distributing digital data as well as photographic data to the user. This central service function linked to users in projects and government agencies should provide data in forms compatible with the available systems. If the RCSSMRS can now play the same role in the dissemination of digital processing technology as it has done with photographic product, the next decade should see a vast improvement in the information available to the natural resources planner and developer. Courses in the use of digital systems and the supply of data in a form compatible with micro-computer systems will be of value at the regional level. If the RCSSMRS can maintain its regional role in this transition and support national agencies as they utilize remote sensing data in their management of natural resources, the whole concept of regional collaboration should be reinforced.

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LEGAL ASPECTS OF REMOTE SENSING

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I. Introduction

One of the practical consequences of the use of Remote Sensing Technology is that countries benefitting from the use of technology can obtain data on natural resources from within their own territories as well as from within the territories of other states. As a result, diverse interests converge which require an appropriate legal framework.

In its recent history, the elaboration of a legal framework to deal with interests that could be contradictory or incompatible has been difficult. There has been a long debate in international legal fora about the ways and means to govern situations which deal with resources and also affect members of the international community.

This debate has been dominated by two schools of thought. One aspires to extend the concept of state sovereignty with the necessary adaptations imposed by geography and other factors. The second school of thought negates the former and favors the introduction of forms of international organizations which would be global in nature and scale. A relevant example of these two approaches is contained in the United Nations Convention of the Law of the Sea. The Convention contains elements of sovereignty with regard to living and non-living resources in the concept of the exclusive economic zones. At the same time, the seabed beyond national jurisdiction is governed by the concept of the Common Heritage of Mankind, which entails an international regime.

The distinctive qualities of outer space, together with other factors, have persuaded the international community to put into effect different legal instruments to govern outer space activities founded on the international organization approach.

To this end, paragraph 1 of article 1 of the Space Treaty states that "the exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific developments". Furthermore, in the same provision, paragraph 2 states that "Outer Space, including the Moon, and other Celestial Bodies, shall be free for exploration and use by all states without discrimination of any kind, on a basis of equality, and in accordance with international law, and there should be free access to all areas of celestial bodies".

There exists, therefore, considerable freedom in the exploration and use of outer space as long as it is "carried out for the benefit of all peoples, irrespective of the degree of their economic or scientific development" (Preambular paragraph 3 of the Space Treaty). In other words, outer space activities are rendered unique by the ethical mandate that it be pursued on behalf of all the world's people. In this context, it is necessary to note that the term "people" used in existing space law, as well as in the United Nations Charter, is broader than the term "states".

The distinctive qualities of outer space, compared with those prevailing on earth, have imposed the obligation that its use be carried out for the benefit of all mankind. Therefore, there exists in Space Law, as in no other branch of international law, a compelling link between the legal, moral and ethical imperatives. Conceptually, that link is expressed by its governing principle, i.e., the concept of Common Heritage of Mankind. The application of this concept is contained in article 2 of the Outer Space Treaty, which states that "Outer Space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means". This statement clearly shows that mankind is the "proprietor" of outer space. It is necessary, however, to stress that the notion of a "Common Heritage of Mankind", with all of its legal implications, is not meant as a barrier to the exploration and free use of outer space. On the contrary, its exploration and use must, in fact, be stimulated and expanded, not only for the benefit of present generations, but also for that of future ones.

As pertinent treaties and documents show, the legal frame of reference of Space Law is General International Law, and more specifically, the United Nations Charter. Space treaties specifically refer to the Charter of the United Nations.

As jurist Manfred Lachs points out [1] "it is worthwhile to offer some comments on the significance and the implications that an extension of international law to outer space, including the moon and other celestial bodies, could have, as they are perceived in the important instrument. Obviously, this implies that in all outer-space-related activities states are governed by International Law. The terms used indicate that the world legal system is mandatory for all states in their mutual relations. This includes the basic laws and principles of the system as they have evolved historically, as well as more recent modifications".

The aforementioned principles are found in the International Law of Development and Cooperation. Their application will assist nations to achieve minimal levels of welfare and development; given that peace, justice and security are at stake, no nation can exempt itself from these provisions. More specifically, one of the principles identified in the United Nations General Assembly Resolution 2625 (XXV), which refers to the seven fundamental principles of International Law drawn from Chapter 1 of the Charter of the United Nations, is the sovereign equality of states and the right to self-determination. The Law of Cooperation, of which one concrete manifestation is Space Law, represents a new perspective on International Law. This view is in harmony with the changing nature of international society and the urgent need to articulate people's legitimate expectations of all nations of the world.

II. Specific Considerations

Through remote sensing of the earth it is possible to detect undiscovered natural resources and in this way increase a nation's productivity, help in meteorological predictions and determine levels of air and water pollution, etc. It can be inferred from this that nations which use outer space are in a position to collect resource data which are under the territorial jurisdiction of other states. Problems of international law can arise from the gathering and dissemination of this information. "It is necessary to first establish if the State has the right to gather information without the consent of the nation observed, then the question of its right to divulge such data without consent would need to be considered. Remote sensing is an activity carried out in outer space, where states cannot claim property rights or exercise sovereignty, but the data on natural sources are gathered for use on earth, where state sovereignty does indeed exist" [2].

It is necessary to keep in mind that political boundaries are invisible to the images gathered by satellites. Nevertheless, from a legal point of view, the principle of self-determination is applicable to remote sensing activities. This principle includes: a) equality of rights, b) the prohibition of intervention, c) the principle of the sovereign individuality of states. In order to realize the principle of self-determination, the right to maintain, secure and perfect the legal, political, economic, social and cultural sovereignty of each country must be assured. This right is immutable and not exhausted by time, exercise or other factors, and constitutes a general provision of universally accepted international law.

These principles are enumerated in Resolution 2625 (XXV) of the General Assembly of the United Nations. It follows that every state has the right to acquire, under reasonable conditions, the information about its own resources obtained by satellites. At the same time, a malicious manipulation, as a means of pressure to obtain an illicit advantage, is contrary to these principles. Furthermore, a state is put at a disadvantage when it lacks easy and unconstrained access to data to which it has rights. This could constitute, under certain circumstances, an act of intervention and certainly one of violation of its sovereignty.

It should be further emphasized that the permanent sovereignty of peoples over their own natural resources results from the aforementioned principles, and is a right inherent to sovereign states. Each nation is free to determine the proper use of its resources and to set the conditions of their use. This right is based on the control of its natural resources in order to reserve for itself the benefits obtained from their exploitation.

In this sense, Resolution 2625 has been labeled one of "jus cogens" by jurists and legal doctrine, which makes it inviolable by agreements or conventions aimed at overturning it. Resolution 1803 (XVII) of the General Assembly of the United Nations, which concerns permanent sovereignty over natural resources, and Resolution 2131 (XX), dealing with national rights to independence and sovereignty in internal affairs, are also inviolable.

In the field of Space Law, Article III of the Space Treaty is one of the most direct provisions related to remote sensing. This article states that "the States included in the Treaty must carry out the exploration and use of outer space, including the Moon and celestial bodies, in accordance with International Law, including the Charter of the United Nations, and in pursuit of space and international understanding".

The text of the article does not contain a prohibition of the inspection of resources and collection of data by one state in the territory of another state. The constraints of the norm are general, but the question of remote sensing requires a more specific treatment, which must include three elements: the freedom of space, the territorial sovereignty of states, and free scientific investigation. In order to make sure no one of the above elements will prevail, a legal compromise must be found to allow the continued development of space activity, while necessarily protecting the interests of the nation being observed.

Taking into account these core features, it is also necessary to define clearly the international responsibility of states when the legal foundation of remote sensing is violated. In this regard, it is important that specific provisions determine an indemnity to be paid when the legal requirements of remote sensing are not carried out.

The interests of the observed state, as previously noted, are considered inviolable under the aforementioned resolutions of the General Assembly. Therefore, discrimination would entail a violation of international law. It must be understood that this discrimination arises not only when a state is not given, in a timely way and subject to a reasonable cost, the data of its own territory but also when it does not have priority access to strategic data that are held by another country. It is also necessary to determine, in the context of possible liability, the scope of the concept of "dissemination" of the data. Thus in the case of a malicious handling of the information, liability should fall not only on the State owner of the satellite but also on the operator of a remote sensing network of the station, all of which use the information in a damaging way to the state whose resources originated the data.

The use of remote sensing satellites for military purposes deserves special mention. A debate has developed, centering on the correct interpretation of the term "peaceful uses", intended to constrain military use of remote sensing satellites. The Space Treaty of 1967 was not able to resolve the debate and two diverse positions persisted. One group asserted that this term prohibits only "aggressive" uses, while the other maintained that all military use of outer space is prohibited. The latter group believed that the conditions of "peaceful use" should be examined in light of the principles of Contemporary International Law (International Law of Cooperation), upon which Space Law is founded.

This would lead to the conclusion that peace involves economic and social aspects. Therefore, the only acceptable legitimate activities in space would be those that have peaceful purposes. It is necessary at this point, however, to take note of the fact that the Space Treaty refers to this problem, albeit in a limited way. It supports the argument that the term "peaceful uses" prohibits only the aggressive use of outer space that is equivalent to the use of armed force. While the letter of the law may support this interpretation, it is not in keeping with the spirit of the treaty itself. The Charter of the United Nations, and some resolutions of the General Assembly, such as the one defining "aggression", provide an interpretation of the problem which prohibits the use or threat of force in broad, general terms. The question, for example, of strategic reconnaissance by satellite, should be examined with the participation of the state in whose territory this is verified, in addition to the state carrying out the mission.

The lawfulness criteria should be gathered by the provisions of numeral 1 of the Article 1 of the Outer Space Treaty. Therefore, no activity can be justified by the absence of a specific provision that prohibits it.

As has been stated by the legal doctrine, espionage and any other malicious conduct which affects a nation's territorial integrity, constitute a criminal act affecting the security of that nation. Espionage aims to obtain information on the operating zones of a belligerent in either a clandestine manner or under false pretenses with the intention to share this knowledge with a hostile party (The Hague Regulations of 1907). In our judgment, the criminal nature of this act is not restricted to a military conflict, but also allows a broader interpretation, considering that in many cases the international community lives in a state of undeclared conflict. The case of remote sensing is particularly illustrative of this when the data obtained are used in a clandestine way with a view to destabilize the economy or the culture of a nation. The clandestine nature of the crime of espionage would be only an aggravating factor because the mere fact of seeking to destabilize a state would in itself give origin to a punishable illicit act.

There do exist certain remote sensing satellite activities which are permissible and convenient, such as "early warning" satellites, which act as deterrents to any kind of war, and that can be used to verify compliance with Arms Control Treaties. The secrecy of a behaviour does not necessarily make it illegitimate if it contributes to international stability. While each state does have a right to privacy, this must harmonize with the superior right of the international community to pursue world peace and security. In any case, in general terms the collection of secret information, even if not through espionage, would not be permitted under Customary Law [3].

III. Conclusions

The importance of remote sensing activity, the way in which it affects the rights of developing countries, the way in which these general rights are recognized by international norms, and the absence of specific laws, are all factors which determine the creation of rules to control this field. The framework described in the introduction could provide appropriate guidance regarding the legal foundations of remote sensing. An interpretation of modern international law and of the "relevant norms of space law" (which paragraph 3 of the preamble of the Resolution of the General Assembly 40/162 and the articles already cited on Space Law allude to), allows us to conclude that such activity should be conducted with respect for the freedom of exploration, and for the benefit of all the world's people. It is important, however, that there exist regulations which deal more specifically with this problem and that present and combine the aforementioned concepts considering, above all, the relevant juridical and ethical concept of the Common Heritage of Mankind.

This idea would become established if it were explicitly recognized that all states could gain access to a share of the benefits achieved by the more technologically sophisticated states. A legislative task which aims to follow the rules of Contemporary International Law must be guided by these juridical norms, and in pursuit of the exploration and use of outer space, the Moon and other Celestial Bodies, for peaceful ends benefitting all of mankind.

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CONSIDERATIONS ON REMOTE SENSING TECHNOLOGY TRANSFER IN DEVELOPING COUNTRIES

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Abstract

Space remote sensing systems have proved to be very suitable for assessment and to monitor the earth's resources.

Many applications are very useful for developing countries, where much work is to be done on topics like training, organization, coordination and conscientization of decision makers.

The Iberoamerican case is described, and the proposal to establish a "Network on remote sensing applications for natural resources management" can be an adequate method to improve the technology transfer among countries of the region.

SELPER (Sociedad de Especialistas L.A. en Percepción Remota) is a good example and a starting point of a more ambitious program of cooperation. Nevertheless, the developing countries are having difficulties in obtaining actual benefits from this technology and they need a more generous attitude from industrialized countries.

I. Introduction

For centuries man has attempted to view his surroundings from some vantage point so that he could better understand and control his environment. In recent years, this desire has taken man to outer space, from where the world can be viewed with new eyes.

With the 1972 launching of the first Earth Resources Technology Satellite (ERTS), now called Landsat 1, and the subsequent launches of Landsat 2, 3, 4 and 5, worldwide attention focused on gathering pertinent and timely information to aid planners and scientists through the use of remote sensing. In 1983, the Landsat 4 satellite was launched and provided continuity of Multispectral Scanner (MSS) data, it also ushers in the new era of Thematic Mapper (TM) image data, with its increased resolution of 30 m signal sensitivity and additional spectral bands.

Recently, on February 22nd, 1986, SPOT-1 was launched and excellent imagery was obtained on February 23rd, with 20 and 10 meters resolution. These and other systems have produced a vast quantity of data not fully exploited. For different reasons (economic, social, political, underdevelopment, etc.) all these data have not produced the expected useful information for earth resource management, mainly on developing countries. We estimate that the technological gap between developing and developed countries is increasing.

II. Background

1. *Different Systems of R.S.*

Space remote sensing systems have proved to be very suitable for assessment and monitoring of the earth's renewable resources and a good help for non-renewable ones.

We can mention briefly different remote sensing systems developed and operated by developed countries in the last 15 years:

The LANDSAT family 1, 2, 3, 4 and 5, including the thematic mapper (TM), the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR), the French Système Probatoire d'Observation de la Terre (SPOT), the German Shuttle Pallet Satellite (SPAS) Modular Optoelectronic Multispectral Scanner (MOMS), the European Space Agency (ESA), Spacelab Metric Camera, the National Aeronautics and Space Administration (NASA) Large Format Camera (LFC) and Shuttle Imaging Radar (SIR-A and B), the Russian Meteor Satellite BIK-E and "fragment" experiments and MKF-6M and KATE-140 Camera Systems, the ESA Earth Resources Satellite (ERS-1), the Japanese Marine Observation Satellite (MOS-1) and Earth Resources Satellite (JERS-1), the Canadian Radarsat, the Indian Resources Satellite (IRS). We can also include the concepts for a 6-

channel Shuttle Imaging Spectroradiometer, a 128-channel Shuttle Imaging Spectrometer Experiment (SISEX), and the U.S. Mapsat.

Among these systems ground resolution, or instantaneous field-of-view (IFOV), varies from 10 m to 1 km; spectral band width from 10 nanometers to broad-band panchromatic; temporal coverage from multiple coverage each day to coverage every few weeks; swath widths from 10 to 2,400 km; and orbital inclinations from near-equatorial to polar.

During the past several years significant activities in earth remote sensing satellite technology have also been conducted by the Soviet Union.

In 1974, the Soviet Union launched the first of a series of satellites, subsequently referred to as the Meteor-Priroda program, for the purpose of gathering earth resources data. The principal sensing system on early missions of this program consisted of two separate low-resolution multi-spectral scanners, the MSU-S and the MSU-M.

In 1980 the Soviet Union launched a more advanced Meteor-Priroda sensor package into a 650 km high near-polar sun-synchronous orbit, with three instruments on board.

Earth remote sensing data acquired by the Soviet Union are not routinely available worldwide. Rather, these data are used internally and are provided to countries with whom bilateral agreements have been made. Reports indicate that data collected by Soviet earth remote sensing systems have been successfully applied to many land resource problems. New systems are proposed or planned by China, Brazil, Indonesia and others.

2. *Applications*

Data collected with the NOAA-6 AVHRR and the Landsat MSS have given users, in general, significant opportunities for resource assessment and management analysis at the province, district, and planning unit levels. The increased spectral and spatial resolution of data collected by the Landsat TM and by France's SPOT satellite offers a potential for more detailed mapping and assessment of land resources.

For example, the NOAA-6 AVHRR data have been used for regional applications to:

— Monitor vegetation phenology and growth
— Map National Fire Danger Rating System fuel types
— Monitor fuel condition and loading

— Assess drought occurrence
— Map recently burned areas
— Perform time series flood assessments

The Landsat MSS data have been used, in a complementary fashion, with the NOAA-6 AVHRR data, to

— Develop generalized land cover maps
— Map range capability units in support of a range inventory
— Improve the efficiencies of conducting a soil survey
— Monitor Federal mineral trespass
— Assess vegetation changes
— Provide a base for allocating field samples
— Plan various management activities, including locating firewood collection areas, re-establishing wildlife habitat, and improving range conditions.

The increased spectral sensitivity and spatial resolution of data collected by the Landsat TM and the SPOT system offer the potential for even more detailed mapping and assessment of land resources. Potential application of Landsat TM data includes:

— Mapping land cover at the plant community level
— Assessing ecological status of range land vegetation
— Locating and assessing stock water sources
— Evaluating grazing distribution and use
— Determining desirability of wildlife habitat

Likewise, potential applications of the SPOT system include:

— Providing stereoscopic images for soil mapping
— Providing increased spatial detail for vegetation mapping
— Assessing wildlife habitat
— Locating and assessing stock water sources
— Determining area accessibility

Resource managers will begin to realize the full potential of these new data sources as both the data and research results become available, and especially as these data are used in conjunction with other forms of digital data.

Landsat have been used to produce image mosaics registered to specific map bases for various cartographic applications and for use as base maps for natural resources surveys by many countries around the world. The U.S. Geological Survey has been making experimental image maps of the United States and of non-U.S. areas in cooperation with many foreign countries from Landsat data for over 10 years. These maps have been produced from MSS, RBV and TM data at scales ranging from 1:1,000,000 to 1:100,000.

Several countries have also been conducting extensive research and development of image processing techniques to digitally rectify, mosaic, and enhance data from satellite remote sensing systems. This research led to the development of systems and capabilities to produce digitally enhanced satellite image maps rectified to a standard map projection and printed at standard map scales.

The MSS data with 80 m resolution, properly processed, provide images with resolution and geometric accuracy suitable for map presentation at scales as large as 1:250,000.

The availability of TM data with 30 m resolution provides the opportunity to produce image maps at scales larger than 1:250,000. Research and testing of experimental image maps from TM data indicate that resulting positional errors of approximately 28 meters, which meets U.S. National Map Accuracy Standards at 1:100,000 scale, can be achieved. The availability of these image maps has created significant user interest in additional image map products.

III. R.S. Technology Applied to Developing Nations

Traditionally, economic development depended upon the "spatial relationship" of resources and infrastructure linkages. Remote sensing may be viewed as a mechanism capable of providing the planning assistance necessary for the locations of the production factors such as the proximity of resources to transportation links. The location of resources, population concentrations and land uses may be mapped and monitored for the economically viable use of resources in relation to the "basic human needs".

Several advantages result from remote sensing technology which would be of an inmediate benefit to the user.

Remote sensing provides the basic information on the quantity, quality and location of earth resources that is essential to identify, plan and implement development programs.

Most Third World nations are plagued with inefficient monitoring and inventory techniques, owing to a lack of sufficient financial support required for the provision of equipment and trained individuals. Unaccessible tropical, arid, mountainous or uninhabited areas have inhibited most conventional survey techniques, adding to the fragmented, outdated or incomplete nature of their information systems.

Conventional methods of data acquisition such as ground truth surveys and low or high altitude aerial surveys prove both time-consuming and costly, followed by the lengthy process of data compilation.

The adoption of remote sensing technology not only benefits developing nations by providing an extensive data base required by resource managers and decision-makers, but also increases the nations' technical awareness and capabilities. The technical community in the remote sensing field may gain the opportunity to grow while acquiring new skills in data acquisition. Consequently, the introduction of new equipment and facilities may upgrade existing training and information systems.

Remote sensing technology maintains much potential in developing countries. Several constraints do exist that may limit the optional use of the technology.

The effectiveness of remote sensing is restricted when the recipient nation is not familiar with the capabilities and limitations of the technical applications, making more difficult the integration of such techniques. In some cases, the potentials have been underestimated. Many developing nations influenced by this lack of awareness hesitate to participate, due to the perceived complexity and expense of the remote sensing functions.

Developing nations' decision-makers may provide limited support towards such technologies unless inmediate results or benefits are produced. Remote sensing producers are forced to show positive results, due to the high expectations of this technology.

This may be achieved with reference to similar applications previously completed or by simulating remotely sensed results through airborne techniques.

Most technological benefits are quantifiable, however according to the U.N., there is "no econometrically acceptable methodology available to assess remote sensing benefits at a fair level of significance". Such benefits as increased technical awareness, education, improved standard of living at a better state of mind and health are difficult to quantify, yet are indirect benefits of remote sensing applications directed at national development goals.

At present, most developing nations have little influence on the development of remote sensing applications or techniques. If their involvement were to be increased, one might find a significant increase in their support and commitment to the technology.

The interpretation of the multitemporal data may require the assistance of digital techniques. This increases the percentage of useful information that may be extracted, allowing the user to gain maximum benefits from the data. Obviously, such facilities are expensive and "out of reach" for some less developed countries (LDC), limiting the extent of their own remote sensing applications.

From an economic perspective, one may argue that such capital-intensive facilities should be avoided in an environment starving for employment and fruitful in labour-intensive possibilities that would seem more beneficial to national development.

In terms of the development of a remote sensing program in an LDC at a national level, operational infant institutions feel threatened to compete, thus hindering their growth. Such a phenomenon is not appreciated in developing economies.

Satellite data in some regions may only be available abroad. Lacking a satellite receiving station, African nations, for instance, must deal with the purchase of data outside the continent. As with the purchase of goods from abroad, one must deal with the problems of foreign currency exchange and delays in the processing and delivery of data which may hinder on-going projects, resulting in additional (unnecessary) expenses.

The needs of developing nations are variable. Identified needs range from the basic human requirements for the sustenance of life to the development of mapping and monitoring techniques for the efficient utilization of natural resources. The most common data requirements, as indicated by development aid organizations and Third World nations, include:

— A technology that supplies basic human needs such as food, water and energy.

— Development of the national economy through the development of native natural resources.

— Development or improvement of the national information base.

— Improvement of the standard of living through the development of available human resources.

— The provision of timely focusing on immediate problems and/or natural hazards.

The educated individuals within agencies and institutions of developing countries have been the most instrumental in recognizing the potentials of Landsat information.

The most common applications of remote sensing technology have been the production and updating of maps, providing, in some cases, more information than by conventional methods. Equally important are the resource-based applications such as mining, mineral exploration, forest inventories, land use studies, hydrology and agriculture. The immediate problems of desertification, deforestation, soil erosion, environmental pollution and overpopulation, alongside natural hazards such as flooding or forest fires illustrate further remote sensing application possibilities.

The most-needed geographic information systems (G.I.S.) depend upon accurate and timely data, which remote sensing has the capability of offering; however this technology "is not the panacea of integrated resources analysis. It cannot stand alone as a tool for development, but must work in harmony with existing information bases". Most developing nations have basic information sources, however the knowledge may be limited and inadequate for sound management.

A priority of the least developed nations is the provision of the basic necessities required for the continuing existence of their populations. Landsat projects based in West Africa have proven to be successful in more efficiently allocating basic resources. Upper Volta lacks an adequate fresh water supply, a phenomenon common throughout Third World regions. Ground water resources were identified using the data supplied by Landsat, which allowed the accurate positioning for the drilling of wells.

IV. Some Recommendations

As we have seen, most of the hardware, the software and performed applications belong to industrialized countries. As pointed out in the UNISPACE 82 report, developed countries dominate the field of science and technology to the extent that about 95% of all research and development are executed by them, while developing countries, which represent 70% of the world population, have only about 5% of the world's research capacity.

To obtain a real technology transfer for the benefit of developing countries, several conditions and objectives must be achieved in order to permit that space technology in general can help the progress of such countries. Aspects of cooperation, education, training and organization must be considered. Concerning this, we can recall some of the recommendations of the UNISPACE 82 conference applicable to our case:

"Countries planning to use space technology need to pay special attention to the organizational framework and should organize and set up interagency coordination mechanisms appropriate to their situation and needs, leading to fast implementation of efforts. Developing countries should encourage and fully develop their existing technological capabilities and take planned measures to decrease their dependence on foreign expertise.

"It is important that operators of remote sensing satellites should give definite indications regarding continuity and unrestricted availability of data *at reasonable prices*, so that countries can continue investing in ground equipment or devise alternative means to obtain the data. A study should be undertaken to assess the need and viability for a worldwide remote sensing system".

Developing countries recognize the similarity of their problems and the complementarity of their needs and resources. It is highly desirable that they get together and cooperate with each other, so as to collectively make the most of what they have.

There is a strong case for encouraging native fabrication to the maximum extent possible. If equipment has to be imported, developing countries would be well advised to first look for appropriate equipment from other developing countries. Alternatively, they may have to adapt off-the-shelf developed-country equipment. Efforts should be made, both by the country concerned and by international agencies to encourage the flow of equipment made by developing countries to other developing countries.

Cooperation in training among developing countries should be actively encouraged by the United Nations and its specialized agencies by providing available assistance, *inter alia*, funding for fellowships.

The United Nations should support the development of appropriate training centers at regional levels, linked, whenever possible, to institutions implementing space programmes. Necessary funding should be made available through international financial institutions. These training centers should organize (with the United Nations' assistance if necessary) regular training courses of varying durations for different levels of trainees from developing countries.

International financial agencies should provide financial support, as appropriate, for demonstration projects undertaken by developing countries. The United Nations and international financing agencies should consider providing all possible help to developing countries in setting up native centers for the absorption, adaptation and development of space technology. All these recommendations were ratified by the 37th session of the United Nations General Assembly in Resolution 37/90.

Besides these recommendations, each developing country should especially consider the training of their specialists in remote sensing, taking advantage of any opportunity offered by industrialized countries and international organizations in order to obtain the "critical mass" of well qualified human resources. These specialists must play an important role, applying this modern tool of R.S. according to the particular situation and needs of the country. They must interact with resource management planners, decision makers and politicians to establish appropriate programs for the benefit of the country.

The execution of the abovementioned will give the developing countries the actual benefit of technology transfer from industrialized countries.

V. Technology Transfer

Optimistic views of satellite technology have demonstrated the capacity of remote sensing to be molded to the less advanced capabilities of developing nations. As a result of the diverse technical applications provided, the technology may take on a modular character allowing the user to gradually adopt technical methods. Initial exposure to remote sensing would require technical assistance, a few trained individuals and plain equipment, resulting in a low-cost intermediate technology. Expensive data acquisition and processing functions may be handled within remote sensing producer nations, or within neighbouring facilities. The data collected and processed should reflect clear national objectives, thus tailored national approaches may be taken in formulating applications that complement local conditions. Sometimes remote sensing has been considered unappropriate when developing nations have maintained the position of "technology for the sake of technology", demanding sophisticated technologies, expecting sophisticated results in anticipation of quicker economic growth. The consequences of such actions include unappropriate data formats unsuitable for user assimilation and expensive equipment left idle due to under-use.

Several criteria determine the appropriateness of remote sensing technology which is directly linked to the process of technology transfer. Technology transfer is defined as:

The technical method or capability for achieving a practical purpose (to accomplish some task), a material result that is identifiable and of practical significance.

Other authors consider that "the transfer of technology is often a complex process which involves significant differences in perceived needs, institutional structures and available resources".

Technology transfer mechanisms exist within the recipient nation, or externally in the location of technology origin. External mechanisms have Third World students travelling to foreign educational institutions, various symposia, conferences, seminars, etc. Referring to internal mechanisms, conferences have been important vehicles of information transfer, bringing international experts to the "place of need". Exchange programs, on-the-job training, and institute programs have all been regarded as traditional internal transfer mechanisms. More recently, the options of visiting scientist programs and the provision of outside consultants have enhanced the transfer process.

Undeniably, specialized research institutions, universities, government agencies, international organizations and special development programs have been the major actors in the transfer process. The contributions of consultants and private companies are also important, but usually overlooked. However, their "profit-oriented" motives may not necessarily promote methods to the benefit of the clients.

Several considerations exist and should be reviewed prior to transfer activities. Socio-economic variables illustrate that the community of developing countries cannot be observed as one unit but as a conglomerate of nations at various stages of development. Real scientific and technical gaps, combined with differing values and social standards, require that remote sensing technology be molded into the surrounding environment.

Economic considerations reflect the appropriateness of the data collected and equipment used. The efficient allocation of time and money is critical to a growing economy. Geographic considerations reflect the diversity of landscapes and climates, which must be fully observed through existing information sources prior to the assignment of remote sensing applications.

Benefits of technology transfer have been identified as an increase in technological awareness, including the technical capabilities of the native population; permanent development of facilities, equipment and remote sensing programs; an increase in the quality of goods produced due to the expansion and diversification of exports, resulting in a decline of production costs.

VI. The Ibero-American Case

Latin American regions need to share the benefits of space applications, e.g., remote sensing technology, with due consideration for possible differences in their needs and levels of development, but with a lot of things in common which need to be explored in detail in order to obtain the adequate cooperation mechanisms. The language is practically the same; most of them are Spanish-speaking and can understand Portuguese well. Most of them have important resources waiting to be explored, vast rural areas with needs for communication and education and other common problems which could be solved by space applications.

Besides, the level of industrialization in general is not so high and sophisticated, therefore the gap between countries of the region is not so wide compared with the gap between one individual Latin American country and a developed one. The philosophies to solve problems are more similar between developing countries with such a lot of common problems, despite some varying levels of economic, scientific, technological or industrial development.

Space science, technology and its applications are multidisciplinary and it can happen that a particular activity in a given country (e.g., remote sensing) is under the responsibility of a government agency or can be distributed among several secretariats or agencies depending upon the special application: agriculture, hydrology, geology, etc.

In some cases one university or a particular agency is in charge of the principal activity in remote sensing because of its tradition in geophysics, electronics, geography and mapping, etc.

The state of promotion of space applications, the development of remote sensing activities, the research laboratories, the ground and training facilities, etc., are very different in each Latin American country.

The levels of satellite remote sensing activities vary from initial involvement in countries such as Paraguay, Uruguay, most of Central

American countries and Jamaica to intermediate involvement in Perú, Venezuela, Bolivia, Chile, Ecuador and Colombia, to advanced remote sensing activities conducted in Brazil, Argentina and Mexico.

All the region from "Río Grande" to "Tierra del Fuego" and farther south the Antarctic has only two Landsat type receiving stations and no SPOT capability: one receiving station in Brazil and another in Argentina (Fig. 1). Some countries of the region have national remote sensing programmes or use remotely sensed data in one way or another in projects or for resource surveys and management. Nevertheless there is a general feeling that much more use can be made of remote sensing applications. This, however, requires a considerable strengthening of national and regional capabilities, including an intensified transfer of technology and extensive education and training programs.

With reference to education and training, different courses have been given in several leading institutions of the region, such as CNIE (Argentina), INPE (Brazil) and CIAF (Colombia). This was explained in detail in a paper presented at the IV Plenary Meeting-SELPER entitled: "Recursos humanos y consideraciones sobre aplicaciones de la Teledetección en América Latina". Brief courses (one week) about the benefits of using R.S. technology for the management of natural resources and monitoring of the environment, devoted to "decision-makers" and planners, *must be intensified*.

It will be advisable to develop adequate methodology to cooperate and to transfer the remote sensing technology among the countries of the region. A suitable way could be to establish "technical cooperation networks" (t.c.n.) on remote sensing applications.

As we know, the formation of such networks shows the willingness of a country to tighten the bonds of horizontal cooperation in the spirit of the U.N. Conference on T.C.D.C. recommendations. With such ideas in mind, the objectives of a network (t.c.n.) are:

— To accelerate the development through the existing resources and knowledge of the region.

— To promote countries' self-confidence in their own human resources, knowledge and skills.

— To reinforce countries' capabilities in problem identification and finding the respective solutions.

— To strengthen existing technical capabilities.

— To increase and to improve the interchange of experiences and

FIG. 1.

technology transfer among countries, promoting international cooperation for mutual benefit.

— To improve countries' capabilities for absorbing and adapting technologies and skillfulness.

The abovementioned networks must be devoted to a particular application where remote sensing technology could be a useful tool. Some examples are:

1. Land use in humid tropics
2. Regulation of hydrographic basins
3. Rational use of agricultural natural resources
4. Natural resources use and conservation in semi-arid zones, etc.

As we know, R.S. technologies can be used in renewable and non-renewable resources management.

Each country of the region willing to participate in such networks must establish its own priorities according to its general strategy for development, referring to the listing suggested below:

— Data reception format (imagery, tapes, CCT, HDDT)
— Satellite or aircraft data
— Natural resources satellites (Landsat MSS, TM; SPOT, others)
— Meteorological satellites data (GOES, TIROS, others)
— Information on Visible I.R., Radar, etc.
— Visual interpretation; Semi-automatic, Digital
— Teaching and training of specialists in different disciplines (agronomy, forestry, geology, hydrology, etc.)

We consider the advantage of establishing a "NETWORK of R.S. APPLICATIONS for NATURAL RESOURCES MANAGEMENT". For this purpose a meeting of experts must be promoted in the region. The experts from the different countries must attend this meeting with adequate instructions and background on the feasibility of giving or receiving cooperation on different topics using R.S. technology. During the meeting and round tables, they must analyse the feasibility of setting up such network, the possible activities of cooperation and if possible, designate the coordinator for each country.

Another idea for improving the R.S. technology transfer in the region is the strengthening of *regional organizations.*

The first discussion on the creation of a regional organization to promote cooperation in remote sensing was carried out during the UN/FAO Seminar on land use in La Paz (Bolivia) in December 1977. The talks continued during the XII International Symposium on Remote Sensing of Environment organized by the Environmental Research Institute of Michigan (ERIM) in Manila (1978).

During the XIV International Symposium on Remote Sensing of Environment (ERIM) in April 1980 in San José (Costa Rica), the bases for the Sociedad de Especialistas Latinoamericanos en Percepción Remota

(Latin American Experts Association on Remote Sensing) (SELPER) were established. At this time, a Committee for the study of the subject was created. In fact, the chairman of the National Commission for Space Research (CNIE) from Argentina, the General Director of the Institute of Space Research (INPE) from Brazil, the Director of CLIRSEN from Ecuador, the Director of the Inter-American Center of Photointerpretation (CIAF) from Colombia and other officials and specialists from technical organizations in teledetection from other countries such as Mexico, Bolivia, Chile, Costa Rica, Perú, Venezuela and Guatemala, attended the meeting.

The discussion and analysis of the situation was to define the kind of possible organization to be created. Three possibilities arose:

— *Governmental organizations* integrated by representatives from countries of the region interested in the subject of remote sensing.

— *Institutional organizations*, that will be integrated by the leading institution in each country involved in remote sensing activities, with the corresponding official support.

— *Professional organizations*, that will be integrated by the experts in teledetection, acting on their behalf.

As the attending experts did not represent their corresponding government for the establishment of such an organization, the first possibility was rejected.

Furthermore, as the Latin American countries which have a special agency or organization primarily responsible for teledetection were only a few, there was no possibility to establish, for the time being, an organization of the second kind.

It was finally decided to create an association of experts without eliminating the possibility of working in the future on the creation of a "Consejo Latinoamericano en Percepción Remota" (Latin American Council for Remote Sensing). A committee for the study of the new associations was created. The colleagues of Ecuador offered their country as a site to hold the next meeting in order to discuss the aspects referring to the new association (SELPER).

Thus the first Plenary Meeting of SELPER was held in Quito, Ecuador, in November 1980 under the sponsorship of CLIRSEN (Centro de Levantamientos Integrados de Recursos Naturales por Sensores Remotos) and IGN (Instituto Geográfico Nacional) of Ecuador and the U.S. Agency for Inter-American Development (AID).

As we have seen, international events were an adequate forum, very useful in this interchange of ideas, to promote regional and inter-regional cooperation in space activities, mainly in remote sensing.

Concerning SELPER, we know that it is an institution which has gained the necessary vigour through the activity of its members and also through the five plenary meetings, several workshops and symposia already held. The general objectives of SELPER are aimed at promoting national, regional and inter-regional cooperation in remote sensing. Of course, bilateral cooperation is also very important and promoted by SELPER. Other specific objectives of SELPER are:

1. To bring together the most outstanding specialists and Directors of Ibero-American Institutions related to remote sensing.

2. To promote advantages and reduce limitations of remote sensing techniques, as a powerful tool for national development.

3. To improve scientific and technical knowledge of SELPER affiliates through different activities such as regional symposia, research programs and others.

4. To establish a permanent communication among SELPER affiliates.

5. To make known periodically the advances and needs in remote sensing in the region.

6. To promote regional and inter-regional cooperation with similar organizations and institutions belonging to developing countries and also to nations having high advanced technology.

7. To obtain the cooperation of national and international institutions for developing remote sensing activities in benefit of Ibero-America.

8. To improve technical assistance and use of facilities of the region.

9. To create an Ibero-American Council on Remote Sensing hopefully having official support from the different countries in the region. The development of the Annual Plenary Meetings is very important to plan the actions to accomplish these objectives.

The VI Plenary Meeting of SELPER in conjunction with the Latin American Symposium on Remote Sensing will be in Gramado (Brazil) on August 10-15, 1986. A Plenary Meeting under the sponsorship of the Federal Republic of Germany is being prepared to reinforce vertical and horizontal technology transfer mechanisms in Ibero-America through SELPER. The International Meeting organized by the German Agency for International Development (DSE) in Berlin (August 31 - Sept. 5, 1986) will be an important step.

There are several application programs to be carried out among Ibero-American countries through SELPER coordination. One is the Geological Application of Remote Sensing in Amazonic and Andean Zones, sponsored by IUGS/UNESCO. Another is the participation of SELPER affiliates in the COSPAR International Satellite Land Surface Climatology Program (ISLSCP).

VII. Conclusions

— Satellite remote sensing, as an alternative development tool, would greatly benefit the economy of developing countries through improved assessment and management of natural resources.

— Nevertheless, its applications for local scientists and users, in some developing countries, have so far not received enough support from "decision-makers" and high level government officers. This has delayed the establishment of an adequate infrastructure.

— There is a minimum of infrastructures (hardware, software, well trained human resources, etc.) necessary to absorb the R.S. technology and applications transferred from a more advanced country.

— It will be convenient for an L.D.C. to receive transfer of technology from another developing country performing real activities on T.C.D.C. (technical cooperation among developing countries).

— In Ibero-America, SELPER is pioneering cooperation activities to obtain remote sensing technology transfer toward the countries of the region.

— Developed countries must not think of remote sensing technology applications as a totally commercial activity like the satellite communications. Prices for the use of R.S. satellites and products must be kept on adequate levels to be used by the L.D.C.

— Some developing countries made great efforts to establish receiving facilities but have difficulties in maintaining and updating such facilities.

— A great deal of coordination and cooperation among countries will be necessary to solve these problems in order not to increase the technological gap between developed and developing countries.

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THE FAMINE EARLY WARNING SYSTEM

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For nation shall rise up against nation, and kingdom against kingdom: and there shall be famines, and pestilences, and earthquakes, in divers places.
All these are the beginning of sorrows.
. . . .

Saint Matthew 24, 7-8

I. Introduction

In August, 1985, the United States Agency for International Development conducted a survey in western Sudan to find out what food was available for families. It had been a devastating period for farmers since there had been very little rain for nearly two years and rains were below normal for the previous three years.

Many of the households reported that they had enough sorghum or millet to have one meal a day. One family reported that they had eaten leaves from a tree for the last two months to stay alive. Meanwhile, of the 33 refugee settlements and reception centers in eastern Sudan housing 385,000 Ethiopian political refugees in July 1985, there were, on the average, 38 deaths per day. Of these deaths, 12 per day were children under five years old. These children could have been saved with better information. There were 120,000 displaced Chadians in western Sudan and 250,000 Ugandans in southern Sudan. These people were in addition to the famine victims. The 1985 UNHCR report states that over two hundred million persons lived in countries that were affected across Africa.

The years 1984 and 1985 produced record harvests in the United States and parts of Europe; yet there was starvation in Africa on a scale never witnessed before.

Historically, natural resources have been exploited without restraint. They were considered inexhaustible because many had the capability for self-generation. However, it has recently been realized that the process of self-generation is slow and complicated. In addition, if some natural resources are over-exploited, the stock will rapidly decrease, leading ultimately to the complete destruction of the resources on which people depend for sustenance.

It is imperative that we meet the basic needs and requirements of all people on earth without ultimately destroying the resource base from which these needs have to be met; that is, the environment.

Drought has struck the Sahel repeatedly over the centuries. The series of droughts from 1968 to 1973 was catastrophic, shrinking Lake Chad to one-third its normal size. In the winter of 1973, the great Niger and Senegal rivers had failed to flood, leaving much of the best cropland in five countries — Niger, Mali, Upper Volta (Burkina Faso), Senegal and Mauritania — cracked and barren. The water table dropped, drying up wells throughout the Sahel's five million square kilometers and placing nomadic pastoralists and others in deadly peril. After they had consumed the last shreds of dried-up vegetation, famished herds were sold and slaughtered or driven southward in a fruitless search for pasture. Behind them a stripped landscape lay baking in the sun, flecked with patches of newly-created desert that began to link-up and spread, so the great Sahara Desert seemed to be marching southward. In the absence of accurate statistics, particularly difficult to obtain among nomadic peoples, it is difficult to say how many people died as a direct result of the drought, but estimates have reached 250,000. In recent years drought has spread from the Sahel to southern Africa and some parts of eastern Africa. In early 1985, more than 150 million people in 24 western and eastern African nations were faced with the spectre of famine because of four successive years of drought.

In mid-1985, USAID started a program called the Famine Early Warning System (FEWS). This program, not yet fully operational, has already recorded some impressive results. The FEWS effort is described below.

II. Objectives

The FEWS program's main objective is to provide decision makers at several hierarchical levels with detailed, reliable, and timely information concerning populations at risk of nutritional emergencies. Attainment of this objective is seen as the key to opening up policy and program options before a major crisis occurs. In order to determine populations at risk, one needs estimates of both supply of food and demand for food.

In order to know available supplies of food, quantitative estimates of production of all substitutible food and feed must be available. Normally, production estimates require estimates of both area planted and yields per hectare. Since livestock can function as food, it is also important to have estimates of number and kinds of livestock, as well as their conditions.

To know the demand requirements for food, it is important to have estimates of populations and livestock from the food requirements perspective. Population numbers normally change slowly due to normal rates of growth and migration. One estimates birth and death rates, and from these, coupled with baseline estimates of population for some year in the past, reasonable population estimates can be computed, at least in aggregate. Under certain political or famine conditions, however, populations shift rapidly as family members migrate or, in extreme situations, die.

There is enough food in the world to feed all people. Unfortunately, distribution is such that there are areas of large food surplus, offset by areas of large food deficits. Some countries, like the United States, produce a massive consistent surplus every year. Other countries have food deficiencies every year. There is a third category of countries where, in some years, there is a surplus, and other years, there are food deficits. These fluctuating countries are the most difficult to estimate. They are also the most important to have quantitative production estimates of food supplies for, since their situation affects the world supply and market prices dramatically. Estimating too little deficit when, in fact, a larger deficit exists might result in populations at risk suffering from malnutrition or starvation. One might conclude that the answer is to over-estimate the food requirements so no one starves!

When the estimate of food requirements is inaccurate and high, that is, the estimates of imported food requirements indicate that more food aid is needed than is really needed, then donor organizations sometimes provide too much food and food prices drop as a result. In this context, it will be instructive to follow the situation in Ethiopia in 1986, where it is believed, the donors have provided too much food. Local farmers can be forced out of business because of free grain supplied by donor organizations, and farmers are not able to buy seeds, fertilizer, labor and land. Permanent economic damage can occur to the farming sector with effects that can last for years. In India, for example, local farming is said to have been affected adversely for several years after excess food aid was made available to avert mass starvation. Many sources indicate that it would have been better for a few people to be malnourished than to have local farmers destroyed economically as a result of free grain provided from food aid. The point is that "inaccurate information" is not satisfactory. Information has to be good enough to support intelligent decision-making.

Another point to consider is that information can be used for many different and often conflicting purposes. For example, crop production information can be used for strategic or military purposes. Another purpose for having crop production information can be for economic reasons. The best example here is the case that occurred in the United States in 1972, when the Soviet Union had experienced several years of very low crop production. They needed wheat desperately and United States farmers had produced a huge surplus of wheat, causing prices in the U. S. to be very low. If the U. S. farmers had known that the Soviet Union was in the market for a vast quantity of grain, many farmers would not have sold their grain to the storage facilities at the prevailing world low price, but could have waited and sold their own stocks at a more profitable time. A few months later, wheat prices nearly doubled and the farmers who had waited to sell their wheat more than doubled their profits.

The final, and yet the most important, reason for needing crop production estimates is for humanitarian reasons. Our intent is to avert starvation, malnutrition, and improve the quality of life for all people of our world. To do this requires, at a minimum, high quality information for decision-making related both to relief and to development assistance.

III. Methodology

FEWS methodology involves integrating physical data with socio-economic data, using a computerized geographic information system (GIS) to store and analyze the results. It is clear that organizing and synthesizing data from many sources is a major task. This task is essential, however, if the results are to be useful for decision-making to support both relief and development programs. Data incorporated in the FEWS system come from a variety of sources. Often, data are conflicting, even when estimating the same phenomenon. The analytical process used by FEWS, though aided by high-technology, depends ultimately on human judgment, weighing the conflicting data and filling in the holes between the data to arrive, hopefully, at a point where the convergence of evidence is strong enough to permit accurate judgments to be made.

A. *Physical System*

Physical data include climate, weather and rainfall data, vegetative vigor, crops planted and harvested, crop yields, crop production, transport networks, fleets of trucks and airplanes, water reserves, food supplies and storage facilities.

To obtain physical data, data gatherers have assembled information from many sources, including government agencies and ground surveys. Satellites are being used to produce data that can be collected from space. There is a research component that is evolving that will support other operational tasks.

1. *Advanced Very High Resolution Radiometer*

The Advanced Very High Resolution Radiometer (AVHRR) Local Area Coverage (LAC) and Global Area Coverage (GAC) data are used in conjunction with World Meteorological Organization (WMO) rainfall data to assess yields and growing conditions of plants. The National Oceanographic and Atmospheric Administration (NOAA) of the U. S. Government has been providing crop assessments using weather models supplemented by photo-interpreted AVHRR images. In addition, AVHRR imgaes are used to assess the vegetative growing conditions across entire countries by using techniques developed by NASA at the Goddard Space Flight Center. By subtracting images, one can observe where vegetation has changed, relative to some historical base.

2. *Multispectral Scanner and Thematic Mapper Data*

In Sudan in 1985, the government was unable to supply crop information from traditional ground surveys in a timely fashion, so the FEWS project supported satellite-based estimates of planted hectares. These satellite-based estimates were successful, and plans are being made to continue their use in 1986. Multispectral Scanner data were used in the east, where the field sizes are large. These data, as it turns out, were very useful, since they located huge farms that were unknown before the analysis. Thematic Mapper data was used in the western part of Sudan, where fields are small.

In spring 1986, the Sudanese Government published results of a first scientific crop survey that employed enumerators and modern survey design for the traditional farm sector in the west. Results of the 1985 survey are being used to calibrate the satellite data analysis that will take place in 1986.

B) *Social Systems*

On the socio-economic side, data are collected on population size and location, health status, nutritional status, prices, food stocks, migration, seed availability, and other socio-economic variables.

Under an AID contract, Tulane University has placed field epidemiologists across the Sahel-Sudan area to assemble socio-economic data from all possible sources: host governments, private voluntary organizations, bilateral and multilateral organizations, etc. These data are assembled on a monthly schedule using portable microcomputers and speical FEWS software, and are reported to FEWS analysts by cable.

D. *Data Integration*

FEWS has personnel to enter data into a computer-based GIS and analyze the results. These analyses are used for country reports that present data in graphic format showing analyses of where the populations are located that are at risk of severe malnutrition and starvation. These reports are based on the best information available, but their accuracy is still doubtful in some situations, due to the wide variations in quantity and quality of source data. The U. S. Agency for International Development is now formulating plans to assist the most seriously affected African nations to establish their own indigenous early warning systems, transferring FEWS techniques and equipment as rapidly as possible. Several field efforts are already under way. Linkages with the UN organizations, PVOs, and other donors are also being established in order to share information and methodologies as widely as possible.

In summary, it is hoped that by the time of the next drought emergency in Africa we will be much better prepared, in terms of forewarning and preplanning, to mitigate its potential deadly effects.

REMOTE SENSING FROM OUTER SPACE: PROBLEMS OF INTERNATIONAL RESPONSIBILITY

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The method of remote sensing of the Earth and its environment from outer space has already proved to be useful and practical for all countries, including developing countries. Practical applications of respective space technology, which consists of space and ground segments, seem to be very promising for economic development.

At the same time some practical applications of remote sensing technology may have a negative impact on sensed states.

At the Second UN Conference on the Peaceful Uses and Exploration of Outer Space, held in Vienna from 9 to 21 August 1982, some delegates expressed the view that in certain instances remote sensing data may be used to the detriment of sensed states. Some delegations were seriously concerned with the misuse of remote sensing data relating to the territories of their states (1).

As is known, some remote sensing data may produce information which is very sensitive for sensed states because its dissemination may expose their economic and strategic status and potentials.

It is practically impossible to draw the line between harmless and harmful dissemination of information obtained through remote sensing. But it is essential to protect the legitimate rights and interests of sensed states from harmful dissemination of information relating to their territories. Thus, the need arises in the legal regulation of this problem by involving the institute of international responsibility.

(1) UN Doc. A/CONF. 101/10, § 174 and 514.

International responsibiliy for national *activities in outer space* has been established by the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (Article VI of the Treaty). But it is not clear whether the term "activities in outer space" embraces operations of both the space and the ground segments of various satellite systems. Some argue that this term means activities in outer space *per se* only, and the Outer Space Treaty establishes international responsibility for manipulations of the space segments of satellite systems. Others hold the opposite view considering manipulations of the ground segments as an inseparable component of the activities in outer space.

To avoid possible misunderstanding and disputes, Socialist States (2) agreed, in the Convention on the Transfer and Use of Data of the Remote Sensing of the Earth from Outer Space, signed in 1978, that "the Contracting Parties shall bear responsibility for national activities in the use of data of the remote sensing of the Earth from outer space relating to the territories of other Contracting Parties" (Article VI) (3).

International responsibility for the ground effects of space activities is recognized in relation to the operation of communication satellites. In the Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting, it has been stated: "States should bear international responsibility for activities in the field of international direct television broadcasting by satellites carried out by them or under their jurisdiction and for the conformity of any such activities with the principles set forth in this document" (4).

In 1986 the Legal Sub-Committee of the Committee on the Peaceful Uses of Outer Space and the COPUOS itself finalized the elaboration of principles relating to remote sensing of the Earth from space. The set of these principles contains the special provision in regard to international responsibility, which reads as follows: "In compliance with article VI of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other

(2) Bulgaria, Hungary, GDR, Cuba, Mongolia, Poland, Romania, USSR and Czechoslovakia.

(3) The Convention is open for accession by all other states. See the text in UN Doc. A/33/168, 29 June 1978.

(4) The Principles were adopted by the UN General Assembly resolution 37/92 of 10 December 1982. 107 states voted in favour of the resolution, while 13 delegations abstained and 13 voted against.

Celestial Bodies, States operating remote sensing satellites shall bear international responsibility for their activities and assure that such activities are conducted in accordance with these principles and the norms of international law, irrespective of whether such activities are carried out by governmental or non-governmental entities or through international organizations to which such states are parties. This principle is without prejudice to the applicability of the norms of international law on state responsibility for remote sensing activities" (principle XIV).

"Remote sensing activities" are defined in the same principles (principle I) as "the operation of remote sensing space systems, primary data collection and storage stations, and activities in processing, interpreting and *disseminating the processed data*" (italics added).

On the one hand, it means that states should bear international responsibility for disseminating the processed data of remote sensing. On the other hand, the reference to article VI of the 1967 Outer Space Treaty may give rise to the argument that states should bear international responsibility only for activities in outer space *per se*, thus excluding international responsibility for the ground activities, i.e., the dissemination of remote sensing data. Furthermore, the last phrase of principle XIV specifically mentions "state responsibility for remote sensing activities", but this fact may be interpreted differently. Firstly, it may mean that reference to the Outer Space Treaty does not exclude state responsibility for remote sensing ground activities. Secondly, it may mean that state responsibility for remote sensing activities should be governed by "the norms of international law on state responsibility", but not by Article VI of the Outer Space Treaty.

Such a dubious formulation caused the interpretation statement by the Soviet delegation at the XXV-th session of the Legal Sub-Committee and the XXIX session of the COPUOS. Interpreting principles IV (5) and XIV of the principles relating to remote sensing of the Earth from space, the Soviet representative said that states shall assure that *all* their national remote sensing activities are conducted in accordance with the adopted principles, irrespective of whether such activities are carried out by their governmental bodies or non-governmental entities under their jurisdiction (6), and that states shall bear international responsibility

(5) According to principle IV, remote sensing activities « shall not be conducted in a manner detrimental to the legitimate rights and interests of the sensed state ».

(6) In other words, Article VI of the Outer Space Treaty is applicable to dissemination of processed data obtained through remote sensing.

for damage caused by their national remote sensing activities to the legitimate rights and interests of the sensed state (7).

As is known, the process of codification of the norms on state responsibility is still going on in the International Law Commission (8). In the meantime state responsibility is governed by customary law.

The conclusion may be drawn that states shall bear international responsibility for damage caused by dissemination of remote sensing information irrespective of whether such dissemination is carried out by governmental bodies or non-governmental entities under their jurisdiction.

Article 11 of the ILC draft on state responsibility states that the conduct of a person or a group of persons not acting on behalf of the state shall not be considered as an act of the state under international law. This is also true in customary international law. But this does not mean that states may not agree otherwise in a special treaty. In fact this has been done in the Outer Space Treaty in relation to activities in outer space. Likewise this approach may be undertaken in relation to disseminating remote sensing information. In the light of the above, this has already been done.

It is clear that members of the COPUOS agreed that remote sensing activities shall not be conducted in a manner detrimental to the legitimate rights and interests of the sensed state. Hence, any conduct to the contrary would constitute a breach of the international obligation. In accordance with Article 17 of the ILC draft, the origin of the international obligation breached by a state does not affect the international responsibility arising from the internationally wrongful act of that state, and an internationally wrongful act constitutes a breach of an international obligation regardless of its origin, be it customary, conventional or other.

According to Article 4 of the ILC draft, an act of a state may only be characterized as internationally wrongful by international law and such characterization cannot be affected by the characterization of the same act as lawful by internal law.

Now, the question arises, what acts should be characterized as internationally wrongful in the process of dissemination of remote sensing information. In other words, what may be characterized as conducting

(7) International responsibility of states arises in every case of causing damage to the legitimate rights and interests of the sensed state by disseminating information in a manner detrimental to the legitimate rights and interests of the sensed state.

(8) 35 articles were adopted on first reading by the International Law Commission (see Doc. ILC (XXXIII)/Conf. Room Doc. 7, 26 May 1981).

dissemination of remote sensing information "in a manner detrimental to the legitimate rights and interests of the sensed state"?

There is no direct and clearcut answer to this question in international law. When speaking about legitimate rights and interests of states, one should first of all pay attention to the generally recognized principles of international law which were formulated in the Declaration on Principles of International Law concerning Friendly Relations and Co-operation among States in Accordance with the Charter of the United Nations [9].

[9] Res. 2625 (XXV) of the UN General Assembly of 24 October 1970.

PARTNERSHIPS IN REMOTE SENSING: A THEME WITH SOME EXAMPLES

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ABSTRACT

In this paper, the author reviews the revolution in remote sensing that has taken place over the last 25 years. This revolution could not have taken place without the closest cooperation among government agencies, industry, and academia. International cooperation is shown to be essential in carrying out the bold missions planned for the next decade. The paper reviews the history of the NASA/NOAA relationship, and the history of international partnerships with emphasis on development of the operational Metsat system. The government/industry partnership is reviewed with case studies put forth examining the evolution of Metsat sensor design, Landsat commercialization, and the NOAA Administrator's new initiative to facilitate development of a commercial Ocean Color Instrument. Government interactions with academia in the form of National Science Foundation programs and government-university "co-operative institutes", is reviewed. The author concludes by showing how plans for integrating research and operations on Space Station Platforms can only succeed through an alliance of *all* the remote sensing players.

INTRODUCTION

We are now well into the third decade of sensing the earth from space. The first meteorological satellite (TIROS-1) was launched in 1960.

There are many lessons we have learned in the last twenty-six years. We learned early the great value of being able to visualize the movement of the atmosphere. We have learned how to extract quantitative information about the atmosphere and the oceans. We have learned how to make measurements routinely and reliably (there has been only one brief "outage" in those twenty-six years). We have learned how to use the vantage point of space to provide a rich variety of data and services. (See for example « Science », January 31, 1986) [1, 2]. But most of all, we have learned that remote sensing is not the function of a single company, a single governmental department, or a single country. Remote sensing from space can only thrive as a series of partnerships. That is my thesis, one which I explore through examples below.

The information provided from satellites is inherently both synoptic and global. It is synoptic in that the satellite is capable of viewing a large area all at once. The higher the orbit, the larger the area. The geosynchronous satellites, at 23,000 miles, view most of one hemisphere of the earth at one time, and view it continuously. The satellites in lower orbits (typically 400 to 500 miles) sweep the whole globe each day. And the way we place them in the orbits makes them synchronized with the sun — they return over any location on the earth at the same time day after day.

The U.S. recognized the global nature of the weather satellites early. In the same year as the launch of TIROS-1, the U.S. played host to an international group of weather experts to share with them the new view from space. This began three decades of international collaboration and partnership in these satellites.

We also recognized early that there was more to this remote sensing business than could be housed in a single agency. It began under the sponsorship of NASA. But NASA's is an R&D role. So, in 1964 the President caused to be created in the National Weather Bureau an Environmental Science Services Administration to manage our "operational" weather satellites. The Department of Defense also set up its own Defense Meteorological Satellite Program. These three agencies have been partners in remote sensing in many ways ever since.

Perhaps the strongest of the partnerships is that among the government sponsors, the industry that supports us, and the academic community that provides the foundation in knowledge that is the basis for what we do in remote sensing. In the industry and our academic institutions reside most of the innovative ideas which we, the sponsors, adopt. When we traced the dream of the operational meteorological satellites to its roots last year in our celebration, we found more than twenty people who deserved recognition as pioneers in the field. They came from the government, from the aerospace industry, and from the academic community — in about equal numbers.

I would like to share some of my thoughts on the very rich partnerships, among countries, among government agencies, among sectors of our society, and between the government sponsors of these programs and our industrial colleagues.

These are partnerships with very real humanitarian payoffs. They have substantial economic returns. But most exciting to me, they enrich enormously our knowledge of this third planet of an obscure star on which we all live.

Let me recite a few examples of these partnerships. They are not at all the only examples. I expect everyone can add to the list. But these examples show the scope of the larger partnership in remote sensing.

The NASA/NOAA Partnerships — Research Serves Operations that Serve the Nation and the World

Whenever NASA is mentioned, the average person thinks of manned space flights, visits to the moon, or flybys of incredibly distant planets. We in NOAA, however, think of NASA as an essential partner in an equally amazing and successful space adventure — the development and deployment of the weather satellite.

These spacecraft have brought unique and invaluable benefits to the American people and to the world community, and are essential in detecting, tracking, and giving early warning of hurricanes, severe local storms, flash floods, and other life-threatening natural hazards.

Weather satellites also have contributed significantly to improvements in the accuracy of daily weather forecasts. In addition, they have evolved into true environmental satellites that monitor ocean conditions, snow and ice cover, frost, vegetation, forest fires, and even volcanic eruptions.

The global coverage of these satellites has also made possible a dramatic new international humanitarian service: search and rescue from space. The program has saved more than 535 lives since it began in 1982.

These achievements have all contributed significantly to U.S. leadership in satellite technology and in the peaceful uses of outer space. And all are the result of the highly successful NASA/NOAA partnership that began early in the development of our present environmental satellite system.

In this partnership, NASA has done the research in remote-sensing techniques and has developed and demonstrated experimental, prototype satellites and instruments, while NOAA has operated the satellite system to support weather forecasting and other applications. Both agencies have contributed money and commitment to this joint program.

NOAA "requirements" for data about the atmosphere and the ocean surface provided the impetus for vigorous research programs in NASA laboratories and academia. In turn, NASA-sponsored research and technology development provided the tools needed in NOAA's daily satellite operations.

It was NASA's vision that led to the first multispectral imagery from the High Resolution Infrared Radiometer flown on Nimbus-1. This imagery became one of the major elements of the global weather observing system.

It was NOAA's need that drove development of the first microwave sounding technology to allow all-weather measurement of atmospheric temperature profiles. But it was NASA engineers at the Jet Propulsion Laboratory who developed the microwave sounding sensor to do it.

The list goes on and on. There now are a dozen instruments in weather satellites; all of them come directly from concepts developed in NASA programs. And all of them were developed in response to the needs of NOAA service programs. It is safe to say that neither of the partners could have succeeded in providing such a rich array of capabilities without the other.

At another level, the immense pool of technical talent in the NASA research centers (particularly the Goddard Space Flight Center) has provided NOAA with "on-call" access to temporary help with technical problems as they developed. Had NOAA had to duplicate this pool of talent, the weather satellite program would have become incredibly, perhaps prohibitively, expensive.

From the beginning, then, we have had a partnership wherein NASA has acted not only as the R&D partner, but also as the "technical manager" for NOAA. In addition, NASA has also functioned as NOAA's "procurement agent" and satellite launcher.

Earlier, I mentioned the financial partnership. Over the years, NASA has invested about $ 208 million in R&D and in the flight of prototype spacecraft and sensors. This was the "risky" part of the investment. NOAA has contributed about $ 1.4 billion to buying copies of NASA-developed hardware, setting up ground systems, and operating the meteorological satellite system. This was the follow-through or payoff for NASA's developmental investment. Appropriately, as the technology has matured, the NOAA portion of the costs has risen steadily. Today, NOAA pays all costs directly attributable to the weather satellite program.

Before the advent of the meteorological satellite system, weather observations were available for less than one-fifth of the globe. Little if any information was obtainable for the polar regions or for vast stretches of Asia, Africa, and South America. Over the oceans, tropical storms formed and grew to maturity, undetected until they sank a ship or devastated an inhabited island or coastline.

Today, these satellites provide practically continuous monitoring of both atmosphere and ocean on a global scale, allowing scientists of all nations to follow the ebb and flow of worldwide weather and ocean patterns. And since the start-up of the U.S. operational satellite service in 1966, no tropical storm has gone undetected anywhere in the world. It has been a remarkably successful program that has brought great benefit to Americans and to the global community. And NASA has played a major role in this achievement.

More recently than the weather satellites, NASA developed the land remote-sensing capabilities embodied in the current Landsat spacecraft. Management and funding responsibilities for these satellites also were transferred to NOAA (in 1979), in keeping with the respective agency roles for R&D and operational programs. I will have more to say about Landsat in a later example.

Naturally, the NASA/NOAA partnershiy has had its share of strained moments as both the technology and the agencies were maturing. And budget pressures will always keep some tension in the relationship. Despite these strains, however, the partnership is stronger today than ever before. And it needs to remain strong and vital as we move toward the future and the polar platforms of the Space Station era, which I will address later in another example.

International Partnerships — A Firm Foundation

There is *nothing* about remote sensing that respects national boundaries. Remote sensing from space is inherently an international activity, as are the science and the industrial capabilities that make it possible. The oceans and atmosphere are global. Weather forecasters around the world all need to know the same kinds of information and all monitor the same environmental patterns. At the same time, the value of environmental observations is not the least bit diminished when it is shared with other countries. In fact, the value is significantly enhanced when scientists and operational forecasters have access to ground-based or ship-board observations to supplement and calibrate satellite data. We in the U.S., like our space-faring partners, *share* the same interests in science, in developing our industrial capabilities, in understanding our resources, and in monitoring our environment. We also share the constraints of limited financial, technological, and human resources. We therefore need to work together to maximize our return, each country according to its own priorities, but all with substantial common interests. This commonality of needs and capabilities has been well recognized and has formed the basis for an impressive history of international cooperation in remote sensing from space for the mutual benefit of all the participating nations.

Long before there were remote sensing satellites, there was a practice of free, open exchange of meteorological observations. Long before there was a space program, there was international collaboration in research and science. Thus, when we entered the space age and began to supplement our environmental observations with remote sensing space systems, it was only natural to look to international cooperation as one element in our programs. NASA's charter explicitly calls for international cooperation in space. The World Meteorological Organization provides a framework for international exchange of meteorological data. From these foundations, the United States established a practice of global data acquisition without the need for prior approval by sensed countries. This practice was confirmed in the 1967 Outer Space Treaty, which asserts that "Outer space... shall be free for exploration and use for all states..." [3]. The U.S. also practices the nondiscriminatory distribution of remotely sensed data to any requestor as a vital corollary to global acquisition. The "open skies" approach has been beneficial to the U.S. in allowing access to information about global phenomena, and to the rest of the world by providing the opportunity to benefit from vast investments in space technology through access to the resulting data.

This policy has been under constant discussion in the United Nations almost from the day of its introduction. And it has withstood the test of time. It is still the operative paradigm for remote sensing from space. The U.S. Congress most recently affirmed the policy in the Land Remote Sensing Commercialization Act of 1984.

Over the years, NASA and NOAA have entered into hundreds of arrangements with other countries. These range from joint research efforts (like the Global Atmospheric Research Program), to flying foreign-built instruments on U.S. satellites (like the United Kingdom's Stratospheric Sounding Unit on the NOAA satellites), to the establishment of foreign receiving stations to acquire Landsat data. The open skies policy and non-discriminatory data availability are part of the policy foundation to make these successful agreements possible.

The other critical policy element in the international partnership is that of mutual benefit. In each case, for a partnership to endure, it has to contribute to each partner's goals. Remote sensing cooperation provides opportunities for each participant to meet his observational needs while also sharing some of the costs with other countries.

International Partnerships — Some Concrete Examples

From twenty years or more of international partnerships in remote sensing, I have selected just a few for mention here.

A U.S. Contribution to the World Weather Watch

For over sixty years the World Meteorological Organization (WMO) has maintained a "world weather watch", and has been a conduit for the sharing of weather data from all parts of the world. There are established procedures for the taking of the observations; there is a network of stations; there is a global telecommunications network for sending the data around the world; and there is a free flow of all the data that the network can accommodate.

From the inception of the weather satellites, they have been operated within the WMO framework. Temperature profiles of the atmosphere are collected from balloons and from satellites and are then sent through the telecommunications system at predetermined times (so-called synoptic times) to all who wish them. Images from the satellites are sent, in degraded format, through the same network. Thus all may share in the WMO World Weather Watch.

But more importantly, in many respects, all the data from the satellites are directly broadcast to the ground for all who can afford a ground station and care to listen in. That data includes the raw sounding data ("direct sounder broadcast" — DSB), the high resolution images from the polar orbiters ("high resolution picture transmission" — HRPT), low resolution pictures easily received by very inexpensive receivers ("automatic picture transmission" — APT), and the raw pictures from the geosynchronous satellites for reception by anyone in this hemisphere. This was a conscious decision on the part of the U.S. to operate the satellites in the spirit of the WMO World Weather Watch.

Over 1000 receiving stations around the world receive the low resolution images from the APT. There are doubtless far more of which we do not know. Some of these are the sole source of weather information for developing nations. Over 100 more elaborate receivers in other nations tune in on the high resolution pictures from the polar arbiters. We probably know of all of these stations, since they must know the orbit of the satellite to program the tracking antennas. Twenty-nine stations receive the sounding information and make immediate use of it, much as we do. This takes more computational power, and global weather models.

In recent years, the satellites have become the backbone of the World Weather Watch. The WMO is becoming more and more concerned both that nothing threaten the continuation of the satellite data and that expanding needs for such information be met by the system. Our "good neighbor" policy with regard to this important weather information is paying dividends even in foreign policy.

Using Satellite Data to Help Developing Countries

Since 1977, NOAA and the Agency for International Development (AID) Office of Foreign Disaster Assistance (OFDA) have cooperated to improve early warning of drought disasters and to meet OFDA technical assistance objectives on disaster preparedness in the developing world. Since 1979, NOAA has issued weekly and monthly assessment of climate and weather impact on food security in developing countries within Africa, the Caribbean Basin, South and Southeast Asia, and more recently, Central

America, and the Andean countries of South America and the southwest Pacific Island Groups. These qualitative assessment reports, based mainly on rainfall data, are sent by cable to U.S. missions in approximately 80 countries. They are designed to provide American embassies, USAID missions and USG agencies with current information on drought conditions, their impact on subsistence crops, and an early warning alert on the potential for drought induced food shortages. Studies have shown that climate impact assessments issued 30 days before crop harvesting begins can provide at least a 3 to 6 month lead time to decision makers, planners, and economists who must develop food assistance strategies and measures to mitigate potential socio-economic disruption. Because of the reliability and value of these assessments, NOAA is assisting interested developing countries to implement their own national operational assessment programs. Since 1980, approximately 30 developing countries have received NOAA technical assistance, including the eight Sahelian countries.

A combination of daily meteorological satellite products and daily weather data are used as the primary inputs for the Special Climatic Impact Assessments. Operational rainfall reports from the countries are provided to the NOAA Assessment and Information Services Center (AISC) by the NOAA National Weather Service/Climatic Analysis Center (NWS/CAC), which receives these data through the World Meteorological Organization's Global Telecommunication System. NOAA also receives ten-day rainfall reports directly from some countries and, in particular, through the Regional AGRHYMET Center in Niamey, Niger. NOAA uses data from the European Space Agencies' Geostationary Meteorological Satellite (METEOSAT) and the NOAA-9 daily polar-orbiting satellite. METEOSAT images are used as one method to assess regional rainfall and to monitor large-scale weather patterns. Weather analysis products and data provided by NWS/CAC are also used in this large-scale analysis. NOAA-9 data are used to assess vegetation/biomass patterns and to estimate rainfall.

This integration of conventional and satellite weather data provides us with a powerful tool to help fight the devastating impact of drought on the world's more vulnerable populations. This is an excellent example of the impact that remote sensing can have on the individual.

Sharing Flight Opportunities

The U.S. has flown more earth-orbiting satellites than any other nation in the free world. These have been "flight opportunities" for other nations to try their own technologies. They have also been an opportunity for the U.S. to enrich its scientific and operational programs at less-than-usual expense.

NASA, under the mandate given it by the 1958 National Aeronautics and Space Act "may engage in a program of international cooperation in work done pursuant to this Act, and in the peaceful application of the results thereof..." The earliest cooperation took the form of agreements for ground tracking support for early NASA missions. Small tracking stations were established in Chile, Antigua, and Ascension in 1956, followed by a more extensive Spaceflight Tracking and Data Acquisition Network (STADAN), which has expanded and then contracted as programmatic requirements and technological developments dictate. Once TDRSS is fully operational, the ground-based network will no longer be needed.

Sounding rocket cooperation began with NASA in 1961 with both Australia and Sweden. Actual cooperation in space began with NASA's cooperation in launching and analyzing data from the Canadian Alouette-1 spacecraft, which carried a topside sounder to measure electron densities in the ionosphere (launched September 29, 1962), and the UK's Ariel-1, which carried instruments to measure the spectrum of primary cosmic ray energies and its variations, local electron densities and temperature, ion mass composition and temperature, energy spectrum of solar hard x-rays, and solar UV emissions (launched April 26, 1962). The first foreign experiment carried on a NASA mission was an ion mass spectrometer provided by the UK, which flew on the Explorer-20 mission in 1964.

In the area of weather satellites, the first TIROS spacecraft transmitted imagery to some 42 national weather services around the world for evaluation and comparison with ground-based observations. Nimbus-4, launched in 1970, carried a radiometric temperature probe contributed by Reading University and Oxford University in the UK. Other experimental British instruments were carried on Nimbus-5, 6, and 7 [4].

An Emerging International Operational System

Perhaps the most significant of the international partnerships in space (as opposed to on the ground) is the providing of operational instruments to the U.S. polar-orbiting meteorological satellites by other countries.

The list has grown longer over the years, and today the United Kingdom provides a "stratospheric sounding unit", the French and Canadians provide search and rescue transponders and processors, and the French provide a data collection and platform location system called "ARGOS". All three parties have agreed to continue that collaboration. Both the British and French have just signed Memoranda of Understanding with the U.S. (NOAA) to provide improved versions of the sounding unit and the ARGOS system on the next few polar orbiting metsats.

This is not an insubstantial contribution. We estimate that the annual costs of these foreign payloads is on the order of $ 15 million. And the operating costs of the ARGOS system must be added to that contribution, though partly offset by user charges.

All of these are long-term commitments by the respective governments — commitments that have their roots in a concept of partnership.

In recent years the U.S. has sought to increase foreign contributions to the polar orbiters. Under the auspices of the Economic Summit of 1983, a group called IPOMS (for International Polar Orbiting Meteorological Satellite group) has discussed such contributions for two years. France, the UK, and Canada have reaffirmed their contributions. The UK and France are considering further contributions. Italy is very interested and on the verge of committing an instrument. The Federal Republic of Germany has several candidates, as does Canada. Norway is considering contributing to the ground network. Australia is seeking a suitable contribution, possibly including space hardware. Even Japan, which has steadfastly maintained that it has an independent national remote sensing program, has now expressed interest in contributing to an international enterprise. I shall return to this theme when I cover the Space Station's Polar Platform.

One of the satellite systems is already coordinated internationally in an informal manner. That is the geosynchronous weather satellites. In many respects these are the most visible set of satellites in the United States. They produce the "satellite maps" we all see on almost every TV weather report. They are also the closest to being internationally coordinated.

These geosynchronous weather satellites are operated by four entities — the U.S. NOAA, the European Space Agency, the Japanese Meteorological Agency, and most recently the Indian Meteorological Department. The USSR plans a system in the next few years.

For 14 years, an informal group of the operators (and likely operators), called CGMS (for Coordination on Geosynchronous Meteorological Satellites) has convened yearly, or more often if needed, to assess the status of the programs and plan for mutual compatibility. The The mechanism works well, and it has needed no treaties nor formal international documents. Each party has recognized the need for coordination, and has willingly made the small adjustments in plans and programs to make it possible.

Another newer example of remote sensing partnership internationally is the Committee on Earth Observation Satellites (CEOS), a merger of two earlier groups which focussed on individual disciplines of land and ocean remote sensing. CEOS brings together current and potential operators of earth observation space systems with the aim of coordinating those system attributes which will make the results of the missions more meaningful to the user community. For example, through the CEOS working group on intercalibration, scatterometers and altimeters flying on separate missions (ERS-1, NROSS) will be calibrated in a coordinated program so that users can apply the results from either spacecraft with confidence. In the data management working group, for example, plans for data processing procedures are being examined to maximize consistency across missions in the interest of enhanced usability. As with CGMS, all the CEOS members are free to make whatever decisions they choose, but they see it in their interest to work in a coordinated way to increase global benefits from their programs.

There is now almost uniform recognition among the space-faring nations that remote sensing is an international partnership in which all may and should contribute. This matches the awareness under the "open skies policy" and the WMO framework that all may share in the benefits.

Government-Industry Partnership — A Long Standing Thing

Let me just make a bold-faced assertion of a truth that I find compelling. We in the government, the operators of all these systems, could not have even begun to do the job without the enormous talent in our U.S. industry. We in the government like to think that we at least "managed" the development of these capabilities, but the source of the ideas and the actual building of the hardware have always been in industrial plants.

The idea for flying a TV camera in space may have been invented in government offices, but the camera came from industry — namely RCA. And it goes without saying that the idea of flying one could not have occurred without the existence of the technology at RCA. It worked on the first try (well, almost the first try). The idea for a multi-spectral imager (now embodied in the Advanced Very High Resolution Radiometer) came from the HRIR on Nimbus-1 and the MRIR on Nimbus-2. The technological capability to do such jobs now is in place in at least five industrial firms. The idea of a microwave sounder came from D.H. Staelin at M.I.T. The first of these were built at JPL, but from now on, they will be built in industry. The Advanced Microwave Sounding — a vast improvement over the old unit — has just been placed under contract to Aerojet Electro Systems Company.

The list of firms that have contributed to only the operational meteorological satellites includes:

— RCA (Astro Division);
— Hughes (Space and Communications Division and Santa Barbara Research Corporation);
— Ford Aerospace (and Philco-Ford before it);
— ITT;
— Barnes Engineering;
— Ball Aerospace;
— TRW;
— Westinghouse;
— Aerojet Electro Systems Company;
— General Electric.

To keep the list short, I have not tried to include those who have had such an immense impact on the remote sensing through providing instruments to NASA's research missions.

Many of these companies have made substantial contributions of their own research funds in developing their talents. Hardly a week goes by that I or my staff does not get a visit from some firm with a new idea they think might be of interest sometime in the future.

There is a myth that permeates the business press today that business planners are short-sighted and demand immediate return (a very few years) on any investment. I will testify to the contrary. In many respects, the aerospace companies have a vision of the future that peers farther into the fog than any government planners. Just last week I talked to a company that is spending on an instrument capability that, while exciting, is unlikely to see a flight opportunity till the end of the century.

This is one of the most exciting of the partnerships in remote sensing — exciting because it involves such visionary thinking.

I have only one regret about the traditional government-industry partnership. That regret is that recently the partnership has seldom had the opportunity to be a real partnership with a sharing of responsibilities and risks and rewards. Instead, it has too often been confined to the arm's-length (almost adversarial) relationship of the government procurement. In many ways, I believe the Japanese and the European countries have a better partnership between government and industry. Ours is good, and it is sound, but there is significant room for improvement.

I fear that that improvement will come only (and only after great debate) from legislation. Both the industry and the executive are now almost hamstrung by the procurement process. That process was invented and grew (like Topsy — it often just grew) to protect the taxpayer and the "government's interest". Sadly, it often restricts both sides in how we might be innovative in doing something that might be in the best interest of both the industry and the government, and in the best interest of the taxpayer.

I will return to this theme again as well, because I believe that there are a few opportunities today to break out of that old mold.

Landsat — Could it be a Real Partnership?

In 1983 the Reagan Administration decided that the civil operational satellites should be "commercialized" or "privatized". The Department of Commerce (in which NOAA, the operational agency, sits) set out to do just that. I had the "pleasure" of leading the final portions of that effort.

Initially the Administration position was that all of the operational satellites, weather satellites and Landsat should make the transition. It was an idea promulgated by COMSAT and embraced by OMB and the Deputy Secretary of Commerce. It was a controversial idea, and the debate raged for years. But the debate revolved more around the question of whether the weather satellites should go to the private sector. Putting Landsat into the private sector was less controversial, probably because the government rhetoric had always maintained that there was a commercial potential for the sort of information that could be derived from Landsat. Few really believed that the weather satellites had any future as a commercial enterprise. The only customer big enough to support them is the government.

The idea of commercializing the satellites finally got into trouble on two fronts. First, the Deputy Secretary was discovered to be in the midst of discussions about employment with the major proponent of commercialization of both systems — Comsat. Even if the idea had had intrinsic merit, this would have dampened any hopes of its acceptance. Secondly, and more importantly, the Congress found the weather satellites to be one of their favorite programs. This, added to the suspicion of "foul play", caused the commercialization of weather satellites to be declared illegal and prohibited in Public Law 98-365. After the clear statement of policy regarding the weather satellites, the Administration proceeded, painfully, to "commercialize" the Landsat system. That process was widely documented in the scientific press, perhaps best by Mitch Waldrop in a series of articles in *Science* [5, 6, 7].

A tenuous and delicate partnership emerged from the process between the government and private industry. The "mating dance" was strained, the government procurement process was poorly suited for developing a partnership, but a partnership was clearly called for.

Along the way we discovered beyond a shadow of a doubt that the industry could not "go it alone". Some sort of significant government support was clearly required. The Landsat Commercialization Act of 1984, as well as no less than five Presidential actions [8, 9, 10, 11, 12] recognized that need. Yet at this writing the Administration's budget has backed away from the partnership.

My purpose here is not to rehearse the history of the commercialization of Landsat, but to set the context for a description of that partnership. That partnership is not without precedent, but the precedents are old rather than new.

In the 1840's the U.S. Government set about establishing a system of railroads in the country. To spur private investment, the government gave land grants of immense right-of-ways. Later, in the 1920's, the government decided that airplanes were of national interest, and it established the National Advisory Committee on Aeronautics to promote the development of air travel. This was a real partnership, where the government supported the technological development, and the industry invested in the transfer of that technology into commercial application. These and many other examples have a common theme — a partnership between the private sector and the government for the national good.

The "partnership" between the commercial firm that "won" (some argue that they lost) the competition has several dimensions, some of them established, and some yet to be worked out.

First, there is an initial subsidy for getting the operation started. This has been limited to just under $ 300 million when all the pieces are taken into account. It is probably adequate, but not extravagent. In any case, it is settled in principle.

The second aspect is continuing government support for the enterprise in the form of the still unproven market with the government for purchase of the data from Landsat. This market was explored in several government research programs, the most visible of which was called AgRISTARS [13]. This program is finished, and some market was developed in the process. EOSAT seems content to take normal marketing steps to fully develop that government market.

The third part of the partnership is the continuing support of the enterprise by technology development. This is the model used in the NACA and the continuing aeronautical research of NASA. It is a part of the overall concept for the commercialization of Landsat laid out by the Congress in the 1984 Act, but it is largely absent in the federal budget.

Such support was specifically precluded in the "deal" struck between the Department of Commerce and OMB in settling on a subsidy during the summer of 1984. More recently, however, a NASA advisory committee has recommended that NASA continue to support the enterprise with technology development funding [14]. At this writing, the issue is unsettled.

My opinion is now and has always been that the longer term viability of the EOSAT program depends on advanced technology being available in the early 1990's. The market for geological assessments must depend on continual advances in the quality of the data. That market will be sated when orders for specific data have been filled once. The data is quite "non-perishable".

The final point I would make about the emerging Landsat partnership is that it is "emerging". There is an opportunity now to break the old model of "arm's-length" relationships between industry and government. The relevant models of support of new enterprises are old enough that we are largely charting new courses. The government role now is to nurture our (the U.S.) industry to succeed in the face of competition from foreign systems, French and Japanese. We have the lead now, but will give that lead away if we do not make EOSAT succeed. Some of us are committed to making it succeed. But the acid test of the market-place is yet to be run.

An Industrial Ocean Color Sensor — A New Opportunity?

In 1978 NASA launched an instrument on the Nimbus-7 satellite intended to measure the distribution of chlorophyll in the coastal oceans. It was called the Coastal Zone Color Scanner or "CZCS". That instrument survives today, but in a much degraded condition. And the prospects are that it will "die" within days of this writing.

During the eight years that it has been in orbit, the CZCS has proven its capability to measure chlorophyll and its scientific and operational usefulness. Of the several oceanographic instruments launched in 1978 on Nimbus and Seasat, the CZCS has the longest experience, and thus the most proven capability.

Hundreds of scientific papers have made use of the CZCS data. Some oceanographic field experiments have used the data in real-time to direct ships to the appropriate place in the ocean for *in situ* sampling of the biology. The scientific worth of satellite ocean color measurements has been demonstrated.

NASA and NOAA, together with several oceanographic industries, have undertaken demonstrations of the commercial utility of the CZCS. Near real-time analyses of the data have been provided to commercial fishermen on both coasts with significant results in time saved and improved catches. These were recently featured on the second of the "Planet Earth" TV series on the Public Broadcasting System stations. Operators of offshore oil rigs and shipping companies have found important use for the data in near real-time for planning movements and station keeping. These demonstration have led to a number of processing techniques and special products tailored for such commercial use. The commercial market for satellite ocean color data has been tested in a small and preliminary way.

An instrument more advanced than the CZCS has now been designed by the government based on the CZCS experience. This new design is called the Ocean Color Imager — an apt title, since the original CZCS worked even better in the open ocean than it did in the coastal regions. This government OCI design could form the basis for a commercial ocean color instrument. But even if another design is chosen, the rationale for ocean color information is well established in the design studies for the OCI.

There is a large continuing interest in the scientific and industrial communities in the information derived from ocean color data. Under NASA sponsorship, there have been several years of planning, from which the new design has evolved and the mission parameters (such as orbit) have been defined.

The scientific community has prepared a glossy brochure extolling the virtues and value of global ocean color data like that from the OCI. The need for global ocean color information is featured prominently in a number of reports from the National Academy of Sciences and other scientific bodies [15, 16, 17]. Those reports call for the flight of a satellite-borne ocean color sensor as soon as practicable. The scientific community has mounted a letter-writing compaign to convince the government to build and fly such an instrument.

The Marine Technology Society and the National Ocean Industries Association, representing the industrial interests, have also expressed substantial interest. The former organized two symposia in September and November 1985 at two national meetings.

The participants at the November symposium urged a follow-up, which has taken the form of a survey of all industries on several mailing lists. That survey took place in February 1986.

Finally, several firms are investigating possible investment in a satellite sensor for ocean color. They are carrying out their own market studies.

The Department of Commerce has established that the flight of an ocean color instrument is a proper role for industry. Under that philosophy, the industry would make the capital investment in the instrument, and market the data from the instrument for their own profit. The government would facilitate the venture within its normal activities.

The measurement of ocean color from a satellite requires that the satellite be in a sun-synchronous polar orbit, preferably near noon (within a 10:30 to 13:30 equatorial crossing time). There are potentially five U.S. satellites which offer a "ride" in such a polar orbit. They are the next three NOAA polar-orbiting meteorological satellites (NOAA-K, L&M) and the next two Landsats (numbers 6 and 7). All would be launched in the 1989 to 1993 time period. The orbits of these satellites are still under some discussion, and they may not all be equally suitable for ocean color measurements.

All these satellites will be owned by the government (NOAA). All will be operated by or for the government. NOAA will directly control the operation of the meteorological satellites for the support of weather forecasting. The Landsats will be operated for the government by EOSAT, and EOSAT will control the operations to support their profit-making enterprise.

The government role today is the collection of important environmental information and the use of that information for the production of forecasts, warning, and other services, especially where life and property are at risk. In carrying out that role, the government purchases and operates the meteorological satellites, and it purchases (and operates under contract) the Landsat satellites. In addition, the government preserves certain environmental data in archives for retrospective uses. The government's role in the satellite ocean color program should fit within the same kind of activities.

The U.S. industry is already in the business of producing specialized information products for specific business sectors based on satellite data. The U.S. government has just provided support to industry (EOSAT) to initiate a commercial land remote sensing program. Thus, the industry roles now also include commercial remote sensing from space. The industry role in an ocean color program should fit within a scope similar to these established activities.

Finally, the government is a customer (present or future) for information derived from satellite data from an ocean color instrument. The government uses include research and operational activities, in both near real-time and retrospective applications. These data and information needs include global productivity (largely for science), mapping of open ocean circulation patterns, and major applications in the Exclusive Economic Zone (EEZ). In the EEZ examples include biomass assays, primary productivity estimates, environmental quality assessments, pollution impact assessments, mapping of sediment transport, and surveillance of dredging activities. The government would buy data as necessary to serve its needs. Some government use of the data might be allowed as a "quid-pro-quo" for the government portion (e.g., the "ride" for the instrument) of the joint program.

The key component to such a scheme seems at this writing to be a tenuous market for the foreseeable future. Assume for the moment that industrial investment requires a market of $ 4 to $ 5 million per year to amortize the investment and make a reasonable return on that investment.

There might be a market of $ 1 to $ 2 million readily accessible. This makes the investor face a real possible loss.

If the scientific community were to give the instrument a high enough priority that it deserves some institutional support in the form of a purchase of data, an attractive arrangement could be developed. It would not take nearly as much per year as the cost of fielding one major ship for field activities. Let's say the community would support $ 2 million a year for the period of a major initiative like the Global Ocean Flux Study. This makes the financial situation supportable by reducing the risk to a level within more usual bounds.

Here is an opportunity for a partnership between government, the academic community and private industry. While it may not be unprecedented, I can find no parallel.

The Polar Platform of the Space Station — The Next Big Partnership

I said that I would return to the Space Station's Polar Platform. I maintain that it is the next logical big step in a partnership in remote sensing. It is a big step to take all at once. It has a lot of "partners".

The use of the polar platform for remote sensing is now the subject of a great pile of reports [16, 17, 18, 19, 20, 21, 22]. They fill a corner of my bookshelf. And they present a compelling rationale for that program.

There are five converging trends that demand a partnership in remote sensing on the polar platform. I will note them here, but allow the reader to be convinced by the reports already in the literature.

First, NASA has selected the Space Station as its next big initiative. As an R&D agency, NASA must have such a thrust or be turned into another NSF. The President, and the administration (through the budget approval) have fully endorsed this initiative. The Congress seems to be in a mood to approve it as well (though perhaps with some funding constraints). In short, the Space Station is in our future.

Among the key ingredients of any space station is "servicing" and repair in orbit provided by the Shuttle and some array of other capabilities. We are now setting out on a course of being able to do work in space like we can do work on the ground. The tools will necessarily be different, but the concepts are familiar and even homely. That is not a weakness of the program, it is a strength. It makes space more accessible to "normal" activities.

For remote sensing, it has two major features. It allows larger structures and more elaborate utilities (like "real estate" and electrical power). Second, it means that we no longer have to throw away everything when the first big part breaks.

This implies two things. We can make more measurement simultaneously from the same vantage point. And we can assure continuity of key measurements for a long time. It is the "platform" for making an emerging dream of "global earth sciences" come true. It is almost a magic carpet.

The second trend that converges on the polar platform is that of "global earth sciences". There is an emerging thirst in the scientific community for a global view [23, 24, 25]. It is now conceivable for a young scientist to devote a career to such a thrust with some hope of making a significant contribution, and more importantly (perhaps) of achieving tenure through a recognition of that contribution.

The National Science Foundation won a major new initiative in the FY 1987 budget that they call "Global Geosciences". It includes contributions by (or maybe "for") all the major disciplines in the Directorate of Astronautical, Atmospheric, Earth and Ocean Sciences at the Foundation. Only Polar Programs is not represented in the initiative, and that is an oversight on their part, in my mind. This is an enormous vote on the part of the Foundation for the academic community for a global view of geology, oceanography, atmospheric sciences, and biology. It provides the scientific funding framework for major advances.

NASA has been doing its part as well. It has in its early "new start" queue the important initiatives of the same genre:

— The Upper Atmospheric Research Satellite, to measure the composition and dynamics of the atmosphere from roughly 10 km. to 120 km. [26];

— TOPEX, which if successful will measure the mean circulation pattern of the ocean and perhaps give the same sort of dominant paradigm to oceanography that plate tectonics gave to geology;

— the Gravity Research Mission to map the geoid — a Scatterometer of the Navy's NROSS mission to measure global surface wind fields and surface wind stress over the oceans; and

— the Earth Observing System, the use of the polar platform with major new instruments to view the earth.

The UARS, TOPEX and the Scatterometer are approved programs.

The others are well on their way to reality, though not yet through the budget battles.

Meanwhile, the NOAA operational satellites — both weather and Landsat — continue to provide routine, reliable and timely measurements of many key scientific parameters. A number of these, like temperature soundings, will be vastly improved in the next few years with the addition of soundings from geosynchronous orbit and microwave soundings from the polar orbiters to make those soundings available from almost all weather conditions.

The U.S. Navy and the European Space Agency are soon to fly ocean remote sensing satellites that will make winds, waves, sea surface temperature, and several kinds of "imagery" available for the first time since Seasat (June to September 1978).

In short, the global view is now or soon to be available in a totally unprecedented way.

The third trend is both simple and essential — the conceptual and mathematical models capable of handling such massive amounts of data are here or on the drawing boards. Such a model is described in the latest report of NASA's Earth System Sciences Committee [27].

Fourth, the technology is mature. We have been "flying" remote sensing satellites for 25 years. The satellites are nothing new, and reliability is no longer an art. The fundamental sensing instruments have either been flown, or are soon to fly. There is no mystery about the technological capability, nor is there a big mystery about how to extract useful information out of their returned data.

Furthermore, there are now a number of experienced "practitioners" throughout the world. The technology is familiar to them, just like automobiles are familiar to western civilization and personal computers are familiar to our children. There will be no fear or aversion to the technology.

Finally, there is a dawning "political" awareness of the need to understand the workings of the globe on a scale beyond the local scale. The recent concerns about the El Niño, the Sahelian drought, the "Nuclear Winter", Acid Rain, and pollution of bodies of water as large as Chesapeake Bay are manifestations of the awareness. There is now and will continue to be a thirst by the legislature and parts of the executive branch to have the basis for informed decisions. And, of course, if it makes headlines, as many of the above topics have in the last few years, there will be an increasing call for public discussion of global scale earth sciences.

It is hardly unexpected that some of the discussion of these trends should focus on the Space Station's Polar Platform. What is perhaps more remarkable is the converging consensus among agencies in many nations.

Through the mechanism of the Economic Summit, NOAA has pursued international interest in the serviceable polar platform among operational agencies (mostly meteorological agencies). This has produced heartening results. All the participants in the discussions to date have agreed on a core set of measurements (and instruments to make the measurements) for operational purposes.

Meanwhile, in international scientific fora, and through the international Space Station negotiations, NASA has pursued international interest in such a mission for scientific purposes. Here too the agreement has been remarkable.

These two efforts have converged in a joint NASA/NOAA study of the platform that seems destined to reach full agreement on a joint program. At this writing, the findings of the study have reached the Associate and Assistant Administrators of the agencies and met with full agreement.

On the other side of the Atlantic, under the "Columbus Program" of the European Space Agency, a study called the Polar Orbiting Platform Element [28] has reached almost identical conclusions. There is an operational set of measurements, and a set for research. The lists on the two sides of the Atlantic are again almost identical.

But the partnership in the polar platform includes so many players that it gives any experienced bureaucrat pause. The partners include all that I have mentioned in the previous examples — industry, government and academia. They include all the international players I listed above. In short, they include almost everyone involved today in remote sensing. Keeping such an alliance together is an enormous challenge. But the consensus already achieved bodes well for its future. Some of its strength may be the confluence and possible union of its many interests.

The minefields ahead in the polar platform partnership are not technical. The technology is almost ready, and some of it is off the shelf. The mines in the field involve the management of the development and even more so the management of the operation of the system after it is developed. They are questions of control, of decision authority, and of competing demands all of which cannot be satisfied. While these really tough decisions are still in the future, they have been recognized, and discussions have begun to lay a framework.

Government and Academia — A Mighty Alliance for Science and more

There is an old axiom that deals with the strength of the government/academia partnership. I could repeat it here in general terms and describe its merits and its benefits. Instead, let me use a very real example of one of those partnerships in a tangible manner.

The example I choose is a cooperative institute at the University of Wisconsin in Madison. On that campus sits the Cooperative Institute for Meteorological Satellite Studies (CIMSS). It is an administrative unit of the University, and the head of the Institute is a university employee. However, within the Institute sit both university employees — professors and technical staff — and a small group of NOAA employees. All are research scientists.

The Institute has been in existence for 10 years, and its founding director is Dr. Verner Soumi, one of the leading figures in meteorological satellites over the years. Over those years, the Institute has had an enormous impact on the geosynchronous satellites. In fact, it may have had the largest impact on those satellites and their use of any single institution. I will list just a few of the accomplishments that have come from this government/academia partnership.

The first of the geosynchronous satellites in 1965 were intended to give a synoptic and continuous view of this hemisphere. The instrument that was carried on these satellites, the spin scan radiometer, was the invention of Dr. Soumi and his colleagues. They succeeded, providing a black and white image of this side of the globe every 30 minutes. Later an infra-red channel was added to provide pictures at night.

The Institute pioneered the computation of wind speeds at cloud heights by tracking cloud features from image to image. These are now a staple product provided from the satellites to the global models at the National Meteorological Center.

In 1969 the idea came from this Institute for having multispectral images, allowing for crude soundings of the atmosphere. This could be done with the simple insertion of filters in the optical path and allowing the spin scanning instrument to "dwell" on a single line of its image for the time necessary to produce several spectral intervals.

All of this leads to one of my favorite acronyms, a nested acronym. The original instrument is called the Visible and Infrared Spin Scan Radiometer (VISSR). The new instrument is called the VISSR Atmospheric Sounder, or VAS.

For a while, the VAS mode of operation was done as an experiment. During that time, the Institute made the soundings and winds derived from following features in water vapor patterns (as opposed to the clouds) available to the Weather Service, in an almost operational way. This experimental mode of operating the satellite has proven successful, and is now being declared "operational", i.e., available for reliable and regular service. The Institute will soon be out of the business of providing the data to the Weather Service.

There was never an adequate budget in the government for saving the satellite data for posterity. So the Institute devised a simple way to do it for their own use by modifying a Sony video recorder to operate in a digital mode, and simply stored the images from the geosynchronous satellites on video cassettes. Although the government can now store the data in a better manner, without the innovative thinking of the Institute much of the old data would have been lost.

Most recently, a set of techniques developed in the Institute for a Man Computer Interactive Data Access System (McIDAS) was transplanted into an operational setting at the National Weather Service's Severe Storms Forecasting Center in Kansas City. The machine was placed there as a research device to be used for resarch in that operational setting. It was also viewed as a way for the forecasters to try some of the new techniques developed at the University in their spare time.

Called CSIS, for Centralized Storm Information System, this machine allows the manipulation and overlaying of many sets of information, key among them the satellite data. The demand for the use of CSIS during actual forecasting duties grew so rapidly, that other centers have begun to demand installation of similar capabilities far in advance of the plans for a new system in the 1990's. This is being done in several of the Weather Service offices.

The above examples from this one Institute, this one partnership, include three occasions (cloud winds, archiving the images, and soundings from the VAS) where the Institute played an interim role in an operational activity, thus allowing those activities to reach the forecasters sooner. All of the examples are typical of the best ways in which the government/academia partnership can work to our enormous benefit.

Science and Services — In Maturity Working Together

There is always a tension between the research objectives of an institution and the operational objectives. The latter tend to provide goods or services that have tangible near-term worth. The research tends to have benefits in a less tangible and certainly more distant future. When budget or other resource pressures develop, it is the usual view that the research objectives take a secondary position in the priorities. Indeed, that is often (but not always) the case.

The same is true in remote sensing. On the one hand, there are the needs to buy replacement satellites and instruments (with appropriate improvements) for the operational systems. When NASA carried the burden for all new systems, there was a competition between these needs and the "new starts" for research missions. With the shift to NOAA carrying the majority of the burden for the replacements, and now even the improvements, that tension does not exist within the NASA budget, but it still exists in the larger budget pool.

Today, there is a different tension. There is a developing capability to take a global scientific view. Thus a maturing attitude among the earth scientists makes the case that there is significant value in routine, reliable, well characterized data over a long period of time. While the operational satellite services sprang into being to serve the service needs of the forecasters, the definition of what is needed (routine, reliable, etc.) for science is exactly the same as that which serves the forecasters.

I have discussed this trend in scientific thinking in some detail in the example of the Space Station's Polar Platform. The reports and studies noted there are a strong manifesto. The budget recently approved by the Administration for the National Science Foundation is an even stronger vote for the global scientific view.

Therefore, I argue, there is an emerging partnership between the scientific community and the weather services that will define the needs for "operational satellite observations" of the future. This makes sense, because the scientist should be just as legitimate a client or customer as the government forecaster or analyst. The coming definition of "operational" will no longer be "in service of the forecasters" but instead "routine, reliable, and well characterized, in service of society".

COSPAS/SARSAT — AN ULTIMATE EXAMPLE OF HUMANITARIAN USE OF THE SPACE ASSETS

I must cite one example that is not really remote sensing. That is the Search and Rescue program carried on the U.S. polar-orbiting meteorological satellites.

The "Search and Rescue, Satellite Aided Tracking" program was conceived in the mid 1970's by NASA with help from Air Force and the Coast Guard. Emergency transmitters carried by ships and aircraft were out of sight of fixed radio receivers and aircraft that might by chance be flying over. They were simply not as effective as they might have been. What was needed was a system that would always be overhead, or almost always. Furthermore, the system needed to be able to locate the emergency beacon. The polar-orbiting satellites could in principle do the job if a sensitive enough receiver could be developed. Of course, we know now that all the technology worked. It works so well that I could carry a tiny beacon to the high Himalayas with me last year, and test it successfully in the deep valleys there.

The French, at the same time that NASA started its R&D, offered to join the program and committed to supplying the data processor aboard the spacecraft. Along with the French, the Canadian Department of Communications made a similar commitment. Four satellites were needed to get close to the optimum configuration, and the USSR Ministry of Merchant Marine joined the system which was consummated by a Memorandum of Understanding signed in 1979. The technical basis was set.

The first launch of one of the space systems was in June 1982 on the Russian COSMOS 1383. The first U.S. launch was NOAA-8 in March 1983. The full complement of four satellites was established in July 1984 with the launch of COSMOS 1577.

As of this writing, over 650 lives have been saved because the system is in place, in just 3-1/2 years. The record is building, and the recognition is building with it. The system is simple in principle, the emergency beacons are inexpensive, and the cooperation is assured at least through the end of the decade. None doubt that it will continue beyond that time, for as long as anyone is flying satellites in a polar orbit.

This year has seen three major events. First, the partners have declared the second portion of the system, one at the 406 mhz. frequency that can carry digital information about the vessel or airplane in distress, to be operational. It is up and working. Second, the International

Maritime Organization's Maritime Safety Committee has adopted the system as its standard for all ships sailing under the auspices of that organization. This includes ships of approximately 67 countries, numbering nearly 30,000. With this recognition, the future of the system seems assured. Third, several countries have expressed interest in making contributions to the global system. For instance, India may make a major addition to the system with contributions of a ground station, a geosynchronous "early notice" transponder like the U.S. will launch in May, and eventually the addition of the package to their planned polar orbiters.

This is a clear example of what can be done when all the partners share the common goals. It is a partnership that includes four countries today and crosses the iron curtain. It will soon include India and later even others. The four original partners welcome the addition of more partners, and have said as much again and again.

The lesson is applicable to the remote sensing activities as well. Perhaps the Space Station's Polar Platform will provide the mechanism to replicate the Search and Rescue experience in the world of remote sensing.

Conclusions and Speculations

I am convinced beyond any reasonable doubt that remote sensing of the earth, its oceans and its atmosphere is inherently what the physicists call a "many-body problem". The classical single body solutions do not work, or do not work for long. But in this case, my little homely metaphor does not hold up. For we are not mapping collisions among the bodies, I hope, but rather some strong attractive forces.

Remote sensing is inherently a partnership. I have cited little and can think of scant else that indicates that remote sensing is anything but a partnership. NOAA has explored just such a concept. Private industry, government and academia are all involved. A recent symposium [32] made a case for an international régime for remote sensing along the lines of Intelsat. Our own experience (NASA and NOAA) makes it clear that agencies and national representatives can come to a broad consensus about what should be done in a very large context. I am not yet convinced that a formal mechanism like Intelsat is either required or desirable. The other mechanisms have worked, and seem to work well in some cases. But we may need that international mechanism to insulate the remote sensing from budget pressures in individual countries.

Many of us share a dream of a "global observing system" carried aloft on appropriate platforms. But there are a number of intermediate steps and decisions between the present and the larger partnership that we see on the horizon.

The many partnerships I have discussed as examples serve to set the course. Some are real today (COSPAS/SARSAT, international co-operation in space, and the research/operations mutual support). Some are tenuous beginnings (like EOSAT). Others are opportunities that beckon more like a lighthouse on the horizon than a meal on the table (OCI, and polar platform).

I would like to believe that some of the partnerships are "imperatives" or that they have some life of their own. But that has not always proven to be the case in the past. Like courtships and marriages, they need nurturing.

In the near term, I favor courting the OCI, the Landsat, and the Polar Platform. They are concrete things that build on solid foundations in science and technology. They have constituencies. And they have unique challenges.

But they also have powerful returns on the serious intellectual and modest financial investments necessary to make them happen.

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CONCLUSIONS

Introduction

The face of the earth looks to the sky. It follows that the sky is the most favorable vantage point from which to look at the face of the earth. Remote sensing with aerial photographs and space imagery at many different wavelengths, from the visible to the infrared and microwave regions, exploits this principle. Perhaps the most important applications of remote sensing for the benefit of all mankind are through the use of it in monitoring the earth's natural resources and environment — important steps leading to the intelligent management of such resources.

By the end of the 1920s, there was clear evidence that aerial photographs of the Earth's surface often could be used effectively by those at regional and national levels who wished to monitor key environmental variables, and to inventory, monitor, and manage natural resources. More than two decades passed, however, before there was general acceptance and use of this capability at regional and national levels.

Similarly, by the end of the 1960s there was clear evidence that space photographs of the Earth's surface and its atmosphere (when augmented by other forms of remote sensing data acquired from aircraft and spacecraft) often could be used even more effectively than aerial photos alone at the national, regional, and global levels, for environmental monitoring and resource inventory purposes. Nearly two decades have passed since the start of investigating and using remote sensing techniques. Many programs and countries have effectively used the technology. However, additional programs could benefit by using the technology, especially if decision makers were better informed on the potentials of the techniques and if they accepted the use of remote sensing.

This Study Week on the impact of remote sensing on developing nations was a direct outcome of the Study Week held on the Impact of Space Exploration on Mankind, October 1-5, 1984.

Through our economic and technological activity, humanity is now contributing to significant global changes on the Earth within the span of a few human generations. We have become part of the Earth System and one of the forces for Earth change.

The use of available information holds the key for the effective use of renewable and non-renewable resources, and for protection of, and from, the environment. Research holds the key to our global future. Recent studies of the Earth's components have revealed a complex and dynamic world. Analyses have also delineated, with increasing clarity, the fundamental interactions among these components and their profound effects upon Earth's history and evolution. With new insight and technology, humanity can gain a deeper understanding of the Earth and of the consequences of global changes.

The following were the primary reasons for convening this Study Week and bringing to it remote sensing experts from many of the world's developed and developing countries:

(1) to consider the impact, both present and potential, of modern remote sensing technology on developing countries, particulary with respect to the effective monitoring of the environment, and the inventory, and management of their natural resources, and

(2) to determine, for certain instances in which such effective use obviously could be made, various means by which the rate of acceptance and adoption of this remote-sensing-based technology might be accelerated.

The subject matter for this Study Week was organized under the following four headings:

(1) The present status of remote sensing technology;

(2) Its potential usefulness in developing countries with respect to the environment and "renewable" natural resources such as marine, timber, forage, water, minerals, soils, and agricultural crops;

(3) Its potential usefulness in developing countries with respect to such "non-renewable" natural resources as minerals and fossil fuels; and

(4) Related economic, social, and legal considerations.

It seemed apparent that, once our Study Week participants had systematically considered these four aspects, we would be in a favorable position to draw conclusions with respect to the theme of this Study Week: Remote Sensing and Its Impact on Developing Countries.

Summary of Findings

1. Satellite remote sensing is becoming more and more useful in the monitoring of the environment and the inventory and monitoring of natural resources to facilitate their management. The synoptic global view with frequent coverage provides a complement to airborne remote sensing and surface-based measurements.

2. The case examples presented by participants in this Study Week show that various satellite and airborne remote sensing systems, including environmental/meteorological satellites, have been successfully applied in providing management solutions to a variety of environmental and natural resource problems at the local, national, and the global levels.

3. Global efforts are being actively pursued to apply this technology in searching for answers to the world's major problems of environmental hazards, food production, desertification, deforestation, soil degradation, and the destruction or improper use of coastal and marine resources.

4. Full utilization of remotely sensed data in the developing countries has been and is constrained by:

a) the limited access to, and availability of, remotely sensed data, especially from satellites,

b) the increase in costs of satellite data to the user for products and in certain elements of the infrastructure, such as ground receiving operations,

c) the inappropriate and incomplete transfer of the technology including inappropriate equipment for understanding and using remote sensing,

d) the ineffective efforts by scientists to communicate to decision makers the demonstrated advantages of remote sensing,

e) in many cases the inadequate appreciation by decision makers of what remote sensing can do has resulted in a consequent lack of its acceptance,

f) the continuing lack of adequate training,

g) the slow diffusion of the technology between users and user agencies, and,

h) the inability of remote sensing techniques to provide all types and levels of information required for complex resource and environmental problems,

5. Users should derive greater benefits from the application of this technology through:

a) use of optimal combinations of remote sensing methods,

b) the formation of national, regional, and international data/information management facilities and training programs,

c) the development of indigenous and self-sufficient remote sensing programs, and

d) increased use of remotely sensed data from new generations of earth observing satellites and airborne instruments.

6. Countries which have developed the remote sensing technology should provide the proper environment in which developing countries can fully utilize the technology for the management of their natural resources. Continuity and stability of data should be encouraged while costs associated with applications should be held to a minimum.

7. Overall there continues to be only a moderate rate of acceptance for using modern remote sensing technology among the world's developing countries. Remedies to this difficulty should begin with a better understanding of the factors involved in gaining acceptance and use of a new, rapidly growing technology such as remote sensing.

8. The Committee on the Peaceful Uses of Outer Space of the United Nations General Assembly (COPUOS) adopted a draft of « Principles Relating to Remote Sensing of the Earth from Space » at its twenty-ninth session in June 1986. The participants support these principles and consider them of primordial importance.

9. To protect the legitimate rights and interests of sensed countries, legal regulation of dissemination of the data and information of remote sensing is essential. Dissemination of remote sensing information should be regarded as constituting wrongful acts when such activities violate the Declaration of Principles of International Law concerning Friendly Relations and Cooperation among States in accordance with the Charter of the United Nations adopted by the UN General Assembly in 1970.

10. The peaceful uses of outer space and international cooperation in economic and humanitarian spheres are indispensable to provide for wider participation of developing countries in remote sensing activities.

11. Remote sensing may affect economic, social and strategic interest of sensed countries and the international community as a whole. Together

with positive effects, it may cause negative effects on developing countries. To eliminate possible negative effects further, development of international cooperation in this field is required at all levels — bilateral, regional, and multilateral.

Recommendations

1) Remote sensing, by providing information, can make a unique contribution to global food security by monitoring conditions during the growing season, and monitoring the occurrence and intensity of natural disasters such as drought, floods, and plagues of locusts. In this respect, the holding of an international meeting on remote sensing for food security in the next decade is timely and is recommended. Particular attention should be paid to such staple crops as, e.g., rice in the developing countries of Asia, the home of the majority of the world's population.

2) Measures must be taken to ensure long-term continuity and availability of remotely sensed data.

3) There should be a continued effort to formulate and/or strengthen international cooperation, coordination, and programs which study earth processes, productivity, and resources on a global basis.

4) Developed countries should assist developing countries in using information and data analysis systems to assure that all information is available for their decision makers and for their future resource mapping and monitoring programs. An advanced information and data analysis system should be established for use on an international basis. This will permit the use of new and existing remotely sensed data for critical national resource mapping and monitoring programs. It will also facilitate the transfer and cooperative use of data and information to evaluate earth resources and processes on a regional and global basis.

5) There should be a vigorous effort made to promote a clear understanding of the factors that govern the acceptance and use of a new, sophisticated, and potentially very consequential technology, such as remote sensing.

6) Policy makers must be convinced of the need for action through remote sensing with respect to development and management of national

resources and protection of the environment. Policy makers should be briefed at a special meeting organized by the Pontifical Academy of Sciences or the Third World Academy of Sciences. Brief but effective training programs and seminars could be offered to high level decision makers and planners of developing countries to ensure their support of remote sensing programs.

7) Greatly increased efforts must be made to educate potential and existing users. Workshops and training programs should be held for Agriculturists, Environmentalists, Foresters, Hydrologists, Climatologists, Geologists, Data Collectors, Data Reducers, Data Analysts, and other users.

8) Development goals and resource management priorities should be clearly stated so that proper remote sensing techniques can be defined and used.

9) Developing countries should be encouraged to develop self-sufficient and indigenous national remote sensing programs based on their financial and scientific capabilities addressed to their national development needs.

National remote sensing programs should be developed to the extent necessary to meet national planning and development needs and, in the case of developing countries, international agencies and donor countries should be urged to support these programs.

10) Remote sensing efforts, as applied to the developing countries, should be regionally coordinated as appropriate.

11) Developing countries often share the same situations and problems in resource management. Transfer of technology between these countries should be encouraged (in terms of pilot projects, exchange of specialists, technology assessment, software/hardware, training, seminars, etc.).

12) Efforts should be continued to develop all-weather operational capabilities (e.g., utilization of both active and passive microwave techniques).

13) There should be a program to measure costal zone and ocean productivity, an area in which remote sensing capabilities are now deficient.

14) Standards should be defined for remote-sensing-related hardware and software to insure maximum compatibility between satellites and user systems.

15) Attention should be directed to the use of data from environmental monitoring satellites. Regional and international efforts in this program should be encouraged.

16) Countries possessing remote sensing technology should facilitate the following:

Technology transfer in Remote Sensing
— through training,
— through the distribution of applicable equipment and software,
— through assistance to national/regional mapping and exploration,

thereby helping the programs of developing countries which use remote sensing.

17) Developed countries should assist developing countries to locate, archive, and make available existing resources information in order to improve the quality of resource survey and management programs.

18) More funds should be directed to the production of high quality, affordable products for use in resource development and environmental monitoring.

19) Commercialization of satellite remote sensing systems could compromise the national development of national resources in developing countries and thus it is of a grave concern. It is recommended that the impact of commercialization, especially with regard to copyright and cost of these data, should be carefully evaluated in the near future.

20) We recommend that all states support principles relating to remote sensing of the earth from space, adopted by the Committee on Peaceful Uses of Outer Space (COPUOS) on June 13, 1986. In particular, we recommend that states should bear international responsibility for damage caused by the disseminaton of remote sensing information about other countries.

21) Further action by states should be taken to maintain outer space for peaceful purposes and thus to promote international cooperation on a non-discriminatory basis in the field of remote sensing.

22) The study team, in their role as scientists, recognizes that continued applications of remote sensing for development require an ongoing program of research and training. This group strongly recommends that the international university community be encouraged and supported to provide remote sensing training and research.

23) The institutional and organizational framework of international cooperation in the fields of remote sensing and information systems should be further studied.

Conclusion

The benefits to mankind of remote sensing have been demonstrated over the past twenty-five years. Through international cooperation these benefits will continue to be available in the interest of peace and for the welfare of all men and nations, but particularly for those who suffer from hunger and disease.

These Conclusions (pages 669-676) were also published and circulated as an official document (A42/62, 22 December 1986) by the United Nations General Assembly under the item entitled "International co-operation in the peaceful uses of outer space".