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Remote Sensing in Development

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Remote sensing is important for Third World social and economic growth. It supplies information (a powerful resource in itself) about the available natural resources, which must be properly understood and managed if the developing countries are to become self-sustaining. The technology has been absorbed by many developing countries in a manner that is influenced by their developmental strategy. Those that stress economic growth (mainstream, or traditional, development) have focused on specific applications generally related to energy sources. Those following socialist development models tend to be slower and more deliberate in integrating remote sensing into their planning efforts; the benefits, social in nature, may be more difficult to perceive at the early stages than those associated with economic growth.

Summary. Remote sensing is used to acquire statistics on crops in developing countries and to locate petroleum and mineral deposits. It has increasing potential for forest monitoring and subsurface water location. Problems related to Third World use of the technology include sensitivity about the dissemination of data with high spatial resolution, exploitation by multinational companies, absorptive capacity of countries for advanced technology, autonomy in acquiring resource information, and competing foreign policy interests of the industrialized world in the global search for raw materials. The attitude of Third World countries toward use of remote sensing tends to depend on the development model they adopt.

All but a dozen or so countries of the world have followed some combination of these approaches to development, recognizing that natural resources are fundamental to fuel development and represent an asset to be properly managed and sustained. Therefore, a means for quickly and comprehensively mapping this asset had to be found; remote sensing has become this means for almost every country on the earth. In this article we describe some uses of remote sensing data in the developing countries. We conclude by outlining concerns expressed by these countries over existing activities and proposed changes in satellite imaging technology and management.

Remote Sensing

Figure 1 is a map showing the Landsat receiving stations that are in existence or under construction at present (black circles) and those contemplated in the near future (in white, with estimated year of completion). Iran is shown in white, since the station was on-line for only a few weeks before the revolution shut it down. The circles represent the areas of reception of Landsat image data from the receiving station (radius is roughly 2700 kilometers). The symbols on the map indicate the applications that drew remote sensing technology into the region and that tend to be the primary emphasis of the technology today. The map can be misinterpreted, since in development generally many applications are carried out simultaneously. However, there is one application that is primarily responsible for remote sensing being adopted operationally, and the one based on the experience of one of us (C.K.P.) is shown. For example, while East Africa (primarily Kenya and Tanzania) is pursuing multidisciplinary efforts in remote sensing, the quality of rangeland and its effect on competition between wildlife and cattle are the types of information that the Kenya Rangeland Ecological Monitoring Unit (KREMU) required and that led the KREMU to experiment with, and to routinely monitor with, satellite remote sensing. Throughout the western Sahel and Afghanistan, priority was given to understanding the spatial relations among rural villages and population movements, and these demographic applications are indicated by the human symbol in Fig. 1. Much of the history of remote sensing for mineral exploration can be written for the Andean countries of South America, and rice statistics (grain symbol) are vital for Southeast Asian export-import models. The map provides a useful reference to the developmental efforts in which remote sensing is being applied to obtain information in various regions of the world.

Agricultural applications of remote sensing, primarily for crop statistics and soil mapping, have proved difficult to carry out in the developing world. Crop statistics have been acquired by the area frame sampling technique, a labor-intensive method whereby Landsat images and air photos are stratified; that is, land use boundaries are delineated for the purpose of selecting field sites for refined sampling on the ground (*1*). The area frame, because it relies primarily on farm interviews for data, is very precise and can be designed to accommodate socioeconomic as well as physical resource data. The remote sensing contribution is twofold: (i) accurate image interpretation yields samples that truly reflect the agricultural growing conditions (that is, the samples are representative), and (ii) the sample statistics can be scaled up to the province or national level by multiplying them by the ratio of the area in each

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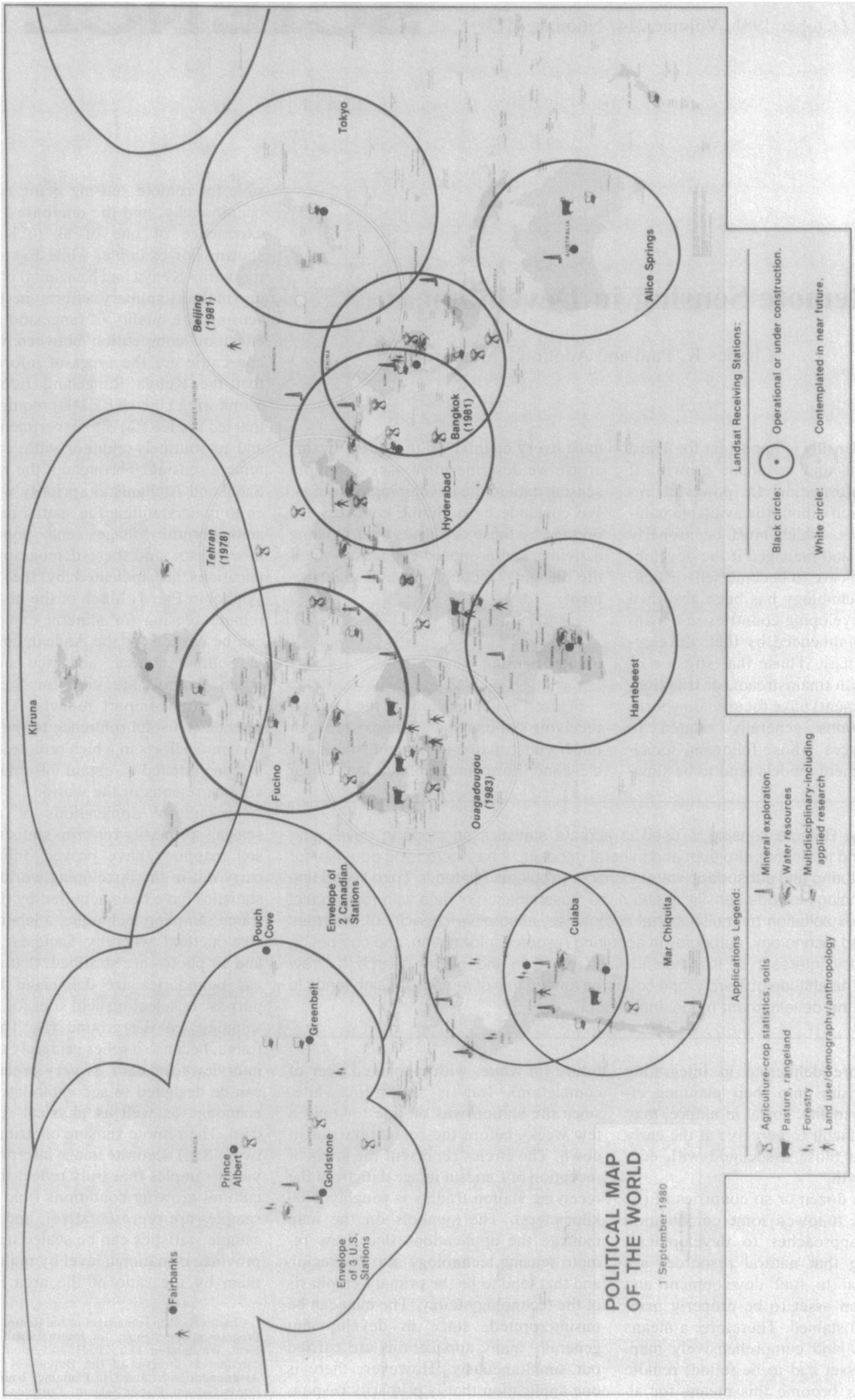

Fig. 1. Global remote sensing map.

stratum to the area of the sample fields, the areas being obtained from the imagery (thus, the term area frame).

Because the area frame is labor-intensive and requires inexpensive visual analysis equipment, it is being implemented in about 20 developing countries. Crop production statistics are vitally important in developing countries: an unexpected shortfall accompanied by a delay in importing grain can result in famine; above-average production accompanied by normal grain imports can result in grain excesses that drive down the price of local crops, thus undermining the agricultural development of countries with inadequate crop-reporting systems.

A second agricultural application is the mapping of land use potential, with associated monitoring of water availability. Figure 2 shows two Landsat images of a broad, shallow land depression in the Sylhet and Mymensingh districts of northeast Bangladesh. These depressions, called haors in Bangladesh, are important in terms of land use since the lowest regions of the haors are permanently flooded and generally used for fish and waterfowl production (*2*). The highest areas, which are without water during the dry season, are used for homesteads, orchards, and permanent pastures. Land in between is used for grazing and the cultivation of jute, vegetable and oilseed crops, and different rice crops. Depending on the economic markets for various crops and the social pressures caused by a population density of 1291 people per square mile, increasing by 3.2 percent per year, the lower areas are sometimes drained to plant a winter (boro) rice. The images of the same haor region in Fig. 2, which were taken in the same infrared band of the Landsat multispectral scanner (MSS), show the difference in flooding conditions and vigor of vegetation (primarily rice) between the dry season and the wet season. Such images permit the government of Bangladesh to understand the changing flood patterns along the Meghna and Kalini rivers for the purpose of designating certain uses of the land. A land use–vegetation map was also produced for the dry-season image (27 March) with all the Landsat MSS bands.

Figure 3 is a land use map of northeast Bangladesh generated by computer from the Landsat data. Fallow fields appear yellow; maturing rice in the low, wetter areas magenta (the darker pink); immature rice fields and upland forests green; surface water blue; and orchards and rabi vegetables lighter pink. Since 1975, Bangladesh has been procuring digital image-processing technology under a grant from the U.S. Agency for Interna-

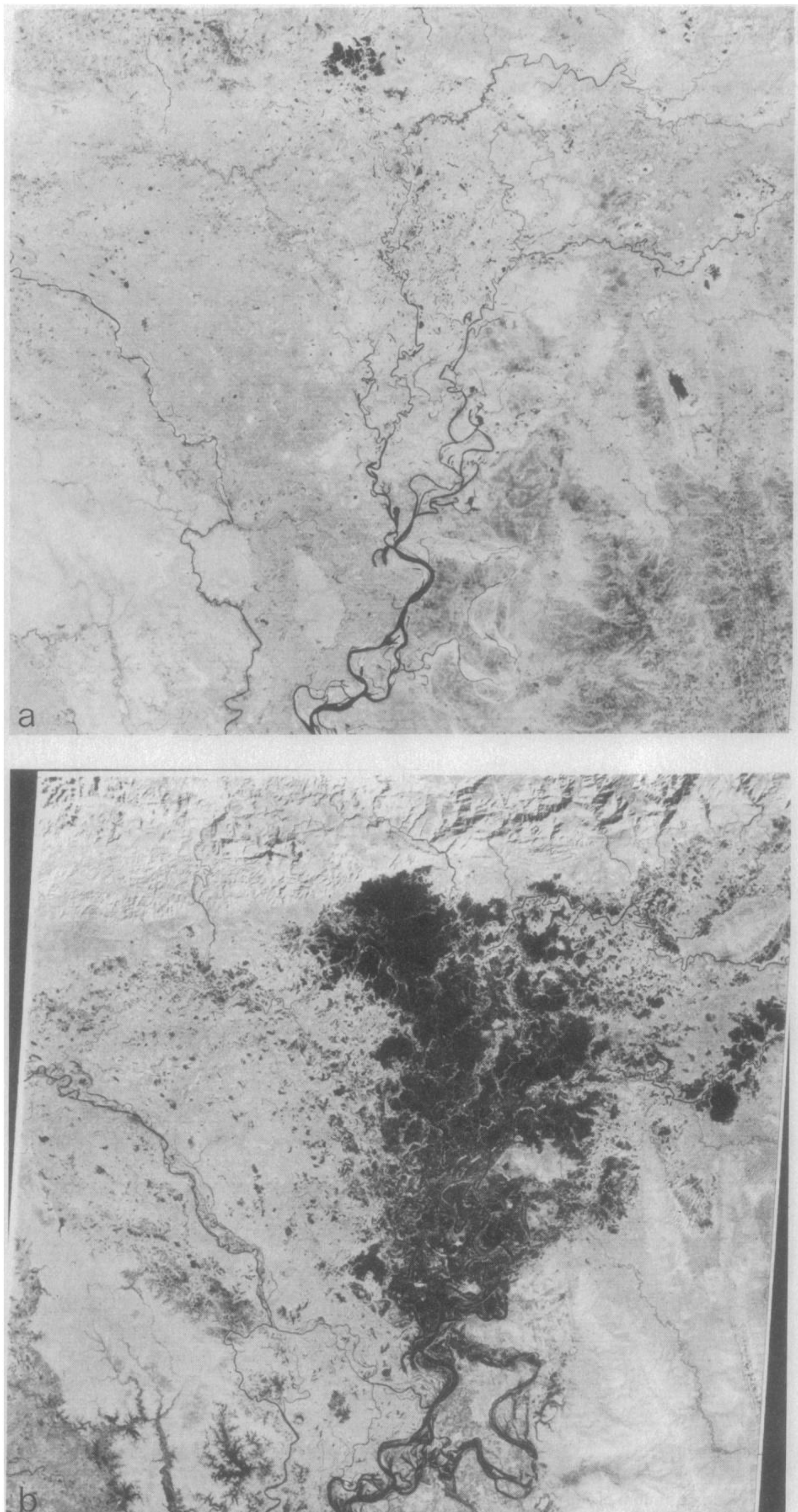

Fig. 2. Landsat images of northeast Bangladesh taken with band 7 (infrared) of the multispectral scanner. The images show the same region during (a) the dry season (27 March 1975) and (b) the wet season (4 December 1975).

tional Development to monitor these changing land use patterns. Information from these maps is used by the nation to estimate the volume of its food resources.

Integration of Landsat data with geophysical measurements in exploration for minerals and especially hydrocarbon deposits has steadily increased in the non-oil producing countries. Many multinational oil companies and smaller geophysical consulting companies have the staff and equipment to digitally process Landsat data in order to analyze fracture patterns, faults, hydrothermal anomalies, anticlines, and other surface features that may indicate subsurface petroleum, gas, copper, uranium, iron, and other mineral resources. A recent paper describing the use of Landsat data in exploration includes a post facto analysis of 15 known giant oil- and gas-producing fields (*3*); it concludes that such fields as the Ghawar in Saudi Arabia and the Samotlor in the Soviet Union would have been identified from Landsat imagery analysis had they not been previously discovered.

Landsat image analysis has resulted in some striking petroleum finds in the

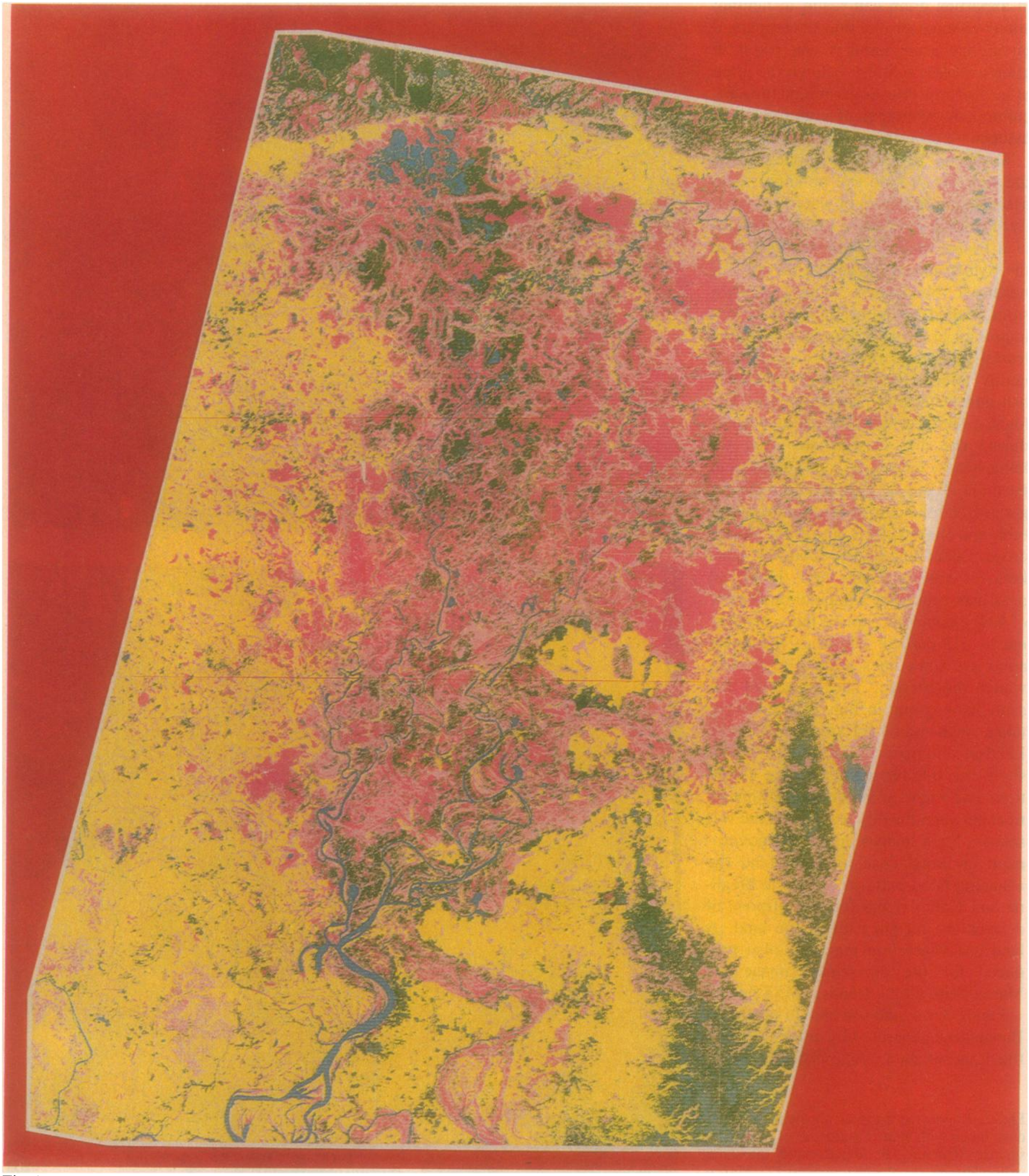

Fig. 3. Land use map of northeast Bangladesh generated by computer processing of Landsat multispectral scanner data. [Map produced by the Environmental Research Institute of Michigan under contract to the U.S. Agency for International Development.]

Third World. Conoco began to drill its first well in Egypt in 1979 after 4 years of correlating Landsat imagery, aeromagnetic surveys, and seismic profiling (*4*). A photogeologist, R. M. Peterson, has developed the technique of interpreting anticlines on Landsat imagery in association with wrench faults and applied this technique to target successful petroleum finds in the Kiryat Gat area of Israel (*5*, *6*). Chevron, using Landsat imagery with aircraft aeromagnetic data, found oil in southern Sudan (*7*), and the subsequent drilling resulted in the first producing oil fields in this country. Three successful wells are producing 12,300 barrels per day.

At the opposite end of the spectrum of remote sensing applications is a land use mapping program for social development in Tanzania. Mainland Tanzania is administratively divided into 20 regions. In the early 1970's, donor agencies from the United States, West Germany, Sweden, and India began assisting the country to map and develop several of the poorer regions. The newly created region of Rukwa presented a unique problem: it was large (68,000 square kilometers) and remote, very little information about its natural resources was available, and it was isolated in the sense that it was poorly served with a communications system. A rural integrated development plan had to be prepared for the benefit of the peasants of the region, whose livelihood depended on agriculture and cottage industries.

Lack of readily assembled data was a particularly formidable problem for Rukwa. Even basic information on soils and vegetation was lacking. The first priority in the planning for Rukwa was an assessment of its natural resources. Use of conventional surveys to collect information on land forms, vegetation, and hydrology would have taken a long time and would have been expensive and difficult, partly because the cartographic base within which to fit this information was poor and technically skilled people were not available in the required numbers. Thus, while there were some maps on a scale of 1:50,000 for Rukwa, these were not topographically contoured and were based on information about social infrastructure that was more than 30 years old. Some smaller scale maps that were used for information on Rukwa at the planning ministry in Dar es Salaam were definitely misleading. For instance, Lake Rukwa, which covers nearly 2000 km^2, was depicted as two separate lakes on these maps. Landsat imagery showed that Lake Rukwa is one large body of water and that 5 percent of the land that was presumed to be lakeshore, potentially suitable for agriculture, was in reality under water.

An attempt was made to carry out an aerial survey at a low altitude in order to obtain information about villages, but the cost of aerial photography depicting 40 villages in an area of about 2300 km^2 was well over \$20,000. Also, it would have taken 6 months to obtain the prints and even longer to process the data. The cost of obtaining six Landsat images of good quality giving a synoptic picture of the whole Rukwa region (68,000 km^2) with its 270 villages was only \$1000.

The greatest potential source of wealth in Rukwa was its natural resources, but they could be developed only if they were properly assessed. General agroeconomic zones of the region, although useful indicators, were inadequate for agricultural planning. The first priority, therefore, was given to demarcating the boundaries of the large physical land regions before attempting to obtain detailed information.

Landsat MSS imagery was useful for this purpose because its gross 80-meter resolution eliminated the definition of surface detail while showing the general pattern of resource availability and major trends of land use. Thus, although it had been known that the Mpanda district had miombo woodland vegetation, it was only through Landsat imagery that the full extent of the miombo woodland and its modification through cultivation became known (*8*). To collect these data through fieldwork alone would have been extremely expensive and probably would have taken about 2 years. The six Landsat frames that cover the whole region provided data on significant geomorphological and geological features, as well as vegetation and hydrological patterns. Fieldwork was substantially reduced, but had to be undertaken so that the representation on the imagery could be verified by ground information. The data on Rukwa from remote sensing and other sources led to the production of a set of land system maps and a series of 15 thematic maps depicting land forms, slopes, and vegetation and indicating the suitability of the land for irrigation and crops such as maize and cotton. This integrated effort of various disciplines, including geomorphology, hydrology, and botany, in a sense emulated nature's own comprehensive processes in shaping the surface of the planet.

The use of a remote sensing platform like Landsat not only allows planning without disturbing the traditional and ongoing agricultural patterns but also allows full latitude for sophisticated and scientific agriculture when it evolves. Since 1976, the Rukwa region has moved to third position in the country as a producer of cereals and food, based on traditional modes of production. There has been a shift from the hoe to ox-drawn ploughs, but as land use intensifies, more knowledge will be required to use expensive inputs efficiently. Remote sensing imagery is being used today to monitor the forests of Rukwa for the purpose of conserving trees and replanting them if and when timber resources appear to fall short of the charcoal needs of the village inhabitants (almost 100 percent of the region's domestic energy needs are satisfied with wood). Cleared areas, especially in watersheds, and resulting erosion are periodically monitored to prescribe remedial actions. Village water supplies are being planned from the imagery. The synoptic picture of the Rukwa region shows the irrationality of trying to serve remote villages along the shores of Lake Tanganyika by roads rather than by boats. Traditionally, people along the lakeshores have used canoes. Improved vessels would open larger areas to isolated communities at a considerable savings in cost, since construction of roads with sealed surfaces costs nearly \$220,000 per kilometer.

Thus, although it is perhaps less dramatic than the eventual discovery of minerals, the Tanzanian experience illustrates the targeting of remote sensing to the basic needs of the rural poor and the slow, methodological process by which remote sensing technology is absorbed into the planning and development of a country's future growth, social as well as economic.

Issues in Third World Remote Sensing

With developing countries using satellite imagery, existing image acquisition activities and proposed changes in earth observations by the industrialized countries, primarily the United States, present a source of concern and problems to the Third World. This concern tends to arise in United Nations forums and in bilateral foreign assistance projects where U.S. project managers and Third World scientists work side by side with satellite imagery. Although each developing country has its own concerns about this technology, the issues can be classified into six interrelated sets.

1) *U.S. Operational Land Remote Sensing System.* The next two Landsat satellites (the D series), which will provide data through the 1980's, might be

followed by operational satellites in the 1990's. Some of the options considered in the plan for this system (*9*) indicate an increase in prices for Landsat data products, an increase in access fees paid by foreign Landsat station operators, imposition of a copyright on all data products, and transfer of operation of the satellite and ground processing systems from the U.S. government to private industry. These four options would affect the Third World, where foreign exchange for data purchases and the access fee (currently $200,000 U.S. per year) is meager. Ownership of copyrighted data by a U.S. firm would undermine the justification for the building of photo labs in the Third World by foreign donors and developing countries, which was based on the capability of these countries to reproduce Landsat imagery at very low unit cost. Most developing countries reproduce images by the thousands for the use of field parties and agricultural extension agents; a copyright fee for each such image would add costs to their operation as well as complexity in keeping records of reproductions. Further, many developing countries prefer that the distribution of Landsat data continue to be handled by the U.S. government, which they trust to maintain the same standards for all products. The U.S. response is that, whether a private or a government entity operates the system, it will be required to work within international treaties and obligations signed by the U.S. government.

2) *Spatial resolution.* The single remote sensing parameter that has caused the greatest controversy in the Third World and the United Nations is spatial resolution. This is unfortunate; if the objective of Third World use of satellite technology is the obtaining of natural resource data, there is no reason for this concern. The present 80-meter resolution and the coming 30-meter resolution of the thematic mapper on Landsat-D have been designed in light of user-defined needs for resource information. The lack of capability to see more is ideal for resource mapping; the objective is to tabulate statistics over large areas, not identify every feature (which could be done to a limited extent on the ground). As resolution becomes finer, the number of developing countries objecting to open distribution of satellite images of their resources will increase. The French plan to launch a remote sensing satellite (SPOT) in 1984 and have adopted a prior consent policy by which they will not sell 10-m-resolution data on any country without that country's agreement. The Soviet Union and France, supported by many developing countries, have been seeking passage of a universal prior consent resolution in the United Nations. The United States maintains a policy of open dissemination of earth resources data, under which all civil remote sensing data are available to anyone who is willing to pay. The United States argues that this is the most practical way of adhering to the obligation, in the 1967 Outer Space Treaty, to share the benefits of space as widely as possible. Some Third World countries, ever vigilant regarding resource mapping along poorly defined frontiers, are not satisfied with the present U.S. position.

3) *Multinational corporations.* The issue of concern among the developing countries is the disparity between the information available to a mineral-rich nation and that available to a multinational firm with advanced satellite processing technology. Negotiations between Third World countries and large mineral companies have always been difficult and today have all but stopped mineral surveys in some developing countries. If the developing countries can acquire the equipment and training to carry out their own surveys and the legal experience necessary to bargain for terms that protect their natural resources, the climate could improve substantially and resource surveys could be viewed as a cooperative effort with both sides gaining from equal availability to information.

4) *Complexity of technology.* Generally speaking, remote sensing does not uniquely identify or locate a specific resource. Minerals and ground water, for example, are inferred by a trained and experienced investigator who has learned the associations among surface features of the planet and hidden resources. As one proceeds from photo interpretation to basic visual analysis with mechanical and optical equipment to more advanced digital computer enhancement and land classification systems, one encounters methods of manipulating solar reflectance values to bring out spectral information not readily seen by the naked eye in a standard false color image. The most sophisticated digital image processor, costing roughly $1 million, is only as useful as the remote sensing investigator who understands the terrain conditions. However, in signature extension, where one is extrapolating surface spectral response from a known site (where ground truth is available) to more remote, unknown sites, a sine qua non for identifying the unique spectral response to that one has to be able to see it. Because Landsat image data (and multispectral data in general) contain more information than can be visually depicted on one image, it is useful to have special computer systems that can manipulate these data and produce processed images in which the spectral signatures are visible to the eye.

Because of the limitation of digital image technology to spectral information and the difficulty of learning to use and maintain equipment associated with the technology, transfer of these systems to the Third World has been quite difficult. These imported processors tend to be poorly maintained and improperly used. With a properly phased approach beginning with a mastery of basic photo interpretation, digital system technology can be acquired by regional cooperation in funding and institutions. To encourage this, the developing countries, the United Nations, the United States, France, and Canada are jointly funding regional training centers in Upper Volta, Kenya, and Thailand.

5) *Information autonomy.* Many developing countries would like to exercise as much control as possible during the flow of data from satellite acquisition to final image product. To partly overcome their dependence on the satellite-operating nations, several developing countries have built (Brazil, Iran, Argentina, and India) or are building (Indonesia and Thailand) their own Landsat receiving stations. These stations, generally financed by the countries rather than foreign donors, represent a level of investment of about $5 million of scarce foreign exchange and indicate the importance the developing countries place on controlling as much as possible the pace and handling of data about their resources. Brazil is planning its own earth resource satellites; India, with the help of the Soviet Union, launched its own this year.

6) *Remote sensing satellites.* In addition to the future U.S. Landsat-D satellites and the French SPOT system, the Japanese have planned a land observation satellite for 1986 and the Soviets have given selected developing countries greater access to photos from their MKF-6 camera flown on several earth-orbiting missions. As the industrialized countries compete for access to raw materials from the Third World, the sense of technical assistance in the use of remote sensing and geophysical technology among the suppliers of the technology is changing from one of promised cooperation to one of increased competition.

Although losers on the supply side may forgo opportunities in scientific advancement and economic benefits associated with earth resources sensing, the developing countries may gain, as the competition may lower the prices of satellite products and ease the terms for obtaining technical assistance in remote sensing.

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Interiors of the Giant Planets

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Summary. Unlike the terrestrial planets, the giant planets—Jupiter, Saturn, Uranus, and Neptune—have retained large amounts of the carbon, nitrogen, and oxygen compounds that were present in their zone of formation. A smaller fraction of the available hydrogen and helium was retained. The distribution and relative amounts of these components in the interiors of the Jovian planets can be inferred from theoretical and experimental data on equations of state and from the planets' hydrostatic equilibrium response to rotation.

Consider a sample of material from the sun or, almost equivalently, from the primordial material out of which the solar system formed. Cooled to planetary temperatures (about 100 K), the sample has the distribution of principal chemical constituents shown in Fig. 1. The various mineral species such as magnesium silicates ("rock") and iron that form the terrestrial planets are an extremely minor component of this distribution. The predominant component consists of gases that would not condense under any plausible primordial conditions, such as hydrogen and helium, as well as gases that could condense in bulk only at rather low nebular temperatures, such as water, methane, and ammonia (*1*). The fact that these gases are largely missing from the terrestrial planets suggests that they were somehow removed from the coexisting solid phase at around the time these planets were formed.

In the outer solar system, evidence indicates that large amounts of the gas-phase component were incorporated in planets, but in amounts that vary from planet to planet. Such inferences are model-dependent, since we have no direct techniques for sampling the bulk composition of planets. Figure 2, a mass-radius diagram for the giant planets, illustrates some of the general conclusions that can be drawn from a consideration of these two basic parameters. Shown are some approximate curves for spherical objects of various compositions at 0 K. As has long been known, hydrogen is a dominant constituent of Jupiter and Saturn but not of Uranus and Neptune (*2*). Therefore Uranus and Neptune represent compositions that have been altered from the original nebular material. From Fig. 2 we might conclude that Jupiter and Saturn are of primordial composition, but more detailed studies, outlined below, prove that they, too, have been somewhat depleted in gaseous constituents.

Current investigations of the interior structure of the Jovian planets are attempting to make the general conclusions above more quantitative and more detailed by means of modeling that takes into account the interaction of the atmosphere and interior, heat flow measurements, and gravitational field parameters. Experimental and theoretical determination of the high-pressure behavior of important likely constituents plays a major role in this work.

In this article I present an assessment of our current understanding of the distribution of density and chemical composition in the Jovian planets. Heat flow measurements and their implications for the structure and evolution of the Jovian planets have been reviewed recently (*3*).

Geophysics of Giant Planets

Detailed knowledge of the earth's interior is provided primarily by seismology, which yields seismic wave velocities as a function of depth by inverting seismic travel times as a function of angular separation on the earth's surface. Such detailed information is unavailable for any other planet so far. For Jovian planets, another geophysical approach comes into play. In this technique, we use the response of the planet to rotation to provide a series of integral constraints on the interior equation of state.

Consider a rotating, liquid planet that is in hydrostatic equilibrium with its own gravitational field and rotational field. For solid-body rotation, we may write

$$Q = \frac{1}{2}\omega^2 r^2 \sin^2\theta = \frac{1}{3}\omega^2 r^2[1 - P_2(\cos\theta)] \quad (1)$$

where Q is the rotational potential in the fluid's comoving frame, ω is the angular rotation rate, r is the distance from the center of mass, θ is the colatitude, and P_2 is a Legendre polynomial. We can regard Q as a perturbation to the spherically symmetric gravitational potential that would prevail in the absence of rotation.

As a result of rotation, the planet's external gravitational potential is expressed as

$$V = \frac{GM}{r}\left[1 - \sum_{l=1}^{\infty} J_{2l}\left(\frac{a}{r}\right)^{2l} P_{2l}(\cos\theta)\right] \quad (2)$$

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