These patterns include, for example, variations in the type of forest cover with soil types and local climate. Not all of the Amazon is covered with dense rain forest; natural grasslands or savannahs occur, and Radam botanists now distinguish open forests in which palm trees occur nearly as frequently as the huge hardwood trees that predominate in denser areas. They have identified more than 400 species of trees and estimate the value of the standing crop of the species with known uses to be in excess of $1 trillion. (Exploitation of hardwood species in a big way is not now contemplated, however, because the trees would sink in water and are so huge, often 60 meters high, that anything other than river transport would be difficult.) The idea of a rain forest itself may be somewhat misleading, Radam investigators say, because only three regions of the Amazon Basin have year-round rainfall. Other areas experience dry seasons 2 to 5 months in length.

Soil patterns are equally surprising. Although much of the soil is poor in nutrients, pockets of good soil exist. Radam scientists found one large area in the westernmost reaches of the Amazon that contains 100,000 square kilometers of thick, fertile soil capable, they say, of supporting intensive agriculture. Netto estimates that at least 2 percent of the Amazon Basin consists of good soil, and he points out that the radar images recently led to the discovery of large deposits of limestone which, if added to neutralize the acidic soils of many plateau areas, could make them productive as well. In large areas, however, the soils will not support use at all, turning to sand or (in laterite areas) to rock when the covering vegetation is cleared.

The land use map is, in a sense, the summation of the information on the other six, but includes as well the results of sociological surveys of any existing inhabitants of the region. They were asked what crops grow well, what institutions and infrastructure (landing strips, schools, and so on) already exist in the region, and the state of the local economy. The map attempts to single out the most promising areas and activities for development, points out restrictions posed by soil or vegetation, and proposes regions for preservation. Specifically considered are any known mineral indications and the potential for lumbering, raising cattle, and agriculture.

A typical example is a 290,000 square kilometer region in the south-central Amazon Basin, straddling the boundary between the states of Amazonas and Para. The Rio Tapajos runs through the region, which is heavily forested. The Radam maps (Fig. 3) indicate that lumbering is, in fact, nearly the only activity that ought to be contemplated, although there are also indications of gold, tin, and several other minerals scattered throughout the region. The soils, however, are too poor to support intensive agriculture, and the existing vegetation is not appropriate for cattle ranching. In a few places, however, especially along river beds, there appears to be a substantial potential for extractive products such as palm oil. A number of areas are marked as unexploitable by law, because the slopes are at angles greater than 45°, or as needing special protection because of their fragility. The proportion of the area covered by the map that falls into each category is summarized on a separate legend.

All these maps, with the exception of the radar images, are made essentially by hand. That is particularly remarkable because the scientific staff of Radam totals about 150, and these same people perform the fieldwork. The operation has been a lean one in other ways as well. The total cost of the effort, which is funded by Radam's parent agency, the Departamento Naciónal da Producão Mineral of the Ministry of Mines and Energy, has been about $40 million for the first 5 years. Radam has also had what seems to be a remarkable degree of autonomy in developing its own sampling and interpretive techniques and deciding what information should be published, and in what form.

Radam is highly regarded in Brazil, as well it might be. More to the point, the information it is providing is being actively sought and used by government planners who have responsibility for development activities in the Amazon Basin. Even the proposed land use designations seem not to have become controversial, and there are indications that they are being adopted by other agencies. In any case, it is clear that Radam has provided the means for what one Brazilian describes as "a rare opportunity—the chance to plan a continent's development before it happens."

—ALLEN L. HAMMOND

# Remote Sensing (III): The Tools Continue to Improve

Remote sensing extends the human perspective not only by offering airborne and satellite platforms from which to look at the earth but also by making possible new and more quantitative methods of gathering information. The aerial camera, for example, has been supplemented by multispectral scanners that record information in digital rather than photographic form. Improvements in methods of processing remote sensing data are extending these tools even more. Two recent examples are an experimental technique for superposing Landsat and side-look radar images, thus combining in a single image information from two complementary approaches normally used in isolation from each other, and the development of new methods of exploiting the information content of digital Landsat data to produce enhanced images.

Microwave radar is less well known as a remote sensing tool than, for example, Landsat, but it is finding increasing use—part of a trend toward applying new portions of the electromagnetic spectrum that also includes the infrared radiometers on weather satellites. Radar remote sensing systems were developed in the United States for intelligence purposes and have since been declassified, and several are commercially available. The version developed jointly by Goodyear Aerospace and Aero Service seems to have been most successful and has been used commercially to survey more than 12 million kilometers on four continents in the past 5 years.

The system transmits microwave pulses at a wavelength (0.03 meter) that is relatively insensitive to weather conditions. The reflected signal is processed electronically, displayed on a cathode ray tube, and recorded on film, pulse by pulse; Doppler variations in signal frequency created by the motion of the plane appear as varying densities in the film emulsion, creating a phase history—in effect, a kind of hologram—of the radar image. This technique synthesizes information from several pulses and can thus distinguish features as close as 10 meters, even from a high-flying aircraft—a resolution otherwise unobtainable without an antenna too large to carry on an aircraft. The image itself is reconstituted, in the final processing step, by illuminating the film with coherent light from a laser and exposing a second film.

The radar images are useful to resource specialists in identifying such features as drainage, geologic structures, and especially topography, even through a layer of dense vegetation. The idea of combining these images with Landsat data seems to have occurred independently to LeRoy Graham of Goodyear Aerospace, Litchfield Park, Arizona, and George Harris, Jr., of the U.S. Geological Survey's EROS data center in Sioux Falls, South Dakota. Landsat images from one of the four individual wavelength bands recorded by the satellite sensors or from a composite can be interpreted to yield information about soil types, vegetation, geology, and many other features of the earth's surface—but not the topography. In addition, the ground resolution of the Landsat data is about a factor of 10 worse than that of the radar, but repeated coverage of the same area is readily available from the satellite to follow seasonal or other changes. Hence the two techniques seem to complement each other well. After initial attempts independently, Graham and Harris conducted a series of joint experiments in which they investigated a number of different techniques for combining the two types of images photographically.

The results are striking (cover photo). In a paper delivered to an international conference in Helsinki last year, Graham and Harris conclude that superposition of the two types of images, while somewhat difficult to do on a routine basis, appears to retain all the information available from either sensor system alone and to expose additional information from the synergistic effect of viewing the two simultaneously. They tried several general techniques of superposition. One is simply to use the radar image in place of one of the Landsat bands in making a color composite, a process that involves successively printing black-and-white transparencies of three different bands with light passed through blue, green, and red filters; however, this gave disappointing results. A second approach consists of preserving the normal Landsat color balance, which is useful in identifying surfaces, and adding the radar information as intensity or density variations that define boundaries and portray relief features in the combined image. Both multiplicative and additive methods of combining the information were tested; the investigators conclude that the additive approach gives the best overall results, even though it requires multiple exposures (six in all). The Goodyear group plans to experiment further and is considering combining the radar and Landsat images digitally (with a computer) rather than photographically.

Fig. 1. Color composite Landsat image of sea ice off the coast of Spitzbergen, an island between Iceland and Norway. This computer-enhanced image shows detail that would otherwise be lost due to film saturation from the brightness of the light reflected from the ice and snow; algorithms automatically adjust the brightness level of the recorded data to the dynamic range of the film. [Source: U.S. Geological Survey EROS Data Center]

Digital manipulation of image data offers a variety of advantages, including ease of processing once the appropriate computer algorithms have been developed. Computer image enhancement is common, in fact, in interpreting intelligence photos and television images radioed back from interplanetary spacecraft. But image enhancement techniques have not been routinely applied to Landsat data, despite the fact that the 64 gray levels distinguished by the multispectral scanner on board the satellite represent a far more subtle store of data than can be portrayed by standard photographic techniques. Recently, however, Harris and his colleagues at the EROS data center have remedied this lack, and they are now operating an image enhancement system for Landsat data which is capable of handling a limited quantity of requests.

Their system incorporates a laser film recorder that focuses to a 50-micrometer spot for more accurate image production and a set of computer algorithms to prepare the Landsat data pixel by pixel for photography. The results are exceedingly sharp and, when combined into a false color composite, yield an image in which much more information is readily discernible than is normally possible (Fig. 1). The algorithms they use are designed to correct for geometric distortions, extremes of contrast, and the scattering effect of the earth's atmosphere and to create more clearly defined boundaries and edge effects. The overall image quality is also higher because there are fewer photographic steps than in normal Landsat image processing, resulting in less degradation.

Improved remote sensing satellites planned for the 1980's are to have better ground resolution and scanners that can distinguish more than 200 gray levels, so that the ultimate in images of the earth's surface is far from achieved. These developments suggest, however, the power of remote sensing methods, their increasing variety and versatility, and the enormous amount of information that can be and is being obtained from them.—Allen L. Hammond