The Role of Terrestrial Vegetation in the Global Carbon Cycle:
Measurement by Remote Sensing
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CHAPTER 5
Remote Sensing to Measure the Distribution and Structure of Vegetation

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ABSTRACT

Three types of primarily aircraft-based remote sensing systems are described with reference to global vegetation monitoring. The advantages, constraints and analysis of aerial photography, multispectral scanning systems, including LANDSAT, and radar systems are discussed. Each system provides information not obtainable from the others. Used in combination under clearly defined conditions, these systems can be applied to assess distribution and structural characteristics of the global vegetation.

5.1 INTRODUCTION

A substantial amount of study of various remote sensing systems during the past decade has shown that no single data collection platform (satellite or aircraft), remote sensing instrument system (camera, scanner or radar), or analysis technique (computer-aided analysis or manual interpretation) is adequate to meet all of the needs of various users. It appears that use of combinations of instrument systems, data collection platforms and analysis techniques will meet most needs, especially when these techniques are coupled with ancillary data. It is the purpose of this paper to examine some of the characteristics of the various instruments and techniques available for measuring the distribution and structure of the world's vegetation.

5.2 AERIAL PHOTOGRAPHY

5.2.1 Introduction

Aerial photographs have been used for many years to identify and map vegetation, to measure their area and to characterize form, size and condition of plants and plant communities. Four types of film are commonly used: black and white panchromatic, black and white infra-red, colour, and colour infra-red.

5.2.2 Black and White Films

Black and white panchromatic is the most commonly used film for aerial photography. There are many types of panchromatic film, each having its own emulsion characteristics, but as a group, panchromatic films have the best resolution of any of the film types. High resolution makes it particularly useful for such measurements as heights of trees or diameters of crowns.

Black and white panchromatic film is sensitive only to the visible wavelengths of the spectrum (0.4 to 0.7 μm), whereas black and white infra-red film is sensitive to the 0.7 to 0.9 μm portion of the spectrum as well as the visible wavelengths. Because coniferous tree species generally have less infra-red reflectance than deciduous species (Figure 5.1), black and white infra-red film is particularly useful for differentiating between these two major groups of forest cover. In some applications a Wratten 89B filter (which prevents any of the

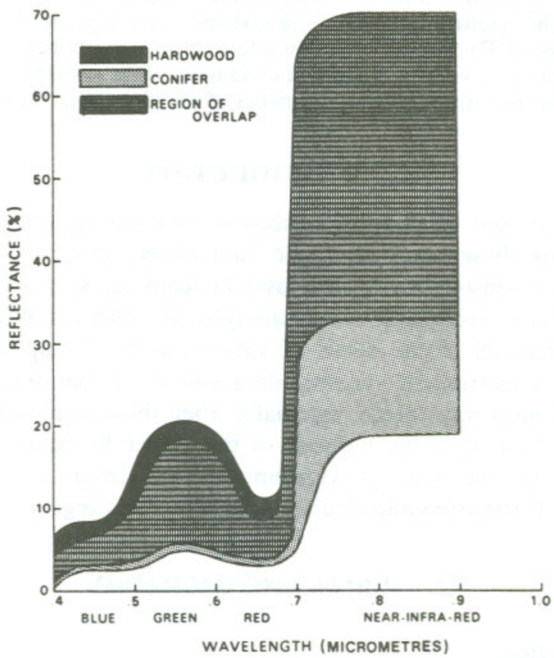

Figure 5.1 Generalized spectral reflectance characteristics of deciduous and coniferous forest species (after Murtha, 1972, reproduced by permission of the Minister of Supplies and Services, Canada)

visible wavelengths from reaching the film) is used, to provide contrast between deciduous and confierous forests. In other cases a Wratten 25 (red) filter is preferred, so that the film is sensitized by both the red visible and reflective infra-red wavelengths. The result is a photograph with less contrast. Such 'modified black and white infra-red' photos are commonly used by the US Forest Service. Because the resolution of black and white infra-red film is not as good as that of panchromatic, the latter film is preferred for mensurational purposes.

Since black and white infra-red film is sensitive to the visible as well as to the infra-red wavelengths, it is the film used for multiband photography. A considerable amount of research was conducted in the late 1960s using multiband cameras, most of which had four lenses, but some of which had as many as nine (Lowe *et al.*, 1964; Yost and Wenderoth, 1967; Colwell, 1968; Lauer, 1971; Reeves, 1975). Different filters on each lens allow only certain wavelengths to impinge on the film. Through the use of a special viewing device and appropriate filters, it is possible to combine images from the blue, green and red visible wavelengths, for example, to create a standard colour image of the scene; or the green, red and reflective infra-red wavelength bands can be combined to create a 'colour infra-red' image. Other combinations can also be defined to enhance a particular feature of interest. Although these methods provide a relatively inexpensive research tool, they have seldom been used on an operational basis.

5.2.3 Colour Films

Black and white photos are generally not as useful as colour or colour infra-red photos for identifying individual species of trees, shrubs, grasses and forbs. This is not surprising, since the human eye can distinguish far more hues and tones of colour than it can distinguish shades of grey (Heller, 1970). Colour films have three emulsion layers that are sensitive to the blue, green and red visible wavelength portions of the spectrum. Some colour films, such as Kodachrome and Ektachrome, are colour reversal films that are developed into a positive emulsion (or transparency) suitable for direct viewing. Other colour films, such as Kodacolor and Ektacolor, produce a film negative from which positive prints are made. The resolution of such prints is not as good as that of the transparencies, but prints are easier to use in the field. There is also a colour film called Aero-neg, which can be developed into either a positive or negative emulsion. Developed as a negative, this film can then produce positive prints, transparencies or diapositive plates in either black and white or colour (Smith, 1968).

5.2.4 Colour Infrared Film

Colour infra-red film (i.e., Kodak Aerochrome Infrared Film, Type 2443) has been tested and used extensively for mapping vegetation and assessing its condition. Because the film is sensitive to wavelengths to which our eyes are not sensitive, it is more difficult to interpret than regular colour film. Colour infra-red is similar to regular colour film, however, in that both types have three emulsion layers. The main difference is that the three emulsion layers of properly filtered infra-red film are sensitive to the green, red and reflective infra-red wavelengths. Since all three emulsion layers of colour infra-red are also sensitive to the blue wavelength portion of the spectrum, it is used with a yellow (or 'minus-blue') filter (usually a Wratten 12 or Wratten 15) to obtain a good image. Thus, regular colour film has a sensitivity range of about 0.4 to 0.7 μm whereas properly filtered colour infra-red film is sensitized to wavelengths between 0.5 and 0.9 μm (Kodak, 1976).

It should be pointed out that photographic films used in remote sensing are limited to the ultraviolet, visible and reflective infra-red wavelengths up to 0.9 μm. The thermal infra-red portion of the spectrum, however, extends from approximately 3 to 14 μm. Hence, *colour infra-red film is not sensitive to the thermal infra-red portion of the spectrum*, and *cannot be used* to detect thermal phenomena, such as heated water discharged from hydroelectric plants into rivers or lakes, or heat loss from buildings (Fritz, 1967). Thermal infra-red scanner systems must be used to detect energy in the thermal infra-red portion of the spectrum.

One of the major advantages of colour infra-red film is its ability to enhance subtle differences in reflectance that are barely discernible in the visible wavelengths (Reeves, 1975). Frequently, spectral differences due to variations in plant species or to stress conditions will exist but will be so subtle that they are difficult to see on regular colour film. Although spectral differences may be very small in the visible wavelengths, they may be very distinct in the near infra-red wavelengths and therefore will show up clearly on colour infra-red film. Examination by the author of a large number of colour infra-red photos and corresponding colour photos obtained at the same time, and a careful review of the literature indicate that there are relatively few cases in which spectral differences in vegetation, soils or water that are visible on colour infra-red film cannot be detected on properly exposed colour film. However, there are many cases where the spectral differences are so subtle that they would be missed if the photo interpreter relied only on regular colour film.

A second major advantage of colour infra-red film is its ability to penetrate atmospheric haze better than normal colour film. This is because atmospheric scattering of light is more pronounced in the shorter wavelengths, and the yellow filter normally used with colour infrared film prevents these strongly scattered blue wavelengths from reaching the film.

5.2.5 Interpretation of Colour and Colour Infra-red Films

Whereas the cyan emulsion layer of colour infra-red film is sensitive to the 0.7 to 0.9 μm reflective infra-red wavelengths, the other two emulsion layers are sensitive to the visible wavelength portion of the spectrum (green and red). This implies that spectral variations in either the visible or the reflective infra-red wavelengths, or a combination of both, will cause colour differences on colour infra-red film. Thus, even though different objects have different colours on colour infra-red film, it does not necessarily follow that a difference in infra-red reflectance is present. The difference in colour may be caused solely by differences in reflectance in the visible wavelengths. Frequently, however, differences in colour on the colour infra-red film are caused by spectral variations in both the visible and infra-red wavelengths. This makes colour infra-red film difficult to interpret unless something is known about the spectral characteristics of the material of interest, both in the visible and infra-red wavelengths.

A considerable amount of research has been conducted into the usefulness of colour and colour infra-red films for mapping vegetative types and conditions. Distinguishing between deciduous and coniferous trees can be done very effectively with colour infra-red film, since the higher near infra-red reflectance of the deciduous species cause them to have a much brighter red appearance than the conifers. Determining the amount of vegetative cover present in an area is also much easier with colour infra-red film, which enhances the appearance of vegetation against a soil background. Colour film is much better than black and white panchromatic film for identifying individual species of trees (Heller *et al.*, 1966) and colour infra-red has been shown to be more effective than colour film for identifying a variety of grasses, forbs and shrubs (Driscoll and Coleman, 1974). The effectiveness of colour or colour infra-red film for differentiating species is often dependent on the phenology of the vegetation as well as the scale and quality of the photos used. Because of the increased information content and interpretability of colour and colour infra-red films, efficiency of interpretation is increased significantly (Lauer, 1971). In one study, the time required to classify 50 000 acres of forest land was cut from 44 to 21 hours through the use of small-scale colour infra-red film rather than black and white panchromatic (Lauer and Benson, 1973). The advantages of regular colour film have led the US Forest Service to adopt 1:15 840 colour photography for National Forest mapping activities.

When plants are affected by stress, such as that caused by disease or insect damage, changes occur in the spectral reflectance characteristics of the foliage. Colwell (1956) reported previsual detection of wheat rust using colour infra-red film, provided the photos were obtained under certain conditions of development of the disease, illumination and film exposure. Manzer and Cooper (1967) showed that colour infra-red film can be an effective tool for detecting late blight in potatoes. There have been many other studies concerning the use of colour infra-red film, as well as other film types and remote sensing systems, to detect stress (Colwell, 1960; Heller, 1971; Bauer *et al.*, 1971; Murtha, 1972; Reeves, 1975; Aldrich, 1979). The enhancement capabilities of colour infra-red film clearly make it a very useful tool for monitoring plant diseases and insect infestations. Such conditions cause a difference in tone that makes the stressed vegetation distinguishable from the normal red tone of healthy surrounding vegetation. However, it would appear that there are very few well-documented cases of true previsual stress detection using colour infra-red film. Aldrich (1979) stated that there was no evidence to indicate that previsual stress could be detected in either coniferous or deciduous trees.

To assess the state of the art concerning the capabilities of remote sensing for assessing vegetation damage, a special symposium was sponsored by the American Society of Photogrammetry in 1978, the proceedings of which are available from ASP. The theory and use of remote sensing for vegetation damage assessment are summarized very well in papers by Murtha (1978) and Heller (1978).

5.2.6 Scale of Photography

In addition to the type of film used, the scale of aerial photography affects its utility for vegetation mapping and monitoring. Most activities involving remote sensing to map and characterize vegetative cover are concerned with floristic mapping, physiognomic mapping or stress detection and monitoring. For these purposes, medium to large-scale photos are generally needed to achieve accurate and reliable results. In the United States, foresters have traditionally utilized a scale of 1:15 840 (four inches equals one mile), while agronomists and soil scientists have preferred 1:20 000 scale photos (Colwell, 1960). Improved film resolution, cameras and aircraft capabilities now allow smaller scale photos to be used for some purposes, and 1:40 000 is currently the standard scale used by USDA in many states for crop surveys and soils mapping.

The particular scale and the type of film to be used depend on the degree of mapping detail involved and the accuracy required. For most types of quantitative measurement, as photo scale decreases so does the accuracy of measurement. For example, 1:15 840 is an effective scale for mapping forest cover types, but identification of individual trees by species and measurements of height and crown diameter to obtain volume estimates require stereo photos that have a much larger scale, such as 1:1 000 to 1: 5000 (Heller *et al.*, 1966; Sayn-Wittgenstein and Aldred, 1967; Avery, 1977; Aldrich, 1979). Crown closure estimates can be obtained from somewhat smaller scale photos, such as 1: 5000 to 1:15 000 (Avery, 1977). Rangeland managers require very large-scale (1: 800 to 1:1500) photos to identify individual species of shrubs and range vegetation, although smaller scale photos can be used to delineate vegetation communities and their condition. Colour and colour infra-red photos are much more effective than panchromatic or black and white infra-red photos for these purposes (Driscoll and Coleman, 1974). Table 5.1 provides a good summary of the relationships between the scale of the photography and the degree of detail that can be obtained.

Table 5.1 Utility of different scales for vegetation mapping (from Avery 1977)

Type of imagery or scale	General level of plant discrimination
Earth-satellite imagery	Separation of extensive masses of evergreen versus deciduous forests
1:25 000–1:100 000	Recognition of broad vegetative types, largely by inferential processes
1:10 000–1:25 000	Direct identification of major cover types and species occurring in pure stands
1:2500–1:10 000	Identification of individual trees and large shrubs
1:500–1:2500	Identification of individual range plants and grassland types

Careful consideration should always be given to the purpose for which the photos are to be used since, as the scale increases, complete coverage of an area will require more flight-lines and also result in a much larger number of photos, thereby increasing both data collection and handling costs significantly. For example, 23 cm × 23 cm (9 in × 9 in) stereo photos for an area of 1000 km^2 would require 45 photos at a 1:40 000 scale, 177 photos at a 1:20 000 scale, 705 photos at a 1:10 000 scale and 2778 photos at a 1:5000 scale (Avery, 1977). It is apparent, therefore, that the smallest-scale photo that is adequate to provide the information required is the most economical scale to use.

5.2.7 Use of Small-scale Photography

Several studies during the past decade have helped to define many of the potentials and limitations of small-scale aerial (1:120 000) and space (1:500 000 to 1:2 400 000) photos (Draeger *et al.*, 1971; Aldrich, 1971; Lauer and Benson, 1973; Hay, 1974; Marshall and Meyer, 1977; NASA, 1978). Small scale colour infra-red photos have been shown to be effective for distinguishing forest from non-forest classes and for differentiating deciduous from coniferous forest cover. Individual forest cover types (i.e., species associations) generally could not be identified directly, but in some cases the boundaries of different cover types could be delineated, and through comparison with larger scale aerial photos or existing reference data, the type could be identified. The degree of detail that could be defined depended on the season and the characteristics of the forest and other vegetative cover types present.

Time of year has been shown to be particularly critical in agricultural applications of small scale aerial and space photographs, since crops develop rapidly and different species are often at different stages of development at any particular time. Most studies of agricultural applications have concluded that data are needed at more than one time during the growing season, and that dates when photos are needed are a function of the crop calendars for the various species (Colwell, 1960; Reeves, 1975; Bauer, 1975; NASA, 1978).

When using medium to large scale photos from aircraft altitudes, the interpreter generally utilizes many (if not all) of the commonly defined principles of photo interpretation to identify cover types. These principles include size, shape, tone and colour, texture, shadow, pattern and association (including site). However, when using the very small-scale photos obtained from spacecraft altitudes the interpreter finds himself much more dependent on tone or colour, because such characteristics as shadow and texture or the size and shape of individual trees cannot be discerned. Dependence on the colour of various cover types, and the variability of the colour as a function of time of year and geographic location, also make the interpreter much more aware of the need to be knowledgeable about the spectral reflectance characteristics of various cover types and how such spectral characteristics vary, both as a function of time and of geographic location.

One of the major advantages of spacecraft data is its synoptic view. Hence, the use of small-scale photos to cover an entire area and to delineate or stratify major cover types at a generalized level, in combination with statistically defined samples of medium and large-scale photos to identify individual cover types and their characteristics, seems to be a logical approach to obtain reliable resource information. Such an approach, often referred to as 'multistage' or 'multilevel' sampling, allows one to take advantage of the capabilities of the various scales (Langley *et al.*, 1969; Heller, 1978; Aldrich, 1979).

One obvious limitation of photographs obtained in space is the difficulty of returning them to earth. Other than the Apollo-9 and Skylab EREP projects, there have been relatively few photographic studies of earth resources from space. However, these two projects did create a great deal of interest in mapping and monitoring vegetation and other earth resources from space. Thus, the launch of LANDSAT-1 and the capability to telemeter this type of data received considerable interest from resource managers.

5.3 MULTISPECTRAL SCANNER SYSTEMS (MSS)

5.3.1 Introduction

The launching of the LANDSAT-1 (originally ERTS-1) Earth Observation Technology Satellite in 1972 greatly increased the use of multispectral scanner data. Prior to 1972, multispectral scanner systems (MSS) had been flown at aircraft altitudes, and the possibility of identifying various features of the earth's surface on the basis of spectral reflectance patterns had been shown (Lowe *et al.*, 1964; Hoffer, 1967). The first MSS capable of obtaining data throughout the optical portion of the spectrum and recording the data on tape was developed at the University of Michigan in 1966, and the first single-aperture system became available in 1971 (Hasel, 1972). Early work with MSS data indicated that the increased range of wavelengths in which data could be obtained offered significant potential, but that manual interpretation of subtle differences in reflectance or emittance among many different images was not an effective method for analysing such data (Hoffer, 1967). The concept of applying pattern recognition techniques to the analysis of multispectral scanner data was then developed and in 1967 it was demonstrated that such an approach was feasible (Landgrebe and Staff, 1967; Holter *et al.*, 1970). Since that time, many techniques for computer-aided analysis of MSS data have been developed.

5.3.2 Multispectral Scanner Systems

Multispectral scanner systems differ from photographic systems in several ways, including the optical-mechanical mechanisms for collecting data, the quantitative character of the data collected, and the range of frequencies to which the detectors are sensitive.

In multispectral scanner systems the energy reflected or emitted from a small area on the earth's surface (the resolution element or instantaneous viewing area) at a given moment is reflected from a rotating or oscillating mirror through an optical system which disperses the energy spectrally on to an array of detectors. The motion of the mirror allows the energy along a scan line (which is perpendicular to the direction of flight) to be measured, while the forward movement of the aircraft or spacecraft brings successive strips of terrain into view. The detectors, carefully selected for their sensitivity to energy in the various portions of the spectrum, and appropriately filtered, simultaneously measure the energy in the different wavelength bands. The output signal from the detectors is amplified and recorded on magnetic tape.

The quantitative format of MSS data makes it ideally suited for telemetering to earth and for processing by computer-aided analysis techniques, whereas photographic data are qualitative in format and best suited for manual interpretation. The spatial resolution of scanner data (i.e., the instantaneous viewing area on the ground) is a function of both the characteristics of the scanner and its altitude. Since the data from scanner systems generally do not have spatial resolution as good as can be obtained from photographic systems at the same altitude, small objects cannot be resolved as well. However, the spectral resolution of MSS systems can be much better (i.e., energy from much narrower wavelength bands can be accurately measured). Of perhaps even more importance is the fact that scanners can record data throughout the 0.3 to 14 μm wavelength region, but photographic systems cannot effectively record data at wavelengths longer than 0.9 μm.

5.3.3 Spectral Reflectance Characteristics of Vegetation

The data collected by multispectral scanners represent the spectral reflectance and emittance characteristics of various cover types. It has been determined that different cover types reflect and emit varying amounts of energy in a single spectral band, and that a single object reflects and emits varying amounts of energy as a function of wavelength (Gates *et al.*, 1965; Hoffer and Johannsen, 1969; Howard, 1971; Sinclair *et al.*, 1971; Hoffer, 1978). Therefore, the proper interpretation of multispectral scanner data or other remote sensor data (such as colour infra-red film) requires a knowledge of the spectral characteristics of vegetation, soil, water and other earth surface features.

Figure 5.2 is an example of the spectral reflectance characteristics of typical green vegetation. This curve shows the low reflectance due to chlorophyll absorption bands at approximately 0.45 and 0.65 μm in the visible wavelengths, the typical high reflectance in the 0.72 to 1.3 μm (near infra-red) region, and the distinct water absorption bands at approximately 1.45 and 1.95 μm in the middle infra-red wavelengths. Minor water absorption bands are also evident at about 0.96 and 1.2 μm.

In the visible and reflective infrared portions of the spectrum, the energy incident (I) upon an object that is not reflected (R) by the object must be either absorbed (A) or transmitted (T) through the object. Thus, for any particular wavelength (λ):

$$I_\lambda = R_\lambda + A_\lambda + T_\lambda$$

For turgid green vegetation, most of the energy in the visible wavelengths (below about 0.72 μm) is absorbed by chlorophyll, with less absorption and higher reflectance in the green wavelengths (about 0.55 μm) between the two chlorophyll absorption bands. Very little energy in the visible wavelengths is transmitted through a leaf, but in the near infra-red wavelengths (from about 0.72 to 1.3 μm) only very small amounts of energy are absorbed, and nearly all energy not reflected is transmitted through the leaf. In the middle infra-red

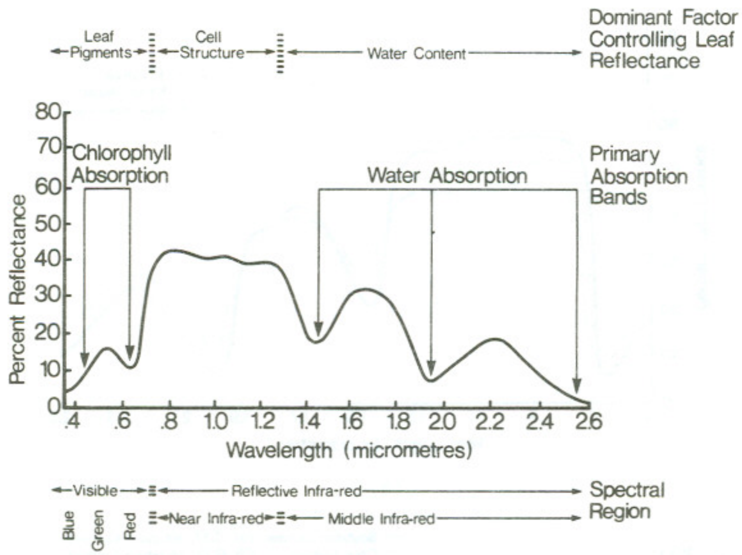

Figure 5.2 Spectral reflectance characteristics of green vegetation (after Hoffer and Johannsen, 1969)

wavelengths from 1.3 to 2.6 μm, most of the energy not absorbed by the water in the leaf is reflected, leaving much smaller amounts to be transmitted (Gates *et al.*, 1965; Hoffer and Johannsen, 1969). In these wavelengths the amount of energy absorbed is a function of the water content of the leaf, which is related to both moisture content and leaf thickness (Hoffer, 1978).

Although some vegetative cover types have significantly different spectral response patterns (as seen in Figure 5.1), many tree species and many agricultural crops have spectral response patterns that are very similar, as indicated in Figure 5.3. Although Figure 5.3 shows differences between the curves of various species, such differences are often not consistent or distinct enough to permit species identification when measurements from multispectral scanner systems at altitudes ranging from a few thousand feet to hundreds of miles are used. However, spectral differences between major cover types, such as green vegetation, dry dead vegetation, light and dark soils, clear and turbid water and snow, are significant and distinct, as indicated in Figure 5.4. It is the spectral differences that enable multispectral scanner systems and either manual or computer-aided analysis techniques to be used to identify and map various surface features and cover types. Use of MSS data from the LANDSAT satellites has been the subject of numerous investigations during the past several years.

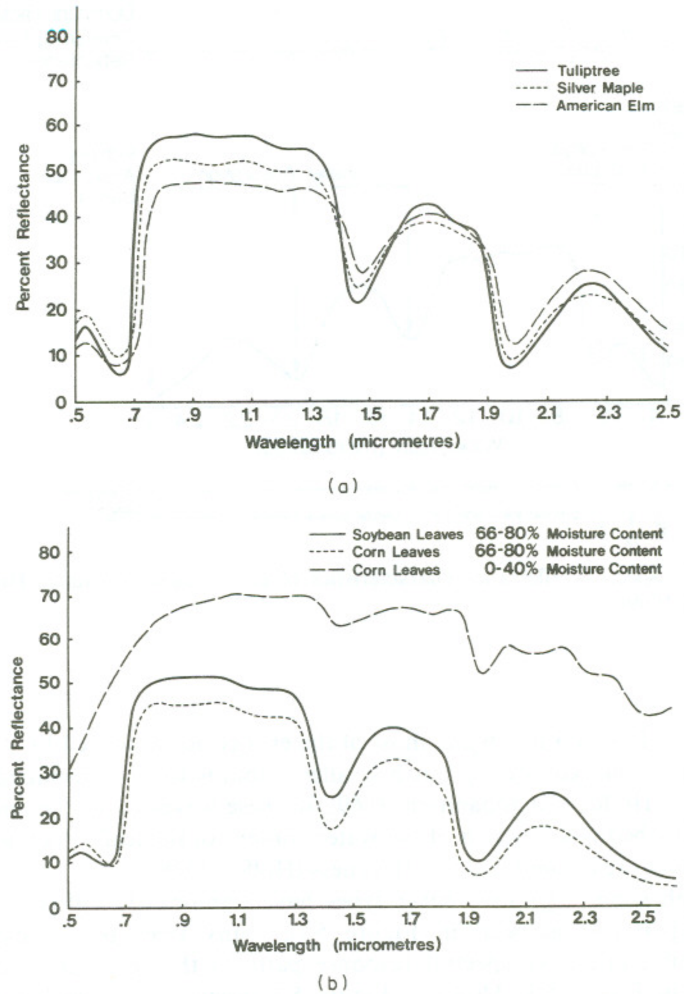

Figure 5.3 Spectral reflectance for (a) three species of trees and (b) corn and soybeans (after Hoffer and Johannsen, 1969)

5.4 THE LANDSAT MULTISPECTRAL SCANNER SYSTEM

5.4.1 Introduction

The launch of LANDSAT-1 in 1972 opened a new dimension in our capability to obtain data over most of the earth's surface at any time of year (cloud cover permitting). LANDSAT-1 was followed by LANDSAT-2 in 1975, LANDSAT-3 in 1978 and LANDSAT-4 (LANDSAT-D) in 1982. The polar orbit of the

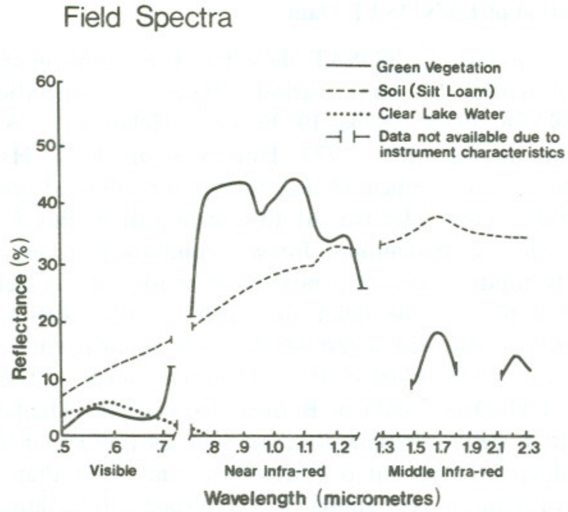

Figure 5.4 Spectral reflectance characteristics of major earth surface cover types (after Bartolucci *et al.*, 1977)

satellites allows data to be collected over virtually the entire surface of the earth every 18 days. The MSS system on the satellites collects data in four wavelength bands, including the 0.5 to 0.6 μm (green visible), 0.6 to 0.7 μm (red visible) and 0.7 to 0.9 μm and 0.8 to 1.1 μm (reflective infra-red). The data are handled in frames, each of which covers an area on the ground of 185×185 km (115×115 statute miles). A frame contains 2340 scan lines, each of which has 3236 resolution elements, resulting in a total of 7 572 240 resolution elements, or pixels, each of which represents an area of approximately 0.46 hectare (NASA, 1972a). Since the data are collected in each of the four bands, more than 30 million individual reflectance measurements are contained on the data tape representing a single frame, which is obtained in only 25 seconds. The Thematic Mapper (TM) scanner on LANDSAT-4 obtains significantly greater quantities of data because it has higher spatial resolution (i.e., 30 m) and seven spectral bands.

LANDSAT data for any portion of the earth's surface for which they exist are available through the EROS Data Center, Sioux Falls, South Dakota. The data can be obtained as a black and white image at scales of 1:1 000 000, 1:500 000 or 1:250 000, or as a 'colour infra-red composite' at one of the same scales (Rhode *et al.*, 1978). The colour infra-red composites are artificially created through appropriate combination of the green, red and one of the reflective infra-red wavelength bands, and are therefore often referred to as 'false' colour infra-red images.

5.4.2 Interpretation of LANDSAT Data

Manual interpretation of LANDSAT data has been used in many studies throughout the world to map various types of vegetation and its characteristics (NASA, 1972b, 1973a, 1973b, 1975; Heller, 1975; Aldrich, 1975, 1979; Adrien and Baumgardner, 1977; Hooley *et al.*, 1977; Hsu, 1978). In general, these studies have indicated that the colour infra-red composite at a scale of 1:250 000 is most effective. At this scale and in this format, major cover types—such as deciduous forest, coniferous forest, rangeland, agricultural lands, tundra, areas of exposed soil or rock and water (both clear and turbid)—generally can be delineated and mapped with a reasonable degree of accuracy. Disturbed forest lands, such as clear-cuts, can also be reliably defined (Lee, 1975; Aldrich, 1975). However, work by Hsu (1978) and the author with LANDSAT data in Bolivia, Taiwan and Thailand indicates that it is difficult to define brushland areas, such as those that develop after clear-cutting, unless the clear-cut is relatively recent. After that, the spectral response from brushland is very similar to the response from jungle canopy.

5.4.3 Computer-Aided Analysis Techniques

Since LANDSAT data are obtained in digital form, and because such a format is well-suited to quantitative data processing, there has been considerable interest in applying computer-aided analysis techniques (CAAT) to LANDSAT data.

Two basic types of computer processing techniques can be applied: enhancement and classification. Enhancement techniques are directed at producing an image which is manually interpreted. This may involve enhancing the spectral characteristics in the data or digitally enlarging the data to allow more effective interpretation of spatial features (Kourtz and Scott, 1978). It may also involve superimposing two sets of data and enhancing the temporal differences.

Classification generally involves a series of steps including data reformatting and preprocessing, definition of training statistics, computer classification of the data, information display and tabulation, and evaluation of the results. These are discussed in more detail below.

5.4.3.1 Data Reformatting and Preprocessing

Data reformatting and preprocessing involves such activities as reformatting scanner data to place a full frame on a single data tape, digital filtering to improve data quality (signal-to-noise ratio), geometrically correcting and scaling the data to a common map base, and digital registration of multiple sets of scanner and other data. Such procedures do not involve analysis of the data. They simply allow data analysis to be carried out in a more effective manner.

5.4.3.2 Definition of Training Statistics

Analysis of MSS data involves a series of steps designed to enable the computer to identify various cover types or earth surface features. The key element is that the computer is 'trained' to recognize the particular combinations of numbers (the reflectance measurements in each of the wavelength bands) that characterize the cover types of interest. This training process involves scanner data from a limited geographic area. After a good set of training statistics has been developed, the computer is programmed to classify the reflectance values for each resolution element in the entire data set. In this way the computer can be used to map and tabulate cover types over a large geographic area at a much faster rate than is possible by using standard image interpretation techniques.

One of the major considerations in developing training statistics is the definition of the classes of material that the computer should be trained to recognize. There are two conditions which must be met by each class in an analysis of multispectral scanner data:

(1) The class must be spectrally separable from all other classes.
(2) The class must be of interest to the user or have informational value (Hoffer, 1976a).

One often finds that the classes of interest to the user cannot be spectrally separated at certain times of the year. Quite often, different species of green vegetation have very similar spectral characteristics, even though their morphological characteristics are quite different. Because a class must both be separable and have informational value, two quite different approaches are used in training the computer system.

The first approach is referred to as the 'supervised technique' and involves the use of a system of $X-Y$ coordinates to designate to the computer system the locations of known earth surface features that have informational value. For example, a certain $X-Y$ location is designated as a stand of ponderosa pine, another as a stand of aspen, and others as grassland, water, etc. This technique has been used quite effectively for agricultural mapping, but experience has shown that it is not as reliable for wildland areas, where the cover types of interest are not as spectrally homogeneous. The primary reason for this is the difficulty of defining locations that are representative of all the variations in spectral response for every cover type of interest (Hoffer and Fleming, 1978).

A second approach is the 'clustering technique' (sometimes referred to as the 'non-supervised technique'). In this approach the analyst designates the number of spectrally distinct classes into which the data to be classified should be divided. The computer is then programmed to classify the data into the designated number of classes and to print a map indicating which resolution elements belong to which spectral class. The analyst then compares this map with surface observation data (usually aerial photos) and determines which materials are represented by each of the different spectral classes on the map (e.g., spectral class one is aspen, class two is ponderosa pine, etc.). One problem with the technique is that the analyst does not know how many spectral classes are actually present. Furthermore, the classes of most interest are often rather similar spectrally, while many of the other classes may be easily separated spectrally but are of little informational value. In spite of these difficulties, much of the early work with the clustering technique indicated that it was more effective than the supervised technique for wildland or natural areas (Smedes *et al.*, 1970). With the advent of LANDSAT-1, computer-aided mapping of relatively large areas became more feasible. It was then found, however, that the amount of data and the number of spectral classes became too large to use the clustering technique effectively.

A 'multi-cluster blocks technique' was therefore developed and has proven to be extremely effective (Hoffer and Fleming, 1978). This technique involves a combination of the clustering and supervised approaches. Several small blocks of data (e.g., 40×40 pixels) are defined, each of which contains several cover types. Each data block is first clustered separately, and the spectral classes for all cluster areas are then combined. In essence, the modified cluster approach entails discovering the natural spectral groupings present in the scanner data and correlating the resultant spectral classes with the desired informational classes (cover types, vegetative conditions, etc.). Often, less than one per cent of the data involved in the final analysis are used for the training phase.

5.4.3.3 Computer Classification of MSS Data

After the training statistics are defined, the MSS data for the entire area of interest must be classified. The basis of the theory behind most of the classification algorithms is illustrated in Figure 5.5. Multispectral scanners are designed to measure the relative reflectance or emittance in designated wavelength bands, as indicated in Figure 5.5(a) by λ_1, λ_2 and λ_3. By plotting the relative reflectance (i.e., response values) of vegetation, soil and water for λ_1, λ_2 and λ_3 (as shown in Figure 5.5(b)), one sees that these cover types occupy very different locations in three-dimensional space. The classification algorithm must divide this three-dimensional space into regions that can be used to 'classify' any unknown data points or vectors. Any unknown data vector is classified into one of the spectral classes which the computer has been trained to recognize. Any one of several algorithms (such as the maximum

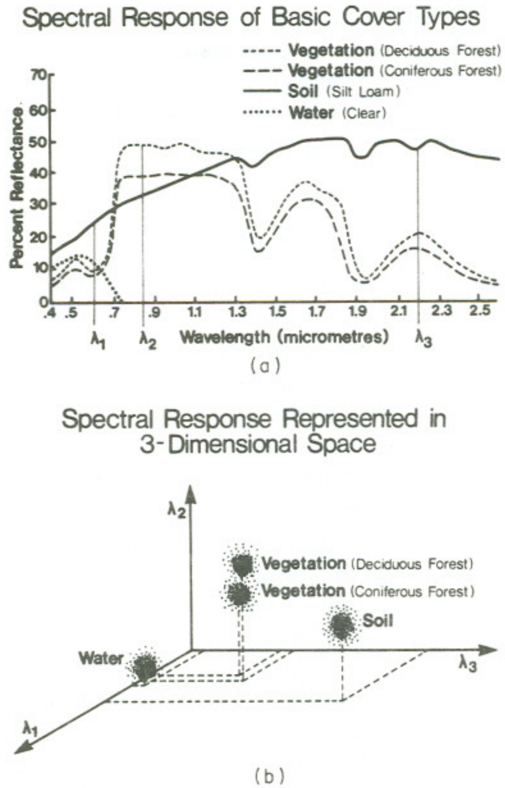

Figure 5.5 Schematic indicating the basis for computer classification of earth surface features

likelihood, parallelepiped, minimum distance to the means, ECHO, etc.) can be utilized for the classification itself. Different algorithms provide more or less accurate classifications and require varying amounts of computer time (Hoffer, 1979). Additional details are beyond the scope of this paper, but the entire subject is well documented in Swain and Davis (1978) and elsewhere.

5.4.3.4 Information Display and Tabulation

After the data are classified the results are stored on magnetic tape, and the analyst can display these results in a variety of map or tabular formats. Maps are usually in the form of 'thematic' maps in which each informational class of interest is displayed as a different colour or symbol.

Tabular outputs of classification results can be obtained easily, and are particularly useful for determining acreage. The analyst designates to the computer the *X–Y* coordinates representing the boundary of the area of interest. The computer then summarizes the number of data points in each of the categories of cover types. Since each data point (or resolution element) represents a certain area of ground, it is a simple matter to determine the number of hectares for each cover type of interest. The percentage of the entire area covered by each of the cover types can also be rapidly calculated.

5.4.3.5 Evaluation of the Classification Results

Classification of large geographic areas can be accomplished very rapidly. It is then desirable, however, to verify the accuracy of the classification. Several techniques have been developed to do so. A qualitative evaluation can be obtained by visually comparing the classification with an existing map of cover types with aerial photos. Although this method is subjective, it does provide a quick, rough estimate of the accuracy of the classification.

Quantitative evaluation techniques, on the other hand, allow more definitive evaluations. One quantitative technique involves a sample of individual areas of known cover types which are defined as 'test areas'. The X–Y coordinates of a statistical sample of test areas are designated, and the computer tabulates the cover types. These results are then compared to the cover type known to be actually present on the ground. It should be noted that the use of test areas can produce rather biased results if proper statistical procedures are not followed in defining the sample (Hoffer, 1975; Hord and Brooner, 1976).

A second quantitative method is to compare acreage estimates obtained from computer classification of satellite data with estimates obtained by some conventional method, such as manual interpretation of aerial photos. If an adequate number of relatively large areas are summarized, a statistical correlation can be obtained.

5.5.4 Results of CAAT for Vegetation Mapping

Computer classification of LANDSAT and Skylab MSS data has shown that forestland, rangeland and agricultural lands can be distinguished from other cover types, and identified and mapped with a fairly high degree of accuracy, i.e., 80 to 95 per cent (NASA, 1972b, 1973a, 1973b, 1975, 1978; Heller, 1975; Hoffer, 1975; Hoffer and Staff, 1975; Dodge and Bryant, 1976; Williams and Haver, 1976; Hoffer and Fleming, 1978; Miller and Williams, 1978). LANDSAT classification estimates of total forest acreage were generally within ± 10 per cent of those obtained by forest survey of the US Forest Service (Dodge and Bryant, 1976; Aldrich, 1979). In one study, estimates of forest acreage for the state of Michigan obtained by classification of LANDSAT data were within two per cent of those obtained by the US Forest Service (Hoffer *et al.*, 1978). Roberts and Merritt (1977) obtained a forest acreage estimate for a nine-county area in Virginia that was within one per cent of the Forest Survey estimate. Thus, it would appear that quite accurate acreage estimates of forestland can be achieved by computer classification, at least over reasonably large areas. Such estimates were less accurate on smaller areas in each study.

In addition to being able to identify forested versus non-forested areas quite accurately, computer classification has the capability to differentiate between deciduous and coniferous cover types unless they occur in mixed stands, in which case the scanner system gives a spectral response that is approximately proportional to the mixture of cover types present but that also is influenced by variations in stand density (Dodge and Bryant, 1976; Williams and Haver, 1976; Hoffer and Fleming, 1978). Identification and mapping of individual forest species generally has been significantly less accurate, with results varying considerably (Hoffer and Staff, 1975; Hoffer, 1975; NASA, 1978). Spectral similarity among species often causes confusion, and variations in stand density as well as topographic effects cause significant differences in spectral response (Hoffer and Staff, 1975; Hoffer, 1975; Williams and Haver, 1976; Strahler *et al.*, 1978).

LANDSAT data can be obtained at regular intervals throughout the year and over a period of years on a worldwide basis, cloud cover permitting. This sequential coverage has made it possible to monitor the 'green wave' in the United States (Ashley and Rea, 1975; Blair and Baumgardner, 1977). Temporal differences in spectral response have also led to significant improvements in the classification of forest cover types (Williams, 1975; Kalensky and Scherk, 1975). Temporal changes in spectral response have been shown to be particularly important in identifying agricultural species (Steiner, 1970). Many studies have reported quite high (80 to 95 per cent) accuracy in classifying individual agricultural species (NASA, 1972b, 1973a, 1973b, 1975, 1978; Bauer, 1975; MacDonald and Hall, 1978). It should also be noted, however, that in many of these studies there were relatively few cover types present and field sizes were large, thereby providing a spectrally simple situation. The LACIE (Large Area Crop Inventory Experiment) project showed that temporal differences in spectral response are particularly important in accurately identifying wheat (MacDonald and Hall, 1978).

The availability of LANDSAT MSS data also raises the possibility of monitoring changes in the areal extent of vegetative cover. For example, Klankamsorn (1976) reported that a comparison of LANDSAT data obtained over Thailand in 1973 with aerial photos obtained in 1961 showed that the total area of forestland in that country had decreased from 55 per cent to 41 per cent. Miller and Williams (1978) have used LANDSAT data to evaluate land-use changes in Thailand, Taiwan, Nigeria and the Dominican Republic, particularly the conversion of forestland to agricultural use. A variety of computer analysis techniques to identify areas of land-use change have been developed and assessed, but the results of such 'change-detection analysis techniques' have been somewhat mixed (Weismiller *et al.*, 1977).

5.4.5 Summary of the Value of MSS Data for Vegetation Mapping and Assessment

The availability of LANDSAT data for most areas of the world, often for several dates encompassing different seasons and different years, offers great potential for mapping and monitoring vegetation. The scale of the imagery produced is small, and the spatial resolution of the LANDSAT scanner (0.46 ha) is such that this type of data should not be considered as a potential substitute for photographic data but rather as suitable for the first stage in a multistage analysis. Both manual and computer-aided analysis techniques have been shown to be useful. The decision as to which one is more appropriate depends largely on the problem to be solved and the degree of detail required. Use of data from different years offers significant potential for monitoring deforestation in many critical areas of the world.

5.5 RADAR SYSTEMS FOR VEGETATION MAPPING

5.5.1 Radar System Characteristics

Radar is the third major type of remote sensing system utilized for vegetation mapping. Since radar systems operate in the microwave portion of the spectrum, they offer certain advantages over both photographic and multispectral scanner systems.

The term 'RADAR' is an acronym for 'RAdio Detection And Ranging', which succinctly summarizes the characteristics of these systems. A radio signal is transmitted from the radar antenna, and the length of time required for the signal to travel to the ground and be reflected back to the antenna allows the distance of the object from which the signal was reflected to be determined. The signals are pulses of very short duration, the duration determining the across-track (range) resolution of the system (see Figure 5.6). Jensen *et al.* (1977) point out that a pulse lasting only 10^{-7} seconds is used in one system and produces a range resolution of 15 m. The along-track resolution is proportional to the width of the beam of the microwave signal, which is inversely proportional to the length of the antenna. The antenna length can be artificially enlarged and the resolution significantly improved through the use of synthetic aperture systems. A unique feature of synthetic aperture systems is that along-track resolution remains the same at all ranges, thereby making it possible to obtain high resolution imagery for objects many miles away. This is due to the fact that as the distance to the object increases the object remains in the antenna beam for a longer period of time. Thus, the effective length of the synthetic antenna is directly proportional to the range to the feature, and since the resolution is proportional to the length of the antenna but inversely proportional to the range, these two effects compensate for each other on synthetic aperture radar (Jensen *et al.*, 1977).

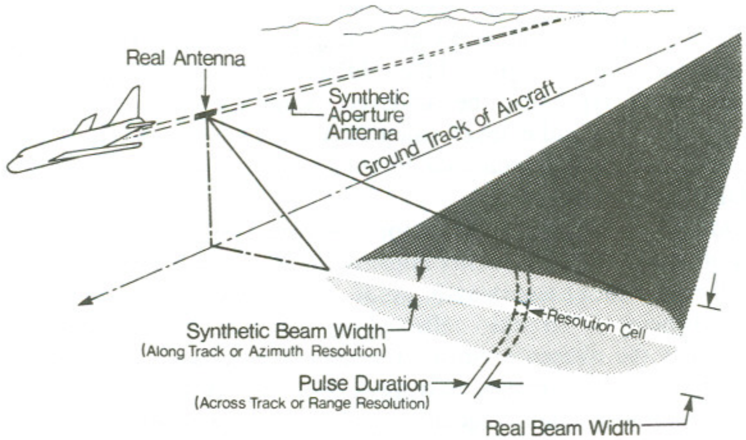

Figure 5.6 Schematic of the basic data collection characteristics of Side-Looking Airborne Radar systems (after Goodyear Aerospace Corp. Staff, 1971)

5.5.2 Interpretation of Radar Imagery

Although the all-weather and day-or-night capabilities afforded by radar systems are probably their most frequently cited advantages, they have several other unique capabilities for mapping and monitoring vegetation. To appreciate these advantages, one must understand some of the characteristics of radar systems and the data obtained from such systems. Key elements that must be considered in the interpretation of radar imagery are related to the radar system characteristics, which include wavelength, spatial resolution, look angle and polarization; the topographic characteristics of the area imaged, including the variations due to slope and aspect, and the effect of radar shadows; and the characteristics of the surface materials, including their geometric properties and dielectric properties (Hoffer, 1976b).

One of the most obvious characteristics of radar systems used in earth resource surveys is that they are side-looking (SLAR = Side Looking Airborne Radar) systems, viewing the terrain from an oblique angle. This enhances many characteristics of the terrain, a fact that has advantages and disadvantages. Areas behind tall terrain features (e.g., mountains) often are in a 'radar shadow' where there is no return of the radar signal, and the area is totally black on the imagery. Mountainsides and slopes facing the radar antenna provide a much higher return than areas of similar cover types on flat terrain. Areas with the same aspect and vegetative cover but with different slopes create different tones on radar imagery, thereby making it difficult to interpret the cause of such variations (Mathews, 1975; Hoffer, 1976b).

The side-look angle offers some advantages for vegetation mapping in that different physiognomic classes of vegetation can be enhanced on SLAR imagery. In forested areas, trees with large crowns cause a rough texture on the radar imagery, as do stands having a very low canopy closure. Brushland areas produce a finer texture. Thus, differentiation and mapping of major vegetative cover types can be achieved. Some agricultural crops can be accurately identified and mapped using SLAR imagery at selected times during the growing season (Morain and Simonett, 1966; Mathews, 1975; Bajzak, 1976; Ulaby and Burns, 1977).

In addition to differences in canopy texture, differences in the moisture content of vegetation significantly influence the radar signal, particularly in the shorter (i.e. K and X) wavelength bands. This is because the radar signal at these frequencies is strongly reflected by material with a high dielectric constant, and the dielectric constant is closely correlated with the moisture content. Therefore, vegetation having a high moisture content, or a fairly complete canopy of turgid vegetation, will produce a relatively light tone on the radar imagery (Morain and Simonett, 1966; Mathews, 1975; Rouse, 1977). The ability of radar to discriminate between agricultural fields with different levels of moisture is one of the primary reasons that certain crop species can be identified at specific times during the growing season. It also offers some hope for detecting stress conditions (Mathews, 1975).

One of the characteristics of radar which has often been misrepresented is its ability to 'see through' vegetative canopies. Longer wavelength systems, such as L-band, do have a significant potential for penetrating surficial cover, but the shorter wavelength systems, such as K-band, do not (Mathews, 1975). Since the spatial resolution of L-band radar is much poorer than that of the shorter wavelength K- or X-band systems, and since it has been primarily the K- or X-band systems that have been available to scientists for vegetation mapping, most of the data obtained thus far has come from K- or X-band systems. With these systems, in situations where the terrain does not cause significant variations, the geometric characteristics and moisture content of the vegetation itself are the dominant factors influencing the texture and tone of the radar image (Morain and Simonett, 1966, 1967; Barr and Miles, 1970; Mathews, 1975).

The polarization of the radar signal can also influence significantly the appearance of different vegetative types on radar imagery. In some cases the HH polarization gives better differentiation between vegetative cover types than the HV; in other cases the reverse is true (Morain and Simonett, 1966; Westinghouse, 1971; Lewis, 1973).

Another characteristic of radar data is the small scale involved and the resultant capability to cover large areas rapidly. One system, for example, is flown at a height of 20 000 ft, obtaining data at a scale of 1:250 000 and covering a swath about 12 miles in width (Francis, 1976). The unique capabilities of synthetic aperture radar systems are of particular interest, since relatively high spatial resolution can be achieved from great distances—e.g., 10 m at a distance of 100 km (Jensen *et al.*, 1977). Very complex navigation and radar recording electronics are required in such systems in order to permit the extremely long antenna to be synthesized.

Radar systems operating in the K- and X-bands (approximately 0.83 and 3.0 cm wavelengths, respectively) have been the most commonly used for vegetation mapping. Such systems have been particularly useful in tropical regions because of the unique capability of radar to penetrate cloud cover. In 1968 the Darien Province of Panama was successfully mapped through the use of a K-band radar system, which obtained imagery of good quality in spite of the almost perpetual cloud cover over the area (Viksne *et al.*, 1969). Synthetic aperture radar systems were released from military classification in 1970, and since that time significant portions of the earth's surface have been mapped using an X-band system (Jensen *et al.*, 1977; Rouse, 1977). One of the most notable achievements of this system involved Project RADAM (van Roessel and deGodoy, 1974), in which SLAR data were obtained for the entire Brazilian Amazon Basin, an area of approximately 4×10^6 km^2, in less than a year's time. Land-use, vegetation, hydrologic, geologic and other types of maps were prepared from this imagery. In 1976 a radar survey of the entire country of Brazil was completed. Large portions of many other countries in Central and South America, Southeast Asia, Africa and the Far East have also been surveyed (Mathews, 1975; Francis, 1976; Jensen *et al.*, 1977).

5.5.3 Summary of Radar's Potential for Vegetation Mapping

Radar has the capability of obtaining small-scale data with relatively high resolution from high-flying aircraft or from spacecraft. Such data can be obtained reliably at specific stages in the growth and development of agricultural crops and forest vegetation types, regardless of cloud cover. Although topographic relief often causes unwanted variations in tone, many major vegetative cover types can still be differentiated and mapped. The physiognomic characteristics of vegetative cover types and the moisture content of the vegetation are the primary causes of differences in texture and tone on radar imagery. Changes such as recent clear-cutting in tropical forest regions are distinct on radar imagery (Mathews, 1975).

5.6 SUMMARY

It is clear that each of the three data collection systems discussed in this paper has unique advantages. LANDSAT provides a relatively economical way of obtaining sequential data at a scale and in a format that is appropriate for monitoring global vegetation, using computer-aided analysis. However, scanner systems operating in the optical wavelengths cannot obtain data in areas where there is persistent heavy cloud cover, whereas radar can. The capability of radar to provide data related to plant physiognomy offers a potential for differentiating among vegetative cover types and sizes that cannot be distinguished through the use of spectral data alone. The advantages of photographic data are that they provide a degree of detail that cannot be obtained by the other types of sensors. Thus, each type of sensor provides the capability of obtaining data that cannot be obtained in any other way. The type and degree of detail of the information needed must be carefully defined, after which the various sensor systems can be matched to the information required. Different analysis techniques must be utilized, depending on the sensor system involved, the scale of imagery obtained, and the degree of detail required. Both manual and computer-aided analysis techniques have distinct advantages and limitations that must be recognized in order to achieve maximum efficiency.

When one considers the various types of sensor systems and analysis techniques available, it is apparent that remote sensing technology offers a powerful and relatively economical tool for assessing the extent, characteristics and condition of the vegetation resources of the world.

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