Chapter 6
Remote Sensing for Monitoring Vegetation:
An Emphasis on Satellites

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ABSTRACT

The use of satellite imagery, especially the imagery from LANDSAT, has been used widely in mapping forested areas of the earth. The details of LANDSAT operation are summarized and the limitations of the system discussed. The applications of satellite imagery are under development, will increase substantially in the future, and include the possibility of measuring changes in the vegetation of the earth.

6.1 INTRODUCTION

LANDSAT imagery has proved to be very effective in both mapping and measuring areas of forests (University of Michigan, 1979), and there is substantial reason to believe that it can be used in measurements of changes in the storage of carbon in forests globally. The characteristics of forests that are used for mapping include stand boundaries, height, density, species, extent of dead and dying timber and site quality (NASA, 1976). The possibility exists, of course, that improvements can be made in the design of future satellites. I have chosen to emphasize the criteria to be used in these developments in addition to the use of the existing systems.

Several important factors must be considered in designing remote sensing instruments for this purpose. Some of the most important are:

(a) Spectral bandwidth. The bandwidth is normally selected to be wide enough to obtain sufficient energy and narrow enough to detect the spectral features of interest.

(b) Spectral selection. If complete spectrum sampling is not employed, the bands will be placed to be coincident with spectral features of interest.

(c) Spectral resolution. This is determined by the spectral spacing between band centres, not by the spectral bandwidth.
(d) Temporal resolution. The time of an image or the time between two images. The question is whether the instrumentation is to be used for routine, repeated monitoring, or to provide information on episodic events. The answer will be a factor in determining the appropriate orbit of the satellite and the timing of the imagery.

(e) Intensity resolution. The utility of finer and finer intervals of measurement of intensity is ultimately limited by the noise of the sensor itself and by the inherent variability in the scene.

(f) Accuracy. The atmosphere often interferes with reception. In addition, there may be a need for absolute calibration of the instrument in addition to normalizing between spectral bands.

(g) Correlation with other data or maps. Remotely sensed information will seldom be all the information required. The data must be prepared and transmitted to the user in a form that is useful in comparisons with other data.

(h) Data delay. Thoughtful instrument design may allow the production of data in forms that minimize the time needed to process it on the ground.

A large part of the instrument designer's and scientist's joint task is mutually to determine a suitable world model which can be solved using available data, and the sensor system to obtain that data.

6.2 DATA SAMPLING

6.2.1 Spectral Sampling Considerations

Approximately 87 per cent of the solar energy that reaches the earth is received in the spectral range of 0.3 to 3.0 micrometres (μm) and most investigations of remote sensing have considered this range (NASA, 1972; Kondratyev et al., 1973; NASA, 1975a; Tucker and Maxwell, 1976; Landgrebe et al., 1977; Ecosystems International, 1977; CORSPERS, 1976; Tucker, 1978a, 1978b; Rao et al., 1977; Abrams et al., 1977). A summary is given in Table 6.1. Figure 6.1 shows some of the bands recommended for investigation, the bands included in various sensors and solar irradiance as seen at sea level. The bands which are normally considered useful are those of low atmospheric attenuation. This requirement eliminates the regions of 0.75 to 0.8, 0.95 to 1.0, 1.1 to 1.18, 1.3 to 1.55, 1.8 to 2.0 and 2.3 to 3 μm. The range of 0.3 to 0.4 μm is usually not considered available because of large atmospheric effects, but it may be a good atmospheric sensing band.

Within these ranges, the chlorophyll absorption (0.47 μm) is sensed only by the Coastal Zone Color Scanner (CZCS); the water absorption band (0.75 to 0.8 μm) is sensed by part of a thematic mapper band and may therefore be a confusion factor as atmospheric water varies, the 1.0 to 1.1 μm band is part of
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Table 6.1 Spectral Happenings

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Description</th>
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<tbody>
<tr>
<td>0.3 -0.35</td>
<td>In combination for atmospheric scattering and haze</td>
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<tr>
<td>0.35-0.42</td>
<td>Chlorophyll absorption (CZCS)</td>
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<tr>
<td>0.43-0.45</td>
<td>Carotenoid absorption</td>
</tr>
<tr>
<td>0.40-0.5</td>
<td>Bathymetry in less turbid waters; soil/vegetation differences; deciduous/coniferous differentiation; soil type discrimination</td>
</tr>
<tr>
<td>0.45-0.52 a</td>
<td>Chlorophyll reflection (CZCS)</td>
</tr>
<tr>
<td>0.51-0.53</td>
<td>Indicator of growth rate and vegetation vigour because of sensitivity to green reflectance peak at 0.55 μm; sediment concentration estimation; bathymetry in turbid waters</td>
</tr>
<tr>
<td>0.52-0.60 a</td>
<td>Chlorophyll absorption/species differentiation; one of best bands for crop classification. Vegetation cover and density; with the 0.53-0.60 μm band it can be used for ferric iron detection; ice and snow mapping</td>
</tr>
<tr>
<td>0.54-0.56</td>
<td>Gelbe stufte in water (CZCS)</td>
</tr>
<tr>
<td>0.63-0.69 a</td>
<td>Chlorophyll absorption/species differentiation; one of best bands for crop classification. Vegetation cover and density; with the 0.53-0.60 μm band it can be used for ferric iron detection; ice and snow mapping</td>
</tr>
<tr>
<td>0.6563</td>
<td>Chlorophyll luminescence line</td>
</tr>
<tr>
<td>0.66-0.68</td>
<td>Chlorophyll absorption (CZCS)</td>
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<tr>
<td>0.7-0.8</td>
<td>Chlorophyll reflectance rise; ground cover variations (CZCS)</td>
</tr>
<tr>
<td>0.76-0.9 a</td>
<td>Water body delineation; sensitive to biomass and stress variations. General observations with low atmospheric effects</td>
</tr>
<tr>
<td>0.82-0.9</td>
<td>Limonite absorption</td>
</tr>
<tr>
<td>1.4-1.5</td>
<td>Leaf turgidity</td>
</tr>
<tr>
<td>1.55-1.75 a</td>
<td>Vegetation moisture conditions and stress; snow/cloud differentiation; may aid in defining intrusives of different iron mineral content</td>
</tr>
<tr>
<td>1.9-2.0</td>
<td>Leaf turgidity</td>
</tr>
<tr>
<td>2.08-2.35 a</td>
<td>Distinguish hydrothermally altered zones from non-altered zones/mineral exploration; soil type discrimination</td>
</tr>
<tr>
<td>2.05-2.15</td>
<td>In combination, for altered rock discrimination</td>
</tr>
<tr>
<td>2.15-2.25</td>
<td>In combination, for altered rock discrimination</td>
</tr>
<tr>
<td>2.2, 3.5, 3.9, 4.8, 13.2</td>
<td>Narrow bands for grey body, surface temperature</td>
</tr>
<tr>
<td>4.5-5.5</td>
<td>With 10 μm, for vegetative temperature, atmospheric water absorption</td>
</tr>
<tr>
<td>9.5-10</td>
<td>Ozone absorption</td>
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<tr>
<td>10.4-12.5 a</td>
<td>Surface temperature measurement; urban versus non-urban land use separation; burned areas from water bodies (CZCS)</td>
</tr>
</tbody>
</table>

* Thematic mapper bands.

the Multispectral Scanner (MSS) 0.8 to 1.1 μm band, and the 1.2 to 1.3 μm band is not covered at all.

Because the Thematic Mapper 0.45–0.52 μm band includes a chlorophyll band, further sensitivity may be obtained by widening the sensor band to include also the 0.44 μm chlorophyll band. The Thematic Mapper 0.76–0.9 μm band should be split to separate the water band from the rest to eliminate the water confusion and provide an adjacent band for normalization.
A multiband linear array sensor may be launched in the mid-1980s. It will be the first of a new generation of multispectral sensors—a ‘pushbroom’ sensor instead of a mechanical scanner (Thompson, 1979; Colvocoresses, 1979). For each band in a pushbroom sensor, a separate detector is provided for each picture element desired in the cross-orbit direction. This in turn provides a dwell time for sensing each element of the ground longer than that of a scanner by a factor of about 3000 for a 3000 pixel line, and provides an increase in signal/noise (S/N) ratio of approximately the square root of this amount, or about 50:1. Advantage may be taken of this higher S/N ratio by increasing the number of intensity levels or by sensing with narrower spectral bands (Collins, 1978; DelGrande, 1975). In particular, it should be possible to use the narrow chlorophyll absorption bands near 0.44 and 0.67 μm with an adequate S/N ratio and good spatial resolution. In addition, it may be possible to form images in the bands of high atmospheric attenuation or in the 0.3 to 0.35 and 0.35 to 0.43 μm bands. These latter images could be used in conjunction with other bands to estimate and correct for effects of atmospheric scattering.

Linear array sensors are limited now to a long wavelength cutoff of about 1 μm. When longer wavelength response can be provided, division of the...
Figure 6.2  The position of the thematic mapper bands relative to average rock spectra and the plus or minus one standard deviation limits for hydrothermally altered rocks versus unaltered rocks. These figures were compiled from unpublished data furnished by Dr A. Kahle of the Jet Propulsion Laboratory in Pasadena, CA, Dr Larry Rowan of the US Geological Survey and other colleagues. (From Salomonson, 1978)

'2.2 $\mu$m' band into 2.05 to 2.18 and 2.18 to 2.35 $\mu$m sub-bands or even finer would allow further discrimination of, for example, altered from non-altered rocks (see Figure 6.2).

Additional bands of atmospheric transmittance occur between 3.4 to 4 $\mu$m and between 4.7 to 5 $\mu$m. These bands have not been given serious consideration because of the very low value of the reflected energy available and because of appreciable interference from thermally emitted energy from the earth. Within this range, narrow bands centred at 3.5, 3.9 and 4.8 $\mu$m avoid both atmospheric absorption regions and the wavelengths associated with anion groups in common minerals, and thus can serve as grey-body regions for the calculation of surface temperature (Del Grande, 1975). Conversely, other bands in this range may serve as indicators of these effects.

Temperature differences appearing in the thermal range have been associated with vegetation stress (Idso et al., 1977; Millard et al., 1978). In addition, it has been suggested by Vincent (1973) and others that the thermal band might be divided into several bands for some types of rock separations. Because of the presence of an ozone-absorbing band between 9.6 and 10 $\mu$m, it is suggested that this band be excluded.

A single pixel over vegetated ground usually records signals from several sources such as plants and soil (Tucker and Miller, 1977; Richardson and Wiegand, 1977a, 1977b, 1979; Westin and Lemme, 1978). Precise spectral
features of vegetation may not be reproduced faithfully at pixel sizes at satellite altitudes. This factor places clear limits on the use of satellite imagery for the direct identification of ground materials until such time as sensors with complete spectrum sampling can be flown.

If the influence of satellite imagery is to be improved, answers to several questions seem important. First, whether the needs would be better served if additional spectral features were surveyed and whether sufficient spectral samples should be taken to satisfy the Nyquist criterion in the spectral domain. Second, whether sensing in the bands sensitive to atmospheric variation would provide normalizing data. Third, whether the potential spectral modifications caused by data compression would be less significant than other vagaries in the system, such as sensor noise and atmospheric and scene variations and whether these are offset by the additional spectral bands. Fourth, whether the entire scheme can be contained within a reasonable data bandwidth.

6.2.1.1 Spectral Data Analysis

Spectral analysis generally takes the form of multispectral classification, in which classification is done by comparing the sample measurement vector to the set of vectors representing all possible classes of known materials and, by using one of several methods, determining which of the knowns it most nearly matches. This subject, treated extensively in the literature, will not be pursued here. Rather, I will consider some of the effects of noise from a generic point of view.

Consider first the probability of correct identification of a pixel from the interior of a field. Reflectivity from such a field will vary with noise in the sensor (NEDR) and inherent variation in the field itself. The combined effect will produce a finite probability of misclassification. The accuracy of the procedure is greatest of course when the classes are well defined; the accuracy drops as noise increases. The drop in accuracy of classification with increasing noise has been defined by Ready et al. (1971) and is shown in Figure 6.3.

The effect may be estimated (Billingsley, 1981) (Figure 6.4). The probability of a sample being within the class limits can be derived by assuming that an ensemble of noise-free signals can have equal probability of being anywhere within the range and by adding a Gaussian noise with a distribution equal to \( \sigma \). The probability distribution of the signal plus noise is found by convolving the probability distribution of the signal with that of the noise. The probability of correct class assignment is then found by integrating the probability distribution between appropriate limits representative of the class boundaries (Friedman, 1965). The resulting curve is given in Figure 6.5.

Sources of noise will be the scene itself and the sensor. A number of pixel measurements may be averaged to reduce the noise before classification. This
6.2.2 Spatial Sampling

The scene noise may itself be useful as a measure of texture. Texture is ordinarily described by terms such as: smooth, fine, rough and coarse. For digital processing, these terms are insufficient, and the spatial distribution of
Figure 6.5  Given a signal uniformly probable over the dynamic range. Gaussian noise of value $= \sigma$. The curves show probability of correctly recognizing a class corresponding to the noise free signal as a function of the ratio $\beta = \text{class size}/\sigma$.

the tones (brightness) of the pixels must be used. The specific attributes must be specified by the investigator (Haralick, 1975; Weszka and Rosenfeld, 1975).

The tradeoff is in sensor pixel size: (1) Large-low noise leading to better multispectral classification, poor delineation of edges, low amplitude texture information, larger fields required; (2) small—poorer multispectral classification, better edge definition, higher amplitude texture, smaller fields allowed, appreciably higher data production rate.

A further topic is ‘how far away from a brightness discontinuity (e.g., edges of different ground cover) must samples be taken to avoid contamination (signature mixture) from adjacent ground areas?’ This question becomes important where small homogeneous areas are encountered in which the fraction of potentially misclassified border pixels is large. Experience shows that a distance of 1–1.5 pixels is sufficient to avoid signature mixing. This places clear limits on the use of satellite imagery available at present in mapping areas as small as 1 ha or less.

The effect of noise upon classification accuracy near field boundaries may be estimated by considering the intensity shift across boundaries as compared to the classification limits and the noise components (including sensor noise) within a ‘uniform’ field. A trace cross-section between two fields is shown in Figure 6.7. As before, finite noise components will cause a finite probability of misclassification even if the average value is well within the classification limits, $S$. As the border of a field is approached the average value will change toward that of the adjacent field (Figure 6.8).

A final observation is that a shift of the signature in any one band will occur if that band is misregistered to the others, so that the pixel value shift is a combination of pixel placement and border displacement due to misregistration. The use of multitemporal data for classification implies that the spectral bands have equal importance and validity, since weighting factors are not generally applied on a band-to-band basis in accordance with their
supposed utility. Therefore, all spectral bands, independent of date, may be considered to be equally valid, and the total misregistration effect may be considered to be the root-sum-square combination of the misregistrations of all of the bands. The effects have been modelled for an average field aspect ratio \( r \) and an average noise \( 3 < \beta < 5 \). The loss in accuracy \( \Delta P \) for a displacement of \( d \) pixels is given in Figure 6.9.

This analysis also has implications for the type of interpolation.
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6.2.3 Temporal Sampling

In sampling of vegetation over time the measurements sought are often the increase in the canopy cover early in the growing season, flowering or ripening, any stress conditions, and the abrupt change at harvest (Kauth and Thomas, 1976; Rabchevsky, 1977; Richardson and Wiegand, 1979; Wiegand et al., 1979). Measurements at selected stages cannot be planned because a given species may be in different growth stages within the same region and cloud cover may obscure some observations. Repeated sensing within short intervals will be required to identify changes in signatures.

Repeat coverage will be obtained when the satellite completes a cycle and
Figure 6.9 Effect of misregistration on multispectral classification accuracy—
Loss of classification accuracy due to misregistration of one band, for various parameter combinations.

$\beta =$ class size/\( \sigma \) of noise.

$r =$ Field shape ratio, long/short sides.

$\tau =$ 10--90 per cent transient distance.

$n_1 =$ length of short side, pixels.

$d =$ displacement, pixels.

$\Delta P =$ loss in probability.

again traces a given orbit position, and when the swaths of nominally different orbits overlap. Within the altitude ranges normally considered (700–1000 km), there are relatively few orbits which are simultaneously sun synchronous and either progressing (such as LANDSAT 1, 2, 3) or skip (with adjacent orbits occurring approximately midway in the cycle) (LANDSAT 4). One such orbit pattern is shown in Figure 6.10. This has overlap coverage to the west and east of 8 and 11 days respectively, for a total cycle of 19 days.

The advantages of a skip orbit will only be realized if the swath is wide enough to give appreciably overlap with the adjacent swath down to the latitudes of interest. It can be shown that:

$$S_0 = \frac{1 - C/2}{W \cos \phi \cos H}$$

where $S_0$ equals trace spacing at the equator, $W$ equals swath width.
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Figure 6.10 Repeat pattern for a sun-synchronous satellite having a 19-day cycle, altitude—768.93 km, inclination—98.47°, 273/19 orbits/cycle, 14½ orbits/day, trace spacing $S_0 = 146.8$ km

Figure 6.11 Minimum latitude for a given per cent coverage as a function of $S_0/W$, for LANDSAT 1, 2, 3, orbit parameters

perpendicular to the trace, $C$ equals fractional coverage (1.0 for 50 per cent sidetrap, 0 for just touching swaths), $\phi$ equals spacecraft latitude at any point and $H$ equals the heading of the spacecraft relative to the rotating earth. A plot of this equation is given in Figure 6.11.

The additional data are not obtained without penalty. A decrease in $S_0$ will require more orbits to complete the cycle. An increase in the swath width requires a greater scan angle for a given altitude and produces greater distortion at the edges of the images. If the distortion cannot be removed by
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ground processing, it must be minimized during the sensing by increasing the altitude. The extra swath width also requires a higher data acquisition and handling rate.

Immediate attention may be given to episodal events only if the spacecraft is there at the time or if the sensor can be pointed at the event from another spacecraft position. This conjunction may also be provided by geosynchronous satellites, but at the cost of launching problems and attainable sensor resolution. Delay before the next acquisition in a low earth orbit may be minimized through the use of a skip orbit similar to the one described above and the use of a pointable sensor.

6.2.4 Accuracy of Data

The radiance measured by the spacecraft is a combination of the energy reflected from the ground (attenuated by the atmosphere) and the radiance of the atmospheric path. The path radiance, in turn, is caused by the illumination of atmospheric components by sunlight, by other components of the atmosphere and by light reflected to the ground. Since the distribution of illuminable particles is unknown and is variable both vertically and horizontally, and since ground reflectivity is spatially quite variable, path radiance has not been modelled adequately. Due to the combined effects of attenuation and path radiance, a given pixel as seen at the spacecraft may appear either lighter or darker than it would at the ground. Sensors are not yet available to measure atmospheric effects.

These effects have typically been estimated by one of two methods, each of which assumes the effects to be spatially invariant: (1) assuming that the darkest pixel in an image has some known low reflectivity, subtract this value from all pixels; or (2) assume that a series of brightness measures made just inside and just outside of a cloud shadow will bear a linear relationship to each other (Calspan, 1976). This relationship may be used to calculate attenuation and brightness. Atmospheric effects modelled by Mie or Rayleigh scattering or a combination thereof will be relatively slow varying functions of wavelength. In this case a ratio image will tend to remove atmospheric effects, although even here dark level subtraction will improve the ratio results. A declaration by the various disciplines as to the necessity of absolute calibration of spacecraft instruments and the need to measure atmospheric effects would help to guide instrument designers.

6.2.5 Correlation of Data

Miller (1979) concluded that it is time to develop techniques for measuring forest depletion by means of LANDSAT. By the time a programme to do so can be set in motion we will have over ten years of LANDSAT data as a
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Figure 6.12 Given a signal uniformly distributed over the quantization intervals. Given a Gaussian noise value = $\sigma$. The curves show probability of correctly assigning a digital value corresponding to the noise-free signal within $\pm 0$, $\pm 1$, $\pm 2$, $\pm 3$, $\pm 4$, $\pm 5$, $\pm 6$, $\pm 7$, $\pm 8$, $\pm 9$ DN (inclusive) as a function of the ratio $\beta = \text{step size}/\sigma$ (from Billingsley, 1975)

In view of the possibilities of deterioration of the older data, it is time to plant its retrieval or at least obtain assurance of its retention. Producing a history of forest depletion will not be simple, however, because of the need to register vast quantities of data on a world-wide scale. The development of mosaicking and registration techniques by NASA could be accelerated and made more available for general use if such a need is acknowledged.

6.2.6 LANDSAT-D and the Thematic Mapper

LANDSAT-D (LANDSAT-4) was launched in 1982, as part of a complete, end-to-end, highly automated earth monitoring system, and is thus a major step forward in remote global sensing (CORSPERS, 1976; Salomonson, 1978).

The LANDSAT-4 spacecraft has improved pointing accuracy and stability characteristics, namely, 0.01 degree and $10^{-6}$ degrees per second, respectively. It was launched into a sun-synchronous orbit near 705 km to provide coverage every 16 days. The principal instruments on the spacecraft are the Thematic Mapper (TM) and the Multispectral Scanner (MSS). The MSS provides the same capability as the MSS on LANDSAT-3, but the Thematic Mapper has capabilities superior to those of the MSS. It has seven spectral bands: 0.45 to 0.52, 0.52 to 0.60, 0.63 to 0.69, 0.76 to 0.90, 1.55 to 1.75, 2.08 to 2.35 and 10.4 to 12.5 $\mu$m. The six visible and near infra-red bands provide a 30-m instantaneous field of view (IFOV), and the thermal band provides a 120-m IFOV. The TM is an eight-bit system; i.e., it has 256 levels. The data rate from the TM is
approximately 85 megabits per second. Table 6.2 lists the pertinent characteristics of the instruments.

### 6.2.7 Microwave Sensing

Approximately 1200 LANDSAT scenes will be required to cover the tropical forest area of the earth. Many of these areas have never been imaged because of pervasive cloud cover. LANDSAT therefore cannot provide all the needed data even if the required frequency of observation is only once a year (CORSPERS, 1977).

An active microwave system with nearly all-weather capability could help fill this gap. The primary need is to distinguish between forested and cleared land, a classification task that appears to be within the capability of existing radar technology. Canopy penetration is not required, and a relatively short wavelength system with a 25-m resolution should be adequate. Polarization does not appear to be critical.

However, much more research must be done before definite statements can be made. A number of research topics have been suggested (Chafaris, 1978):

1. Measurement of stand density. Differences in stand density may show up on radar that are more reliable than LANDSAT MSS data alone.
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(2) Area delineation. Synthetic aperture radar (SAR) may be useful in differentiating forest lands from brush and pasture. Confusion of these features was a problem in the Great Lakes Watershed mapping project of the Environmental Protection Agency (EPA).

(3) Species differentiation. The SAR, in conjunction with the MSS, may assist in differentiating tree species which have spectrally similar signatures in the visible and near-visible infra-red ranges of the spectrum.

(4) Tropical forest inventory. The SAR might become a prime sensor in measuring the areal extent of cloud-covered tropical forests.

(5) Tree height. SAR shadowing may be related to tree height (assuming appropriate incidence angles) and thus aid in ascertaining timber volume.

(6) Detection of tree stress and tree susceptibility to fire. The detection of stress is not a straightforward problem. It is influenced by terrain slopes and the direction of slope as well as the morphology of the forest on the radar backscatter amplitude.

A synthetic aperture radar (SAR) was flown on SEASAT. It operated at 1.3 GHz and an off-nadir angle of 17–23°. The swath width was 100 km, and processing yielded 25 × 25 m pixels. Although the mission met an untimely end, considerable data were obtained over both water and land. Some of these data have been processed.

The registration of SAR imagery to maps and to LANDSAT images is not a simple task, due to the difference in the appearance of tie points and the relief distortion due to the large off-nadir angle. Efforts are under way to solve these difficulties.

The SEASAT SAR was designed primarily to provide data on ocean waves, coastal regions and sea ice. A SAR to provide data on land features, the Shuttle Imaging Radar (SIR-A), was flown on the second Shuttle flight test (OSTA-1) in November, 1981. This experiment used a modified SEASAT SAR to provide imagery in the L-band (23 cm or 1.3 GHz) region, with resolution compatible with LANDSAT imagery. SIR-A operated at an off-nadir angle of 50°, with a 50 km swath. Processing yields 40 m pixels from an optical signal film recorded on-board. SIR-B is expected to be launched in the summer of 1984. It will allow digital acquisition of data at selected incidence angles between 15 and 60°. This method represents a significant step in understanding optimum viewing angles for various applications.

The brightness of the radar image is proportional to the backscatter cross-section of the surface. This, in turn, is related to surface roughness, topography, dielectric constant and vegetation cover. Thus, radar data correlated with LANDSAT images will provide more information than either sensor alone. Because of the responsiveness of radar to so many variables, however, more research is required to determine the best combination of parameters and processing techniques. The following interactions are particularly important (CORSPERS, 1977):
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(a) The interrelationships of soil moisture, soil type, roughness and vegetation cover.
(b) The effective depth of the soil moisture radar measurement and its relationship to the soil moisture profile.
(c) The extent to which microwave radiation penetrates vegetation. This is important not only for soil moisture measurements but also for mapping topographic features flooding and snow cover, and for classifying.
(d) The effect of the complex liquid and crystalline structure of ice and snow on the return radar signal and its penetration depth.

In all sensor applications, the usefulness of the data will depend on the choice of frequency or frequencies and the polarization(s) used. A proof-of-concept mission (SIR-B) will use multiple depression angles of two frequencies (C band and X band), and several polarization combinations. A comparison of SIR-B with SIR-A is given in Table 6.3 (JPL, 1982). Data from such a sensor will allow extensive analysis to optimize the information content of several simultaneously-received signals, both radar alone and radar in conjunction with sensors.

### 6.3 CONCLUSION

Two factors that influence the earth's carbon cycle, deforestation and desertification, can be monitored by remote sensing. Accuracy in identifying changes in vegetation cover may be enhanced by proper selection of spectral bands; narrower bands will be available in the future as linear array

| Table 6.3 Comparative summary of SAR parameters for SIR-A and SIR-B |
|-----------------|-----------------|-----------------|
| Parameters      | SIR-A            | SIR-B            |
| Orbital altitude| 260 km           | 225 km           |
| Orbital inclination | 38 deg       | 57 deg           |
| Frequency       | 1.28 GHz         | 1.28 GHz         |
| Polarization    | HH               | HH               |
| Look angle(s)   | 47 deg           | 15–60 deg        |
| Swath width     | 50 km            | 20–50 km         |
| Peak power      | 1 kW             | 1 kW             |
| Antenna dimensions (m) | 9.4 x 2.16   | 10.7 x 2.16      |
| Antenna gain    | 33.6 dB          | 33.0 dB          |
| Bandwidth       | 6 MHz            | 12 MHz           |
| Azimuth resolution | 40 m (6 look) | 25 m (4 look)    |
| Range resolution| 40 m             | 58–17 m          |
| Optical data collection | 8 h           | 8 h              |
| Digital data collection | 0             | 25 h             |
| Digital link capability | N/A          | 46 Mbits/s       |
technology improves. However, precision analysis will be required if the system relies on mapping, and the use of computer techniques will facilitate the geographic referencing required. LANDSAT-4 provides improved sensing spatially and spectrally. Synthetic aperture radar promises to provide all-weather sensing, although operational spacecraft are still in the future.

6.4 ACKNOWLEDGEMENT

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