APPLICATIONS OF REMOTE SENSING IN HYDROLOGY

by

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Colorado Water
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Part I

by

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Applications of Remote Sensing in Hydrology - Part I

ABSTRACT

This paper is a summary of the potential applications of remote sensing in the field of hydrology. It includes an introduction to remote sensing, the physical principles of electromagnetic energy and many of the available sensors. Operational uses and research applications of remote sensing in areas related to watershed management are summarized.

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1. INTRODUCTION

Since the invention and development of photography in the first half of the 19th Century, man has been intrigued with the idea of taking pictures of the earth's surface from a point above the surface. Utilizing the resources available, early "aerial" photographs were taken using balloons, kites, rockets, and even pigeons as platforms (Reeves, 1975). Although these early photographs were largely curiosities, practical application, especially military application, soon became obvious and the "art" of remote sensing applications was born. The development of the airplane provided a greater degree of control over target selection while improved cameras and films provided better quality imagery. World War II, brought tremendous advances to the practical application of aerial photographic interpretation. All participants in the war utilized aerial photo reconnaissance on a broad scale and many new techniques and instruments were developed. However, it was not until the advent of orbital space flights in the sixties that the tremendous potential for remote sensing applications has begun to be realized. Early photographs from Mercury and Gemini space flights provided unusual detail of land forms and geologic formations and led to the development of the Earth Resources Satellite (ERTS), todays LANDSAT.

Concurrent with the development of orbiting spacecraft platforms has been the development of improved sensors. Multispectral scanners, thermal scanners, side-looking radar, and micro-wave systems provide the application's specialist with a broad range of tools to use in interpreting the features and resources of the earth's surface.

The development of practical applications for the new technology has not been as rapid as the development of sensors and spacecraft. Although enthusiastically promoted by the space agencies, practical applications require considerable compromise between costs and capabilities. For example, a single LANDSAT image covers thousands of square miles within which forest and non-forest area can be determined. However, the nature of the forest cover at a particular point (type, density, volume) cannot be determined easily or accurately. With an increase in spatial coverage comes a decrease in resolution. In spite of these limitations, the utility of broad scale imagery is exceedingly important.

One area of potential application of remote sensing technology is water resource management. Much research over the past five years has been directed at remote sensing applications in hydrology. Practically all processes and states of water in the hydrologic cycle have been investigated with the objective of using remote sensing to determine the magnitude of these storage amounts and processes. In some applications the technology and the objectives are compatable and the particular applications can be considered to be operational, while other applications must be considered as still experimental or in the research stage. It is the purpose of this report to review the state of remote sensing applications in hydrology.

Objectives

The primary objective of this study has been to investigate potential application of remote sensing methods in determining hydrologic operating parameters of remote mountain watersheds. The approach taken was (1) to review remote sensing systems and potential applications in hydrology and (2) to develop a watershed simulation model which utilized traditional data sources plus available remote sensing data as a means of improving simulation results.

Specific objectives are:

1. To review existing remote sensing sensors and systems with reference to potential applications in hydrology.
2. To develop a watershed simulation model which utlizes remote sensing data, in addition to traditional data sources, for simulating snowmelt runoff from remote mountain watersheds.

This Report

This report is presented in two parts. Part I presents a review of remote sensing applications in hydrology. Included are sections on the physics of remote sensing and capabilities of existing remote sensing systems and sensors.

Part II presents a Watershed Information System which utilizes a spatial data system, spatial simulation of snowmelt and runoff processes, and application of remote sensing data as a direct input into the simulation model. The model was developed and tested in the the Williams Fork Watershed in central Colorado.

2. SURFACE WATER

The inventory of surface water resources is probably the most logical application of remote sensing in hydrology. There are tens of thousands of lakes in the glaciated regions of the middle United States. The cost involved in monitoring all of these lakes on any regular basis with standard methods would be prohibitive. However, remote sensing techniques have been employed to accomplish that task for a minimal cost both in time and money. Repetitive measurements to monitor seasonal and annual change entail only a small amount of additional labor.

Inaccessible areas, where water resources are tied up as ice and snow during the winter months, are particularly good areas to demonstrate the capabilities of remote sensing techniques. Standard snow surveys provide limited samples while remote sensing systems can provide comprehensive data in computer compatible format for rapid analysis.

In contrast to many applications of remote sensing, some of the methods for monitoring surface water resources have moved past the research stage into a quasi-operational phase. This chapter discusses both the relative success of these operational attempts and the on-going research. The literature has been grouped into categories: surface water (lakes and reservoirs), wetlands, and snow.

OPEN WATER

The electrical and structural properties of water are substantially different from surrounding soil and vegetation. Consequently, water appears distinctive on most types of remote sensing imagery. Electromagnetic (EM) energy incident upon a body of water is subject to absorption, reflection, or transmission by the water and further scattering by particles suspended in the water. Conventional color photography possesses some capabilities for penetrating water surfaces. The color of water is due to that part of the solar radiation which penetrates the surface and is returned to the surface after selective scattering by the suspended particles or the bottom sediments. This radiation is predominately from the blue and green wavelength regions causing water bodies to appear various shades of blue and green.

While conventional photography does have the capability of revealing shallow features, systems which operate outside the visible wavelengths have some advantages in the mapping of surface water. Beginning in the near infrared and continuing through the longer wavelengths a very thin layer of water will absorb most of the incident energy (Fig. 1). The scattered radiation in these wavelengths is correspondingly less, causing clear water to appear very dark. On color infrared imagery and Landsat false color composites, water shows as a dark blue to a deep black.

Radar images display water as completely black. All of the transmitted energy is either absorbed by the water or specularly reflected by the relatively smooth surface; none of the energy is returned to the receiving unit.

Water Availability

Landsat and high altitude color infrared imagery have been used effectively in mapping the areal extent of surface waters in lakes and reservoirs. Mapping projects of this type are too numerous to list in entirety. Guernsey and Mausel (1978), report that in most areas more than 98 percent of all surface water can be identified through analysis of Landsat imagery. Accurate acreage estimates can be best obtained from digital imagery. The computer analysis required to distinguish between land and water is relatively simple and inexpensive. Estimates made by photointerpretation or density slicing may be less accurate.

McKim et al. (1973) investigated the possible use of Landsat imagery in the national program for the inspection of dams. This research demonstrated the capability of Landsat to locate and map reservoirs greater than five acres and identify dam sites on major rivers. Relative water depths and the direction of streamflow can be determined in most cases. Landsat was found to be unsuitable for identifying dam type and height, absolute water depth, and water bodies less than five acres. Identification of small bodies of water and narrow streams and rivers (less than 80 meters wide) requires greater resolution. This requirement will be satisfied by future satellite sensors. Currently, only aircraft systems provide the resolution necessary for detailed studies.

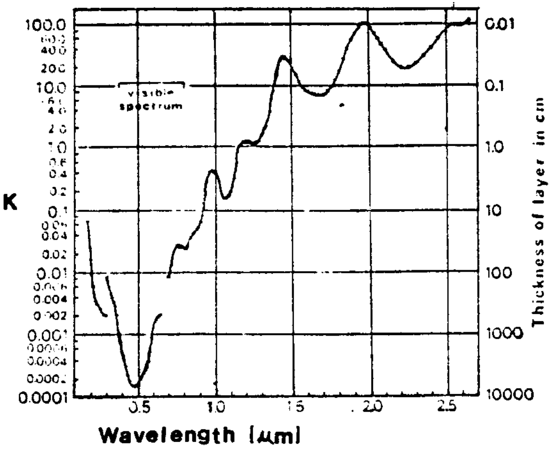

Figure 1. Absorption coefficient (K) for pure water, wavelength range 0.2 to 2.6 μm. (From *Manual of Remote Sensing*, Reeves, 1975).

Aircraft data, both photographic and multispectral, have also been used to determine water depths in lakes and reservoirs. Water depths up to 11 meters have been mapped directly from color transparencies through the use of a stereoplotter. The depth to which water can be mapped is a function of water clarity and the scale of the imagery.

Polycn (1970; 1973) has studied several methods for determining water depths using multispectral scanner (MSS) data. One technique takes advantage of the selective absorption of water to develop a relationship between the output of two or more wavelength channels and the depth of the water. This method has been used to map depths exceeding 8 meters from aircraft MSS data and up to 5 meters from Landsat MSS data.

Measurements of areal extent and depth of water can be used as an index of the quantity of water. Repeated observations can be used to estimate changes in storage. For instance, Maxwell et al, (1980) used receding lake and reservoir boundaries as seen by Landsat, as the first step in identifying drought conditions in Colorado. This type of information may also be used in evaluation of water rights and in planning of water recreation areas.

Water Quality

Another phase in the inventory of open water is an assessment of the quality of that water. Remote sensing can be applied to this problem in a number of ways. Water temperature, suspended sediments, chlorophyll contents and salinity of both ponded and flowing water have been evaluated from remote points. The dynamics of mixing zones have been studied using both dye tracers and thermal sensors. Special techniques, such as the use of lasers, lidar and Raman spectroscopy, have been applied to problems of water quality. Much research has been done in the remote sensing of water quality. However, it is beyond the scope of this paper to pursue water quality any further.

Flood Mapping

Every year many rivers and streams spill over their banks, inundating cities and farmland, causing millions of dollars of damage to public and private property. Remote sensing can be used to monitor the extent of flooding and provide data for streamflow routing. Images can be used to document the need for federal disaster relief funds and verify insurance claims.

Distinguishing sediment-laden flood waters from bare soil can be a difficult problem in conventional photography. The sharp contrast between land and water disappears when the muddy waters spread out in shallow layers over the flood plains. Additional problems arise when floodwaters move into timbered or other heavily vegetated areas. Moore and North (1974) compared the capabilities of panchromatic black and white, color, and color infrared photographs and thermal infrared imagery to display flood boundaries. Their findings show that although all types of imagery can be used satisfactorily, the best sensor for daytime record of flood position and extent is color infrared photography. This is due to the absorbtive properties of water at the infrared wavelengths. Currently, the best nighttime sensor is the thermal infrared scanning system. Moore and North (1974) suggest that if the resolution of side-looking radar is improved that radar may become the best all-round flood mapping system. Its all-weather and vegetation penetrating capabilities give radar a decided advantage over other systems.

There are may examples of the use of remote sensing to monitor floods. Myers, Waltz, and Smith (1973) used color and color infrared photography and thermal infrared imagery to delineat flood boundaries by Rapid Creek at Rapid City, South Dakota. Hallberg, Hoyer and Rango (1973) mapped the Nishnabotna River flood in Iowa using Landsat imagery collected a week after the flood.

Deutsch et al. (1973) used Landsat to delineat the flood waters on the Mississippi River during one of the largest floods to occur within the recorded history of that river. This study investigated the utility of Landsat for flood mapping employing optical techniques at a scale of 1:250,000. The project concluded that Landsat can provide a synoptic view of the areal extent of flood waters throughout the river basin which can be interpreted quickly and relatively inexpensively.

Wiesnet, McGinnis and Pritchard (1974) also monitored the 1973 spring floods in the Mississippi Valley using the Very High Resolution Radiometer (VHRR) of NOAA-2. They found that the NOAA imagery could be used to identify areas of flooding in the case of large floods on large rivers. Although data from the VHRR system is not as detailed as Landsat data, the availability of twice daily imagery can provide a record of flood buildup and subsequent abatement. This information can be used to follow a flood peak down river and to estimate the time period of inundation.

In another 1973 flood, Deutsch and Ruggles (1977) applied a "contrast-stretch" to Landsat imagery of the Indus River in Pakistan. This optical enhancement greatly increased the contrast between wet and dry areas, thereby aiding the interpretation of the inundated areas. Optical enhancements also revealed other information of significance, such as broken and leaking canals, leakage under a dam, and areas of ponding following recession of the flood waters.

WETLANDS

Another type of surface water resource that is frequently of interest is wetlands. These are the low-lying, naturally flooded, usually vegetated swamps, bogs and marshes. Wetlands are of interest, not for the water which they harbor, but for land that could be salvaged by draining the wetlands or for wildlife habitat that wetlands provide. In either case, it is the presence of water which draws attention to the land and increases the feasibility of applying remote sensing techniques to wetland mapping and analysis.

The problems involved in identifying wetlands are similar to those of flood mapping, i..e, turbid waters and vegetative cover. Additional complications arise in long-term analysis due to fluctuations in the water table and the natural and man-made succession that occurs over time.

Aerial photography of all sorts, thermal imagery and Landsat MSS imagery have been applied to this problem. The use of color infrared imagery in detailed vegetation mapping has been the most popular (Carter et al., 1977; Gammon et al., 1977; Seher and Tueller, 1973; Moore and North, 1974). Concentric rings of vegetation have been found around lakes and ponds indicating the levels of succession through which the area has passed. Thermal imagery may be of use to locate areas of groundwater discharge in marshes or swamps during the seasons when trees are bare (Carter et al., 1977).

Wildlife Habitat

The preservation of wetlands and the wildlife that live within them has become an area of local and national concern. The papers cited above deal primarily with the swamps and bogs of the southeast United States but these finds could be applied to wetlands of the water fowl migration corridors which are also of concern.

The Great Dismal Swamp located on the Virginia-North Carolina border is an important center of wetlands research. Carter et al. (1977) found that once a good data base of vegetative and hydrologic information is compiled, routine analysis of Landsat imagery can be used to update the data and identify areas requiring a more detailed analysis. Future plans in the Dismal Swamp include the use of change detection to follow the natural and man-made alterations of the swamp and a study of the application of satellite thermal data to these problems.

Wetlands may also be problem areas. As part of an effort to control mosquitos in areas of eastern Nebraska, Woodzick and Maxwell (1977) used Landsat imagery to detect and map the areal extent of prime mosquito breeding habitat. They found that the unique vegetation and soil moisture conditions required by select mosquito species can be recognized with Landsat and categorized according to breeding potentials. This technique can be applied to the problem of pin-pointing areas where mosquito eradication efforts will be most effective.

SNOW RESOURCES

In the semi-arid western states, snowmelt from the mountains is the primary source of water for agricultural, industrial and residential use.

The areal extent of snow, the snow depth, and its water equivalent must be obtained to provide water users with an estimate of the amount of water stored in the mountain snowpack and its rate of release. Until recently, snow course measurements have been the only source of this data. Data collection sites were limited by accessibility and manpower.

Early in the 1960's remote sensing added a new dimension to the snow survey, the macroscopic view. TIROS-1, the first weather satellite returned pictures in which the snow fields of eastern Canada were visible. Since then, techniques to map and monitor snow with the aid of remote sensing technology have progressed rapidly.

Snow

With remote sensing of snow and ice, there are many constraints not associated with many other materials. The most obvious constraint is temperature. The maximum attainable temperature of a snowpack is 273°K. A second constraint is that at this temperature, water can exist in two states: liquid and/or solid. Occasionally, this dual state will also exist at slightly lower temperatures if the liquid water is tranferred from another location.

An aging snowpack experience changes in density, water equivalent, and surface characteristics. The detection of snow cover and the ability to monitor accumulation and melt with remote sensing techniques is possible due to these constraints.

Snow has an extremely high albedo, ranging from 40% for old snow to as high as 95% for freshly fallen snow. This characteristic makes snow highly visible in aerial photography and imagery from other optical systems. Examination of Landsat data (Barnes et al., 1978) has shown that contrast beween snow covered and snow-free terrain is greatest in MSS band 4 (0.5 - 0.6 μm) and MSS bands (0.6 - 0.7 μm). The MSS-5 appears to be the more useful of the two bands because the band 4 sensors frequently become saturated by the high reflection, causing a loss of detail in the snow pattern.

In the longer wavelengths snow is more difficult to detect. However, the near-IR, thermal-IR, and microwave regions of the spectrum may be useful for snow depth, age, and water content monitoring. O'Brien and Munis (1975) studied the spectral reflectance of snow in the range of 0.6 to 0.5 μm wavelengths (red and near-IR)(Fig. 2).

Snow Cover

Aerial photography and satellite imaging systems are excellent sensors for the identification of snow covered areas. Dry snow has very high reflectance properties which cause it to appear white in visible and false color imagery. Thus, it is easy to identify on

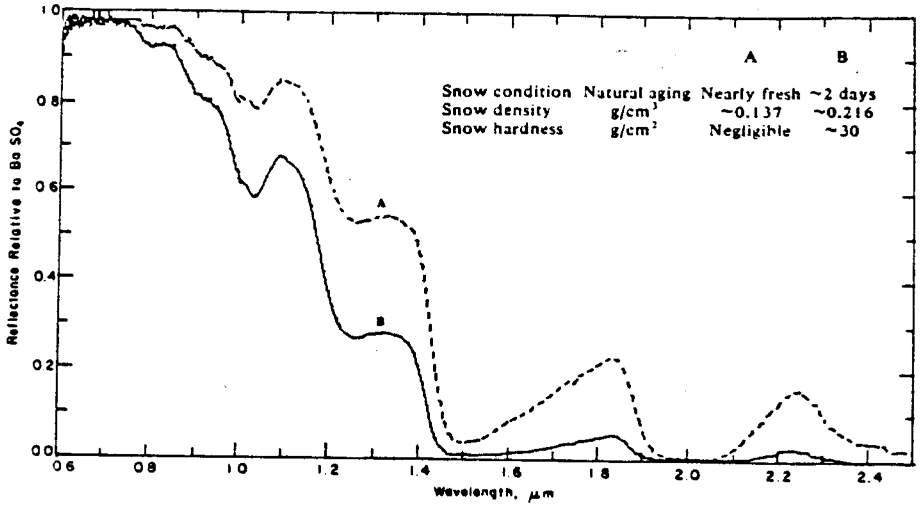

Figure 2. Changes in snow reflectance with aging (O'Brien and Munis, 1975).

imagery. Unfortunately, clouds have a very similar signature. Distinction between snow and clouds is a constant problem. Fritz (1963) reported that snow fields can be distinguished from clouds in satellite pictures when images are taken on successive days since cloud patterns change from day to day, while snow fields remain unaltered over a period of days. McClain and Baker (1967) used this observation in the development of a computer program which in effect "removed the clouds" from digital data by computer selection of the minimum brightness over 5 day periods. Further research (Barnes et al., 1974) report that there are several other characteristics of snow and clouds that make them separable. Snow boundaries are typically sharper than cloud edges. Snow fields usually have a more uniform reflectance than clouds, and terrestrial features are often visible in cloud-free areas. In addition, clouds are usually accompanied by cloud shadows.

There is a second problem in snow identification. Snow that is lying under heavy coniferous forests or in mountain shadow areas has a different signature than snow in a brightly lit scene. In operational applications of Landsat 1 imagery in the San Juan mountains of Colorado, Washicheck and Mikesell (1975) used low altitude air photos to aid in interpretation. U-2 imagery has also been used to compliment satellite imagery in other studies.

Once snow has been identified on imagery, it is very little problem to delineate its boundaries. Barnes and Bowley (1974) published a handbook of techniques for satellite snow mapping, emphasizing the use of the visible imagery of NOAA-VHRR and Landsat. Wiesnet and McGinnis (1974) compared the use of Landsat imagery and high altitude aerial photography and found that snow cover mapping was faster and less expensive when Landsat was used. Salomonson and MacLeod (1972) studied the areal extent of snow cover in the western Himalayas using data from NOAA satellites, Nimbus 3 and 4. Their results indicated that prediction of the seasonal runoff volume and the level of peak discharge may be improved by monitoring the snow areal extent and location of the snowline in the late winter and early spring. Estimates of snow cover for several test watersheds correlated well with observed runoff yields (Rango et al. 1975). Other studies have centered around the use of NOAA-VHRR (McGinnis et al. 1975; Barnes et al. 1974; Seifert et al. 1975).

Skylab's S192 multispectral scanners gave scientists the opportunity to explore applications of the near infrared and the thermal infrared wavelenth bands. Barnes and Smallwood (1975) found that the high reflectivity of snow dropped abruptly in the near-infrared, becoming essentially non-reflective in the S192 thermal band (2.10-2.35 μm). They suggested that near -infrared imagery may be used to detect areas of melting snow and, in conjunction with a visible band, be used to separate snow and water droplet clouds.

Snow Depth

The brightness of snow as recorded by the visible band sensors on board meteorological satellites has been studied as a possible indicator of snow. McGinnis et al. (1975) found that for newly fallen snow up to 30 cm deep, there is a strong correlation ($R^2 = .86$) between snow depth and reflectivity. Above 30 cm reflectance values were uniformly high. The results from this study in southeastern United States are shown in Figure 3.

Water Equivalent of Snow

The water equivalent of the snowpack is one of the most meaningful measurements that the operational hydrologist can have.

Visible and infrared systems are limited by their inability to penetrate the snowpack. Microwave systems, using longer wavelengths have the potential to obtain information from within the snowpack. Boyne and Ellerbruch (1979) found that the amplitude of scattered microwave radiation can be correlated with physical characteristics of the snowpack such as density, hardness, stratigraphy, and moisture content. Snow-water equivalence can be estimated from these observations. Despite this encouraging progress and the results of passive microwave experiments (Meier and Edgerton, 1973; and Chang et al., 1979), no satellite techniques for determining water equivalent are yet available.

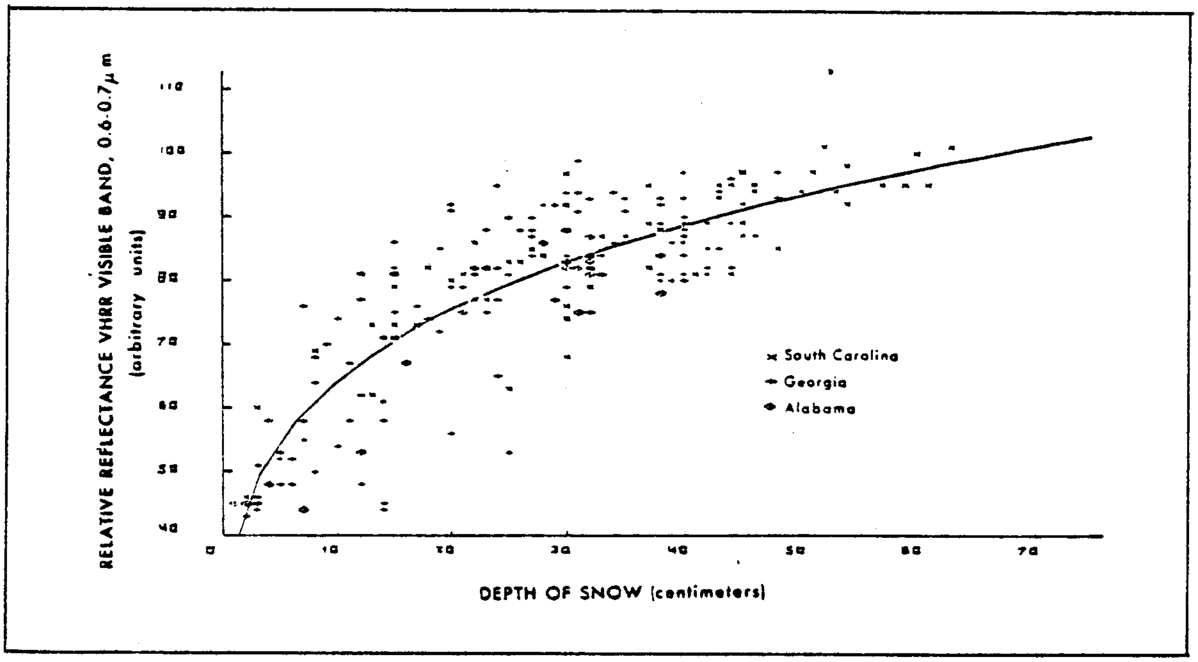

Figure 3. Relation of relative VHRR visible reflectance to depth of snow (McGinnis et al., 1975).

3. WATERSHED FEATURES

The hydrologic behavior of a watershed is determined both by its surface and sub-surface characteristics as well as the characteristics of the precipitation or input to the hydrologic system. Surface characteristics of interest to the hydrologist include soils, vegetation, and physiography. The synoptic view provided by remote sensing systems can be very useful for collecting this type of data. Combined with the storage and speed capabilities of computers, the remote sensing system may prove to be the most efficient method of inventory and update for large scale watershed data.

MORPHOLOGICAL CHARACTERISTICS

The foundations of quantitative geomorphology were laid down by Horton (1945) with additions and revisions including Strahler (1953), Maxwell (1955) and Schumm (1956). Investigations of relationships between landform and runoff, including those of Gray (1961), Hedman (1970), and White (1975). The morphological characteristics of a watershed, including slope, aspect, channel length, gradient, and drainage density influence the efficiency of the watershed's runoff system. Vegetation and soils, also influence the hydrology of the basin and must be included with morphological characteristics to compare basins and to predict the hydrologic behavior of watersheds.

Most morphological characteristics can be determined directly from a good quality topographic map. Unfortunately, good topographic maps are not always available, especially in the western states. Remote sensing can be used to help fill this deficiency.

Watershed Mapping

At the present time, most imagery used in operational mapping is aerial photography flown to produce stereo pairs. However, other types of remote sensing systems are rapidly coming into the picture.

Radar, for instance, is extremely useful in terrain mapping. Using the inherent radar distortions, foreshortening and shadowing, quantitative landform data can be determined. Individual features such as faults, fractures, and drainage patterns are also visible. The application of airborne radar to identification and measurement of drainage-basin variables has been investigated by McCoy (1967) and Lewis (1971). Investigation has shown that different radar systems yield different amounts of detail. However, most systems will provide detail equal to that of 1:24,000 topographic map. Multiple-look angles are necessary, especially in mountainous terrain where shadow is an important factor. Stream network variables including basin area, total channel length, total number of stream segments, and basin perimeter can be measured from radar imagery. Figure 4 illustrates the high correlation between radar imagery and topographic maps.

SURFACE CHARACTERISTICS

In addition to morphological characteristics, information about soils and vegetation is also essential in evaluating watershed hydrology. The processes of interception, evapotranspiration, infiltration, and surface runoff are controlled by these variables. The application of remote sensing techniques to inventory these resources has been studied intensively.

Vegetation

In the remote sensing of vegetation the important factor is the region of the electromagnetic spectrum to be used. Live vegetation has a unique spectral signature. It absorbs strongly is the blue and the red wavelengths primarily because of its chlorophyll content. Figure 5 shows the spectral reflectance pattern of a typical closed canopy. The strong reflectance in the near infrared in the result of matrices of cells and intercellular spaces, differing refractive indices and large critical angles formed by cell walls in the leaves. The longer wavelengths of the microwave region are primarily influenced by the roughness (crop morphology) and dielectric properties rather than the cellular and molecular structure of the plant.

Because of the useful characteristics of color and color infrared films in species identification, these films have proven especially useful in forest and vegetation surveys at all scales. A wildland vegetation and terrain survey in California using high altitude color infrared aerial photography taken at the scale of 1:120,000 has been compared with a survey of the same area using black and white. photography at 1:16,000 (Lauer and Benson, 1966). It was found that the results were comparable, but the small scale CIR was twice as efficient, that is, the work was completed in half the time. This is partly because three CIR photographs covered the same area as 78 photographs at the larger scale, resulting in much less handling.

The feasibility of crop identification from Landsat has been demonstrated for selected crops and test areas: corn, alfalfa, and soybeans in South Dakota; wheat in Kansas; and various field and vegetable crops in California (NASA, 1973). An accuracy of 90% or better has been documented for field sizes larger than 25 acres. Usually, correct identification can be accomplished by knowing each crop calendar in each crop region. An example of a crop calendar is given in Figure 6.

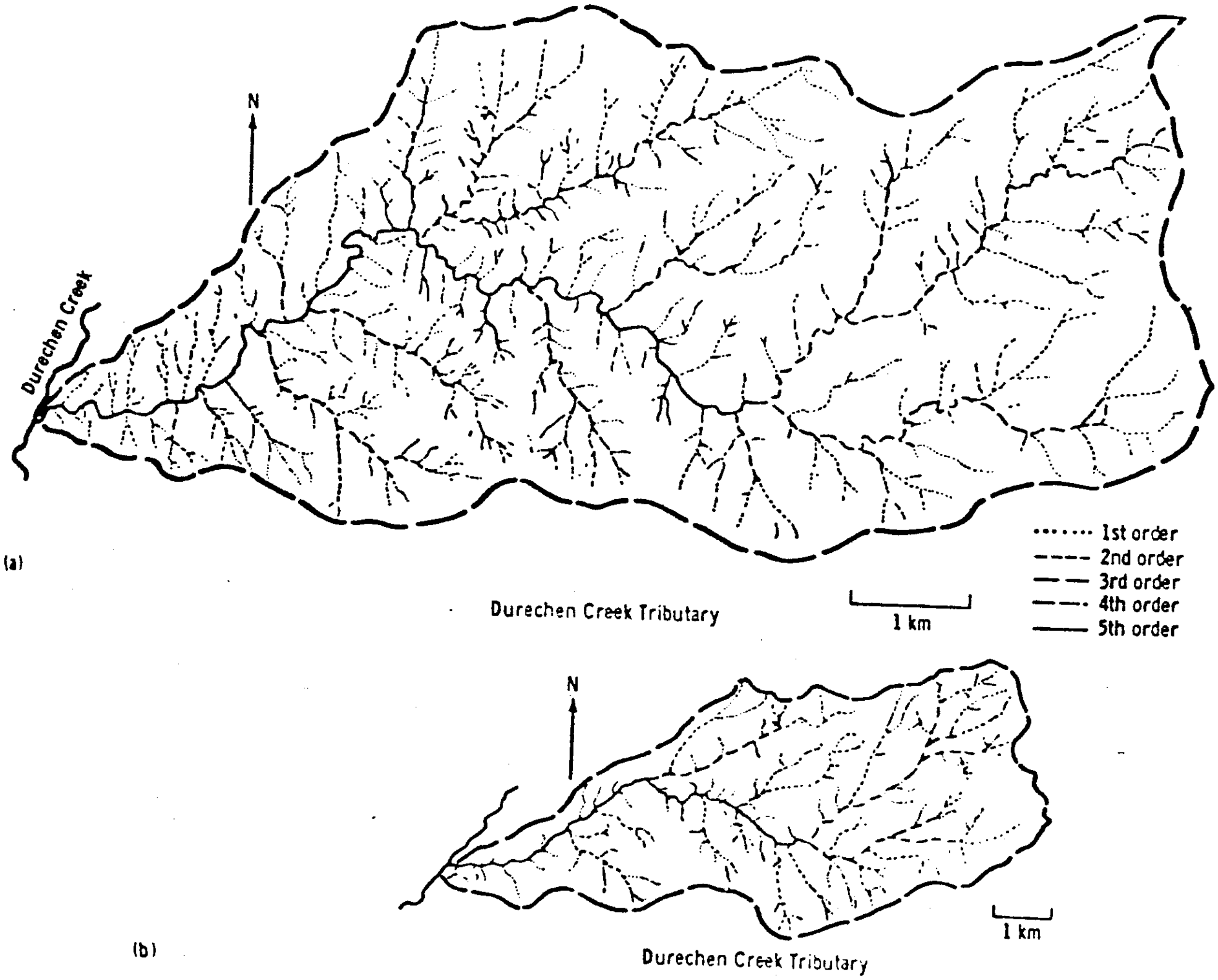

Figure 4. Correlation between drainage basin data derived from topographic map and from radar imagery of the Durechen Creek tributary. (a) Topographic map; scale of 1:24,000. (b) K-band radar. (Rouse and Molly, 1975)

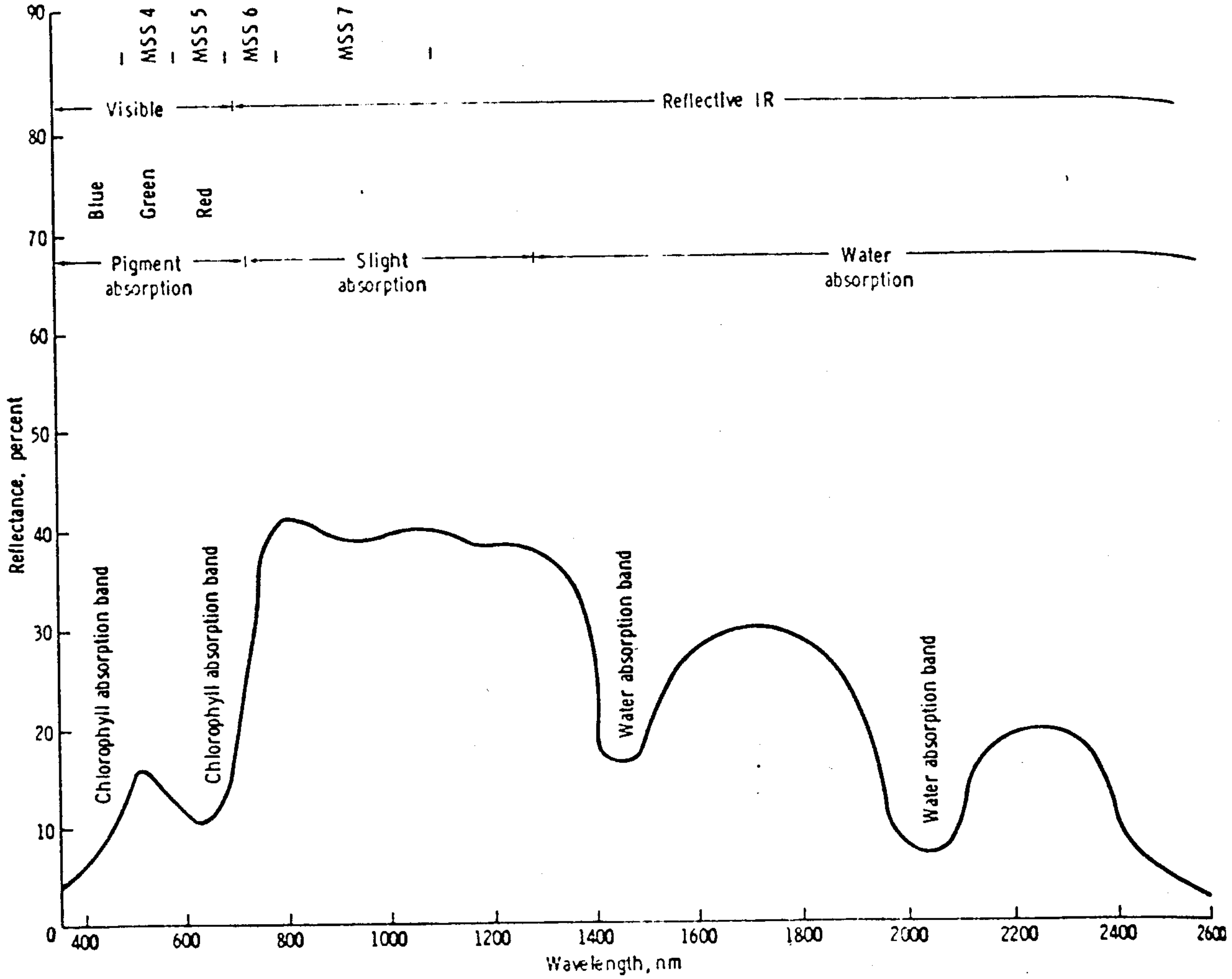

Figure 5. Spectral reflectance of a typical green crop canopy. The spectral response of Landsat MSS bands and the primary absorption bands of chlorophyll and water are shown. (Rouse and Molly, 1975)

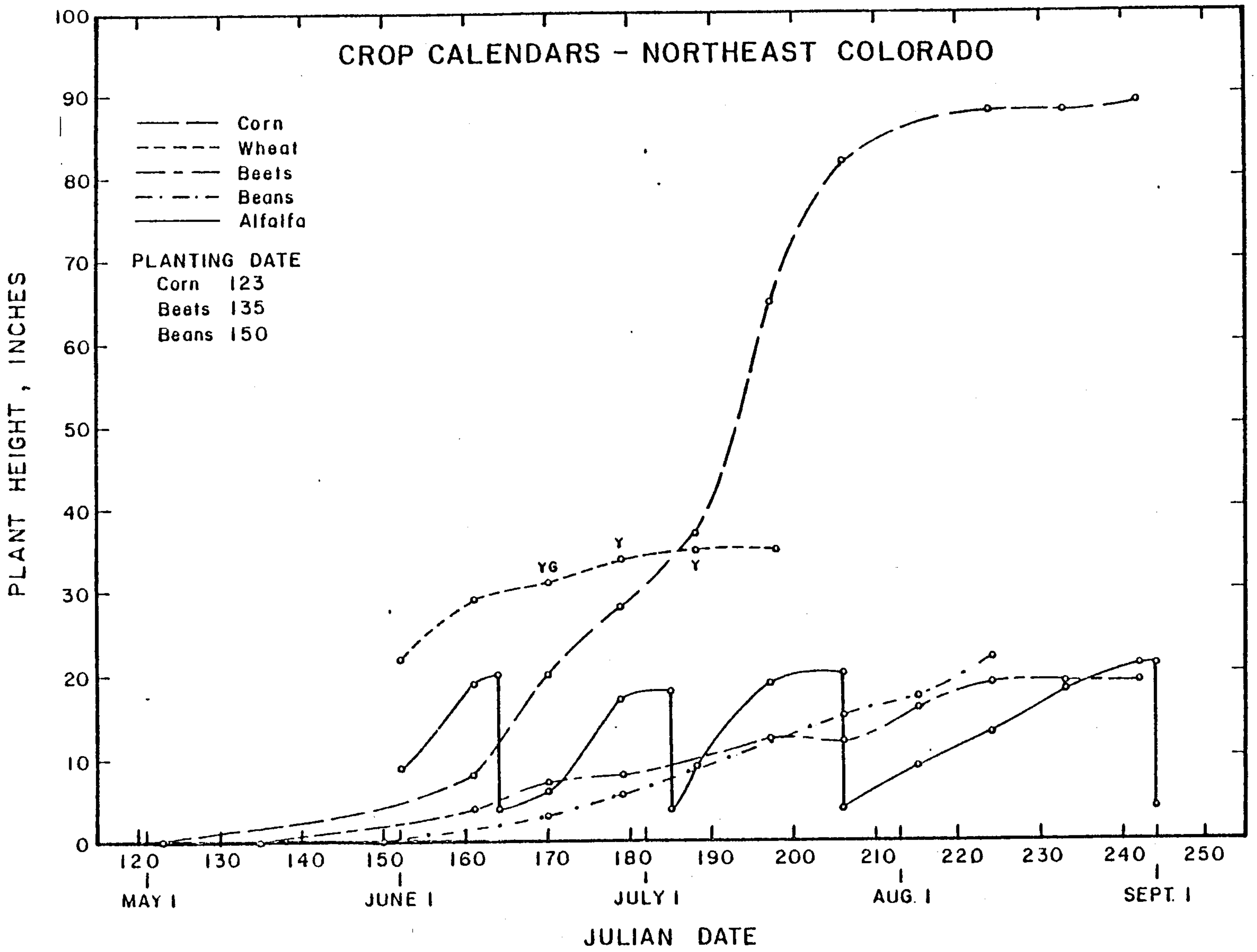

Figure 6. Crop calendars for selected crops in northeastern Colorado for the year 1978. Some variation should be expected from year to year. (from Maxwell et al., 1980).

Identification and mapping major crops is considered feasible. Timely and accurate estimates of the winter wheat acreage were shown to be possible by Morain and Williams (1974). The Large Area Crop Inventory Experiment (LACIE) also estimated the acreage of winter wheat for the entire U.S. and for a number of foreign countries, with relatively high accuracy.

The feasibility for determing plant deficits from Landsat data has also been investigated but remains somewhat inconclusive. Maxwell et al. (1980) attempted to monitor drought in Colorado using Landsat data. The results indicate that Landsat can be used, but that timeliness is a problem. Since Landsat only collects data from a given area every 18 days, one cloudy overpass may preclude the timely detection of plant water stress.

Forest classification into coniferous and deciduous types can be accomplished at a 90 to 93% accuracy level. Using multistage sampling techniques, the timber volume of a national forest district has been estimated at a confidence level acceptable to the U. S. Forest Service at a very favorable cost/benefit time/benefit ratio (Nichols et al., 1974).

The identification of forest types using Landsat imagery has also been investigated. As part of this study, Pernia (1978) identified 17 vegetation type/density categories for the Williams Fork Watershed of western Colorado. Vegetation types included grassland, brushland, deciduous forest (aspen), coniferous forest (lodgepole pine, spruce-fir) and alpine tundra. Using a visual interpretation of computer classified categories, accuracies ranging from 88-93% were obtained. The results indicated that differences between sharply different classes could be readily determined, for example, coniferous vs. deciduous forest, forest vs. tundra, forest vs. grassland, but that identification of similar types was less accurate, for example, grassland vs. tundra, lodgepole pine vs. spruce-fir forest.

MSS data has been used for determining leaf area and percent cover. The ratio of MSS band 4 to 5 has been found to relate to the amount of leaf area for wheat in Kansas, whereas the ratio of MSS band 5 to 7, is best for estimating the leaf area for cotton and sorghum in Texas. The difference may be due to the low leaf area of the wheat as compared to the sorghum and cotton.

Range species and plant community vegetation mapping has been accomplished at various levels of success (70-90% accuracy). Several investigators have obtained encouraging results in range biomass estimation (Tucker, 1973, Tucker and Miller, 1977). This data, obtained by establishing a correlation between biomass and any number of band ratioing techniques will be useful not only for planning purposes but also as range carrying-capacity decision making information for the area manager. Timeliness is again an important factor. A problem in implementing this application is the requirement for prompt data turnaround.

Blanchard (1974) studied the use of Landsat to fill in missing data for the commonly used Soil Conservation Service (SCS) runoff equation:

$$Q = \frac{P-0.2S)^2}{P-0.8S}$$

wheere Q = runoff (inches)
P = precipitation (inches)
S = water storage factor equal to (1000/CN)-10
CN = curve number, a function of soil type, vegetation, and soil moisture

Blanchard showed that the curve number, CN, can be related to the difference between MSS bands 4 and 5 in the southern Great Plains.

Several published examples illustrate the capability of radar to differentiate both cultural and natural vegetation(Haralick et al., 1970; Morain and Simonett, 1966; Morain and Campbell, 1974). From these efforts has come the basic justification for current ground-based microwave research in agriculture (DeLoor and Jurieens, 1971; Ulaby, 1973). These experiments are extending the knowledge of energy interactions with crops and soils under differing cover, moisture, and plant morphology conditions. In general, an increase in plant cover is associated with increasing scene moisture; therefore, the microwave response also increases. As crops decrease in leaf area, mature, or are harvested, signal strength drops. These cyclical trends can be useful for crop identification. However, to monitor seasonal trends,it is clear that sequential data must be obtained at several frequencies-polarizations and viewing angles.

Viksne, (1970) reports on the use of SLAR for forestry purposes in tropical zones. A great advantage of radar is that operations can be started and finished on schedule regardless of the weather. The authors briefly describe the mapping of vegetation over a 17,000 km^2 area in Panama. K-band was chosen for this area because near-perennial cloud cover limits the application of aerial photography. Because K-band signals do not penetrate vegetative cover at low viewing angles, the technique enabled the evaluation of vegetation types as well as terrain features.

Daus and Lauer (1971) also emphasized the potential aspects of radar for vegetation studies. Their principal conclusions are summarized as follows:

1. Two primary characteristics of SLAR imagery were found useful in analyzing wildland vegetation; image tone and texture.

2. Vegetation was the major factor affecting texture, whereas slope and aspect were the major factors affecting tone.

3. A skilled interpreter can delineate differences in major vegetation cover types, especially in areas where the terrain is flat.

4. In flat terrain, timber stands could be consistently distinguished from everything else due to their coarse texture.

5. Slight differences in topographic relief or changes in slope often caused two nearly identical timber stands to appear quite different on the SLAR image.

Soils

During the last 40 to 50 years, aerial photography has been widely used for accurate soil mapping. Now, Landsat can image an 8-million acre scene in one frame, allowing comparisons of soil associations over the entire area. Landsat's four spectral bands and repetitive coverage make subtle differences readily apparent and allow vegetative differences (which are usually a function of varying abilities of soils to produce vegetation) to be used effectively to help separate soil association landscapes. Soil maps produced from this data are useful for irrigation and drainage planning, crop-yield estimates and watershed planning.

There are many soil properties which influence the spectral characteristics of soils. Soil reflectivity is primarily affected by the mineral and organic content, particle size, and soil structure. Figure 7 shows typical reflectance curves for four soils. The radiant energy which is not reflected is absorbed by the soil and transformed mainly into heat. Consequently, temperature patterns at the soil surface may be indicative of soil variations.

Certain non-soil factors also influence the spectral reflectance of soils. The presence of vegetation has the potential to mask the reflectance of soils. Vegetation type and the amount of canopy cover are primary elements in this analysis. Live green vegetation has a pronounced effect on surface reflection, with a strong absorption band at the red wavelengths and high reflectance in the near infrared. Dry and/or dead vegetation has a signature similar to that of soils; so, although dry vegetation may alter the amount of energy reflected from the soil, it does not normally change the slope of the soil reflectance curve (Kornblau, 1979). Research which investigates the interaction of soil and vegetation signatures includes Gausman et al. (1975), Tucker and Miller (1977), and Tucker (1977).

The moisture content of surface soil layers has a pronounced effect on the spectral response of soils to incident energy. The result is that soils with different water holding capacities, but that are otherwise similar, may be distinguished by their soil moisture signatures (Shockley et al., 1962). In other cases, the best contrast between soils can be achieved at low moisture contents because the dominating effect of water is minimized allowing the soil characteristics to show.

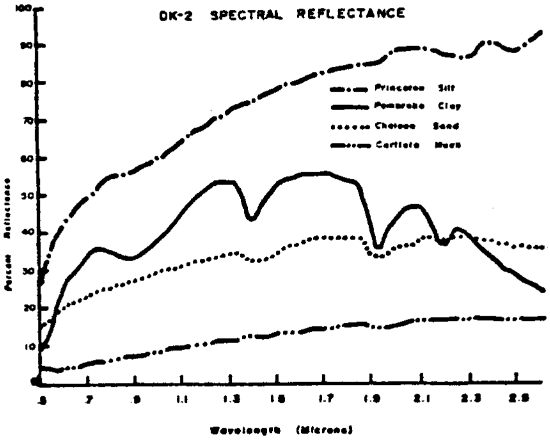

Figure 7. Reflectance measurements from four Indiana soils at similar moisture levels (From Manual of Remote Sensing, Reeves, 1975).

Slope and aspect will also influence the spectral reflectance of soils. Although these factors have not been studied thoroughly, it is logical that slopes and aspects with high irradiance should appear bright while slopes and aspects with low irradiance should appear dark. Computer algorithms can be designed to eliminate the slope/aspect effect from digital data. Topographic features are also likely to affect the vegetation, the temperature and the moisture content of the soil.

Soil Mapping

It is suggested by numerous researchers that multispectral imagery contains more information about soils than conventional photography. Computer-generated maps displaying soil characteristics such as organic matter, color, soil type and texture have demonstrated the classification capabilities of multispectral data (Cipra et al., 1971; Kristof and Zachery, 1971, and others). Both Zachery et al. (1972), and Cipra et al. (1972) found that computer maps did not match perfectly with existing soil maps. In at least one case the computer image was more accurate. Both papers stated that computer processed multispectral imagery is useful for delineating soil boundaries.

Kornblau (1979) studied the use of Landsat as an aid to mapping soils in semiarid regions. Drawing from the work of others he used and compared four different methods of computer analysis of soils in South Park, Colorado. Both early and late summer images were used in this study. Although Kornblau suggests additional research in the statistical analysis and in the selection of optimum dates, he recommends the operational use of Landsat digital data to aid in the production of detailed soil maps in semiarid areas. Computer maps can be used to establish a ground sampling scheme. Where computer maps agree with field observations fewer field samples will be necessary.

Researchers have also examined the use of microwave systems in the study of soils. Morain and Campbell (1974) discuss a number of potential applications. The radar signal is most strongly influenced by soil moisture and surface roughness of the soil. The effect of these factors varies with system parameters including wavelength, polarization, resolution and look angle. Although radar will not replace photography and multispectral imagery, it may be able to provide unique data about surface texture and soil moisture (Cihler and Ulably, 1975). Additional research is necessary.

Erosion and Slope Stability

Many of the watershed characteristics described earlier in this chapter (slope, vegetation type and density, and soil characteristics) are very important in evaluating the erosion hazard of a given area. Consequently, remote sensing techniques, particularly multispectral analysis, have the potential to be very useful in monitoring soil loss as the result of hydrologic activity. Currently, the Iowa Remote Sensing Lab is performing digital analysis of Landsat imagery to define some of the inputs to the Universal Soil Loss Equation for areas in Iowa (Hoyer, 1980).

Another study investigated the use of aerial photography in the identification of the potential for mass wasting in slopes. McKean (1977) suggested that slope failure may be visible as a change in soil moisture at the surface very early in the failure process. The soil moisture and resultant vegetation vigor/density changes will result in spectral responses that differ from the surrounding stable slopes. These differences may be seen as density and color differences on color-infrared aerial photography. McKean used a density slicing technique to display the density anomalies. Future multispectral satellites with increased resolution may also be suitable for this type of observation.

Impervious Surfaces

Vital to any prediction of runoff stage and volume is an estimation of imperviousness of the watershed. In urban watersheds aerial photography has been used to determine impervious area. The areas of roofs, driveways, parking lots, and streets were outlined and measured. This is a tedious, time-consuming process. Additional overflights to update the data are equally costly in time and money.

By assigning imperviousness values to the cover classes separable by digital processing of Landsat data, Ragan (1977) obtained an impervious value of 39% for a very small watershed in Virigina. A comparable study using black and white low level aerial photography calculated a value of 34.4% for the same watershed. The absolute accuracy of these estimates cannot be determined but it should be noted that the difference is small. Ragan (1977) did a cost comparison for the two studies. Manual interpretation of aerial photography required 110 man days at a total cost of $14,000 compared to the computer aided classification which required 7 man days and a cost of $2,350. Computer classification is (according to these results) faster and cheaper than other techniques and sufficiently accurate.

Reed et al. (1977) expanded the Landsat classification technique to make it suitable for large inventories and areas including major metropolitan areas. Landsat data is notorious for its inability to delineate urban-type categories. To solve that problem Reed et al. (1977) manually defined the urban boundaries and performed a separate classification on areas inside and outside these boundaries. Results included regional landcover maps and area tabulations for 140 watersheds in the Washington, D.C. area and estimates of imperviousness for each watershed. In conjunction with other data such as drainage, slope, storm intensity, and soil type, these results may be used in a variety of hydrologic models.

Although Landsat data may be useful in major metropolitan areas, its use in and around smaller towns is less promising. Maxwell (1978) attempted to use Landsat to delineate small towns in southern Colorado. His results indicate that the mixture of lawns, houses, buildings and streets create a signature that is easily confused with the surrounding vegetation. The "urban" land cover classifications were not sufficiently accurate to be used in imperviousness studies, even though other land cover categories were classified with relatively high accuracy.

WATER LOSSES

Another important characteristic of a watershed which affects its yield is its water loss or use. A large proportion of the precipitation which falls on a watershed is returned to the atmosphere before it ever reaches a river or lake. Estimates of evaporation and transpiration can be aided with remote sensing techniques.

Much of the research done to apply remote sensing techniques to water use has been concerned with agricultural areas, especially irrigated crops. This research is discussed in this section. However, some of these techniques may prove to be useful in forested areas, as well.

Evapotranspiration

The evaporation of water from soil is controlled by the energy available at the surface and by the ability of the soil to conduct water to the surface. Transpiration is further controlled by the characteristics of the vegetation in which it occurs. The combined process, evapotranspiration (ET), is a function of a complex integration of these variables tempered by vegetation density and leaf area index.

As described in the previous section, both aerial photography and multispectral imagery have been used to identify vegetation type and density. Information of this nature is very important in nearly all evapotranspiration models.

Jackson et al. (1976) suggested using soil albedo measurements to calculate evaporation rates from bare soils. This method was found to be reliable during the transition, as the soil drys, from potential evaporation(energy-limiting) to soil-limiting evaporation. Previously published models were used to calculate evaporation rates at the wet and dry stages. This work follows directly from a study of the dependence of bare soil albedo on soil water content (Idso et al., 1975a) which presented albedo values for 17 soils, ranging from 0.05 to 0.16 for wet soils and from 0.14 to 0.30 for dry soils. For all soils except sands, dry albedos were about a factor of 2 greater than those of wet soils. Other methods of monitoring soil water content are discussed in Chapter 4.

The U.S. Water Conservation Laboratory, Phoenix, Arizona has conducted much research in thermal measurements applied to evaporation and transpiration. Their research indicates that the evaporation from soils may be inferred from surface soil temperatures (Idso et al., 1975b, 1975c). More recent resaerch extended the thermal measurements to assessing the water requirements of plant canopies (Jackson et al., 1977).

Irrigation

Because of the large impact of irrigated crops, the demand for irrigation water has become a significant concern in many areas of the U.S. Currently in Colorado, the U.S. Bureau of Reclamation and the Northern Colorado Water Conservancy District calculate and publish weekly evapotranspiration quantites (Grunblatt,1978). This information describes the consumptive use of water by particular crops, thereby allowing the farmer to approximate the necessary irrigation application.

These ET estimates can be combined with crop acreage estimates to evaluate the regional demand for water. By comparing the potential regional water demand with water supplies, budgeting of water supplies may be optimized allowing a more judicious allocation of water. Hu (1976) has discussed methods of irrigation scheduling with emphasis on the potential inputs from remote sensing.

To make the most efficient use of the available water and maximize agricultural production, it will be necessary to have near real-time statistics on water demand on a regional basis. Estes et al. (1978) studied the use of Landsat image processing techniques to produce cropland and crop statistics for input into agricultural water demand prediction models. Published reports indicate that cropland can be discriminated from non-cropland with 98% accuracy. Identification of specific crops is possible. The accuracies are somewhat lower but are steadily improved. Without the data provided by remote sensing, large scale water demand modeling becomes essentially an attempt to project historical trends into the future.

4. SUBSURFACE WATER INVENTORIES

Water held within the surface soil layers and the underground aquifers is another important source of water. Remote sensing techniques may be applied to projects of locating and monitoring these water supplies. Inferences about groundwater and soil moisture can be made through careful inventories of the earth's surface. An understanding of the relationship between subsurface water and surface characteristics allows the user to apply many of the techniques suggested in Chapter 3 to problems of subsurface water. In addition, systems which utilize microwave and longer wavelengths have the ability to penetrate several layers of the soil surface and record data pertaining to those layers.

GROUNDWATER

Ground-based techniques used in the evaluation of groundwater sources and discharge zones are relatively expensive and time consuming. Consequently, any method that can provide hydrogeologic information over large areas in a short time and at a reasonable cost is in great demand. Several types of remote sensing systems have displayed capabilities for providing some information of value.

Sources and Seepages

For many years groundwater hydrologists have recognized that geologic structures such as faults and fractures represent potential sites for sources of groundwater. The use of aerial photography as an aid in landform mapping was discussed in Chapter 3. Sonderegger (1970) chose high-capacity well sites in one area of Alabama by determining fracture trace densities from panchromatic, color and color infrared large-scale aerial photography. Results from this research indicated that this technique was successful. The average yield of wells located using the fracture trace density method was found to be two to three times higher than the average yield of well sites chosen by other methods.

Powell et al. (1970) discuss the relationship of lineations seen on Apollo 9 multispectral photography and water sources data including wells, springs, and streamflow gauging points. Conclusions drawn from this research indicate that observation of lineaments can help determine areas of groundwater movement, determine areas where large quantities of groundwater are available, select areas for making low-flow measurements, and aid in locating sites with optimum hydrologic conditions for the placement of dams and reservoirs (Meyers and Welsh, 1975).

In a workshop on groundwater exploration in southcentral Arizona Taranik et al. (1976) describe the use of Landsat Imagery for locating groundwater. In addition to the use of landform analysis, the correlation of drainage patterns and land cover types to groundwater resources was discussed. In this particular study, landform analysis entailed a separation of the mountainous areas, where relatively impermeable bed rock is exposed at the surface, from the unconsolidated alluvial fill where most of the groundwater is found. Image tone and texture of band (.8-1.1 μm) were the key identifiers in this process. Darker tones found in the mountainous terrain were related to the differences in weathering, the relative roughness (with respect to wavelength), and the variation in vegetation of the two ground materials.

Stream drainage patterns, visible in Landsat imagery due to their relative relief, can be classified coarse, medium and fine textured. Major stream drainage in the basins indicates the direction of surface and groundwater flow away from the bed rock exposed in mountainous areas toward areas of potential groundwater storage in the basin (Taranik et al., 1976).

Vegetation was also found to be very important for hydrogeologic interpretation of the area around Tucson. Of particular importance was riparian vegetation, which grows in close proximity to river banks, and phreatophytes, which are capable of extending their roots several tens of feet to reach the groundwater. Xerophytes, plants which are able to survive on very small and ephemeral water supplies, may help to identify areas where groundwater is not available. On false color Landsat imagery of southcentral Arizona, areas of dark pinks and reds may be dense and abundant growths of phreatophytes, good indicators of near-surface groundwater. Dense growth of riparian vegetation along stream bank is also a good indicator of a near surface aquifer. This vegetation appears as reddish brown thin belts that follow stream drainages.

Up to this point the discussion has been related to systems that are subject to visual interpretation, operating mainly in visible portions of the spectrum. Two other types of sensors seem to offer considerable promise in hydrologic investigations. These are thermal infrared and microwave systems.

Patterns appearing on thermal infrared imagery are primarily a function of the temperature of the earth's surface. Both spatial and temporal variations in surface temperature may be related to the presence of an underlying aquifer. For instance, thermal (8-14 μm) remote sensors have been used very successfully to locate the influx of groundwater into surface water body of a different temperature. Examples include the study of the hot springs in Yellowstone National Park (McLerran and Morgan, 1965). the study of large underwater springs on the coast of Hawaii (Fischer et al.1966) and studies of groundwater inflow to streams in the eastern United States (Hollyday, 1969; Wood, 1972).

Souto-Maior (1973) made an in-depth study of the uses of thermal remote sensing in groundwater studies. Working in a study area in Madison, Wisconsin, he indicates three possible applications of large scale thermal imagery: (1) the direct detection of seeps and springs, (2) the indirect evaluation of shallow groundwater flow through its thermal effects on the land surface, and (3) the indirect location of small volumes of groundwater inflow into surface water bodies. This investigation indicates that even though the interpretation of thermal imagery is complicated by many factors, including thermal-spatial resolution of the sensor, vegetation and soil variations, microclimatological effects, and the variations in the volume and temperature of the groundwater inflow, thermal remote sensing can provide an array of hydrogeologic data not easily obtained by ground-based techniques.

The possibility of using the thermal sensors to determine the depth of aquifers was investigated by Huntley (1978). This study indicated that with present technology, it is not practical to estimate water table depth directly from thermal imagery. Correlations between groundwater depth and radiometric temperature noted in other literature may be caused by increased cooling due to the evaporation of soil moisture.

Microwave systems are sensitive not only to thermal but also to electrical parameters of the terrain. They can attain greater depth of penetration than any of the systems discussed. Radar, in addition is sensitive to layered materials. These characteristics hold much promise for application in hydrogeology.

Side-looking radar provides sharp definition of valleys, slopes, and ridges, as well as faults and other geologic structures. This imagery can be used in ways similar to the methods described for aerial photography. It may also be "merged" with Landsat imagery. The detail and relief data of the radar imagery compliments the spectral data of Landsat very well. An example of this type of imagery was reproduced by Lillesand and Kiefer (1979).

Harvey and Skeleton (1972) applied SLAR in an investigation of influent and effluent streams in the Ozark Mountains of Mississippi. They reported that the ability to delineate regions of influent and effluent streams would aid the selection of the best measurement sites.

Other groundwater research utilizing microwave systems, active or passive, is minimal. This may be due to the relative unavailability of microwave systems outside of military installations.

SOIL MOISTURE

The ability to monitor soil moisture from remote platforms would be useful in a variety of hydrological applications. Antecedent soil moisture conditions are important factors in runoff prediction for watershed planning, flood forecasting and reservoir management. The water is lost from the watershed through evaporation and transpiration is closely related to the amount of moisture in the soil. Predicting runoff requires knowledge of spatial and depth distribution of soil moisture content before, during, and after heavy rainfall activities or rapid snow melt, and similar conditions are imposed by other water resource applications. Although results are somewhat variable, remote sensing techniques are being used to supply this information.

Originally, it was noted that photography could be used to show the delineation of regions with high surface soil-moisture content. This is due to the change in the absorption or reflection of visible wavelengths which occurs in soils when water is added. Color infrared film accentuates this effect. The near infrared wavelengths are highly absorbed by water causing very moist soils to appear very dark on the imagery and drier soils to appear light. This technique has been used in agricultural areas to identify poorly drained soils.

The relationship between soil spectral reflectance and soil-moisture content was investigated by MacDowall et al. (1972). In this study, soil reflectance in the wavelength range 0.3 to 0.8 μm was measured for twenty-two soil samples of different textures at different moisture contents. Results showed that the minimum reflectance occurred at the highest moisture contents for all textural classes but that even small variations in soil texture influenced the reflectance. Increasingly fine materials exhibited increasingly high reflectance.

The addition of water to soil also changes the soil's thermal properties. The large heat capacity and thermal conductivity of water enable moist soils to have a large thermal inertia. Thermal inertia (which is a function of thermal conductivity and heat capacity and is directly related to the moisture content of the soil) is an indication of the soil's resistance to temperature change caused by meteorological factors - solar radiation, air temperature, relative humidity, etc. The basic phenomenon is illustrated in Figure 8, which presents surface soil temperatures plotted against time for a bare-field before and after irrigation. The figure demonstrates that as the soil moisture content decreases following irrigation, the resulting diurnal range of surface temperature will also decrease. Consequently, thermal inertia (and soil moisture) can be remotely sensed by observing the diurnal range of surface temperature (Schmugge, 1978).

Reginato et al. (1976) and Schmugge et al. (1978) have experimented with remotely sensed thermal infrared temperatures from an aircraft platform. Their results show good agreement between remotely sensed

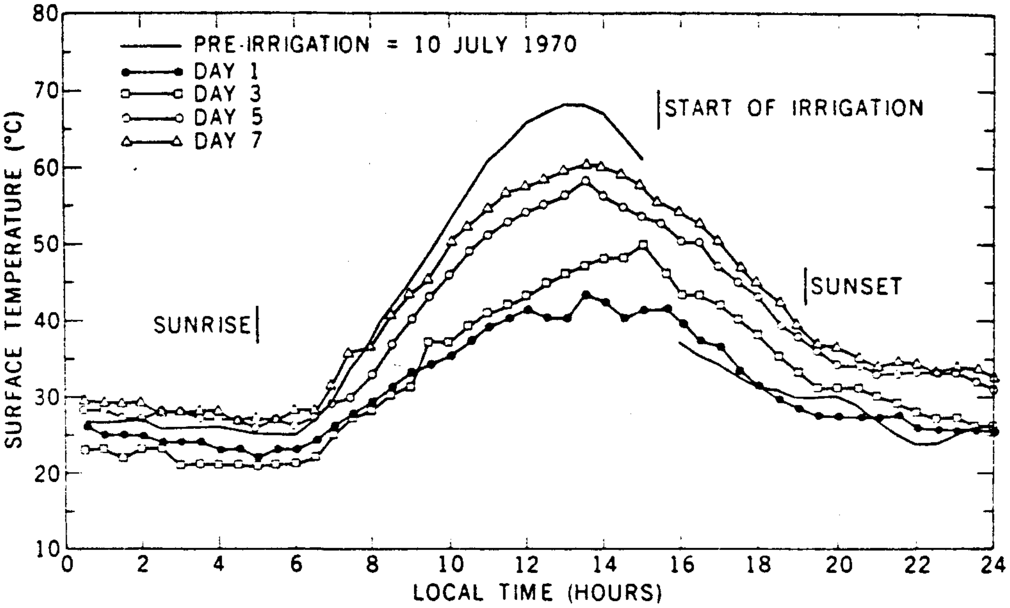

Figure 8. Diurnal Surface Temperature Variation as Measured by a Thermocouple. (Data from U.W. Water Conservation Laboratory in Phoenix, Arizona, Schmugge et al. 1978).

temperatures and ground measurements. The Heat Capacity Mapping Radiometer launched in April 1978, is currently providing data for further research.

Direct thermal techniques are not applicable to fields with a vegetative canopy. However, the difference between canopy temperature and ambient air temperature has been shown to be indicator of moisture status of the canopy (Jackson et al., 1977). This may also be an indication of moisture status of the root layers of the soil. If this approach was applied to unirrigated pasture grasses, the condition of rangeland could possibly be used as an index of the local soil moisture conditions.

The unique dielectric properties of water present a third possibility for remotely sensing the moisture content of the soil. The dielectric constant of water is very large, approximately 80 as compared with 3 or 4 for dry soils, at microwave wavelengths. As a result the surface emissivity and reflectivity for soils at these wavelengths are closely tied to its moisture content. Differences in emissivity can be observed through the use of passive microwave systems and the differences in reflectivity can be observed with active systems (radar). Both approaches have been investigated with some success.

Microwave radiometers have been used to measure the emissivity of soil surfaces at a variety of moisture contents in the laboratory and field (Poe et al., 1971; Newton, 1976), from aircraft (Schmugge et al., 1974) and from satellites (Eagleman et al., 1975). Results from these investigations indicate that emissivity of soils is highly correlated with the surface layer (~5 cm) soil moisture measurements. Coefficients as high as 0.9 have been obtained.

Surface roughness is believed to be the largest source of confusion in the use of passive microwave techniques (Newton, 1976). Increased roughness generally has the effect of decreasing the surface reflectivity thereby increasing the emissivity. This effect is most pronounced in wet soils.

Active microwave systems (radar) have also been used in soil moisture investigation for a number of years. In June 1970, a 13.3 GHz NASA JSC scatterometer was used to image an agricultural test area in Kansas. This instrument showed that backscatter increased sharply as it was flown between recently irrigated fields and dry fields. Roughness characteristics also affected the amount of backscatter from the scene.

Because radar systems provide their own source of illumination, sensor parameters (wavelengths, polarization and incidence angle relative to the nadir) must be chosen carefully. Batlivala and Ulaby (1977) studied these parameters extensively and reported that a 4.25 GHz system with an angle of incidence of between 5° and 10° yielded the best sensitivity to surface soil moisture independent of surface roughness.

Additional research has used microwave systems, with methods similar to those described in the section dealing with snow surveys, to study soil moisture in the soil layers below the surface. By using several wavelengths, each with a different penetration capability, brightness temperatures of the soil can be measured at varying depths. Figure 9 presents the results from one such survey, a one-half mile traverse across the San Andreas fault, along the field soil moisture measurements that were sampled at regular intervals across the section. Analysis of this type of data requires a good understanding of properties of microwave radiation. For example, although each progressively longer wavelength may attain progressively greater penetration, the actual depth varies with amount of moisture present in the soil. This fact is important to the interpretation of microwave data.

While it is clear that no one sensor system will satisfy all of the requirements that may be necessary for optimal soil moisture observation, microwave remote sensing systems have a number of advantages over both the thermal and optical systems. Microwave radiation has a greater penetration capability than the systems utilizing short wavelength radiation. This characteristic allows microwave systems to "see" through

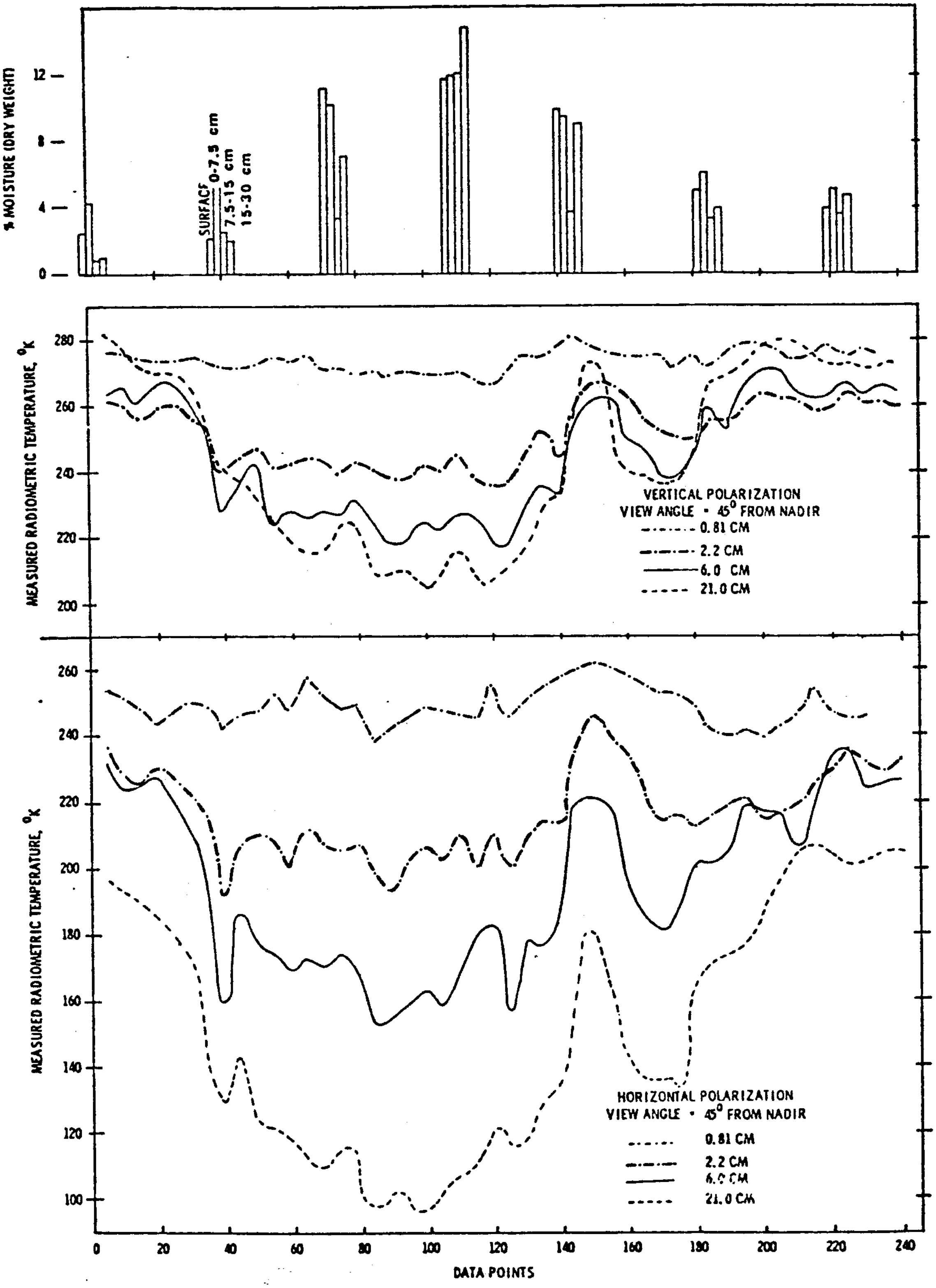

Figure 9. Radiometric traverse across trace of the San Andreas fault, Salton Sea area, California. (From Manual of Remote Sensing, Reeves, 1975).

most types of clouds and to maintain their sensitivity to soil moisture in the presence of some vegetation. Radar systems, with their own source (known) of energy, are virtually time-independent and can provide spatial resolutions from air and space platforms compatible with the needs of water resource applications. However, active systems are strongly affected by angle of incidence and surface roughness. Schmugge (1978) suggests that a passive microwave system with 10-20 m resolution, supplemented by either the thermal infrared or radar high resolution data, mounted onboard a satellite to provide frequent wide-area coverage, on a global basis, may be the most practical system for remote sensing of soil moisture.

5. CONCLUDING REMARKS

This paper has presented a summary of remote sensing applications in hydrology. It is evident from this review that NASA and many of the water resource agencies have placed a great deal of emphasis over the past several years, on remote sensing applications in water resources in general and hydrology in particular. It is also evident from the many symposia and specialty conferences on the subject.

It is equally evident that remote sensing applications have met with varied success. Some applications such as snow cover mapping, geological mapping, and vegetation mapping have been exceedingly successful and can be considered to be operational tools. Other applications, such as microwave sensing of soil or snow water contents and estimation of evapotranspiration processes have met with partial or qualified sucess and must be considered as still in the experiment stage.

Remote sensing is a tool and should be treated as such. Its greatest value comes when it is used in conjunction with other data sources. Field data or "ground truth" is necessary to establish the reliability and improve the efficiency of data interpretation. Only a few applications permit the use of remote sensing data by itself.

Although remote sensing has many limitations its value has been clearly demonstrated. As new sensors and methods of interpretation are developed, and as present methods are refined, remote sensing will become increasingly valuable to hydrologists and resource managers.

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Appendix A

THE REMOTE SENSING SYSTEM

Probably the easiest way to view remote sensing is as a system made up of three basic components: the scene, the sensor subsystem and its platform, and the processing subsystem. These components are illustrated in Figure A-1. The concept is simple; the actual components are complex. This section will describe each of these components as they pertain to all remote sensing systems. The capabilities of some specific sensor subsystems will be described in detail in Appendix B.

THE SCENE

The scene includes everything in front of the sensor. Its elements interact with electromagnetic energy to produce measurable phenomena. The scene includes not only the ground or the object surface but also a certain part of the total object volume and the atmosphere between the surface and the sensor. The proportion of the total volume of an object that is included in the scene depends upon the physical properties of the object (conductivity, dielectic constant and magnetic permeability) and the wavelength which the sensor is capable of detecting. The effects of the atmosphere on the total remote sensing system are also dependent upon the choice of the sensor.

In general, it is safe to say that the scene is very complex and that it has a large number of variables. A large quantity of information about the scene can be conveyed to the sensor by variations in the energy radiating from the scene. Some of these variations contain the desired information. This is called signal. Any variations in the energy levels, not related to the desired signal are considered to be scene noise. In natural resource applications of the remote sensing system the user has little or no opportunity to control or change the scene. Therefore, it is important that the user choose a sensor subsystem which is capable of detecting the maximum signal and the minimum noise from the scene; that is, maximize the signal to noise ratio (S/N).

THE SENSOR SUBSYSTEM

There are many sensor systems currently available for a wide variety of applications. Although a sensor's function is to gather data about the scene, each sensor type is unique in order to meet the specific needs of the user. Systems may use different energy sources. Passive systems detect, measure and record the intensity of existing energy reflected and/or emitted by an object. Photographic systems and multispectral scanners are examples of passive systems. Active systems provide their own illumination of the target. Radar is an active sensor. It generates and emits its own energy pulse and measures the backscatter of that energy from the scene.

Sensors also vary in the way that the wavelength and its intensity are recorded. Photographic systems use a photo-chemical response of films to record the intensity of visible energy reflected by the scene. Combinations of films, filters, and lens may be selected to limit the range of sensitivity. Electro-optical scanners use optical energy (the visible and infrared wavelengths) to create an electrical signal which is recorded in a digital format.

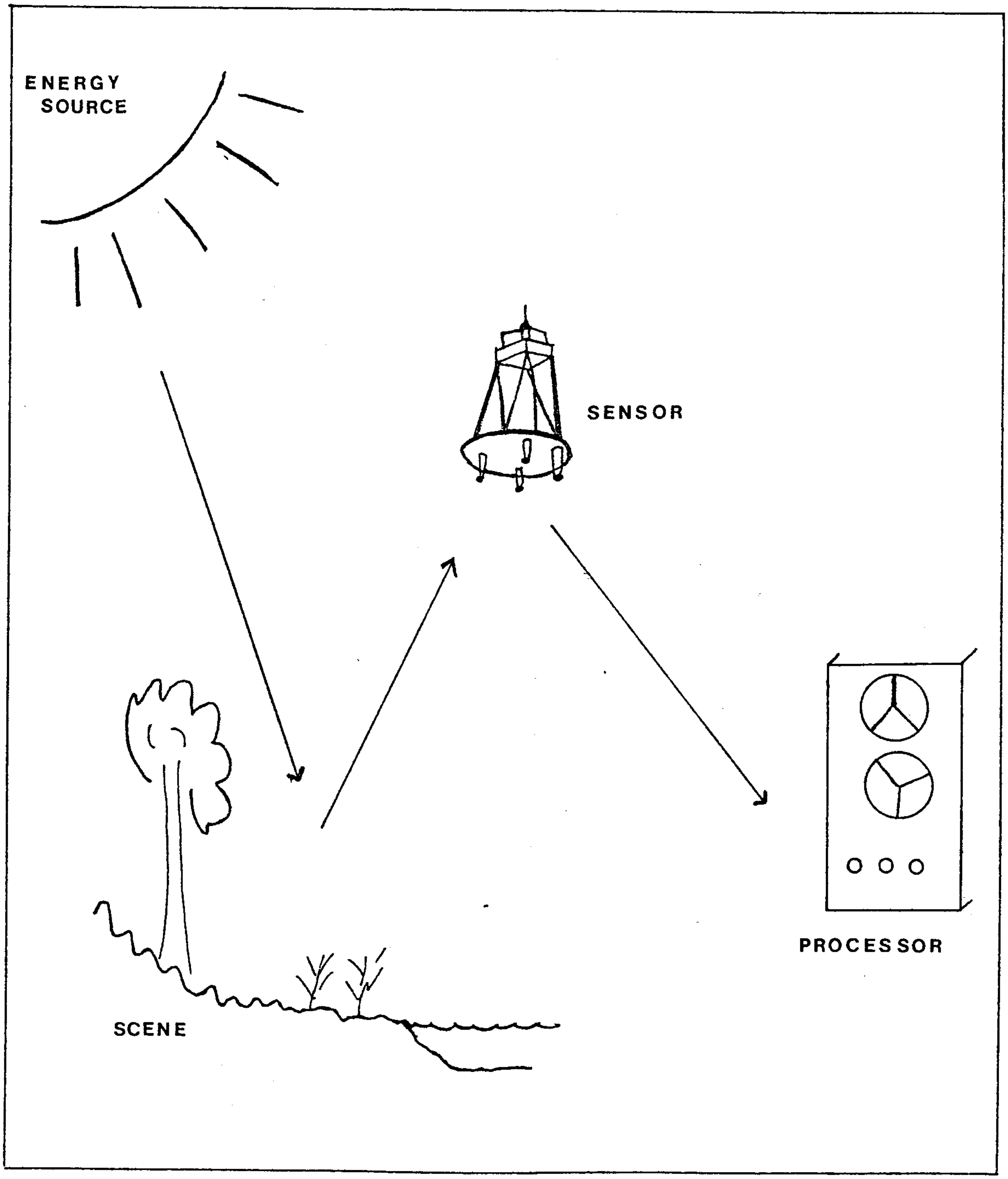


Figure A-1. The basic remote sensing system is shown with its three components: the scene, the sensor, and the processor.

Not all sensors produce an image. Some radiometers for example, read out a single number, a measure of the intensity of the energy with a specified wavelength that is detected by the sensor.

There are a number of basic specifications that are applicable to all of the sensor systems. These are:

1. Spatial resolution of instantaneous field of view (IFOV)
2. Spectral resolution
3. Detectibility and S/N
4. Scale
5. Temporal characteristics

When these specifications are properly understood they can be used to describe each system in terms of the characteristics and the capabilities of the data it can collect. As researchers continue to explore the nature of electromagnetic interactions with matter and the "signal" is identified for new applications, these specifications will be used to define parameters of new systems designed to meet the user's needs.

Resolution

Resolution is defined by Swain and Davis (1978) as a measure of the ability of an optical system to distinguish between signals that are spatially near or spectrally similar. In order to fully understand the concept, it is easier to divide it into its two components, spatial and spectral, and discuss each one separately.

Spatial Resolution

Spatial resolution has been defined in many ways. Swain and Davis (1978) and Sabins (1978) among others, define spatial resolution as the minimum separation (usually expressed in meters or radians) at which two objects appear separate and distinct in an image. Objects that are spaced closer appear to be one. Colvocoresses and McEwen (1973) described spatial resolution as the minimum size of objects that are uniquely recorded. Although these definitions are similar, they represent different perspectives on the role of spatial resolution in modern systems.

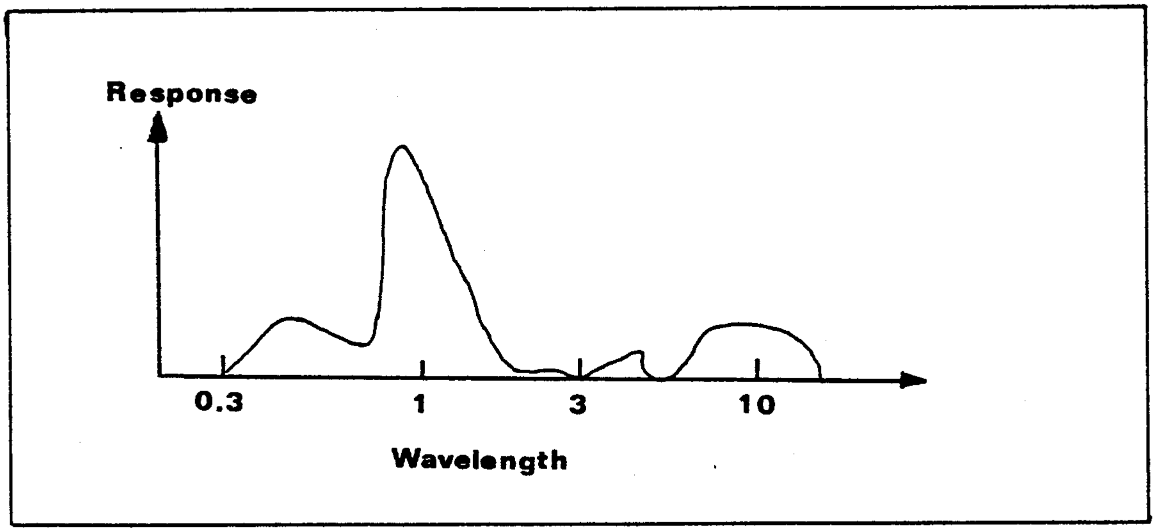
The first definition is related to an image-oriented approach to data analysis. In this type of analysis, spatial resolution becomes a prime consideration. It is the major information-bearing attribute of the data. Spatial structure of the scene provides a basis for much of manual photo-interpretation.

When multispectral pattern recognition is the main type of analysis, spatial resolution takes on a new role. It limits the type of informational classes that may be recognized by the analysis. For example, data gathered over an urban scene by a system with a 100 m instantaneous field of view (IFOV) would permit direct classification of land use categories such as rural, residential, industrial, etc. The same scene recorded by a system with one meter resolution, could be classified as grass, trees, concrete and rooftops, i.e., all of those components that go together to make up one information class in the system with lower resolution (Landgrebe, 1976).

The choice of spatial resolution is based on the desired informational classes.

Spectral Resolution

Spectral resolution is defined by Swain and Davis (1978) as the measure of both the width of the spectral band(s) to which the sensor(s) is sensitive and the sensitivity of the sensor. In this case, sensitivity refers to the number of levels of energy that the sensor can distinguish. Other spectral characteristics are also important. The basis for multispectral remote sensing is the concept that each type of matter reacts to EM energy in a unique pattern if the entire spectrum is considered. This pattern, as shown here for a vegetative canopy,

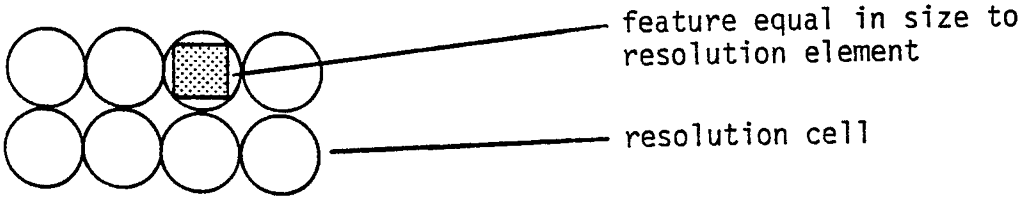


is called a spectral signature. The user must consider which wavelength regions or "spectral windows" and how many of these windows will best identify the objects and phenomena of interest. The choice of desired informational classes and discrimination of these classes is the prime factor in the development of spectral requirements.

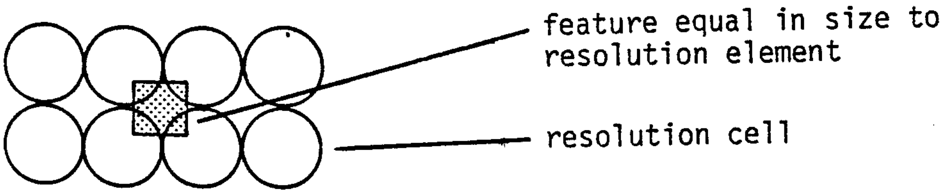
Detectability

The primary function of a sensor is to detect the presence or absence of an object or phenomenon within a scene by recording variations in the radiant energy from that scene. The detection of ground features is dependent upon two properties. First, the sensitivity (ability to measure small changes in radiance) of the sensor must be great enough so that variations in the radiance of the different scene elements may be separated from the random noise input of the system. Sensitivity is usually specified by the signal-to-noise ratio (S/N), where the signal is defined as the radiance value of the scene. The greater the signal-to-noise ratio the greater the number of discrete levels of radiation that can be discriminated by the sensor.

Secondly, because all of the radiation arising from the scene within the instantaneous field of view is integrated and measured as a unit, the detection of ground features is dependent upon the relationships between the size of a feature and its brightness with respect to the brightness of the background against which the feature is imaged. For example, if a feature equal in size to the spatial resolution element (IFOV) is to be detected, the feature must have a brightness of at least one increment (gray level) greater than the background noise of the system and the resolution cell must fit exactly over the feature during the imaging process.



More often, however, the resolution cell covers only a part of the feature.

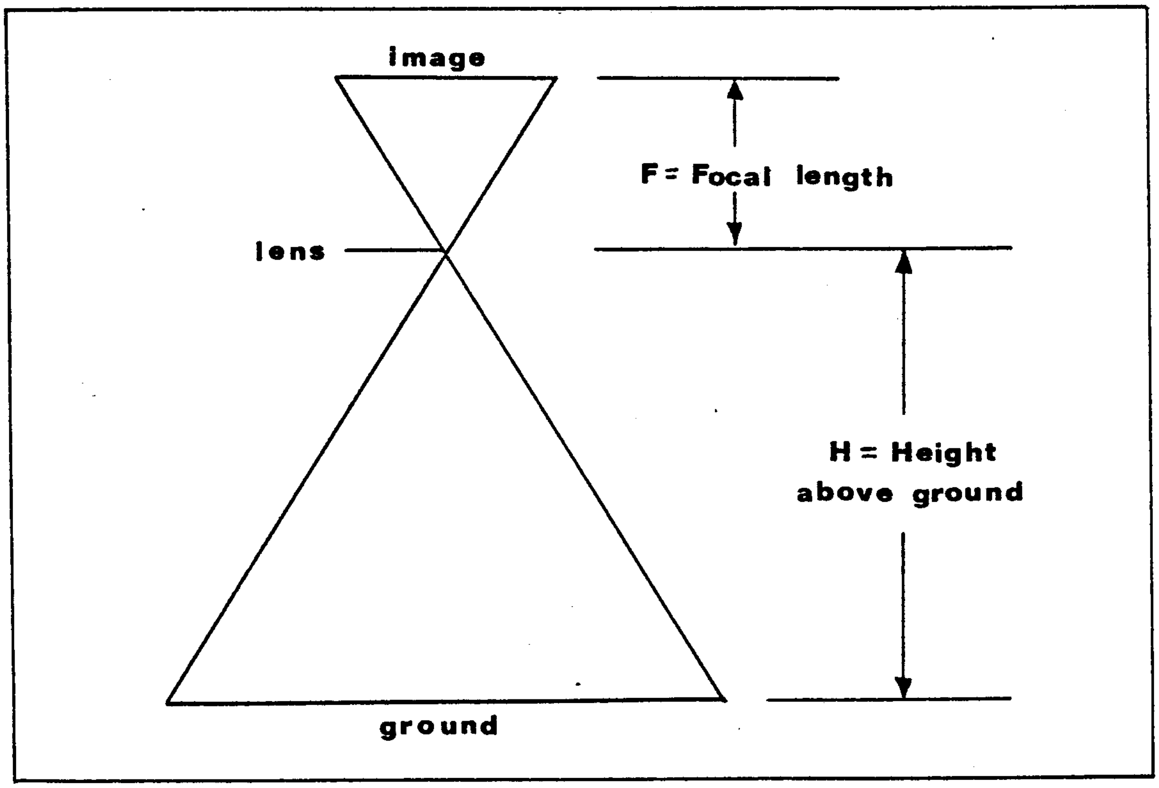


In this case, the feature will not be detected unless the portion of the feature, included in any one of the IFOV's, has sufficient brightness to influence the recorded brightness of that resolution element. Similarly, a feature smaller than the resolution element may be detected only if its brightness is sufficient to affect the brightness of the resolution element by at least one increment. Depending upon the spectral characteristics of features and the background against which they are imaged, features detected in one spectral band may not be detected in another spectral band.

Detectability is strongly tied to both spectral and spatial resolution. Since the total energy radiating from any portion of the scene is a finite quantity per unit time per unit area the spectral and spatial resolution of the sensor must be selected carefully in order to achieve the desired signal-to-noise ratio in each spectral band. For instance, a system with very fine spatial resolution may need a very wide spectral bandwidth in order to receive enough energy during the imaging period to maintain an appropriate signal-to-noise ratio. Conversely, a similar sensor but one that has low spatial resolution may be sensitive to only a very narrow spectral band and still receive enough total energy to have the same signal-to-noise ratio.

Scale

Scale is the ratio of the size of an object in an image to the actual size of the object.



Scale can be calculated from the following formulas:

$$\text{Scale} = \frac{\text{image size}}{\text{actual size}} - \frac{F}{H}$$

In much of the literature, scale has been used interchangeably with resolution. Scale is a characteristic of imagery that is established at the time of imaging, but can be changed by enlarging or reducing the image. Resolution is also established at the time of imaging, but unlike scale, once established, resolution cannot be increased by optical processes. Resolution is related to the characteristics of the sensor such as the lens quality and the film sensitivity of a photographic system, the scene characteristics such as scene brightness and contrast, as well as the original image scale. These factors and the variation of the system response are discussed by Welch (1971) and Colvocorresses and McEwen (1973).

The confusion between resolution and scale is probably related to early days of aerial photography when the finest detail recorded in the image could be seen by the unaided eye. At that time, the scale did correspond to the finest detail that could be expected. Today much of the imagery that is available may be magnified many times before the finest detail is visible. However, it is generally true that as the image scale increases, the resolution also increases. Conversely, small scale images usually have poor spatial resolution (O'Malley, 1978). For the remainder of this paper it should be assumed that all references to scale refer to original scale unless otherwise stated and that the above relationship is true.

Selection of the proper scale depends almost entirely on the intended use of the imagery. For example, information relating to surface soil drainage in cultivated fields can be obtained from color infrared imagery at a scale of 1:60,000 by making precise delineation between well drained and poorly drained land areas. These same features may also be identified from small scale imagery (1:120,000) but the process will be more time consuming and information will be less precise (Richardson, 1978). However, if the objective of the study had been to differentiate bare soil from vegetated areas, either of these scales would have proved satisfactory.

Scale variations are a function of both the sensor system and the altitude of the platform from which the image was recorded. Platforms vary from the very low altitude cherry picker, a few feet above the earth's surface, to the very high altitude satellite, many miles above the ground. Each level has its advantages and disadvantages. Low altitude imagery with scales ranging from 1:2,000 to 1:20,000 provides detailed coverage of a small area. This type of imagery is very applicable in small area inventories and some model building studies, but may become expensive and time consuming when applied to large area studies. A special problem related to low altitude imagery is the scale distortions caused by changes in surface relief.

Scale distortions are reduced in high altitude imagery (1:60,000 to 1:120,000) because the change in relief is small relative to the altitude of the aircraft. Each high altitude photograph covers a large area. Consequently, it takes only a few photos to provide coverage for a large area study. High altitude color infrared photography has been used very successfully in many resource inventories for such applications as wildland management, timber survey, flood mapping, and urban planning to name only a few.

The "big picture" of satellite imagery more than makes up for its smaller scale (1:500,000 to 1:5,000,000). The synoptic view provided from the very high vantage point of space offers scientists visible proof of some phenomenon that have been sampled and theorized about for many years. Ocean currents, weather patterns, regional structure, and water resources are visible in satellite images.

Often, a combination of scales may be desirable. Large scale imagery to provide detailed information and small scale imagery to present the regional view.

Temporal Features

With the addition of satellite imagery to the remote sensing family the importance of temporal characteristics has increased. Some of the satellite systems such as LANDSAT and the NOAA weather satellite GOES, are designed to supply repeat coverage of any area at regular intervals. For many applications such as monitoring landcover change, crop-yield and irrigation water demand, repetitive coverage on a seasonal basis is very valuable. For other applications such as temperature analysis, repetition at different times of the day is necessary.

THE PROCESSING SUBSYSTEM

Once the sensor system has collected the available data, the user must choose a method to process that data into meaningful information. Processing usually involves a compression of the data from an unwieldy bulk to a manageable volume, the addition or application of ancillary data, and/or the interpretation of the data in terms of the desired information. The selection of data processing techniques depends upon the form of the raw data as it comes from the sensor, the type of information the user is hoping to extract from the data, and the desired form of the output.

Raw data may take a variety of forms. The most common systems, including photographic, multispectral scanner, and side looking airborn radar, are imaging systems. Of these, some systems produce an image directly, usually on film or paper. Others like the multispectral scanner, have a digital data form of putput where each piece of data has a spatial component. This data may be processed to form a picture on paper or film or it may be analyzed in its digital form.

To understand image analysis techniques, it is necessary to be familiar with the term, image, in its analytical sense. An image can be considered as a two dimensional distribution of the intensity of radiant energy which is a representation of a scene as recorded by a particular sensor from a particular viewing angle. A black and white image is a two-dimensional distribution of one dependent variable-intensity. By assigning a color to this intensity distribution and combining it with intensity distributions, recorded by sensors with different sensitivities, each assigned a unique color, a color image is produced. If the sensors are measuring energy in spectral regions other than the visible part of the spectrum, a color image is usually referred to as false color. Staying with the original definition of image, a color image is, then, a two-dimensional representation of the scene described by two spatially dependent variables - color and intensity.

When images are to be processed by a digital computer, they can be regarded as matrices where each element of the matrix is called a picture element or pixel. The values in the matrix are selected from a set of finite values to represent the energy intensity from that location of the scene.

Photointerpretation of Optical Products

Manual interpretation of images is the most basic method of extracting information from images. In addition to the identification clues that can be obtained from the color and intensity of each pixel, an experienced interpreter can begin to appreciate and understand the spatial arrangements of scene components. In large scale aerial photography, shape and size of ground objects when combined with the interpreter's knowledge of the area are probably the most important features of objects which will lead the interpreter to understand the image. Factors of scale and the vertical view may cause some objects to assume greater or lesser importance than in a ground level view. This makes interpretation by association very important. Shadows provide information about the objects which made them; recognition of a cluster of farm buildings may help the interpreter to identify silos, sheds and cow paths; and certain geologic formations are associated with certain drainage and vegetation patterns.

In cases where the objects of interest are smaller than the resolution size of the image, other spatial characteristics become increasingly important. Texture and pattern are primary keys for this level of interpretation. For example, in aerial photos texture can be useful in the study of fields because mottled textures may indicate variations in soil moisture content. A lined texture results if plowing, planting or harvesting are in parallel rows. On radar images, texture is an indication of the degree of roughness or nonhomogeneity on an image. A forested area may appear speckled and groves of trees may appear as small bumps. Texture has been an aid in inferring rock types, differences in soils, crop types and urban land use features. In most types of imagery, settlement patterns, rock outcrop patterns, and forest patterns give appropriate clues. Patterns which might be indistinguishable at lower altitudes are often apparent on imagery from high altitude platforms. Pattern identification emphasizes the interrelationships of cultural and natural features, which can lead to a reliable assessment of the encroachment of people on the environment.

For aerial photography and imaging radar, manual photointerpretation is the most common form of evaluation. For multispectral and other very high altitude imagery, manual interpretation may be just the beginning of the image interpretation process. Manual methods may be used to locate the image geographically to allow the application of ancillary data. If the user has the appropriate equipment available he may choose to use the more sophisticated techniques of image enhancement and/or pattern recognition. These techniques require digital data. Transparencies may be digitized or in the case of LANDSAT the original raw data may be purchased on computer compatible tapes (CCTs).

Image Enhancement

Image enhancement is one of the more important tools used to process raw data. Its purpose is to modify the image to increase the interpretability of the image. The most commonly used techniques can be divided into two classes: point operations, where each image point is operated upon without reference to neighboring points, and local operations which involve consideration of the values of neighboring scene elements in the performance of the operation.

Density slicing is one example of a point operation. In this operation the density range of the image is subdivided into a specified number of intervals and a distinct gray level or color is assigned to each interval. Its purpose is to enhance subtle density differences in the image. The most common usage of density slicing is for identifying similar colors or density levels across an image.

Other point operations include contrast stretching, which accentuates the intensity variation between the elements of the image, and image addition, subtraction, and ratioing. In the latter operations two images of the same area are simply registered properly and then combined mathematically point by point. Subtraction has been used to detect changes over time. Ratioing techniques used between spectral regions have been successful in monitoring biomass in rangeland studies (Tucker, 1973).

Image smoothing and edge enhancement are the two most common types of local operations. These operations have considerably more power and more versatility than point operations, but require correspondingly greater amounts of computation. The number of neighboring points which are considered is limited only by acceptable degree of complexity in the computation that is acceptable. Most procedures are limited to consideration of only the adjacent pixels.

Pattern Recognition: The Multispectral Approach

In the process of image analysis, the interpreter's primary interest is to choose a technique which will make optimal use of variations in the spatial, spectral, and temporal characteristics of the scene. In manual photointerpretation and image enhancement the spatial characteristics of the scene receive the greatest consideration in the analysis. Although a large amount of research effort has been expended, very few practical methods have been developed for the computer analysis of data as complex as earth observational imagery, on the basis of spatial variations in the scene. Therefore, if the routine and repetitive aspects of image analysis are to be successfully turned over to a machine so that low-cost, high throughput can be obtained, a simpler approach is needed.

Fortunately, spectral variations show promise for computer analysis and form the basis for pattern recognition. This numerical branch of remote sensing uses spectral variations as the fundamental portion of the analysis and adds spatial, temporal, and ancillary data as circumstances require and permit.

Pattern recognition techniques are designed to aid the interpreter in recognizing an object or phenomenon from data related to that object or phenomenon. In multispectral remote sensing systems, the data consists of radiance values for a number of spectral bands, which relate directly to the land cover characteristics. The variables may be original data for the spectral bands, enhanced data, or a combination of both. Ancillary data such as slope, aspect and soil parameters may be included to increase the number of variables. In many instances the identification procedure will be improved if the radiance values from two or more dates are combined.

After the variables are selected and the data collected, a pattern (spectral signature) can be established for each land cover category by calculating the mean vector and covariance matrix for each category. These signatures are then used in a computer program to classify each picture element of the scene according to the pattern which it most closely matches.

Figure A-2 demonstrates how this system might operate. Figure A-2a shows relative response (reflectance) as a function of wavelength for green vegetation, soil, and water. Assume the two wavelengths, marked λ_1 and λ_2, were selected as the variables for pattern recognition. Figure A-2b shows the same data for the three ground cover classes at the selected wavelengths, plotted with respect to each other. From the figure it is apparent that materials whose reflectance for the selected wavelengths are different will lie in different portions of the two-dimensional spectral space. As additional variables are selected, the effect is an increase in the number of dimensions of the spectral space and a more precise definition of the spectral signature of each ground cover class.

Techniques of computerized pattern recognition are the most powerful methods for analyzing multispectral data. Most of the information in multispectral images is spectral information which can be interpreted most accurately with the aid of any of a number of multivariate pattern recognition algorithms. These algorithms are described in detail in a number of publications including Duda and Hart (1973), Fu (1968), Swain and Davis (1978) and Langrebe (1976).

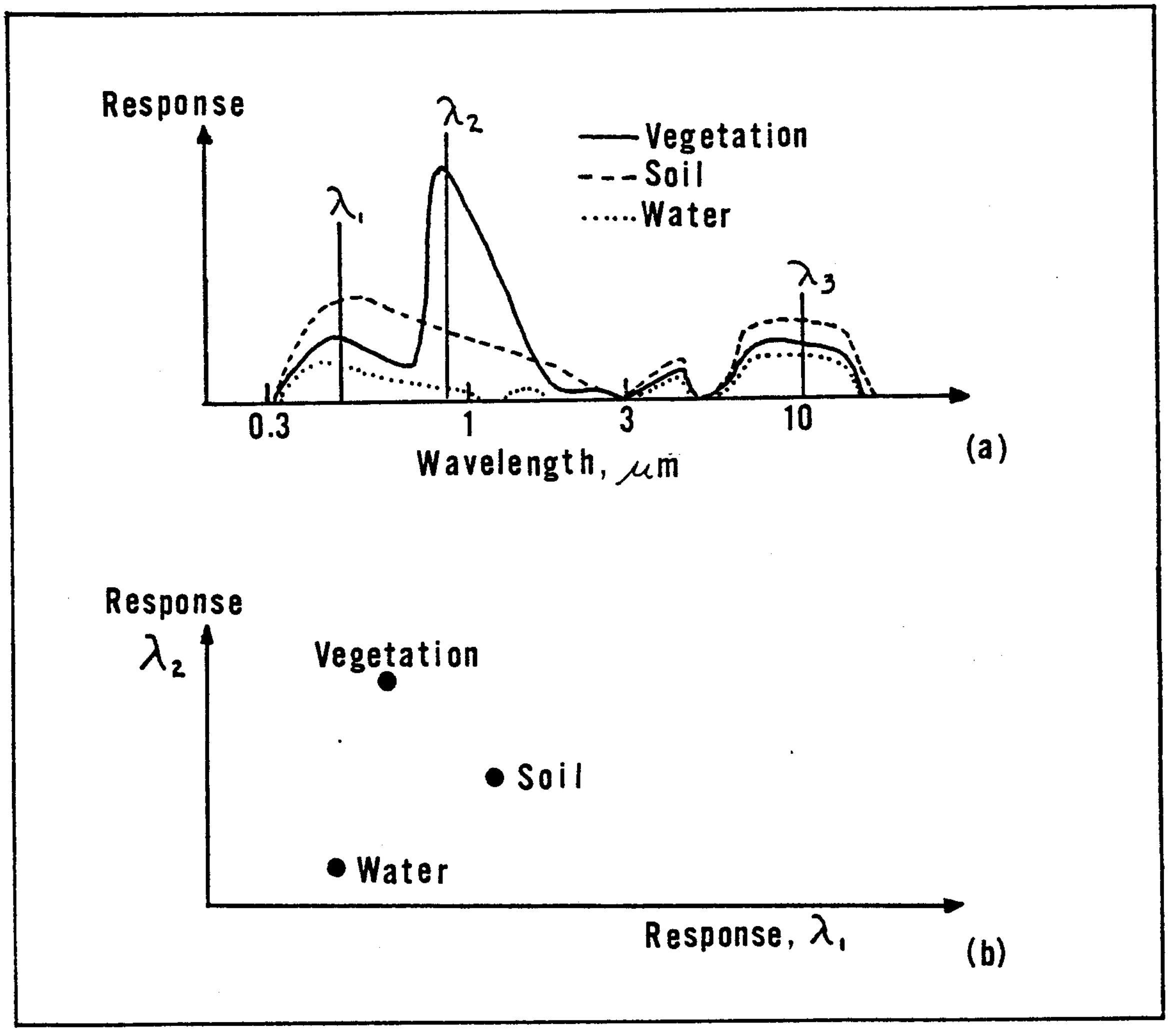


Figure A-2. Multispectral data may be presented in several ways. Figure (a) shows reflectance plotted as a fundtion of wavelength. Figure (b) shows spectral data in two-dimensional spectral space. (After Landgrebe, 1976).

APPENDIX A REFERENCES

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APPENDIX B

THE SENSORS AND THEIR CAPABILITIES

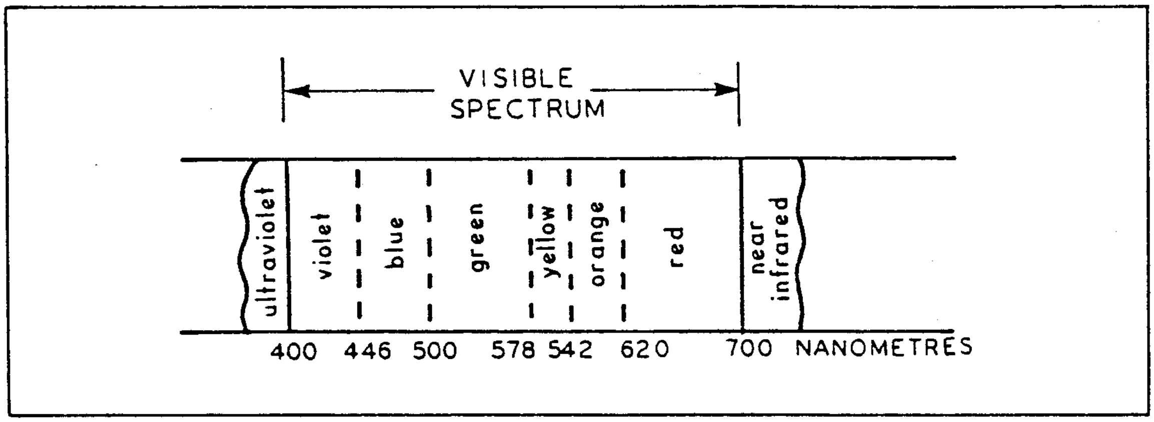
The basic problem in remote sensing instrumentation is to develop devices which are able to detect and measure electromagnetic energy of a specific wavelength and to convert the resulting signal into a form which can be perceived by the human senses. Within the visible range of the spectrum, all that is necessary is a method of recording the measurements. Camera systems and television vidicon systems are two methods of accomplishing that purpose. Outside of the visible region, the sensors have the additional task of changing the signal into potentially meaningful information.

This paper reviews some of the sensor systems, both available and proposed. For the most part the discussion is very general, describing the capabilities and potential applications of the sensors in the various references cited in this chapter. Much more detailed information concerning any of the systems discussed is available.

PHOTOGRAPHIC SYSTEMS

The photographic system is a logical first step into the world of remote sensing. The black and white process developed by Daguerre and the improvements which followed in rapid succession use the energy of visible light to produce an image. Over the years, the versatility of photographic systems increased. Advancing technology in optical sciences brought increased resolution through better lenses and finer grained films, and photography expanded into the near-infrared region of the spectrum. But always, the image, or the picture, produced by the system appeared similar to the picture perceived by the human brain through the process of sight. Consequently, these images, especially natural color, can be easily interpreted and understood without a high degree of training.

Although ground-level photography can and does yield valuable information, this section will deal with photography from aircraft and satellites. From these platforms, high above the ground, a sizable area of the earth's surface is visible. This vantage point often allows the interpreter to recognize relationships among the terrain or cultural features that may not be apparent from the ground.



Aerial Photography

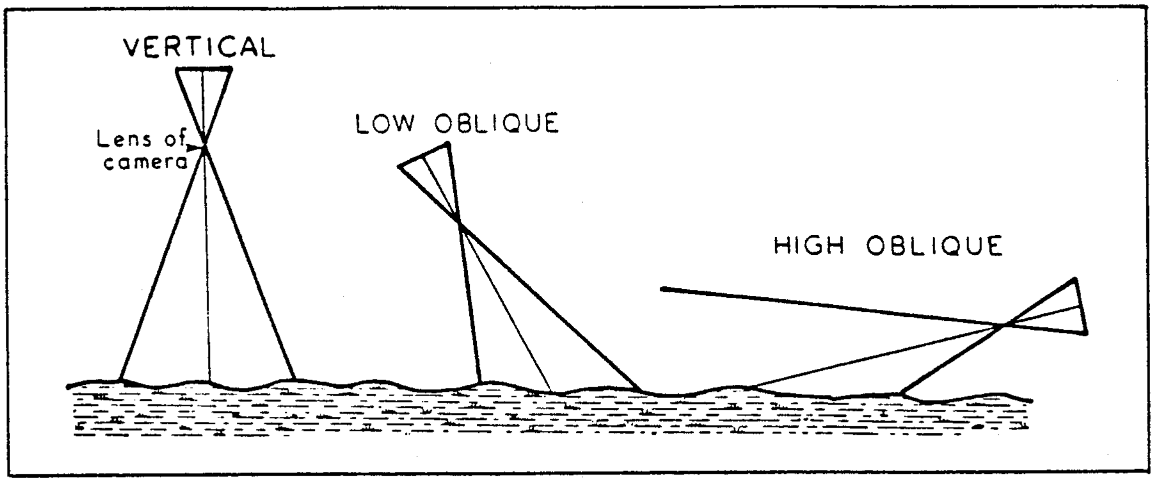
The military was probably the first group to actively make use of the "big view" provided by airborne cameras. Photographic mensuration was of great value in military manuevers. In the United States the first photogrammetric compilations were completed by the Union Army during the Civil War. Later, during the 1880's and the 1980's, aerial photography was used to survey the United States-Canada boundary. Through World War II the science of aerial photography was continuously improved until it had become a sophisticated intelligence system. Since that time the use of aerial photography has gradually become increasingly commonplace in non-military professions. The ability to effectively understand an aerial photograph has become a common denominator for such diverse fields as recreational management, transportation planning, geologic exploration, flood control and many more.

Aerial photography may be the most versatile of the remote sensing systems. The user is allowed a choice of cameras, films, filters, and platforms which correspond to a choice of scale, resolution, sensitivity, and angle of view. The standard output of photographic systems is a picture of the scene which may be manually interpreted. Overlapping images may be viewed through a stereoscope to produce a three-dimensional view. Images may also be digitized and analyzed with computer techniques.

The variety of available film and filter combinations is a valuable asset to aerial photographic systems. Films include black and white panchromatic films, black and white infrared films, and various color films, some of which are sensitive only in the visible part of the spectrum, whereas others are sensitive in the near infrared portion as well. Filters are used to screen out the wavelengths which are not of interest. For example, a yellow, or minus blue, filter is used with panchromatic films to screen out the blue wavelengths which were scattered by the atmosphere. This reduces the haze that would otherwise appear in the image. Color films are also frequently used with filters to eliminate this haze. Films that are sensitive to the near-infrared wavelengths have superior haze penetration capabilities because they are not sensitive to the blue wavelengths and are frequently used on hazy days.

Both black and white and color infrared films are used for vegetation studies. Healthy broad-leaved vegetation has very high near-infrared reflectance and, therefore, appears very light on black and white films or bright red on color infrared films. When vegetation becomes unhealthy (e.g., due to disease, insect infestation, drought, etc.) its appearance on infrared films will change. In some cases this change may occur before the damage is visible. The possibility of "previsual" stress detection is currently being studied in many areas.

Aerial photographs may be either vertical or oblique in orientation. Vertical aerial photographs are formed when the camera axis is perpendicular to the ground. These photographs are particularly good for mapping activities, such as landform and drainage analysis and soil mapping. Scale is relatively constant throughout vertical images so measurements, including distance, can be made directly from the photographs. Oblique photographs offer a view that is more like the view seen by man from his ground reference point, or from an airplane window. Consequently, oblique photos are often easier to interpret even though the geometry of the photograph is not as easy to understand.



Aerial cameras include the conventional mapping camera, the panoramic camera, and the multiband camera (Colwell, 1976). Most aircraft platforms are fixed wing aircraft ranging from Beechcraft and Apache for low altitude imagery to NASA's U-2 and RB-57F, for high altitude imagery. Helicopters are used occasionally for special applications. Camera mounts are gyro-stabilized against the roll, pitch, and yaw motions of the aircraft and insulated against aircraft vibrations that might otherwise cause blur. Roll film of very high dimensional stability insures the quality and precision of the images.

Aerial photography also provides better resolution than any other remote sensing system. This allows the most detailed inventory of earth features. However, the qualities of the synoptic view are lost in this greater resolution. Figure B-1 shows the relationship between the resolution required for each level of resource surveys and the resolution capabilities of three remote sensing systems. Future satellite systems, such as SPACE SHUTTLE and LANDSAT-4 with resolution capabilities similar to SKYLAB, may begin to replace aircraft photography in many micro-scaled surveys.

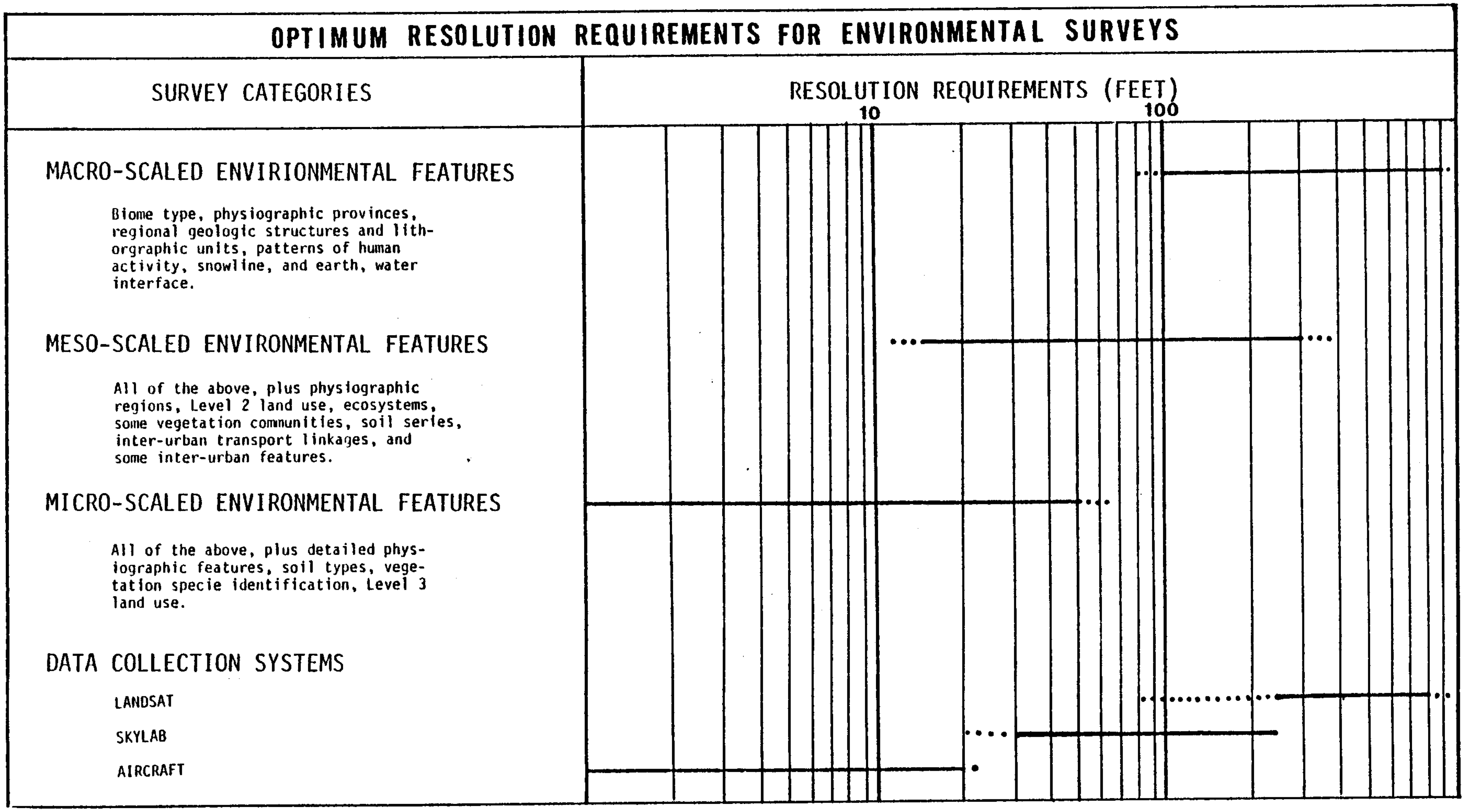
Aerial photography of most regions of the United States is easily obtainable. Imagery is available through many local, state and federal governmental agencies and some private agencies. The EROS Data Center is Sioux Falls, South Dakota has the most complete listing of available aerial photography of all scales. This listing is arranged according to geographical location so the user may request a complete list of available imagery for any specific location.

Manned Spacecraft

Observing the earth was an important part of crew activities during Project Mercury, Gemini and Apollo Programs, and many spectacular photographs of the land, oceans, and atmosphere were obtained. With the exception of the photographic experiments on Apollo 7 in 1968 and Apollo 9 in 1969, observations were made and photographs were taken at the discretion of the individual crew member. Nevertheless, the earth orbital photography from these manned programs provided geologists and geomorphologists with a new perspective for the study of earth terrain features.

The successful launch of the Skylab workshop on May 14, 1973, enabled man to observe and study the earth for periods of 28, 59 and 84 days during the Northern Hemisphere summer, fall and winter seasons. Part of the Skylab program was a visual observations experiment. The purpose of this experiment was to determine the quality and the quantity of photographic and observational data that could be acquired from space. The crew was supported by multidisciplinary scientific training before liftoff, by realtime science mission planning and by a comprehensive onboard set of procedures, maps and photographs.

During the 84 days the Skylab 4 crew orbited the earth at 435 km (235 n.mi.) above the surface, more than 850 verbal descriptions were made and approximately 2000 photographs were taken. Binoculars (10x) and hand-held Hasselblad (70 mm) and Nikon (35 mm) cameras were the principle instruments used by the crewmen. The camera and lens combinations provided wide, medium, and narrow fields of view. Color Ektachrome film was used almost exclusively for the photography, the few frames of Ektachrome color-infrared film that were exposed for specific features were generally not as satisfactory as the natural color photos.



Biome type, physiographic provinces, regional geologic structures and lithorgraphic units, patterns of human activity, snowline, and earth, water interface.

All of the above, plus physiographic regions, Level 2 land use, ecosystems, some vegetation communities, soil series, inter-urban transport linkages, and some inter-urban features.

All of the above, plus detailed physiographic features, soil types, vegetation specie identification, Level 3 land use.

Figure B1. This figure shows the optimum resolution requirements for environmental surveys. It can be seen that although aircraft photography is most suitable for detailed surveys, other remote sensors may provide a better view of macro-scale features (after Everett and Simonett, 1976).

The results of the Skylab mission were rather spectacular and provided scientists with a unique set of space photographs (NASA-JSC, 1977).

Skylab should be viewed as a remote sensing experiment rather than an operational system. Its results have been very informative and are being incorporated into the more recent future projects. For instance, high sun angles (more than 50^{o} from the horizontal) were found to be best for making color discriminations, whereas low angles (less than 20^{o} from the horizontal) were best for detection of topographic and meteorological relief. In most cases vertical viewing was found to be most desirable. However, oblique views were helpful for discerning the regional framework. It was found that snow cover enhanced many land features and that haze and cirrus clouds are not as serious a problem as had been anticipated.

OTHER OPTICAL SYSTEMS

The optical region of the EM spectrum is the region where optical techniques of refraction and reflection can be used to focus and redirect radiation. This region encompasses the ultraviolet, visible and infrared wavelengths. Current technology would set the boundaries of this region at 0.2 and 1000 μm. For purposes of remote sensing from the air and space this region is further limited to the atmospheric windows between 0.32 and 13.5 μm. In these wavelengths, radiation can be transmitted through the atmosphere with little change.

This section will discuss some of the sensors which are designed to detect and record optical radiation. These sensors may be imaging or nonimaging. Optical systems can also be active or passive. However, most are passive relying on solar illumination or self-emission as a source of radiation.

Imaging Systems (Optical-mechanical scanners)

Most imaging systems, operating in visible through the thermal infrared wavelengths are optical-mechanical scanners. When compared to photographic systems, optical-mechanical systems are complex instruments, but they have some distinct advantages. Most important, optical systems can be used to obtain imagery outside the photographic regions and many wavelength channels can be recorded simultaneously. The output signal is in electrical form which can be transmitted, recorded, analyzed, or processed to suit the purpose of the individual user.

Optical-mechanical scanners operate using techniques similar to television cameras, translating variations in scene brightness into electrical video signals. There are two main types of passive scanners - infrared scanners and multispectral scanners.

Infrared scanners are generally designed to observe thermal emissions from the scene. For the most part thermal mapping is limited to the atmospheric windows of 4.5 - 5.5 μm and 8.5 - 13.5 μm where 4.5 - 5.5 μm is used primarily for locating small hot spots such as cooking fires, forest fires and geothermal activity and the longer wavelengths, 8.5 - 13.5 μm, are used in general terrain mapping. Imagery from infrared scanners may be interpreted using methods similar to those used in photointerpretation. Shape, texture and tone are the clues to interpreting the imagery, except that in this case, tone is a function of surface temperature and the emissivity of the object.

Diurnal variation plays a key role in the use of thermal imagery. Daytime measurements relate to the heating properties of the incident sunlight and nighttime measurements relate to cooling of materials. Variations are controlled by local meteorology, the properties of the materials and internal heat generation, such as man-made heat sources and surface oxidation.

As its name indicates the multispectral scanner observes the scene in a number of discrete wavelength bands. Specific techniques for accomplishing this task vary from system to system but basically the intensity of energy in each wavelength interval is measured by a separate detector. Video signals from each detector are recorded simultaneously usually on magnetic tape. These signals can then be analyzed by computer or visually displayed on a video monitor.

Multispectral scanners range from simple, two-channel systems currently used on board the NOAA weather satellites to the 24-channel airborne scanner developed by the Bendix Corporation. These systems are continually being improved. Once perfected, multispectral scanner systems will probably become the key to many survey and monitoring programs. Already systems such as LANDSAT, and the NOAA satellites, are being used routinely for many applications. Plans for future remote sensing systems revolve around multispectral techniques.

NOAA Satellites

Since early in 1972 satellites under the supervision of the National Oceanic and Atmospheric Administration (NOAA) have been providing daily, high-resolution imagery over the North American Continent. The NOAA space program includes two sensors which have proven valuable to hydrologic programs. These are the Very High Resolution Radiometer (NOAA/VHRR) and Geostationary Operational Environmental Satellite (GOES).

The VHRR is carried onboard the NOAA series of polar-orbiting satellites. It is sensitive to two parts of the electromagnetic spectrum, the VIS is .4 - .7 μm (visible) and 10.5 to 12.5 μm (near infrared) wavelengths. Coverage of North America is available daily in the visible region and twice daily in the infrared region of the spectrum. Images from this sensor system cover approximately 4,410,000 sq. km. These are normally reproduced at a scale of 1:10,000,000 and a resolution of 1 km (at the nadir). Lateral coverage is obtained through continuous horizon-to-horizon scanning by a mirror oriented perpendicular to the forward motion of the satellite. This type of data collection results in an image which is distorted at the horizons. This distortion can be corrected through optical rectification or by specialized computer processing.

The GOES satellites are termed "geostationary" because their position relative to the earth's surface remains fixed. Currently, there are two GOES satellites operating over the United States. GOES-2 operating over the East Coast and GOES-3 operating over the West Coast. The sensor on-board these satellites is the Visible and Infrared Spin Scan Radiometer (VISSR). As its name implies, this sensor is sensitive to both the visible and infrared portions of the spectrum. Imagery can be recorded as often as every half-hour.

The original intent of the NOAA satellites was to support meteorologists in their efforts to study weather patterns. Shortly after the satellites became operational, hydrologists determined that this imagery could be used to create timely maps depicting snowcover over river basins of varying size, location and topography (Wiesnet and McGinnis, 1973). Research has continued to expand this use of the NOAA imagery. Currently, areal snowcover measurements are made routinely on 30 critical river basins in the United States and Canada.

Landsat Satellites

A great advance in remote sensing of the environment came in 1972 when NASA launched the first Earth Resources Technology Satellites (ERTS-1). The primary objective of the ERTS mission was to acquire repetitive multispectral data of the earth's surface. As the project gained success, its name was changed to LANDSAT (Land Satellite) and the follow-on program launched LANDSAT-2 in 1975, LANDSAT-3 in 1978 and is planning for the future. Since its first transmission, LANDSAT has been providing new insight into man's continuing efforts to better manage the earth's limited resources as well as aiding in the assessment and understanding of environmental change.

LANDSAT was launched in a near-polar orbit at an elevation of about 918 km (575 miles) above the earth's surface. The orbit was designed so that the satellite is sun-synchronous. That is, the angle formed between the sun, the satellite, and the center of the earth is constant and consequently the satellite is imaging each location at the same local sun time on each overpass. There is some seasonal variation in sun angle. Landsat circles the earth 14 times a day. During this orbit the earth is continuing its rotation so that the next orbit is imaging the earth at a new location several hundred miles away. The following day the orbit ground tracks are offset slightly from the day before. Figure B-2 illustrates the groundcoverage pattern. On the 19th day, LANDSAT is again imaging its original position. In this way data may be collected for any location of the earth every 18 days. Until recently, with LANDSAT-2 and LANDSAT-3 orbiting in orbits separated by 180°. Data was collected every nine days. Currently, only LANDSAT-3 is operational collecting data every 18 days. The standard policy is to collect all data over the United States and over other areas when requested.

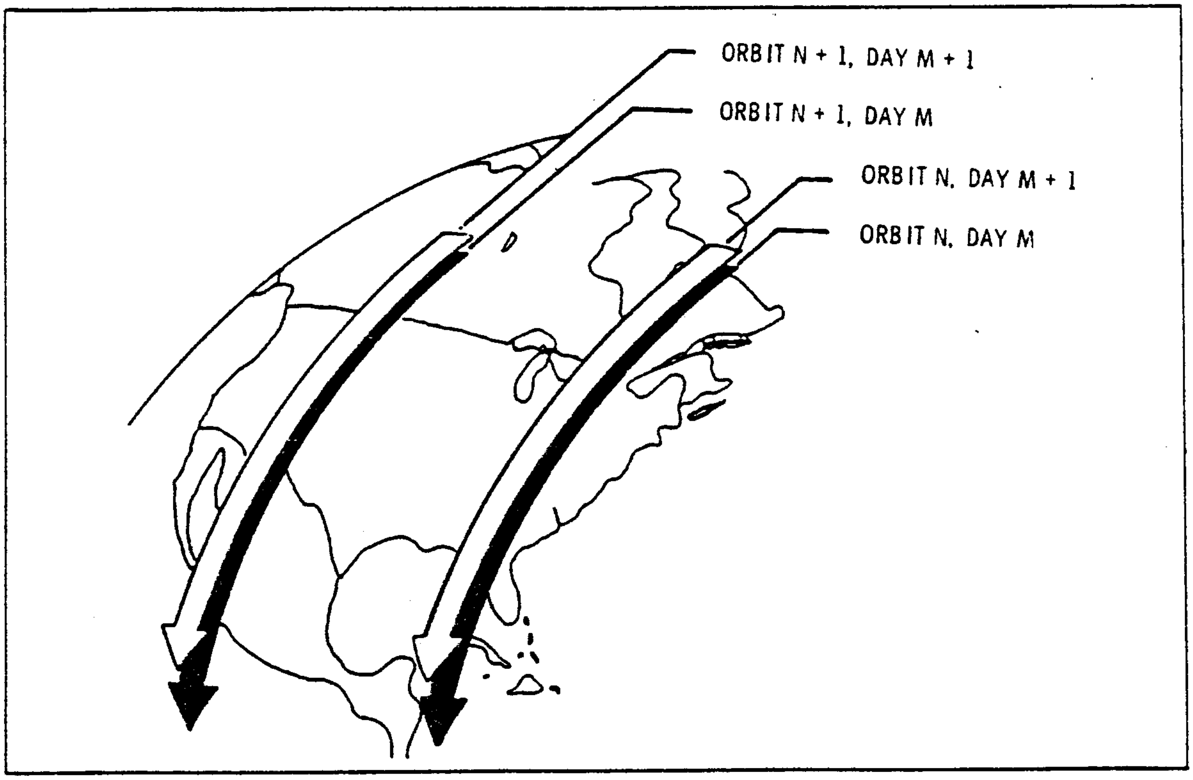


Figure B2. Landsat ground coverage pattern.

Each of the three LANDSAT satellites is carrying two imaging instruments called the multispectral scanner subsystem (MSS) and the return beam vidicon subsystem (RBV), a data collection system (DCS) transmitter and receiver, and two wide-band video tape recorders (Figure B3). The RBV and MSS provide independent images of the same 185 km by 185 km area of the earth in various spectral bands. The DCS is a real-time data relay system which can relay as many as eight ground measurements to Goddard Space Flight Center, one to three times every hour. The DCS has been used to monitor volcanoes, hydrologic phenomena, and production platforms in the Gulf Coast.

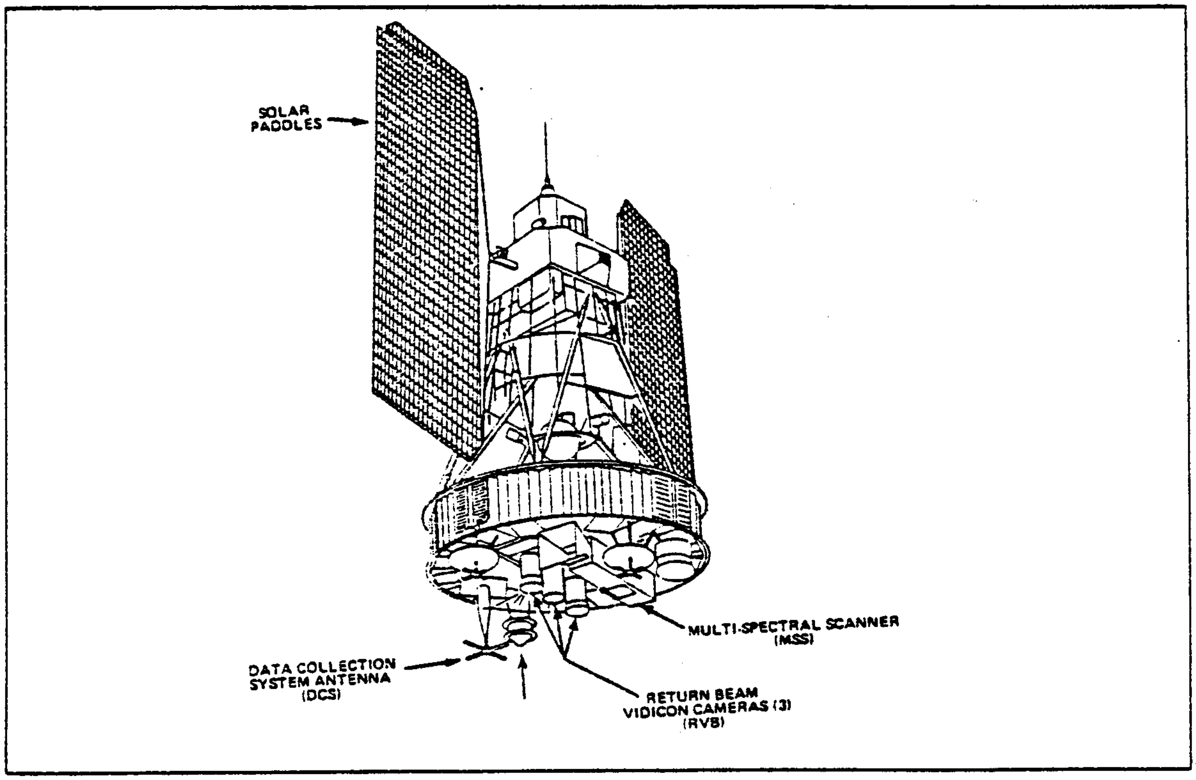
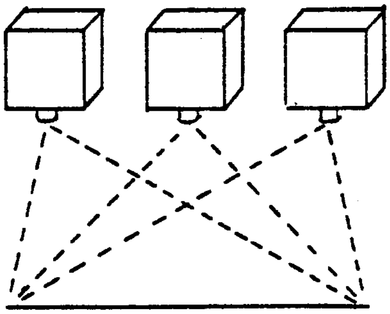


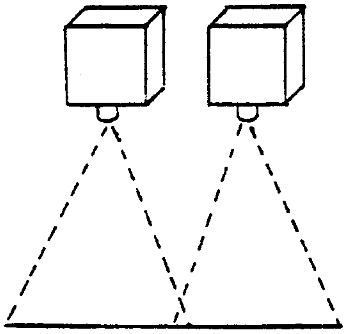
Figure B3. Landsat Spacecraft.

On LANDSAT-1 and LANDSAT-2 the RBV system was made up of three return beam vidicon cameras (similar to TV cameras) each of which imaged the earth in a different spectral band.



Full color images can be produced when each of the separate images is processed and superimposed in its respective color on a single frame. Technical malfunctions forced the RBV systems to be shut down shortly after launch.

The RBC system of LANDSAT-3 is a modification of its predecessors. It includes two panchromatic cameras which generate two side-by-side images rather than superimposed images of the same target. This system has been returning imagery when requested since its launch in 1978.



The RBV system was designed for cartographic use. Its principal advantage over the MSS system is its geometric quality, or potential mapping accuracy. However, it has been found that the MSS imagery can also be used satisfactorily for mapping purposes.

The Multispectral Scanning System collects data by continually scanning the Earth directly beneath the spacecraft. Optical energy is sensed by an array of detectors in four spectral bands ranging from 0.5 to 1.1 micrometers (Table B1). On LANDSAT-3 a fifth detector, sensitive to the thermal infrared portion of the spectrum, was added to the MSS package. Scanning is achieved by means of a mechanically oscillating mirror that rotates from side to side about 13 times a second as the satellite progresses southward in its orbital path. Radiation from the earth's surface, and its atmosphere is directed onto the detectors. The voltage produced by the detectors is an analog signal which is converted to digital values by the system. These values represent brightness values related to the radiance of an area on the earth's surface in one wavelength band.

Data collected by LANDSAT's three systems, is transmitted in real time (immediately) via microwave to ground receiving stations located around the world. Up to 30 minutes of information may be recorded by the satellite and transmitted at some later time. When the data is received it is recorded in a digital format on computer compatible tapes (CCT's) and sent to Goddard Space Flight Center in Greenbelt, Maryland. Here 70 mm (scale 1:3,369,000) B & W transparencies of the MSS data are made. These 70 mm transparencies are sent to the EROS Data Center (EDC) in Sioux Falls, South Dakota for storage. The EDC produces copies and enlargements of black and white and full color composites (FCC) to the public. Standard products include paper prints

TABLE B1

LANDSAT--MSS SPECIFICATIONS

Band	Wavelength (μm)	IFOV (m)
4	0.5 - 0.6	79
5	0.6 - 0.7	79
6	0.7 - 0.8	79
7	0.8 - 1.1	79
8 (Landsat-3)		240

at scales of 1:1,000,000, 1:500,000 and 1:250,000 and transparencies at scales of 1:3,396,000 and 1:1,000,000. Special products are available on request. The digital data (CCT's) are also available for computer analysis.

Heat Capacity Mapping Mission

The Heat Capacity Mapping Mission (HDMM), launched April 26, 1978 is one of a series of "budget satellites" (about $5,000,000) designed by NASA for feasibility studies. The onboard system is a radiometer which operates in two spectral channels: visible and near IR (0.5 to 1.1 μm) and thermal IR (10.5 to 12.5 μm). The satellite moves in a sun synchronous orbit which passes over the U. S. at approximately 1:30 p.m. and 2:30 a.m. These times were selected to correspond with the time of maximum and minimum temperatures of the soil surface.

It is anticipated that HCMM's improved temperature measurements will be a great help in snowmelt monitoring, measuring soil moisture parameters, and mapping thermal effluents. It will also be useful for discriminating rock types and possibly identifying such features as subsurface faults and fractures.

Seasat-1

Seasat-1 was the first of a proposed series of satellites oriented toward oceanographic research. The Seasat-1 satellite was launched on June 26, 1978, into an 800 km near-polar orbit. The satellite was designed to provide alternating day and night coverage each 36 hours. Approximately 95 percent of the earth's oceans were to be covered by the system. Unfortuantely, system failure 99 days after launch severely limited the image data produced by the satellite.

The sensors onboard Seasat-1 were many and varied. An important "first" realized with Seasat-1 was an L-band (25 cm), synthetic aperature imaging radar system. It was designed to generate imagery across a 100 km swath (from 230 km to 330 km to one side of the satellite track) with a 25 m resolution. Although the operating life of the radar system was a very brief one, the limited coverage it provided gave the scientific community a different look at the earth.

Non-Imaging Sensors

Non-imaging sensors are designed to give a single measure of the intensity of the electromagnetic radiation emitted from or reflected by all of the objects included in their field-of-views as a function of time and wavelength. There are three main types of non-imaging sensors; radiometers, spectrometers, and polarimeters. These systems are all very similar. A radiometer integrates all of the EM radiation within a designed wavelength range emanating from all objects within its field-of-view. A spectrometer is nearly the same except that it contains a dispersing element which allows the system to measure the radiation as a function of wavelength. Polarimeters are radiometers or spectrometers with the addition of a device which will only permit detection of only the EM radiation which is polarized in a specific plane.

These systems have been flown on the NOAA satellites, Nimbus III and IV. Their measurements were used primarily for atmospheric measurements. These instruments are also used in the ground phase of experimental remote sensing research.

MICROWAVE SYSTEMS

The microwave portion of the electromagnetic spectrum is generally considered to include the electromagnetic energy having wavelengths between 0.1 cm and 100 cm (or frequencies from 100 MHz to 30,000 MHz). This broad region of the spectrum encompasses wavelengths longer than those of thermal infrared energy and shorter than those of the radiowaves which are used for communication. A number of sensors, active and passive, have been developed to detect, measure, and display the microwave energy either reflected or emitted by the objects in a scene.

As is the case in aerial photography, the credit for the development of the original microwave sensors goes to the military. Most microwave systems were designed to operate in one of a number of sections, or bands, of the microwave region which, for reasons of military security, were originally assigned letter designations. These letter assignments have become part of the microwave vocabulary and are frequently used in the literature. Table B2 shows the microwave region divided into these bands.

TABLE B2

TABLE OF RADAR BANDS AND FREQUENCIES

Band	Wavelength (cm)	Frequency Range (MHz)
P	136 - 77	220 - 390
UHF	100 - 30	300 - 1000
L	30 - 15	1000 - 2000
S	15 - 7.5	2000 - 4000
C	7.5 - 3.75	4000 - 8000
X	3.75 - 2.40	8000 - 12500
Ku	2.40 - 1.67	12500 - 18000
K	1.67 - 1.18	18000 - 26500
Ka	1.18 - 0.75	26500 - 40000
Millimeter	< 0.75	40000 <

The unique characteristics possessed by microwave systems, including the ability to operate day or night and in all types of weather and the ability to penetrate vegetation or thin soil to obtain information about the underlying terrain, have proven to be useful in land and earth observations as well as in the military. Microwave images are not as familiar to photointerpreters as are photographs; consequently, microwave data is freqeuntly used to compliment other types of imagery rather than playing a primary role. Trained interpreters can, however, assimilate large amounts of information directly from microwave displays.

Passive Microwave Systems

Passive microwave systems (radiometers) are designed to measure the effective or radiometric temperatures (also referred to as brightness temperature) of the earth's surface features and the intervening atmosphere. Brightness temperature is the radiation attributed to thermal motion of the electrons and protons of the material. It is not the actual temperature of the object but it is related to the emissivity and the real object temperature. Surface roughness, polarization, and the viewing angle also influence this apparent temperature.

In general, the radiometer consists of an antenna, a very sensitive broad-band receiver, an absolute temperature reference, and a magnetic tape recorder (Janza, 1976). The antenna collects the thermally generated microwave radiation and concentrates it on the sensitive receiver where it is detected, amplified and recorded either as a voltage time record or as an image on photographic film.

Most passive microwave sensors operate at wavelengths between .1 cm and 3.0 cm. This represents a compromise. At these wavelengths the microwave signal is not seriously attenuated by clouds, moderate rain, or other atmospheric phenomena, and has an acceptable resolution. At longer wavelengths the atmospheric penetration would be increased but balanced by a decrease in resolution (Henderson and Merchant, 1978).

Active Microwave Systems

Active microwave systems, as the name implies, provide their own illumination of the scene and measure the backscatter of that energy. Because these systems are not dependent on the energy that is existing in the scene, they may operate in longer wavelengths than the passive systems and still maintain a resolution that is satisfactory for earth resource observations. In addition to the night and day, all weather capabilities of passive systems, active microwave provides a much greater ability to penetrate vegetation, soil, and other surface features to provide information about the underlying terrain. Most users find active systems of maximum value because of the finer resolution, the greater penetration, and the geometric information available (Moore, 1975).

Active microwave systems are commonly referred to collectively as radar. The term radar was originally the acronym for the military RAdio Detecting and Ranging system. Taken literally, this term would not be appropriate for systems that do not perform a "ranging" function; however, the term has gained acceptance meaning any active microwave system and is widely used in that sense.

In simplest terms, radar could be thought of as a flash-camera system that uses microwaves instead of light waves to image the target. Short powerful pulses of microwave-frequenty energy are sent out at regular intervals from an antenna. When this energy strikes the scene some of the energy is reflected, or scattered, back to the receiving antenna. This may be the same antenna that was used for transmitting. The time, distance to the target, and the intensity of the reflected energy are then measured and displayed by the system.

There are many types of radar systems. For earth observations, side-looking-airborne-radar (SLAR) is the most important. Henderson and Merchant (1978) give a good brief description of SLAR, and also describe methods for interpreting radar imagery. The Manual of Remote Sensing (Reeves, 1975) is more detailed and describes some of the other types of radar systems.

Table B3 summarizes potential applications of microwave systems and compares the capabilities of the microwave systems with the visible-region sensors. At an Active Microwave Workshop held at the Johnson Space Center, 1975, the Earth/Land Panel studied the current state-of-the-art in earth observations by microwave systems. Their findings

TABLE B3

A COMPARISON OF ACTIVE MICROWAVE SENSORS AND VISIBLE REGION SENSORS (after Rouse and Molly, 1975)

Application	Unique capabilities of active microwave sensors	Unique capabilities of visible-region sensors	Capabilities shared by both sensors
Disaster monitoring	Floodwater boundaries in vegetated areas can be detected. Earthquake-caused surface changes can be enhanced. Storm and fire damage can be assessed through clouds and smoke, day or night. Disaster events can be recorded on timely basis.	High-resolution color information	Two-dimensional broad-area images.
Lake-ice monitoring.....	Sensor is sensitive to ice type/thickness. Ridges, open water, and shoreline under snow cover can be delineated. Temporaral behavior can be recorded on timely basis through clouds.		Two-dimensional broad-area images. Computer-compatible data.
Flood forecasting and monitoring	State of soil (i.e., frozen) may be recordable. Floodwaters under vegetation may be recordable. Soil water retention characteristics may be recordable. Soil moisture may be recordable. Temporal behavior can be recorded on timely basis through clouds.	More sensitive to flood-induced vegetation stress	Two-dimensional images. Areal extent of floods. Computer-compatible data.

TABLE B3
(continued)

Application	Unique capabilities of active microwave sensors	Unique capabilities of visible-region sensors	Capabilities shared by both sensors
Crop identification and assessment	Plant moisture condition may be recordable. Soil moisture condition may be recordable. Temporal behavior can be recorded on timely basis.	Spectral reflectance data	Plant structure. Canopy cover. Areal extent. Computer-compatible data.
Soil moisture determination	Vegetation and surface can be penetrated Moisture changes on diurnal cycle may be recordable. Temporal behavior can be recorded on timely basis.	No quantitative capability	Vegetation response to soil moisture change. Computer-compatible data.
Soil type and property mapping	Vegetation and surface can be penetrated. Dielectric characteristics may be recordable. Soil moisture retention characteristics may be recordable. Temporal behavior or indicator vegetation can be recorded on timely basis.	Soil color	Vegetation identification for soil-type mapping. Computer-compatible data
Range inventory and biomass assessment	Plant moisture condition may be recordable. Soil moisture condition may be recordable.	Spectral reflectance data	Plant structure. Canopy cover. Areal extent and distribution Computer-compatible data.

TABLE B3
(continued)

Application	Unique capabilities of active microwave sensors	Unique capabilities of visible-region sensors	Capabilities shared by both sensors
Coastal wetlands Mapping	Soil mositure may be recordable. Plant moisture may be recordable. Vegetation can be penetrated. Polarization-dependent soil conditions can be recorded. Temporal behavior can be recorded on timely basis.	Spectral reflectance data.	Plant strucutre. Canopy cover. Areal extent. Computer-compatible data.
Frozen Water Hydrologic Observations	Soil below surface can be penetrated. Snow cover can be penetrated. Sensor is sensitive to snow moisture content. Sensor is sensitive to subsurface dielectric properties. Temporal behavior can be recorded on timely basis through clouds.	Albedo of snow cover recordable.	Image format data. Computer-compatible data.

indicated a current lack of adequate experimental results to verify the feasibility of active microwave sensors for these applications. In many cases, theoretical studies of basic electromagnetic interaction mechanisms suggest potential application, but many of these models are inadequately supported by experimental results (Rouse and Molley, 1975).

PROPOSED SATELLITES

As researchers explore new applications of remote sensing technology, they become better able to specify their system requirements. New systems, designed to meet these needs, are constantly being planned and constructed. This section discusses three of these proposed systems.

Thematic Mapper (LANDSAT-D)

In addition to a four channel MSS similar to ones onboard LANDSAT-1, LANDSAT-2, and LANDSAT-3, LANDSAT-D (scheduled for launch in 1981) will have an advanced multispectral scanner, the Thematic Mapper (TM). As its name implies, the system data will be processed through pattern recognition techniques to produce classified images (thematic maps).

The thematic mapper is scheduled to be a seven-channel scanner designed to maximize vegetative analysis capabilities for agricultural applications. The following are the proposed bands of operation of the Thematic Mapper (Lilesand and Kiefer, 1979).

Band one	(0.45 to 0.52 μm) - designed to provide increased penetration into water bodies as well as supporting analyses of land use, soil, and vegetation characteristics.
Band two	(0.52 to 0.60 μm) - primarily designed to look at the visible green reflectance peak of vegetation lying between the two chlorophyll absorption bands. Responses in this band are intended to emphasize vegetation discrimination and vigor assessment.
Band three	(0.63 to 0.69 μm) - the most important band for vegetation discrimination. It resides in one of the chlorophyll absorption regions and emphasizes contrast between vegetation and non-vegetation features as well as contrasts within vegetation classes.
Band four	(0.76 to 0.90 μm) - chosen to be responsive to amounts of vegetation biomass present in a scene. This will aid in crop identification, and will emphasize soil-crop and land-water contrasts.
Band five	(1.55 to 1.75 μm) - a band known to be important to the determination of crop type, crop water content, and soil moisture conditions.

Band six	(2.08 to 2.35 μm) - an important band in the discrimination of rock formations.
Band seven	(10.40 to 12.50 μm) - a thermal infrared channel known to be contributory to vegetation classification, vegetation stress analyses, soil moisture discrimination and a host of other thermally related phenomena.

The spatial resolution will also be substantially increased. Bands one through six will have a spatial resolution of 30 m. Band seven will have a 120 m resolution. Other proposed changes from LANDSAT-1, LANDSAT-2, and LANDSAT-3 include an 11:00 a.m. overflight time, nine day repetitive coverage, and a lower 705 km altitude to facilitate maintenance from Space Shuttle.

Multispectral Resource Sampler

Another satellite which is planned for the mid-1980's is the Multispectral Resource Sampler (MRS). The MRS will be the first satellite with a multispectral linear array (MLA) arrangement of the sensors. Its purpose is to develop, test and demonstrate the performance improvement possible through any of the following:

increased spatial resolution
increased spectral resolution
increased temporal resolution
correction of atmospheric effects
sampling mode (v.s. inventory mode)
polarization measurements

The system will also test data compression techniques and demonstrate the feasibility of in-flight sensor parameter selection.

The MRS will provide unique research opportunities for earth survey applications with capabilities beyond those possible with the thematic mapper.

Space Shuttle

The Space Shuttle has profound potential applications to remote sensing from space, even though earth observation is only one aspect of the Shuttle Program. Its impact on remote sensing from space will come both from its use as a launch and maintenance vehicle for future satellites and its role as a primary sensor platform itself.

A primary payload onboard the Shuttle orbiter is a large space laboratory, called Spacelab. Spacelab will provide a "shirtsleeve" environment for scientists to operate their equipment in space. The advantages of manned systems for some types of remote sensing were demonstrated by Skylab and the Apollo-Soyuz Mission -- the scientist can make visual observations, note the worthwhile features, and concentrate on specific areas for a limited time. The specific role of Spacelab has been the subject of many studies. But in general, the Shuttle Program will offer many advantages in the remote sensing of earth resources from space.

APPENDIX B - REFERENCES

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