Energy Interactions with Atmosphere and Earth Surface

Summary

Electro-magnetic radiation (EMR) or energy interactions with atmosphere and with the earth surface play a vital role in Remote sensing. Energy interactions with the atmosphere dictates the spectral regions through which only we can do the remote sensing which are known as Spectral windows (the spectral regions where atmosphere is more or less transparent). Knowledge of energy interactions with different features of the earth surface help us in interpreting the remotely sensed image. A given feature will have different reflection properties in different wave lengths of the energy spectrum. Thus combinations of information obtained in multi spectral regions help better in interpreting an image. Energy interactions with the earth surface, especially with three major features Vegetation, Soil and Water are detailed in this article.

1. INTRODUCTION

In many respects, remote sensing can be thought of as a reading process. Using various sensors, we remotely collect data that may be analysed to obtain information about the objects, areas or phenomena being investigated. In most cases the sensors are electromagnetic sensors either airborne or spaceborne for inventorying. Two basic processes involved in electromagnetic remote sensing of earth resources are Data Acquisition and Data Analysis. The elements of Data Acquisition are (a) Energy source, (b) Propagation of energy through the atmosphere, (c) Energy interactions with earth surface features, (d) Airborne and/ or spaceborne sensors, (e) Generation of sensor data. Data analysis process involves examining the data in pictorial form or numerical form, analysis and presentation to the end users. In this article electromagnetic energy interaction in atmosphere and with earth surface are presented.

2. ENERGY INTERACTION IN ATMOSPHERE

Irrespective of its source, all radiation detected by remote sensors passes through some distance, or path length, of atmosphere. The path length involved can vary widely. For example, space photography results from sunlight that passes through the full thickness of the earth's atmosphere twice on its journey from source to sensor. On the other hand, an airborne thermal sensor detects energy emitted directly from objects on the earth, so a single, relatively short atmospheric path length is involved. The net effect of the atmosphere varies with these differences in path length and also varies with the magnitude of the energy signal being sensed, the atmospheric conditions present, and the wavelengths involved.

Because of the varied nature of atmospheric effects, we treat this subject on a sensor-by-sensor. The atmosphere can have a profound effect on, among other things, the intensity and spectral composition of radiation available to any sensing system. These effects are caused principally through the mechanisms of atmospheric scattering and absorption.

2.1 Scattering

Atmospheric scattering is unpredictable diffusion of radiation by particles in the atmosphere. **Rayleigh scatter** is common *when radiation interacts with atmospheric molecules and other tiny particles that are much smaller in diameter than the wavelength of the interacting radiation.* The effect of Rayleigh scatter is inversely proportional to the fourth power of wavelength. Hence, there is a much stronger tendency for short wavelengths to be scattered by this scattering mechanism than long wavelengths.

A "blue" sky is a manifestation of Rayleigh scatter. In the absence of scatter, the sky would appear black. But, as sunlight interacts with the earth's atmosphere, it scatters the shorter (blue) wavelengths more dominantly than the other visible wavelengths. Consequently, we see a blue sky. At sunrise and sunset, however, the sun's rays travel through a longer atmospheric path than during mid-day. With the longer path, the scatter (and absorption) of short wavelengths is so complete that we see only the less-scattered, longer wavelengths of orange and red.

Rayleigh scatter is one of the primary cause of "haze" in imagery. Visually, haze diminishes the "crispness," on an image. In colour photography, it results in a bluish-grey cast to an image, particularly when taken from high altitude. Haze can often be eliminated, or at least minimized, in photography by introducing, in front of the camera lens, a filter that does not transmit short wavelengths.

Another type of scatter is **Mie scatter**, which exists *when atmospheric particle diameters essentially equal the energy wavelengths being sensed*. Water vapour and dust are major causes of Mie scatter. This type of scatter tends to influences longer wavelengths compared to Rayleigh scatter. Although Rayleigh scatter tends to dominate under most atmospheric conditions, Mie scatter is significant in slightly overcast ones.

A more bothersome phenomenon is **nonselective scatter**, which comes about *when the diameters of the particles causing scatter are much larger than the energy wavelengths being sensed*. Water droplets, for example, cause such scatter. They commonly have a diameter in the 5 to 100 μm (mocro meter, 10^{-6} m)range and scatter all visible and reflected IR wavelengths about equally. Consequently, this scattering is "nonselective" with respect to wavelength. In the visible wavelengths (Approx. 0.4 to 0.7 μm), equal quantities of blue, green, and red light are scattered, making fog and clouds appear white.

2.2 Absorption

In contrast to scatter, atmospheric absorption results in the effective loss of energy to atmospheric constituents. This normally involves absorption of energy at a given wavelength. The most efficient absorbers of solar radiation in this regard are water vapour, carbon dioxide, and ozone. Because these gasses tend to absorb electromagnetic energy in specific wavelength bands, they strongly influence "where we look" spectrally with any given remote sensing system. The wavelength ranges in which the atmosphere is particularly transmissive of energy are referred to as **atmospheric windows**.

Figure 1 shows the atmospheric absorption characteristics of electromagnetic energy. The most common sources of energy is solar energy and the energy emitted from earth. In Figure 1, spectral regions in which the atmosphere blocks energy are shown. Remote sensing data acquisition is limited to the nonblocked spectral regions, called "atmospheric windows". The spectral sensitivity range of the eye (the "visible" range) coincides both with an atmospheric window and the peak level of energy from the sun. Emitted "heat" energy from the earth, is sensed through the windows at 3 to 5μm and 8 to 14μm using such devices as thermal scanners. Multispectral scanners sense simultaneously through multiple, narrow wavelength ranges that can be located at various points in the visible through the thermal spectral region. Radar and passive microwave systems operate through a window in the 1 mm to 1 m region.
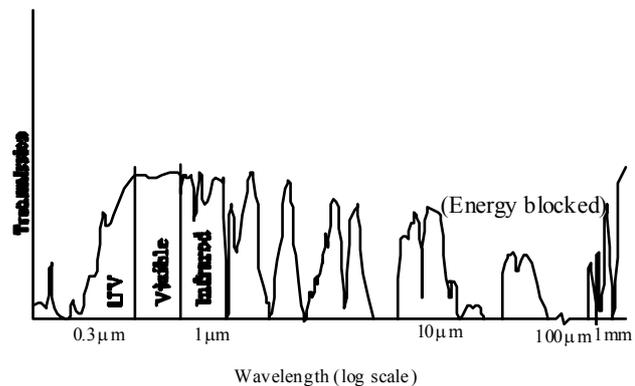
**Figure 1.** Spectral characteristics of Atmospheric transmittance

The important point to note from Figure 1 is the interaction and the interdependence between the primary sources of electromagnetic energy, the atmospheric windows through which source energy may be transmitted to and from earth surface features, and the spectral sensitivity of the sensors available to detect and record the energy. One cannot select the sensor to be used in any given remote sensing task arbitrarily; one must instead consider: (1) the spectral sensitivity of the sensors available, (2) the presence or absence of atmospheric windows in the spectral range(s) in which one wishes to sense, and (3) the source, magnitude, and spectral composition of the energy available in the these ranges. Ultimately, however, the choice of spectral range of the sensor must be based on the manner in which the energy interacts with the features under investigation. It is to this last, very important, element that we now turn our attention.

3. ENERGY INTERACTIONS WITH EARTH SURFACE FEATURES

When electromagnetic energy is incident on any given earth surface feature, three fundamental energy interactions with the feature are possible. This is illustrated in Figure 2 for an element of the volume of a water body. Various fractions of the energy incident on the element are reflected, absorbed, and or transmitted. Applying the principle of conservation of energy, we can state the interrelationship between these three energy interaction as

$$E_I(\lambda) = E_R(\lambda) + E_A(\lambda) + E_T(\lambda)$$

where E_I denotes the incident energy, E_R denotes the reflected energy, E_A denotes the absorbed energy and E_T denotes the transmitted energy, with all energy components being a function of wavelength λ. The above equation is an energy balance equation expressing the interrelationship between the mechanisms of reflection, absorption, and transmission.
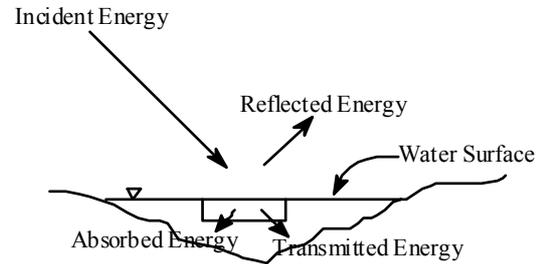
Figure 2. Basic interactions between Electromagnetic energy and an Earth Surface feature

Two points concerning this relationship should be noted. First, the proportions of energy reflected, absorbed, and transmitted will vary for different earth features, depending on their material type and condition. These differences permit us to distinguish different features on an image. Second, the wavelength dependency means that, even within a given feature type, the proportion of reflected, absorbed, and transmitted energy will vary at different wavelengths. Thus, two features may be indistinguishable in one spectral range and be very different in another wavelength band. Within the visible portion of the spectrum, these spectral variations result in the visual effect called colour. For example, we call objects, "blue" when they reflect highly in the blue portion of the visible spectrum, "green" when they reflect highly in the green spectral region, and so on. Thus, the eye utilizes spectral variations in the magnitude of reflected energy in the visible region to discriminate between various objects.
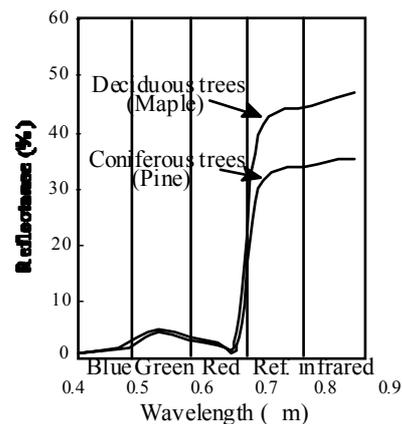
The geometric manner in which an object reflects energy is also an important consideration. This factor is primarily a function of the surface roughness of the object. Specular reflectors are flat surfaces that manifest mirror like reflections, where the angle of reflection equals the angle of incidence. Diffuse (or Lambertain) reflectors are rough surfaces that reflect uniformly in all directions. Most earth surfaces are neither perfectly specular nor diffuse reflectors. Their characteristics are somewhat in between the two extremes. The category that characterizes any given surface is dictated by the surface's roughness in comparison to the wavelength of the energy incident upon it. for example, in the relatively long wavelength radio range, rocky terrain can appear smooth to incident energy. In comparison, in the visible portion of the spectrum, even a material such as fine sand appears rough. In short, when the wavelength of incident energy is much smaller than the surface height variations or the particle sizes that make up a surface, the surface is diffuse. Diffuse reflections contain spectral information on the "colour" of the reflecting surface, whereas specular reflections do not. Hence, in remote sensing, we are most often interested in measuring the diffuse reflectance properties of terrain features.

The reflectance characteristics of earth surface features may be quantified by measuring the portion of incident energy that is reflected. This is measured as a function of wavelength, and is called spectral reflectance, R_λ. It is mathematically defined as

$$R_\lambda = \frac{E_R(\lambda)}{E_I(\lambda)} = \frac{Energy\ of\ wavelength\ \lambda\ reflected\ from\ the\ object}{Energy\ of\ wavelength\ \lambda\ incident\ upon\ the\ object} x\ 100$$

where R_λ is expressed as a percentage.

A graph of the spectral reflectance of an object as a function of wavelength is termed a spectral reflectance curve. The configuration of spectral reflectance curves gives us insight into the spectral characteristics of an object and has a strong influence on the choice of wavelength region(s) in which remote sensing data are acquired for a particular application. This is illustrated in Figure 3, which shows highly generalized spectral reflectance curves for deciduous and coniferous trees. (In this discussion, we use the terms deciduous and coniferous somewhat loosely, referring to broad-leaved trees such as oak and maple as deciduous, and needle-bearing trees such as pine and spruce as coniferous). Note that the curve for each of these object types is plotted as a "ribbon" (or "envelope") of values, not as a single line. This is because spectral reflectances vary somewhat within a given material class. That is, the spectral reflectance of one deciduous tree species and another will never be identical. Nor will the spectral reflectance of trees of the same species be exactly equal.
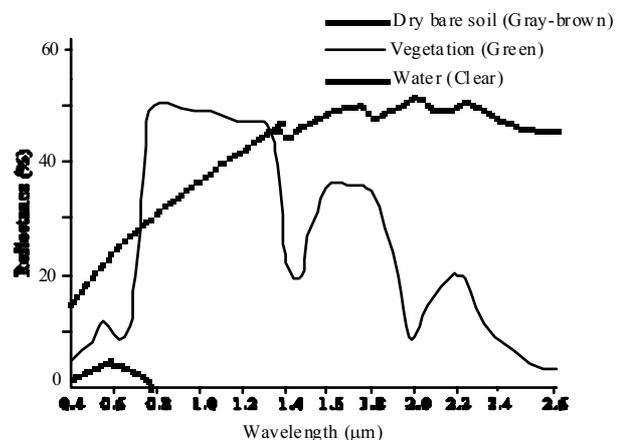

Figure 3. Generaised Spectral reflectance curves for Deciduous (broad-leaved) and Coniferous (needle-bearing) trees.

In Figure 3, assume that we are given the task of selecting an airborne sensor system to assist in preparing a map of a forested area differentiating deciduous versus coniferous trees. One choice of sensor might be the human eye. However, there is a potential problem with this choice. The spectral reflectance curves for each tree type overlap in most of the visible portion of the spectrum and are very close where they do not overlap. Hence, the eye might see both tree types as being essentially the same shade of "green" and might confuse the identity of the deciduous and coniferous trees. Certainly one could improve things somewhat by using spatial clues to each tree type's identity, such as size, shape, site, and so forth. However, this is often difficult to do from the air, particularly when tree types are intermixed. How might we discriminate the two types on the basis of their spectral characteristics alone? We could do this by using a sensor system that records reflected infrared energy. A camera loaded with black and white infrared film is just such a system. On black and white infrared photographs, deciduous trees (having higher infrared reflectance than conifers) generally appear much lighter in tone than do conifers. In fact, if we could electronically scan this type of image and feed the results to a computer in terms of image tone, we might "automate" our entire mapping task. Many remote sensing data analysis schemes attempt to do just that. For these schemes to be successful, the materials to be differentiated must be spectrally separable.

Experience has shown that many earth surface features of interest can be identified, mapped, and studied on the basis of their spectral characteristics. Experience has also shown that some features of interest cannot be spectrally separated. Thus, to utilize remote sensing data effectively, one must know and understand the spectral characteristics of the particular features under investigation in any given application. Likewise, one must know what factors influence these characteristics.

4. SPECTRAL REFLECTANCE OF VEGETATION, SOIL, AND WATER

Figure 4 shows typical spectral reflectance curves for three basic types of earth features: Healthy green vegetation, Dry bare soil (grey-brown loam), and Clear lake water. The lines in this figure represent average reflectance curves compiled by measuring a large sample of features. Note how distinctive the curves are for each feature. In general, the configuration of these curves is an indicator of the type and condition of the features to which they apply. Although the reflectance of individual features will vary considerably above and below the average, these curves demonstrate some fundamental points concerning spectral reflectance.

For example, spectral reflectance curves for healthy green vegetation almost always manifest the "peak-and-valley" configuration illustrated in Figure 4.

Figure 4. Typical reflectance curves for Vegetation, soil and water

The valleys in the visible portion of the spectrum are dictated by the pigments in plant leaves. Chlorophyll, for example, strongly absorbs energy in the wavelength bands centered at about 0.45 and 0.65 µm. Hence, our eyes perceive healthy vegetation as green in colour because of the very high reflection of green energy. If a plant is subject to some form of stress that interrupts its normal growth and productivity, it may decrease or cease chlorophyll production. The result is less chlorophyll absorption in the blue and red bands. Often the red reflectance increases to the point that we see the plant turn yellow (combination of green and red).

As we go from the visible to the reflected infrared portion of the spectrum at about 0.7 µm, the reflectance of healthy vegetation increases dramatically. In the range from about 0.7 to 1.3µm, a plant leaf reflects about 50 percent of the energy incident upon it. Most of the remaining energy is transmitted, since absorption in this spectral region is minimal. Plant reflectance in the 0.7 to 1.3 µm range results primarily from the internal structure of plant leaves. Because this structure is highly variable between plant species, reflectance measurements in this range often permit us to discriminate between species, even if they look the same in visible wavelengths. Likewise, many plant stresses alter the reflectance in this region and sensors operating in this range are often used for vegetation stress detection.

Beyond 1.3 µm, energy incident upon vegetation is essentially absorbed or reflected, with little to no transmittance of energy. Dips in reflectance occur at 1.4, 1.9, and 2.7 µm because water in the leaf absorbs strongly at these wavelengths. Accordingly, wavelengths in these spectral regions are referred to as **water absorption bands**. Reflectance peaks occur at about 1.6 and 2.2 µm, between the absorption bands. Throughout the range beyond 1.3 µm, leaf reflectance is approximately inversely related to the total water present in a leaf. This total is a function of both the moisture content and the thickness of a leaf.

The soil curve in Figure 4 shows considerably less peak-and-valley variation in reflectance i.e., the factors that influence soil reflectance act over less specific spectral bands. Some of the factors affecting soil reflectance are moisture content, soil texture (proportion of sand, silt, and clay), surface roughness, the presence of iron oxide, and organic matter content. These factors are complex, variable, and interrelated. For example, the presence of moisture in soil will decrease its reflectance. As with vegetation, this effect is greatest in the water absorption bands at about 1.4, 1.9, and 2.7 µm (clay soils also have hydroxyl absorption bands at about 1.4 and 2.2 µm). Soil moisture content is strongly related to the soil texture: coarse, sandy soils are usually well drained, resulting in low moisture content and relatively high reflectance; poorly drained fine textured soils will generally have lower reflectance. In the absence of water, however, the soil itself will exhibit the reverse tendency: coarse textured soils will appear darker than fine textured soils. Thus, the reflectance properties of a soil are consistent only within particular ranges of conditions. Two other factors that reduce soil reflectance are surface roughness and the content of organic matter. The presence of iron oxide in a soil will also significantly decrease reflectance, at least in the visible wavelengths. In any case, it is essential that the analyst be familiar with the conditions at hand.

Considering the spectral reflectance of water, probably the most distinctive characteristic is the energy absorption at reflected infrared wavelengths. In short, water absorbs energy in these wavelengths whether we are talking about water features per se (such as lakes and streams) or water contained in vegetation or soil. Locating and delineating water bodies with remote sensing data is done most easily in reflected infrared wavelengths because of this absorption property. However, various conditions of water bodies manifest themselves primarily in visible wavelengths. The energy/matter interactions at these wavelengths are very complex and depend on a number of interrelated factors. For example, the reflectance from a water body can stem from an interaction with the water's surface (specular reflection), with material suspended in the water, or with the bottom of the water body. Even with deep water where bottom effects are negligible, the reflectance properties of a water body are not only a function of the water per se but also the material in the water.

Clear water absorbs relatively little energy having wavelengths less than about 0.6 µm. High transmittance typifies these wavelengths with a maximum in the blue-green portion of the spectrum. However, as the turbidity of water changes (because of the presence of organic or inorganic materials) transmittance - and therefore reflectance - changes dramatically. For example, waters containing large quantities of suspended sediments resulting from soil erosion normally have much higher visible reflectance than other "clear" waters in the same geographical area. Likewise, the reflectance of water changes with the chlorophyll concentration involved. Increases in chlorophyll concentration tend to decrease water reflectance in blue wavelengths and increase it in the green wavelengths. These changes have been used to monitor the presence and estimate the concentration of algae via remote sensing data. Reflectance data have also been used to determine the presence or absence of tannin dyes from bog vegetation in lowland areas, and to detect a number of pollutants, such as oil and certain industrial wastes.

Many important water characteristics, such as dissolved oxygen concentration, pH, and salt concentration cannot be observed directly through changes in water reflectance. However, such parameters sometimes correlate with observed reflectance. In short, there are many complex interrelationships between the spectral reflectance of water and particular characteristics. One must use appropriate reference data to correctly interpret reflectance measurements made over water. Further details on the spectral characteristics of vegetation, soil, and water can be found in Swain and Davis (1978).

4.1 Spatial and Temporal Effects

Having looked at the spectral reflectance characteristics of vegetation soil, and water, we should recognize that these broad feature types are normally spectrally separable. However, the degree of separation between types is a function of "where we look" spectrally. For example, water and vegetation might reflect nearly equally in visible wavelengths, yet these features are almost always separable in reflective infrared wavelengths. Because spectral responses measured by remote sensors over various features often permit an assessment of the type and/or condition of the features, these responses have often been referred to as spectral signatures. Spectral reflectance and spectral emittance curves (for wavelengths greater than 3.0 μm) are often referred to in this manner. The physical radiation measurements acquired over specific terrain features at various wavelengths are also often referred to as the **spectral signatures** for those features.

Although it is true that many earth surface features manifest very distinctive spectral reflectance and/or emittance characteristics, these characteristics result in spectral "response patterns" rather than in spectral "signatures". The reason for this is that the term signature tends to imply a pattern that is absolute and unique. This is not the case with the spectral patterns observed in the natural world. As we have seen, spectral response patterns measured by remote sensors may be quantitative but they are not absolute. They may be distinctive but they are not necessarily unique.

Although the term "spectral signature" is used frequently in remote sensing literature, the student should keep in mind the variability of spectral signatures. this variability might cause severe problems in remote sensing data analysis if the objective is to identify various earth features types spectrally. However, if the objective of an analysis is to identify the condition of various objects of the same type, we may have to rely on spectral response pattern variability to derive this information. This pertains to such applications as identifying stressed versus healthy vegetation within a given species. Therefore, it is extremely important to understand the nature of the ground area one is "looking at" with remote sensor data, not only to minimize unwanted spectral variability, but also to maximize this variability when the particular application requires it.

We have already looked at some characteristics of objects per se that influence their spectral response patterns. Temporal effects and spatial effects can also enter into any given analysis. Temporal effects are any factors that change the spectral characteristics of a feature over time. For example, the spectral characteristics of many species of vegetation are in a nearly continual state of change throughout a growing season. These changes often influence when we might collect sensor data for a particular application.

Spatial effects refer to factors that cause the same types of features (for example, corn plants) at a given point in time to have different characteristics at different geographic locations. In small area analysis, the geographic locations may be meters apart and spatial effects may be negligible. When analysing satellite data, the locations may be hundreds of kilometres apart where entirely different soils, climates, and cultivation practices might exist. Temporal and spatial effects influence virtually all remote sensing operations. These effects normally complicate the issue of analysing spectral reflectance properties of earth resources. Again however, temporal and spatial effects might be the keys to gaining the information sought in an analysis. For example, the process of change detection is premised on the ability to measure temporal effects. An example of this process is detecting the change in suburban development near a metropolitan area by using data obtained on two different dates. An example of a useful spatial effect is the change in the leaf morphology of trees when they are subjected to some form of stress. For example, when a tree becomes infected with disease, its leaves might begin to cup and curl, changing the reflectance of the tree relative to healthy trees that surround it. So, even though a spatial effect might cause difference in the spectral reflectances of the same type of feature, this effect may be just what is important in a particular application.

In addition to being influenced by temporal and spatial effects, spectral response patterns are influenced by the atmosphere. Regrettably, the energy recorded by a sensor is always modified to some extent by the atmosphere between the sensor and the ground.

5. DATA ACQUISITION AND INTERPRETATION

Up to this point, we have discussed the principal sources of electromagnetic energy, the propagation of this energy through the atmosphere, and the interaction of this energy with earth surface features. Combined, these factors result in energy "signals" from which we wish to extract information. We now consider the procedures by which these signals are detected, recorded and interpreted.

The detection of electromagnetic energy can be performed either photographically or electronically. The process of photography uses chemical reaction on the surface of a light sensitive film to detect energy variations within a scene. Photographic systems offer many advantages: they are relatively simple and inexpensive and provide a high degree of spatial detail and geometric integrity. Electronic sensors generate an electrical signal that corresponds to the energy variations in the original scene. A familiar example of an electronic sensor is a television camera. Although considerably more complex and expensive than photographic systems, electronic sensors offer the advantages of a broader spectral range of sensitivity, improved calibration potential, and the ability to electronically transmit image data. Anoother mode of electronic sensor is recording with the help of **charge coupled device** which is used to convert electrical signal to digital signal.

By developing a photograph, we obtain a record of its detected signals. Thus, the film acts as both the detecting and recording medium. Electronic sensor signals are generally recorded onto magnetic tape. Subsequently, the signals may be converted to an image form by photographing a TV-like screen display of the data, or by using a specialized film recorder. In these cases, photographic film is used only as a recording medium.

We can see that the data interpretation aspects of remote sensing can involve analysis of pictorial (image) and/or numerical data. Visual interpretation of pictorial image data has long been the workhorse of remote sensing.. Visual techniques make use of the excellent ability of the human mind to qualitatively evaluate spatial patterns in a scene. The ability to make subjective judgments based on selective scene elements is essential in many interpretation efforts. Visual interpretation techniques have certain disadvantages, however, in that they may require extensive training and are labour intensive. In addition, spectral characteristics are not always fully evaluated in visual interpretation efforts. This is partly because of the limited ability of the eye to discern tonal values on an image and the difficulty for an interpreter to simultaneously analyze numerous spectral images. In applications where spectral patterns are highly informative, it is therefore preferable to analyse numerical, rather than pictorial, image data. In this case, the image is described by a matrix of numerical brightness values covering the scene. These values may be analyzed by quantitative procedures employing a computer, which is referred to as **digital interpretation**.

The use of computer assisted analysis techniques permits the spectral patterns in remote sensing data to be more fully examined. Digital interpretation is assisted by the image processing techniques such as image enhancement, information extraction etc. It also permits the data analysis process to be largely automated, providing cost advantages over visual interpretation techniques. However, just as humans are limited in their ability to interpret spectral patterns, computers are limited in their ability to evaluate spatial patterns. Therefore, visual and numerical techniques are complementary in nature, and consideration must be given to which approach (or combination of approaches) best fits a particular application.

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