Introduction to Remote Sensing and Image Processing

Of all the various data sources used in GIS, one of the most important is undoubtedly that provided by remote sensing. Through the use of satellites, we now have a continuing program of data acquisition for the entire world with time frames ranging from a couple of weeks to a matter of hours. Very importantly, we also now have access to remotely sensed images in digital form, allowing rapid integration of the results of remote sensing analysis into a GIS.

The development of digital techniques for the restoration, enhancement and computer-assisted interpretation of remotely sensed images initially proceeded independently and somewhat ahead of GIS. However, the raster data structure and many of the procedures involved in these *Image Processing Systems* (IPS) were identical to those involved in raster GIS. As a result, it has become common to see IPS software packages add general capabilities for GIS, and GIS software systems add at least a fundamental suite of IPS tools. IDRISI is a combined GIS and image processing system that offers advanced capabilities in both areas.

Because of the extreme importance of remote sensing as a data input to GIS, it has become necessary for GIS analysts (particularly those involved in natural resource applications) to gain a strong familiarity with IPS. Consequently, this chapter gives an overview of this important technology and its integration with GIS. The Image Processing exercises in the **Tutorial** illustrate many of the concepts presented here.

Definition

Remote sensing can be defined as any process whereby information is gathered about an object, area or phenomenon without being in contact with it. Our eyes are an excellent example of a remote sensing device. We are able to gather information about our surroundings by gauging the amount and nature of the reflectance of visible light energy from some external source (such as the sun or a light bulb) as it reflects off objects in our field of view. Contrast this with a thermometer, which must be in contact with the phenomenon it measures, and thus is not a remote sensing device.

Given this rather general definition, the term *remote sensing* has come to be associated more specifically with the gauging of interactions between earth surface materials and electromagnetic energy. However, any such attempt at a more specific definition becomes difficult, since it is not always the natural environment that is sensed (e.g., art conservation applications), the energy type is not always electromagnetic (e.g., sonar) and some procedures gauge natural energy emissions (e.g., thermal infrared) rather than interactions with energy from an independent source.

Fundamental Considerations

Energy Source

Sensors can be divided into two broad groups—*passive* and *active*. Passive sensors measure ambient levels of existing sources of energy, while active ones provide their own source of energy. The majority of remote sensing is done with passive sensors, for which the sun is the major energy source. The earliest example of this is photography. With airborne cameras we have long been able to measure and record the reflection of light off earth features. While aerial photography is still a major form of remote sensing, newer solid state technologies have extended capabilities for viewing in the visible and near-infrared wavelengths to include longer wavelength solar radiation as well. However, not all passive sensors use energy from the sun. Thermal infrared and passive microwave sensors both measure natural earth energy emissions. Thus

the passive sensors are simply those that do not themselves supply the energy being detected.

By contrast, active sensors provide their own source of energy. The most familiar form of this is flash photography. However, in environmental and mapping applications, the best example is RADAR. RADAR systems emit energy in the microwave region of the electromagnetic spectrum (Figure 3-1). The reflection of that energy by earth surface materials is then measured to produce an image of the area sensed.
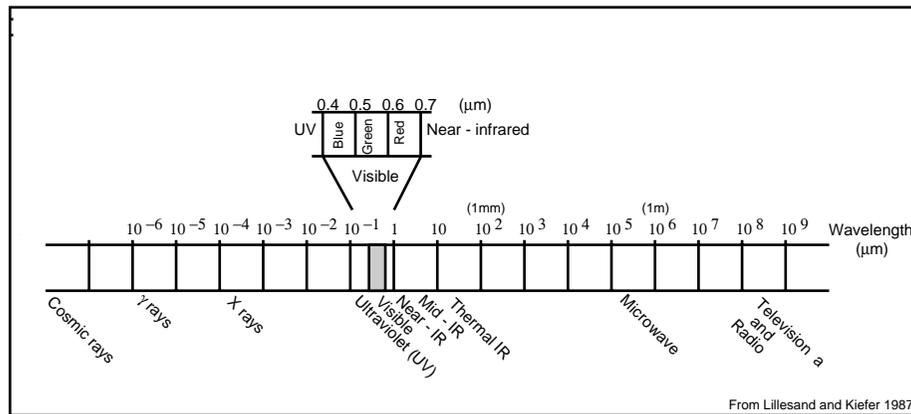

Figure 3-1: The Electromagnetic Spectrum

Wavelength

As indicated, most remote sensing devices make use of electromagnetic energy. However, the electromagnetic spectrum is very broad and not all wavelengths are equally effective for remote sensing purposes. Furthermore, not all have significant interactions with earth surface materials of interest to us. Figure 3-1 illustrates the electromagnetic spectrum. The atmosphere itself causes significant absorption and/or scattering of the very shortest wavelengths. In addition, the glass lenses of many sensors also cause significant absorption of shorter wavelengths such as the ultraviolet (UV). As a result, the first significant *window* (i.e., a region in which energy can significantly pass through the atmosphere) opens up in the visible wavelengths. Even here, the blue wavelengths undergo substantial attenuation by atmospheric scattering, and are thus often left out in remotely sensed images. However, the green, red and near-infrared (IR) wavelengths all provide good opportunities for gauging earth surface interactions without significant interference by the atmosphere. In addition, these regions provide important clues to the nature of many earth surface materials. Chlorophyll, for example, is a very strong absorber of red visible wavelengths, while the near-infrared wavelengths provide important clues to the structures of plant leaves. As a result, the bulk of remotely sensed images used in GIS-related applications are taken in these regions.

Extending into the middle and thermal infrared regions, a variety of good windows can be found. The longer of the middle infrared wavelengths have proven to be useful in a number of geological applications. The thermal regions have proven to be very useful for monitoring not only the obvious cases of the spatial distribution of heat from industrial activity, but a broad set of applications ranging from fire monitoring to animal distribution studies to soil moisture conditions.

After the thermal IR, the next area of major significance in environmental remote sensing is in the microwave region. A number of important windows exist in this region and are of particular importance for the use of active radar imaging. The texture of earth surface materials causes significant interactions with several of the microwave wavelength regions. This can thus be used as a supplement to information gained in other wavelengths, and also offers the significant advantage of being usable at night (because as an active system it is independent of solar radiation) and in regions of persistent cloud cover (since radar wavelengths are not significantly affected by clouds).

Interaction Mechanisms

When electromagnetic energy strikes a material, three types of interaction can follow: reflection, absorption and/or transmission (Figure 3-2). Our main concern is with the reflected portion since it is usually this which is returned to the sensor system. Exactly how much is reflected will vary and will depend upon the nature of the material and where in the electromagnetic spectrum our measurement is being taken. As a result, if we look at the nature of this reflected component over a range of wavelengths, we can characterize the result as a *spectral response pattern.*
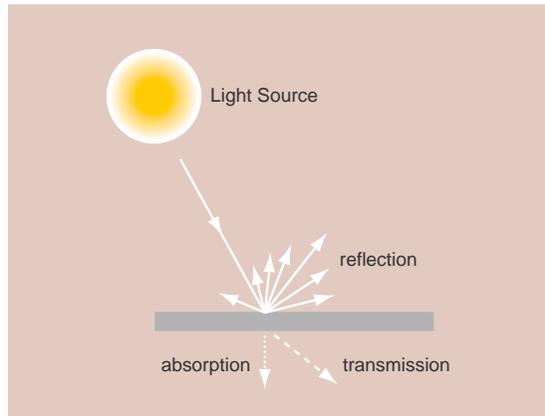

Figure 3-2

Spectral Response Patterns

A spectral response pattern is sometimes called a *signature.* It is a description (often in the form of a graph) of the degree to which energy is reflected in different regions of the spectrum. Most humans are very familiar with spectral response patterns since they are equivalent to the human concept of color. For example, Figure 3-3 shows idealized spectral response patterns for several familiar colors in the visible portion of the electromagnetic spectrum, as well as for white and dark grey. The bright red reflectance pattern, for example, might be that produced by a piece of paper printed with a red ink. Here, the ink is designed to alter the white light that shines upon it and absorb the blue and green wavelengths. What is left, then, are the red wavelengths which reflect off the surface of the paper back to the sensing system (the eye). The high return of red wavelengths indicates a bright red, whereas the low return of green wavelengths in the second example suggests that it will appear quite dark.
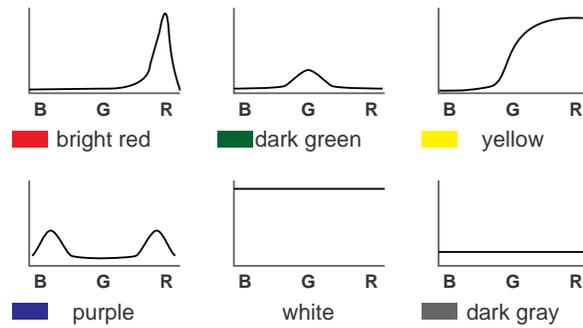
Figure 3-3

The eye is able to sense spectral response patterns because it is truly a multi-spectral sensor (i.e., it senses in more than one place in the spectrum). Although the actual functioning of the eye is quite complex, it does in fact have three separate types of detectors that can usefully be thought of as responding to the red, green and blue wavelength regions. These are the *additive primary colors*, and the eye responds to mixtures of these three to yield a sensation of other hues. For example, the color perceived by the third spectral response pattern in Figure 3-3 would be a yellow—the result of *mixing* a red and green. However, it is important to recognize that this is simply our phenomenological perception of a spectral response pattern. Consider, for example, the fourth curve. Here we have reflectance in both the blue and red regions of the visible spectrum. This is a bimodal distribution, and thus technically not a specific hue in the spectrum. However, we would perceive this to be a purple! Purple (a color between violet and red) does not exist in nature (i.e., as a hue—a distinctive dominant wavelength). It is very real in our perception, however. Purple is simply our perception of a bimodal pattern involving a non-adjacent pair of primary hues.

In the early days of remote sensing, it was believed (more correctly *hoped*) that each earth surface material would have a distinctive spectral response pattern that would allow it to be reliably detected by visual or digital means. However, as our common experience with color would suggest, in reality this is often not the case. For example, two species of trees may have quite a different coloration at one time of the year and quite a similar one at another.

Finding distinctive spectral response patterns is the key to most procedures for computer-assisted interpretation of remotely sensed imagery. This task is rarely trivial. Rather, the analyst must find the combination of spectral bands and the time of year at which distinctive patterns can be found for each of the information classes of interest.

For example, Figure 3-4 shows an idealized spectral response pattern for vegetation along with those of water and dry bare soil. The strong absorption by leaf pigments (particularly chlorophyll for purposes of photosynthesis) in the blue and red regions of the visible portion of the spectrum leads to the characteristic green appearance of healthy vegetation. However, while this *signature* is distinctively different from most non-vegetated surfaces, it is not very capable of distinguishing between species of vegetation—most will have a similar color of green at full maturation. In the near-infrared, however, we find a much higher return from vegetated surfaces because of scattering within the fleshy mesophyllic layer of the leaves. Plant pigments do not absorb energy in this region, and thus the scattering, combined with the multiplying effect of a full canopy of leaves, leads to high reflectance in this region of the spectrum. However, the extent of this reflectance will depend highly on the internal structure of leaves (e.g., broadleaf versus needle). As a result, significant differences between species can often be detected in this region. Similarly, moving into the middle infrared region we see a significant dip in the spectral response pattern that is associated with leaf moisture. This is, again, an area where significant differences can arise between mature species. Applications looking for optimal differentiation between species, therefore, will typically involve both the near and middle infrared regions and will use imagery taken well into the development cycle.
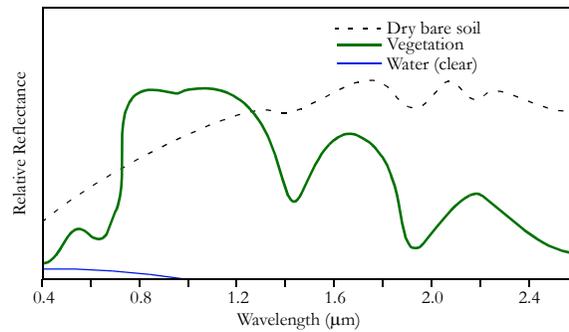
Figure 3-4   Adapted from Lillesand and Kiefer 1987

Multispectral Remote Sensing

In the visual interpretation of remotely sensed images, a variety of image characteristics are brought into consideration: color (or tone in the case of panchromatic images), texture, size, shape, pattern, context, and the like. However, with computer-assisted interpretation, it is most often simply color (i.e., the spectral response pattern) that is used. It is for this reason that a strong emphasis is placed on the use of multispectral sensors (sensors that, like the eye, look at more than one place in the spectrum and thus are able to gauge spectral response patterns), and the number and specific placement of these spectral *bands*.

Figure 3-5 illustrates the spectral bands of the LANDSAT Thematic Mapper (TM) system. The LANDSAT satellite is a commercial system providing multi-spectral imagery in seven spectral bands at a 30 meter resolution.

It can be shown through analytical techniques such as Principal Components Analysis, that in many environments, the bands that carry the greatest amount of information about the natural environment are the near-infrared and red wavelength bands. Water is strongly absorbed by infrared wavelengths and is thus highly distinctive in that region. In addition, plant species typically show their greatest differentiation here. The red area is also very important because it is the primary region in which chlorophyll absorbs energy for photosynthesis. Thus it is this band which can most readily distinguish between vegetated and non-vegetated surfaces.

Given this importance of the red and near-infrared bands, it is not surprising that sensor systems designed for earth resource monitoring will invariably include these in any particular multispectral system. Other bands will depend upon the range of applications envisioned. Many include the green visible band since it can be used, along with the other two, to produce a traditional false color composite—a full color image derived from the green, red, and infrared bands (as opposed to the blue, green, and red bands of natural color images). This format became common with the advent of color infrared photography, and is familiar to many specialists in the remote sensing field. In addition, the combination of these three bands works well in the interpretation of the cultural landscape as well as natural and vegetated surfaces. However, it is increasingly common to include other bands that are more specifically targeted to the differentiation of surface materials. For example, LANDSAT TM Band 5 is placed between two water absorption bands and has thus proven very useful in determining soil and leaf moisture differences. Similarly, LANDSAT TM Band 7 targets the detection of hydrothermal alteration zones in bare rock surfaces. By contrast, the AVHRR system on the NOAA series satellites includes several thermal channels for the sensing of cloud temperature characteristics.
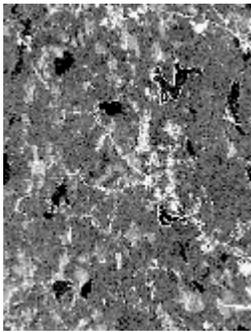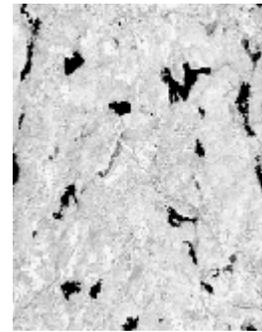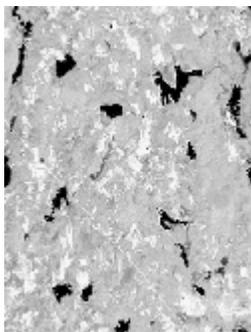
Band 1, visible blue
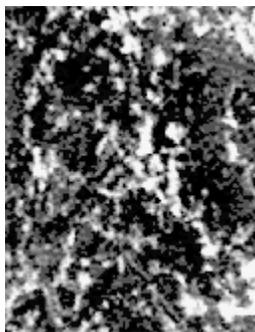0.45-0.52 mm
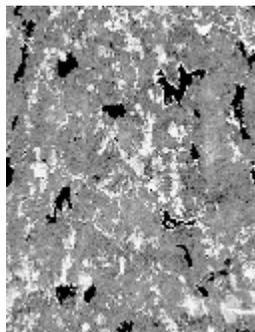
Band 2, visible green
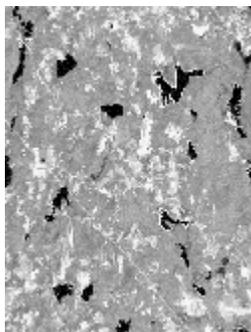0.52-0.60 mm
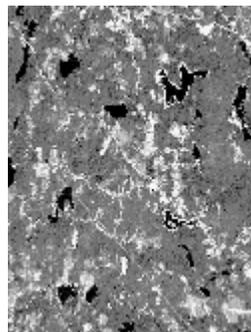
Band 3, visible red
0.63-0.69 mm

Band 4, near-infrared
0.76-0.90 mm

Band 5, middle-infrared
1.55-1.75 mm

Band 6, thermal infrared
10.4-12.5 mm

Band 7, middle-infrared
2.08-2.35 mm

Figure 3-5

Hyperspectral Remote Sensing

In addition to traditional multispectral imagery, some new and experimental systems such as AVIRIS and MODIS are capable of capturing *hyperspectral* data. These systems cover a similar wavelength range to multispectral systems, but in much narrower bands. This dramatically increases the number of bands (and thus precision) available for image classification (typically tens and even hundreds of very narrow bands). Moreover, hyperspectral signature libraries have been created in lab conditions and contain hundreds of signatures for different types of landcovers, including many minerals and other earth materials. Thus, it should be possible to match signatures to surface materials with great precision. However, environmental conditions and natural variations in materials (which make them different from standard library materials) make this difficult. In addition, classification procedures have not been developed for hyperspectral data to the degree they have been for multispectral imagery. As a consequence, multispectral imagery still represents the major tool of remote sensing today.

Sensor/Platform Systems

Given recent developments in sensors, a variety of platforms are now available for the capture of remotely sensed data. Here we review some of the major sensor/platform combinations that are typically available to the GIS user community.

Aerial Photography

Aerial photography is the oldest and most widely used method of remote sensing. Cameras mounted in light aircraft flying between 200 and 15,000 m capture a large quantity of detailed information. Aerial photos provide an instant visual inventory of a portion of the earth's surface and can be used to create detailed maps. Aerial photographs commonly are taken by commercial aerial photography firms which own and operate specially modified aircraft equipped with large format (23 cm x 23 cm) mapping quality cameras. Aerial photos can also be taken using small format cameras (35 mm and 70 mm), hand-held or mounted in unmodified light aircraft.

Camera and platform configurations can be grouped in terms of oblique and vertical. Oblique aerial photography is taken at an angle to the ground. The resulting images give a view as if the observer is looking out an airplane window. These images are easier to interpret than vertical photographs, but it is difficult to locate and measure features on them for mapping purposes.

Vertical aerial photography is taken with the camera pointed straight down. The resulting images depict ground features in plan form and are easily compared with maps. Vertical aerial photos are always highly desirable, but are particularly useful for resource surveys in areas where no maps are available. Aerial photos depict features such as field patterns and vegetation which are often omitted on maps. Comparison of old and new aerial photos can also capture changes within an area over time.

Vertical aerial photos contain subtle displacements due to relief, tip and tilt of the aircraft and lens distortion. Vertical images may be taken with overlap, typically about 60 percent along the flight line and at least 20 percent between lines. Overlapping images can be viewed with a stereoscope to create a three-dimensional view, called a *stereo model*.

Large Format Photography

Commercial aerial survey firms use light single or twin engine aircraft equipped with large-format mapping cameras. Large-format cameras, such as the Wild RC-10, use 23 cm x 23 cm film which is available in rolls. Eastman Kodak, Inc., among others, manufactures several varieties of sheet film specifically intended for use in aerial photography. Negative film is used where prints are the desired product, while positive film is used where transparencies are desired. Print film allows for detailed enlargements to be made, such as large wall-sized prints. In addition, print film is useful when multiple prints are to be distributed and used in the field.

Small Format Photography

Small-format cameras carried in chartered aircraft are an inexpensive alternative to large-format aerial photography. A 35mm or 70mm camera, light aircraft and pilot are required, along with some means to process the film. Because there are inexpensive commercial processing labs in most parts of the world, 35mm systems are especially convenient.

Oblique photographs can be taken with a hand-held camera in any light aircraft; vertical photographs require some form of special mount, pointed through a belly port or extended out a door or window.

Small-format aerial photography has several drawbacks. Light unpressurized aircraft are typically limited to altitudes below 4000 m. As film size is small, sacrifices must be made in resolution or area covered per frame. Because of distortions in the camera system, small-format photography cannot be used if precise mapping is required. In addition, presentation-quality wall-size prints cannot be made from small negatives. Nonetheless, small-format photography can be very useful for reconnaissance surveys and can also be used as point samples.

Color Photography

Normal color photographs are produced from a composite of three film layers with intervening filters that act to isolate, in effect, red, green, and blue wavelengths separately to the different film layers. With color infrared film, these wavelengths are shifted to the longer wavelengths to produce a composite that has isolated reflectances from the green, red and near-infrared wavelength regions. However, because the human eye cannot see infrared, a false color composite is produced by making the green wavelengths appear blue, the red wavelengths appear green, and the infrared wavelengths

appear red.

As an alternative to the use of color film, it is also possible to group several cameras on a single aircraft mount, each with black and white film and a filter designed to isolate a specific wavelength range. The advantage of this arrangement is that the bands are independently accessible and can be photographically enhanced. If a color composite is desired, it is possible to create it from the individual bands at a later time.

Clearly, photographs are not in a format that can immediately be used in digital analysis. It is possible to scan photographs with a scanner and thereby create multispectral datasets either by scanning individual band images, or by scanning a color image and separating the bands. However, the geometry of aerial photographs (which have a central perspective projection and differential parallax) is such that they are difficult to use directly. More typically they require processing by special photogrammetric software to rectify the images and remove differential parallax effects.

Aerial Videography

Light, portable, inexpensive video cameras and recorders can be carried in chartered aircraft. In addition, a number of smaller aerial mapping companies offer videography as an output option. By using several cameras simultaneously, each with a filter designed to isolate a specific wavelength range, it is possible to isolate multispectral image bands that can be used individually, or in combination in the form of a color composite. For use in digital analysis, special graphics hardware boards known as *frame grabbers* can be used to freeze any frame within a continuous video sequence and convert it to digital format, usually in one of the more popular exchange formats such as TIF or TARGA. Like small-format photography, aerial videography cannot be used for detailed mapping, but provides a useful overview for reconnaissance surveys, and can be used in conjunction with ground point sampling.

Satellite-Based Scanning Systems

Photography has proven to be an important input to visual interpretation and the production of analog maps. However, the development of satellite platforms, the associated need to telemeter imagery in digital form, and the desire for highly consistent digital imagery have given rise to the development of solid state scanners as a major format for the capture of remotely sensed data. The specific features of particular systems vary (including, in some cases, the removal of a true scanning mechanism). However, in the discussion which follows, an idealized scanning system is presented that is highly representative of current systems in use.

The basic logic of a scanning sensor is the use of a mechanism to sweep a small field of view (known as an *instantaneous field of view*—IFOV) in a west to east direction at the same time the satellite is moving in a north to south direction. Together this movement provides the means of composing a complete raster image of the environment.

A simple scanning technique is to use a rotating mirror that can sweep the field of view in a consistent west to east fashion. The field of view is then intercepted with a prism that can spread the energy contained within the IFOV into its spectral components. Photoelectric detectors (of the same nature as those found in the exposure meters of commonly available photographic cameras) are then arranged in the path of this spectrum to provide electrical measurements of the amount of energy detected in various parts of the electromagnetic spectrum. As the scan moves from west to east, these detectors are polled to get a set of readings along the east-west scan. These form the columns along one row of a set of raster images—one for each detector. Movement of the satellite from north to south then positions the system to detect the next row, ultimately leading to the production of a set of raster images as a record of reflectance over a range of spectral bands.

There are several satellite systems in operation today that collect imagery that is subsequently distributed to users. Several of the most common systems are described below. Each type of satellite data offers specific characteristics that make it more or less appropriate for a particular application.

In general, there are two characteristics that may help guide the choice of satellite data: *spatial resolution* and *spectral resolution*. The spatial resolution refers to the size of the area on the ground that is summarized by one data value in the imagery. This is the Instantaneous Field of View (IFOV) described earlier. Spectral resolution refers to the number and width of

the spectral bands that the satellite sensor detects. In addition, issues of cost and imagery availability must also be considered.

LANDSAT

The LANDSAT system of remote sensing satellites is currently operated by the EROS Data Center of the United States Geological Survey. This is a new arrangement following a period of commercial distribution under the Earth Observation Satellite Company (EOSAT) which was recently acquired by Space Imaging Corporation. As a result, the cost of imagery has dramatically dropped, to the benefit of all. Full or quarter scenes are available on a variety of distribution media, as well as photographic products of MSS and TM scenes in false color and black and white.

There have been seven LANDSAT satellites, the first of which was launched in 1972. The LANDSAT 6 satellite was lost on launch. However, as of this writing, LANDSAT 5 is still operational. LANDSAT 7 was launched in April, 1999.

LANDSAT carries two multispectral sensors. The first is the *Multi-Spectral Scanner* (MSS) which acquires imagery in four spectral bands: blue, green, red and near infrared. The second is the *Thematic Mapper* (TM) which collects seven bands: blue, green, red, near-infrared, two mid-infrared and one thermal infrared. The MSS has a spatial resolution of 80 meters, while that of the TM is 30 meters. Both sensors image a 185 km wide swath, passing over each day at 09:45 local time, and returning every 16 days. With LANDSAT 7, support for TM imagery is to be continued with the addition of a co-registered 15 m panchromatic band.

SPOT

The *Système Pour L'Observation de la Terre* (SPOT) was launched and has been operated by a French consortium since 1985. SPOT satellites carry two High Resolution Visible (HRV) pushbroom sensors[7] which operate in multispectral or panchromatic mode. The multispectral images have 20 meter spatial resolution while the panchromatic images have 10 meter resolution. SPOT satellites 1-3 provide three multi-spectral bands: Green, Red and Infrared. SPOT 4, launched in 1998, provides the same three bands plus a short wave infrared band. The panchromatic band for SPOT 1-3 is 0.51-0.73μ while that of SPOT 4 is 0.61-0.68μ.

All SPOT images cover a swath 60 kilometers wide. The SPOT sensor may be pointed to image along adjacent paths. This allows the instrument to acquire repeat imagery of any area 12 times during its 26 day orbital period. The pointing capability makes SPOT the only satellite system which can acquire useful stereo satellite imagery.

SPOT Image Inc. sells a number of products, including digital images on a choice of magnetic media, as well as photographic products. Existing images may be purchased, or new acquisitions ordered. Customers can request the satellite to be pointed in a particular direction for new acquisitions.

IRS

The Indian Space Research Organization currently has 5 satellites in the IRS system, with at least 7 planned by 2004. These data are distributed by ANTRIX Corp. Ltd (the commercial arm of the Indian Space Research Organization), and also by Space Imaging Corporation in the United States. The most sophisticated capabilities are offered by the IRS-1C and IRS-1D satellites that together provide continuing global coverage with the following sensors:

IRS-Pan: 5.8 m panchromatic

IRS-LISS3[8]: 23.5 m multispectral in the following bands:

Green (0.52-0.59)

---

7. The pushbroom sensor produces output like a scanner. However, there is no actual scanning motion. Rather, the sensor consists of a dense array of detectors—one for each raster cell in the scan line—that is moved across the scene like a pushbroom.

8. LISS = Linear Imaging and Self Scanning Sensor. Image format is approximately 140 km x 140 km.

Red (0.62-0.68)

Near-Infrared (0.77-0.86)

Shortwave Infrared (1.55-1.7)

IRS-WiFS[9]: 180 m multispectral in the following bands:

Red (0.62-0.68)

Near-Infrared (0.77-0.86)

NOAA-AVHRR

The *Advanced Very High Resolution Radiometer* (AVHRR) is carried on board a series of satellites operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). It acquires data along a 2400-km-wide swath each day. AVHRR collects five bands: red, near-infrared, and three thermal infrared. Spatial resolution of the sensor is 1.1 km and this data is termed Local Area Coverage (LAC). For studying very large areas, a resampled version with resolution of about 4 km is also available, and is termed Global Area Coverage (GAC).

AVHRR may be "high" spatial resolution for meteorological applications, but the images portray only broad patterns and little detail for terrestrial studies. However, they do have a high temporal resolution, showing wide areas on a daily basis and are therefore a popular choice for monitoring large areas. AVHRR imagery is used by several organizations engaged in famine prediction and is an integral part of many early warning activities.

RADARSAT

RADARSAT is an earth observation satellite launched in November 1995 by the Canadian Space Agency. The data is distributed by RADARSAT International (RSI) of Richmond, British Columbia, Canada (or through Space Imaging in the US). Spatial resolution of the C-band SAR imagery ranges from 8 to 100 meters per pixel and the ground coverage repeat interval is 24 days. Sensors can be pointed at the location of interest which enables collection of stereo RADAR imagery. RADAR signals also penetrate cloud cover, thus accessing areas not available to other remote sensing systems. In contrast to other remotely sensed imagery, the returned RADAR signal is more affected by electrical and physical (primarily textural) characteristics in the target than by its reflection and spectral pattern, therefore requiring special interpretation and spatial georegistration techniques. Compared to other types of remotely sensed imagery, the use of RADAR data is still in its infancy, but has strong potential.

ERS

ERS-1 and ERS-2 (European Remote Sensing Satellite) were developed by the European Space Agency. These identical systems provide an interesting complement to the other commercial imagery products in that they offer a variety of C-band RADAR imagery output formats. For GIS applications, the main output of interest is the side-looking airborne RADAR (SAR) output that provides 100 km wide swaths with a 30 meter resolution. This should prove to be of considerable interest in a variety of applications, including vegetation studies and mapping projects where cloud cover is a persistent problem.

JERS

The Japanese Earth Resource Satellite offers 18 m resolution L-band side-looking RADAR imagery. This is a substantially longer wavelength band than the typical C-band used in earth resources applications. L-band RADAR is capable of penetrating vegetation as well as unconsolidated sand and is primarily used in geologic, topographic and coastal mapping applications. JERS data is available in the United States from Space Imaging Corporation.

---

9. WiFS = Wide-Field Sensor. Image format is 810 km x 810 km.

AVIRIS

AVIRIS is an experimental system developed by the Jet Propulsion Lab (JPL) that produces hyperspectral data. It captures data in 224 bands over the same wavelength range as LANDSAT.

MODIS

The MODIS sensor onboard the EOS AM-1 platform (scheduled for launch in July, 1999) will provide a logical extension of the AVHRR by providing no fewer than 36 bands of medium-to-coarse resolution imagery with a high temporal repeat cycle (1-2 days). Bands 1 and 2 will provide 250 m resolution images in the red and near-infrared regions. Bands 3-7 will provide 500 m resolution multispectral images in the visible and infrared regions. Finally, bands 8-36 will provide hyperspectral coverage in the visible, reflected infrared, and thermal infrared regions, with a 1 km resolution.

Digital Image Processing

Overview

As a result of solid state multispectral scanners and other raster input devices, we now have available digital raster images of spectral reflectance data. The chief advantage of having these data in digital form is that they allow us to apply computer analysis techniques to the image data—a field of study called *Digital Image Processing.*

Digital Image Processing is largely concerned with four basic operations: ***image restoration***, ***image enhancement, image classification, image transformation.*** *Image restoration* is concerned with the correction and calibration of images in order to achieve as faithful a representation of the earth surface as possible—a fundamental consideration for all applications. *Image enhancement* is predominantly concerned with the modification of images to optimize their appearance to the visual system. Visual analysis is a key element, even in digital image processing, and the effects of these techniques can be dramatic. *Image classification* refers to the computer-assisted interpretation of images—an operation that is vital to GIS. Finally, *image transformation* refers to the derivation of new imagery as a result of some mathematical treatment of the raw image bands.

In order to undertake the operations listed in this section, it is necessary to have access to Image Processing software. IDRISI is one such system. While it is known primarily as a GIS software system, it also offers a full suite of image processing capabilities.

Image Restoration

Remotely sensed images of the environment are typically taken at a great distance from the earth's surface. As a result, there is a substantial atmospheric path that electromagnetic energy must pass through before it reaches the sensor. Depending upon the wavelengths involved and atmospheric conditions (such as particulate matter, moisture content and turbulence), the incoming energy may be substantially modified. The sensor itself may then modify the character of that data since it may combine a variety of mechanical, optical and electrical components that serve to modify or mask the measured radiant energy. In addition, during the time the image is being scanned, the satellite is following a path that is subject to minor variations at the same time that the earth is moving underneath. The geometry of the image is thus in constant flux. Finally, the signal needs to be telemetered back to earth, and subsequently received and processed to yield the final data we receive. Consequently, a variety of systematic and apparently random disturbances can combine to degrade the quality of the image we finally receive. Image restoration seeks to remove these degradation effects.

Broadly, image restoration can be broken down into the two sub-areas of *radiometric restoration* and *geometric restoration*.

Radiometric Restoration

Radiometric restoration refers to the removal or diminishment of distortions in the degree of electromagnetic energy reg-

istered by each detector. A variety of agents can cause distortion in the values recorded for image cells. Some of the most common distortions for which correction procedures exist include:

uniformly elevated values, due to atmospheric haze, which preferentially scatters short wavelength bands (particularly the blue wavelengths);

striping, due to detectors going out of calibration;

random noise, due to unpredictable and unsystematic performance of the sensor or transmission of the data; and

scan line drop out, due to signal loss from specific detectors.

It is also appropriate to include here procedures that are used to convert the raw, unitless relative reflectance values (known as digital numbers, or DN) of the original bands into true measures of reflective power (radiance).

See the chapter on **Image Restoration** in the **IDRISI Guide to GIS and Image Processing Volume 2** for a more detailed discussion of radiometric restoration and how it can be implemented in IDRISI.

Geometric Restoration

For mapping purposes, it is essential that any form of remotely sensed imagery be accurately registered to the proposed map base. With satellite imagery, the very high altitude of the sensing platform results in minimal image displacements due to relief. As a result, registration can usually be achieved through the use of a systematic *rubber sheet* transformation process[10] that gently warps an image (through the use of polynomial equations) based on the known positions of a set of widely dispersed control points. This capability is provided in IDRISI through the module RESAMPLE.

With aerial photographs, however, the process is more complex. Not only are there systematic distortions related to tilt and varying altitude, but variable topographic relief leads to very irregular distortions (differential parallax) that cannot be removed through a rubber sheet transformation procedure. In these instances, it is necessary to use photogrammetric rectification to remove these distortions and provide accurate map measurements[11]. Failing this, the central portions of high altitude photographs can be resampled with some success.

RESAMPLE is a module of major importance, and it is essential that one learn to use it effectively. Doing so also requires a thorough understanding of reference systems and their associated parameters such as datums and projections. The chapter on **Georeferencing** later in this volume provides an in-depth discussion of these issues.

Image Enhancement

Image enhancement is concerned with the modification of images to make them more suited to the capabilities of human vision. Regardless of the extent of digital intervention, visual analysis invariably plays a very strong role in all aspects of remote sensing. While the range of image enhancement techniques is broad, the following fundamental issues form the backbone of this area:

---

10. Satellite-based scanner imagery contains a variety of inherent geometric problems such as skew (caused by rotation of the earth underneath the satellite as it is in the process of scanning a complete image) and scanner distortion (caused by the fact that the instantaneous field of view (IFOV) covers more territory at the ends of scan lines, where the angle of view is very oblique, than in the middle). With commercially-marketed satellite imagery, such as LANDSAT, IRS and SPOT, most elements of systematic geometric restoration associated with image capture are corrected by the distributors of the imagery. Thus, for the end user, the only geometric operation that typically needs to be undertaken is a rubber-sheet resampling in order to rectify the image to a map base. Many commercial distributors will perform this rectification for an additional fee.

11. Photogrammetry is the science of taking spatial measurements from aerial photographs. In order to provide a full rectification, it is necessary to have *stereoscopic* images—photographs which overlap enough (e.g., 60% in the along-track direction and 10% between flight lines) to provide two independent images of each part of the landscape. Using these stereoscopic pairs and ground control points of known position and height, it is possible to fully recreate the geometry of the viewing conditions, and thereby not only rectify measurements from such images, but also derive measurements of terrain height. The rectified photographs are called *orthophotos*. The height measurements may be used to produce digital elevation models.

Contrast Stretch

Digital sensors have a wide range of output values to accommodate the strongly varying reflectance values that can be found in different environments. However, in any single environment, it is often the case that only a narrow range of values will occur over most areas. Grey level distributions thus tend to be very skewed. Contrast manipulation procedures are thus essential to most visual analyses. Figure 3-6 shows TM Band 3 (visible red) and its histogram. Note that the values of the image are quite skewed. The right image of the figure shows the same image band after a linear stretch between values 12 and 60 has been applied. In IDRISI, this type of contrast enhancement may be performed interactively through Composer's Layer Properties while the image is displayed. This is normally used for visual analysis only—original data values are used in numeric analyses. New images with stretched values are produced with the module STRETCH.
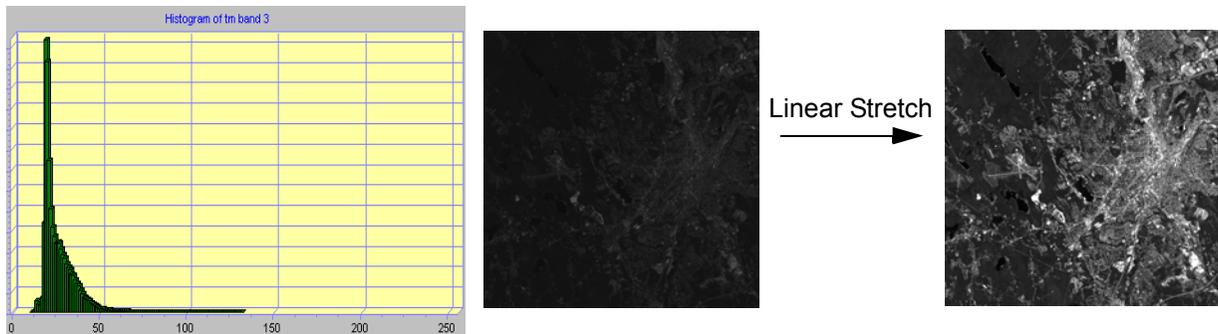

Figure 3-6

Composite Generation

For visual analysis, color composites make fullest use of the capabilities of the human eye. Depending upon the graphics system in use, composite generation ranges from simply selecting the bands to use, to more involved procedures of band combination and associated contrast stretch. Figure 3-7 shows several composites made with different band combinations from the same set of TM images. (See Figure 3-5 for TM band definitions.) The IDRISI module COMPOSITE is used to construct three-band composite images.

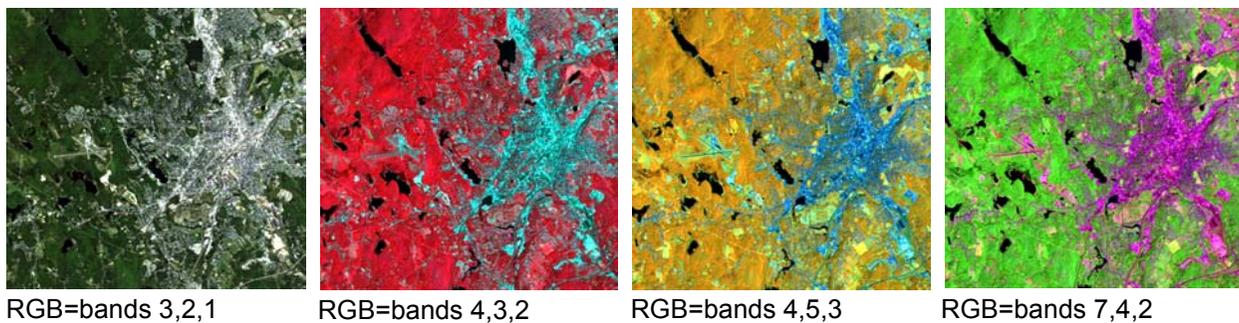RGB=bands 3,2,1   RGB=bands 4,3,2   RGB=bands 4,5,3   RGB=bands 7,4,2

Figure 3-7

Digital Filtering

One of the most intriguing capabilities of digital analysis is the ability to apply digital filters. Filters can be used to provide edge enhancement (sometimes called *crispening*), to remove image blur, and to isolate lineaments and directional trends, to mention just a few. The IDRISI module FILTER is used to apply standard filters and to construct and apply user-defined

filters.

Image Classification

Image classification refers to the computer-assisted interpretation of remotely sensed images. The procedures involved are treated in detail in the **IDRISI Guide to GIS and Image Processing Volume 2** chapter **Classification of Remotely Sensed Imagery**. This section provides a brief overview.

Although some procedures are able to incorporate information about such image characteristics as texture and context, the majority of image classification is based solely on the detection of the spectral signatures (i.e., spectral response patterns) of land cover classes. The success with which this can be done will depend on two things: 1) the presence of distinctive signatures for the land cover classes of interest in the band set being used; and 2) the ability to reliably distinguish these signatures from other spectral response patterns that may be present.

There are two general approaches to image classification: *supervised* and *unsupervised*. They differ in how the classification is performed. In the case of supervised classification, the software system delineates specific landcover types based on statistical characterization data drawn from known examples in the image (known as training sites). With unsupervised classification, however, clustering software is used to uncover the commonly occurring landcover types, with the analyst providing interpretations of those cover types at a later stage.

Supervised Classification

The first step in supervised classification is to identify examples of the information classes (i.e., land cover types) of interest in the image. These are called *training sites*. The software system is then used to develop a statistical characterization of the reflectances for each information class. This stage is often called *signature analysis* and may involve developing a characterization as simple as the mean or the range of reflectances on each band, or as complex as detailed analyses of the mean, variances and covariances over all bands.

Once a statistical characterization has been achieved for each information class, the image is then classified by examining the reflectances for each pixel and making a decision about which of the signatures it resembles most. There are several techniques for making these decisions, called *classifiers*. Most Image Processing software will offer several, based on varying decision rules. IDRISI offers a wide range of options falling into three groups depending upon the nature of the output desired and the nature of the input bands.

hard classifiers

The distinguishing characteristic of hard classifiers is that they all make a definitive decision about the landcover class to which any pixel belongs. IDRISI offers three supervised classifiers in this group: Parallelepiped (PIPED), Minimum Distance to Means (MINDIST), and Maximum Likelihood (MAXLIKE). They differ only in the manner in which they develop and use a statistical characterization of the training site data. Of the three, the Maximum Likelihood procedure is the most sophisticated, and is unquestionably the most widely used classifier in the classification of remotely sensed imagery.

soft classifiers

Contrary to hard classifiers, soft classifiers do not make a definitive decision about the land cover class to which each pixel belongs. Rather, they develop statements of the degree to which each pixel belongs to each of the land cover classes being considered. Thus, for example, a soft classifier might indicate that a pixel has a 0.72 probability of being forest, a 0.24 probability of being pasture, and a 0.04 probability of being bare ground. A hard classifier would resolve this uncertainty by concluding that the pixel was forest. However, a soft classifier makes this uncertainty explicitly available, for any of a variety of reasons. For example, the analyst might conclude that the uncertainty arises because the pixel contains more than one cover type and could use the probabilities as indications of the relative proportion of each. This is known as *sub-pixel* classification. Alternatively, the analyst may conclude that the uncertainty arises because of unrepresentative training site data and therefore may wish to combine these probabilities with other evidence before *hardening* the decision

to a final conclusion. IDRISI offers three soft classifiers (BAYCLASS, BELCLASS and FUZCLASS) and three corresponding hardeners (MAXBAY, MAXBEL, and MAXFUZ). The difference between them relates to the logic by which uncertainty is specified—Bayesian, Dempster-Shafer, and Fuzzy Sets respectively. In addition, the system supplies a variety of additional tools specifically designed for the analysis of sub-pixel mixtures (e.g., UNMIX, FUZSIG, MIXCALC and MAXSET).

hyperspectral classifiers

All of the classifiers mentioned above operate on multispectral imagery—images where several spectral bands have been captured simultaneously as independently accessible image components. Extending this logic to many bands produces what has come to be known as *hyperspectral* imagery.

Although there is essentially no difference between hyperspectral and multispectral imagery (i.e., they differ only in degree), the volume of data and high spectral resolution of hyperspectral images does lead to differences in the way that they are handled. IDRISI provides special facilities for creating hyperspectral signatures either from training sites or from libraries of spectral response patterns developed under lab conditions (HYPERSIG) and an automated hyperspectral signature extraction routine (HYPERAUTOSIG). These signatures can then be applied to any of several hyperspectral classifiers: Spectral Angle Mapper (HYPERSAM), Minimum Distance to Means (HYPERMIN), Linear Spectral Unmixing (HYPERUNMIX), Orthogonal Subspace Projection (HYPEROSP), Absorption area analysis (HYPERABSORB) hyperspectral classifiers. An unsupervised classifier (see next section) for hyperspectral imagery (HYPERUSP) is also available.

Unsupervised Classification

In contrast to supervised classification, where we tell the system about the character (i.e., signature) of the information classes we are looking for, unsupervised classification requires no advance information about the classes of interest. Rather, it examines the data and breaks it into the most prevalent natural spectral groupings, or clusters, present in the data. The analyst then identifies these clusters as landcover classes through a combination of familiarity with the region and ground truth visits.

The logic by which unsupervised classification works is known as *cluster analysis*, and is provided in IDRISI primarily by the CLUSTER module. CLUSTER performs classification of composite images (created with COMPOSITE) that combine the most useful information bands. It is important to recognize, however, that the clusters unsupervised classification produces are not information classes, but spectral classes (i.e., they group together features (pixels) with similar reflectance patterns). It is thus usually the case that the analyst needs to reclassify spectral classes into information classes. For example, the system might identify classes for asphalt and cement which the analyst might later group together, creating an information class called pavement.

While attractive conceptually, unsupervised classification has traditionally been hampered by very slow algorithms. However, the clustering procedure provided in IDRISI is extraordinarily fast (unquestionably the fastest on the market) and can thus be used iteratively in conjunction with ground truth data to arrive at a very strong classification. With suitable ground truth and accuracy assessment procedures, this tool can provide a remarkably rapid means of producing quality land cover data on a continuing basis.

In addition to the above mentioned techniques, two modules bridge both supervised and unsupervised classifications. ISOCLUST uses a procedure known as *Self-Organizing Cluster Analysis* to classify up to 7 raw bands with the user specifying the number of clusters to process. The procedure uses the CLUSTER module to initiate a set of clusters that seed an iterative application of the MAXLIKE procedure, each stage using the results of the previous stage as the training sites for this supervised procedure. The result is an unsupervised classification that converges on a final set of stable members using a supervised approach (hence the notion of "self-organizing"). MAXSET is also, at its core, a supervised procedure. However, while the procedure starts with training sites that characterize individual classes, it results in a classification that includes not only these specific classes, but also significant (but unknown) mixtures that might exist. Thus the end result has much the character of that of an unsupervised approach.

Accuracy Assessment

A vital step in the classification process, whether supervised or unsupervised, is the assessment of the accuracy of the final images produced. This involves identifying a set of sample locations (such as with the SAMPLE module) that are visited in the field. The land cover found in the field is then compared to that which was mapped in the image for the same location. Statistical assessments of accuracy may then be derived for the entire study area, as well as for individual classes (using ERRMAT).

In an iterative approach, the error matrix produced (sometimes referred to as a *confusion matrix*), may be used to identify particular cover types for which errors are in excess of that desired. The information in the matrix about which covers are being mistakenly included in a particular class (*errors of commission*) and those that are being mistakenly excluded (*errors of omission*) from that class can be used to refine the classification approach.

Image Transformation

Digital Image Processing offers a limitless range of possible transformations on remotely sensed data. Two are mentioned here specifically, because of their special significance in environmental monitoring applications.

Vegetation Indices

There are a variety of vegetation indices that have been developed to help in the monitoring of vegetation. Most are based on the very different interactions between vegetation and electromagnetic energy in the red and near-infrared wavelengths. Refer back to Figure 3-4, which includes a generalized spectral response pattern for green broad leaf vegetation. As can be seen, reflectance in the red region (about $0.6 - 0.7\mu$) is low because of absorption by leaf pigments (principally chlorophyll). The infrared region (about $0.8 - 0.9 \mu$), however, characteristically shows high reflectance because of scattering by the cell structure of the leaves. A very simple vegetation index can thus be achieved by comparing the measure of infrared reflectance to that of the red reflectance.

Although a number of variants of this basic logic have been developed, the one which has received the most attention is the *normalized difference vegetation index* (NDVI). It is calculated in the following manner:

NDVI = (NIR - R) / (NIR + R)

where   NIR = Near Infrared

and   R   = Red

Figure 3-8 shows NDVI calculated with TM bands 3 and 4 for the same area shown in Figures 3-5, 3-6 and 3-7.
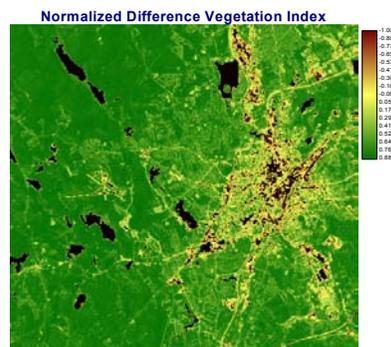

Figure 3-8

This kind of calculation is quite simple for a raster GIS or Image Processing software system, and the result has been shown to correlate well with ground measurements of biomass. Although NDVI needs specific calibration to be used as

an actual measure of biomass, many agencies have found the index to be useful as a relative measure for monitoring purposes. For example, the United Nations Food and Agricultural Organization (FAO) Africa Real Time Information System (ARTEMIS) and the USAID Famine Early Warning System (FEWS) programs both use continental scale NDVI images derived from the NOAA-AVHRR system to produce vegetation index images for the entire continent of Africa every ten days.[12]

While the NDVI measure has proven to be useful in a variety of contexts, a large number of alternative indices have been proposed to deal with special environments, such as arid lands. IDRISI offers a wide variety of these indices (over 20 in the VEGINDEX and TASSCAP modules combined). The chapter on **Vegetation Indices** in the **IDRISI Guide to GIS and Image Processing Volume 2** offers a detailed discussion of their characteristics and potential application.

Principal Components Analysis

Principal Components Analysis (PCA) is a linear transformation technique related to Factor Analysis. Given a set of image bands, PCA produces a new set of images, known as components, that are uncorrelated with one another and are ordered in terms of the amount of variance they explain from the original band set.

PCA has traditionally been used in remote sensing as a means of data compaction. For a typical multispectral image band set, it is common to find that the first two or three components are able to explain virtually all of the original variability in reflectance values. Later components thus tend to be dominated by noise effects. By rejecting these later components, the volume of data is reduced with no appreciable loss of information.

Given that the later components are dominated by noise, it is also possible to use PCA as a noise removal technique. The output from the PCA module in IDRISI includes the coefficients of both the forward and backward transformations. By zeroing out the coefficients of the noise components in the reverse transformation, a new version of the original bands can be produced with these noise elements removed.

Recently, PCA has also been shown to have special application in environmental monitoring. In cases where multispectral images are available for two dates, the bands from both images are submitted to a PCA as if they all came from the same image. In these cases, changes between the two dates tend to emerge in the later components. More dramatically, if a time series of NDVI images (or a similar single-band index) is submitted to the analysis, a very detailed analysis of environmental changes and trends can be achieved. In this case, the first component will show the typical NDVI over the entire series while each successive component illustrates change events in an ordered sequence of importance. By examining these images, along with graphs of their correlation with the individual bands in the original series, important insights can be gained into the nature of changes and trends over the time series. The TSA (Time Series Analysis) module in IDRISI is a specially tailored version of PCA to facilitate this process.

Other Transformations

As mentioned in earlier, IDRISI offers a variety of other transformations. These include color space transformations (COLSPACE), texture calculations (TEXTURE), blackbody thermal transformations (THERMAL), and a wide variety of ad hoc transformations (such as image ratioing) that can be most effectively accomplished with the image calculator utility.

---

12. An archive dataset of monthly NDVI images for Africa is available on CD from Clark Labs. The Africa NDVI data CD contains monthly NDVI maximum value composite images (1982-1999), average and standard deviation of monthly NDVI images for each month over the same time period, monthly NDVI anomaly images, and ancillary data (DEM,land use and land cover, country boundaries and coast line) for Africa in IDRISI format. Contact Clark Labs for more information.

Conclusions

Remotely sensed data is important to a broad range of disciplines. This will continue to be the case and will likely grow with the greater availability of data promised by an increasing number of operational systems. The availability of this data, coupled with the computer software necessary to analyze it, provides opportunities for environmental scholars and planners, particularly in the areas of landuse mapping and change detection, that would have been unheard of only a few decades ago.

The inherent raster structure of remotely sensed data makes it readily compatible with raster GIS. Thus, while IDRISI provides a wide suite of image processing tools, they are completely integrated with the broader set of raster GIS tools the system provides.