Remote Sensing in Precision Agriculture: An Educational Primer

Contents

Abstract

This paper will provide a general description of some of the concepts used in remote sensing and how this technology is used in precision farming. The scope of this paper is very basic and brief. The intended audience is the non-engineering or non-technical businessperson. Interested readers include students, farmers, agribusiness managers, and agricultural teachers.

Section 1: What is Remote Sensing?

Definitions

Remote sensing refers to the process of gathering information about an object, at a distance, without touching the object itself. The most common remote sensing method that comes to most people's minds is the photographic image of an object taken with a camera. Remote sensing has evolved into much more than looking at objects with our eyes. It now includes using instruments, which can measure attributes about objects which unaided human eyes can't see or sense.

Some other definitions of Remote Sensing are:

"Photogrammetry and Remote Sensing are the art, science and technology of obtaining reliable information about physical objects and the environment, through a process of recording, measuring and interpreting imagery and digital representations of energy patterns derived from noncontact sensor systems" (Colwell, 1997).

"Remote sensing may be broadly defined as the collection of information about an object without being in physical contact with the object. Aircraft and satellites are the common platforms from which remote sensing observations are made. The term remote sensing is restricted to methods that employ electromagnetic energy as the means of detecting and measuring target characteristics" (Sabins, 1978).

"Remote sensing is the art and science of obtaining information from a distance, i.e. obtaining information about objects or phenomena without being in physical contact with them. The science of remote sensing provides the instruments and theory to understand how objects and phenomena can be detected. The art of remote sensing is in the development and use analysis techniques to generate useful information"(Aronoff, 1995).

History

In 1858 a French photographer, Gaspaed Felix Tournachon was the first to take aerial photos from a tethered balloon. A few years later in 1861, aerial photographs became a tool for military intelligence during the civil war. Aerial photographs were also taken from cameras mounted in kites (1858), and on carrier pigeons (1903). In 1909 Wilber Wright flew the first airplane to take the first photographs in flight. The first aerial photographs used in the process of creating maps was presented in a paper in 1913, by Captain Tardivo at a meeting of the International Society for Photogrammetry.

Military aerial photos were used on a large scale during World War I. The military trained hundreds of people to process and interpret aerial reconnaissance photos. The French aerial units developed 56,000 photos in four days during the Meuse-Argonne offensive in 1918 (Colwell, 1997). After World War I and through the 1930's, commercial aerial survey companies employed many former military personnel to process aerial photos to produce maps such as topographic maps, forest management maps, and soil maps.

World War II saw the development of color-infrared film for the US Army in 1942. These images were used to detect enemy forces and equipment that were camouflaged. A majority of Allied intelligence gathered about the enemy during this war was the direct result of aerial photoreconnaissance.

The U.S. military and other government agencies such as National Aeronautics and Space Administration (NASA) continued to develop the use of remote sensing during the cold war years. The 1960's also saw the expansion and development of earth remote sensing from space. The first military space photo reconnaissance satellite, Corona, was launched in 1960. Corona took pictures of the Soviet Union and its allies using photographic film. The exposed film was then transferred into unmanned recovery vehicles in space. The recovery vehicles then de-orbited and returned to earth by parachute carrying the film, which was then processed and analyzed in the lab. The first series of weather satellites called the Television Infrared Observation Satellites (TIROS) began launching in 1960. NASA continued collecting images for its earth observation surveys, from outer space, with the Apollo and Gemini spacecraft.

Figure 1.1 Cuban missile site 1962

Figure 1.2 SR-71

Aerial photographs taken from high-altitude U-2 and low-altitude RF101 aircraft, uncovered missile installations in Cuba such as that shown in figure 1.1. These images were televised to the world during the Cuban Missile Crisis in 1962. In 1964 the U.S. Air Force started flying the SR-71 Blackbird reconnaissance aircraft shown in figure 1.2. The SR-71 flies at speeds in excess of Mach 3 or 2,000 miles per hour and at altitudes greater than 85,000 feet.

Scores of U.S. meteorological and earth observation satellites were launched during the 1970's. Also during the 1970's manned spacecraft such as the Skylab space station collected images of earth from outer space. In 1972 Landsat-1 shown in figure 1.3 with an original resolution of only 80 meters was the first satellite launched into space for nonmilitary earth resource observation. Landsat contained sensors capable of taking multispectral digital images.

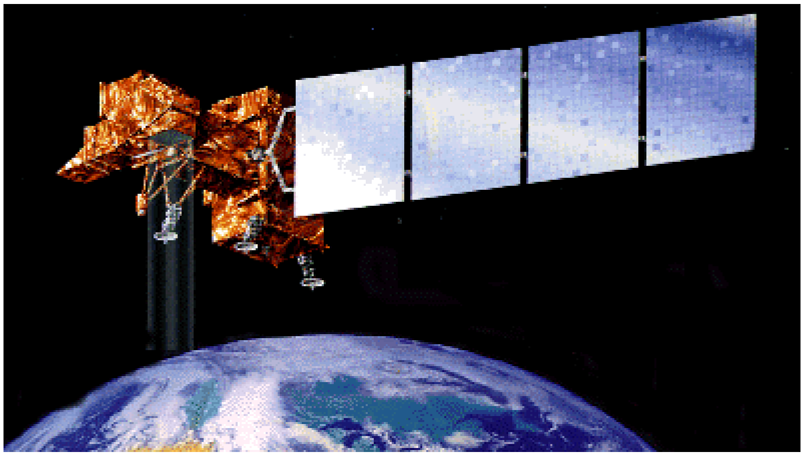


Figure 1.3 Landsat Satellite

U.S. military photoreconnaissance satellites have been keep secrete and unavailable to the general public. Starting in 1976 the U.S. military started deploying more sophisticated high-resolution satellites capable of relaying digital images to earth. Eight Keyhole-11 satellites were launched between 1976 and 1988. Three improved Keyhole-11B satellites were launched between 1992 and 1996. They are able to produce images with estimated resolutions of nearly ten centimeters (four inches) (Vick et al, 1997).

Nonmilitary satellite images have been used to monitor the degradation and pollution of the environment. These images also can be used to assess the damage of floods and natural disasters, assist in forecasting the weather, locate minerals and oil reserves, locate fish stocks, monitor ocean currents, assist in land use mapping and planning, produce geologic maps, and monitor range, forestry and agricultural resources.

Fundamental Properties and Concepts

The Electromagnetic Spectrum

All objects including plants and soil emit and or reflect energy in the form of electromagnetic radiation. Electromagnetic radiation travels in waves propagating through space similar to that shown in figure 1.4. Three major components of these waves are frequency, amplitude and wavelength. Frequency is the number of cycle crests passing a point during a given period of time. One cycle per second is referred to as one hertz. Amplitude is the energy level of each wave measuring the height of each wave peak. Wavelength is the distance from the top of one wave peak to the top of the following wave peak

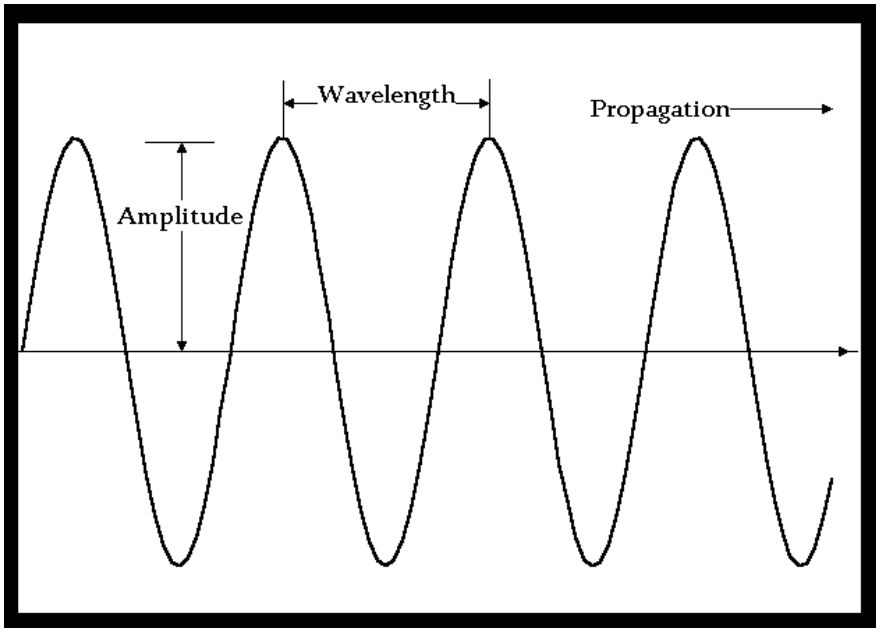


Figure 1.4 Electromagnetic Radiation

The most common source of electromagnetic radiation that we are familiar with is the sun. The sun radiates energy covering the entire electromagnetic frequency spectrum as shown in figure 1.5.

Remote sensors act similar to the human eye. They are sensitive to images and patterns of reflected light. A major difference between the human eye and remote sensors is the frequency range of the electromagnetic spectrum that they are sensitive to.

The electromagnetic spectrum range varies from very short wavelengths of less than ten trillionths of a meter known as gamma rays, to radio waves with very long wavelengths of several hundred meters. The electromagnetic spectrum can be sliced up into discrete segments of wavelength ranges called bands, also sometimes referred to as a channel.

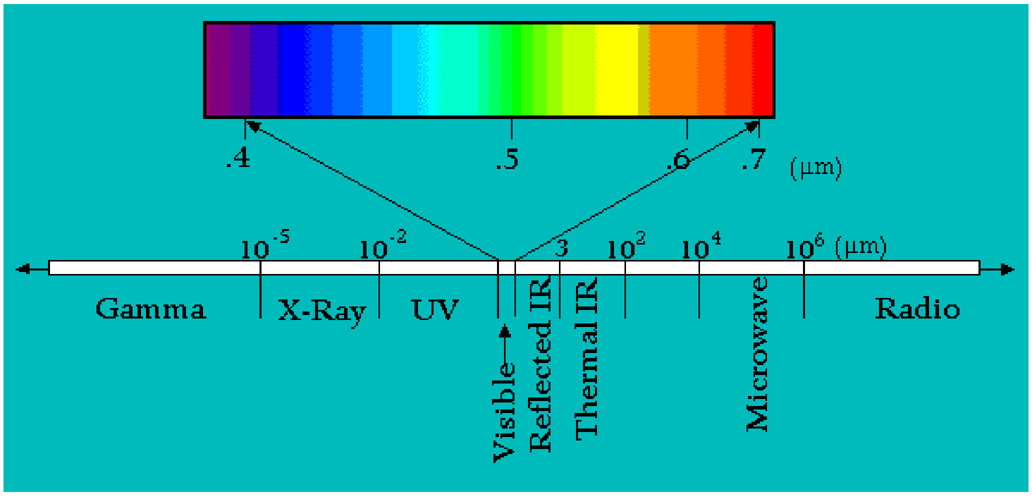


Figure 1.5 Electromagnetic spectrum

It is the sun that most often provides the energy to illuminate objects (figure 1.6). The sun's radiant energy strikes an object on the ground and some of this energy that is not scattered or absorbed is then reflected back to the remote sensor. A portion of the sun's energy is absorbed by objects on the earth's surface and is then emitted back into the atmosphere as thermal energy.

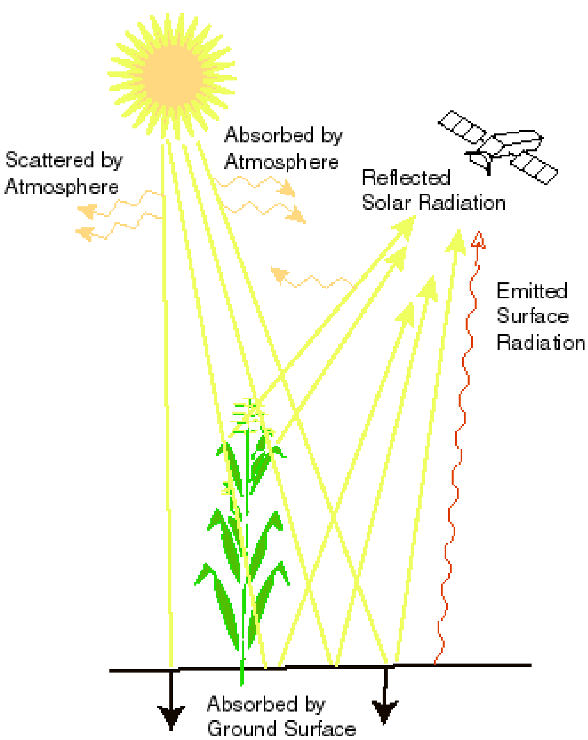


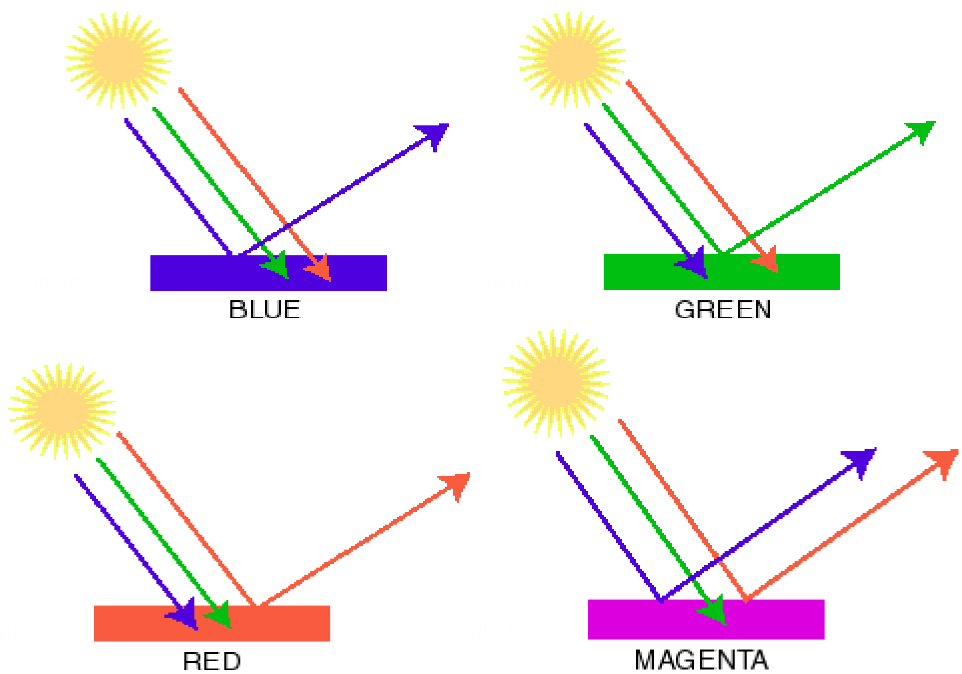
Figure 1.6

Visible Region

The visible light portion of the electromagnetic spectrum ranges from 0.4 micrometers ("µm") (shorter wavelength, higher frequency) to 0.7 µm (longer wavelength, lower frequency). This is the frequency range of light that the human eye is sensitive to. Every object reflects, absorbs and transmits electromagnetic energy in the visible portion of the electromagnetic spectrum and also other non-visible frequencies. Electromagnetic energy which completely passes through an object is referred to as transmittance. Our eyes receive the visible light reflected from an object.

The three primary colors reflected from an object (figure 1.7) known as *additive primaries* are the blue, green and red wavelengths. Primary colors cannot be formed by the combination of any other primary colors. Intermediate colors are formed when a combination of primary colors are reflected from an object. Magenta is a combination of reflected red and blue, cyan a combination of reflected blue and green, and yellow a combination of reflected red and green.

Color film produces colors by using layers of dyes which filter out various colors. The three colors which absorb the primary colors, known as *subtractive primaries*, are magenta, cyan and yellow. Magenta absorbs green and reflects red an blue, cyan absorbs red and reflects blue and green, and yellow absorbs blue and reflects red and green. The absorption of all colors produces black. If no color is absorbed then the film produces white.



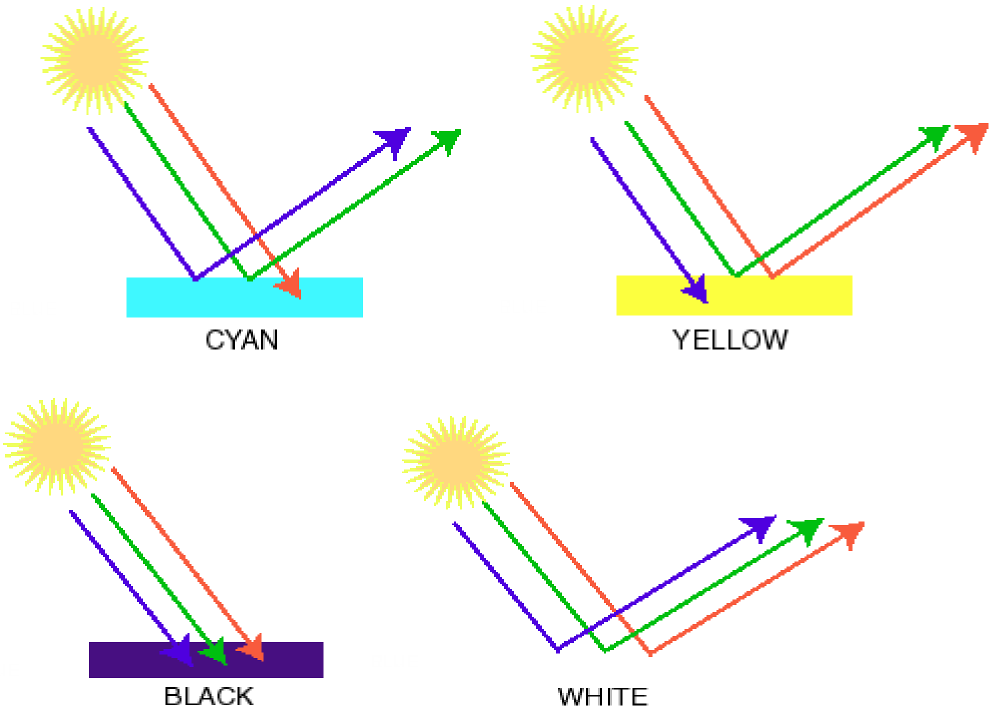


Figure 1.7

Infrared Region

The non-visible infrared spectral region lies between the visible light and the microwave portion of the electromagnetic spectrum. The infrared region covers a wavelength range from .7 µm to 14 µm. This broad range of infrared wavelengths is further subdivided into two smaller infrared regions. Each of these regions exhibits very different characteristics.

The infrared region closest to visible light contains two smaller bands labeled near infrared and short-wave infrared with wavelengths ranging from .7 µm to 1.1 µm, and from 1.1 µm to 3.0 µm respectively. These infrared regions exhibit many of the same optical characteristics as visible light. The sun is the primary source of infrared radiation, which is reflected from an object. Cameras used to capture images in the visible light spectrum can capture images in the near infrared region by using special infrared film.

The other infrared region with longer wavelengths ranging from 3.0 µm to 14.0 µm is composed of two smaller bands labeled mid-wave infrared and long-wave infrared with wavelengths ranging from 3.0 µm to 5.0 µm, and from 5.0 µm to 14.0 µm respectively. Objects generate and emit thermal infrared radiation thus these objects can be detected at night because they are not dependent on reflected infrared radiation from the sun. Remote sensors operating in this infrared wavelength range measure an object's temperature.

Interaction Between Plants and Electromagnetic Radiation

Leaf Structure

The structure of a leaf is shown in Figure 1.8. The cuticle is a thin waxy layer covering the epidermis cells on the surface of the leaf. Tiny pours in the epidermis layer of cells are called stomata. The stomata are surrounded by guard cells, which cause the stomata to open or close. The guard cells regulate the water evaporation from the leaf and also control the gas exchange between the leaf and the atmosphere.

The interior layer of the leaf is composed of two regions of mesophyll tissue. This is where most photosynthesis takes place. The palisade mesophyll lies just below the upper epidermis. These cells are elongated, lined up in rows and contain most of the leaf's chloroplasts. Chloroplasts of most plants contain pigments and two different kinds of chlorophyll. Chlorophyll a is the most abundant and is bluish green in color. Chlorophyll b is yellowish green in color and absorbs light and then transfers that energy to chlorophyll a. Pigment molecules within the chloroplasts also absorb light energy and transfer the energy to the chlorophyll. The spongy mesophyll is the leaf lower interior composed of loosely arranged and irregular shaped cells. These cells contain chloroplasts and are surrounded by air spaces.

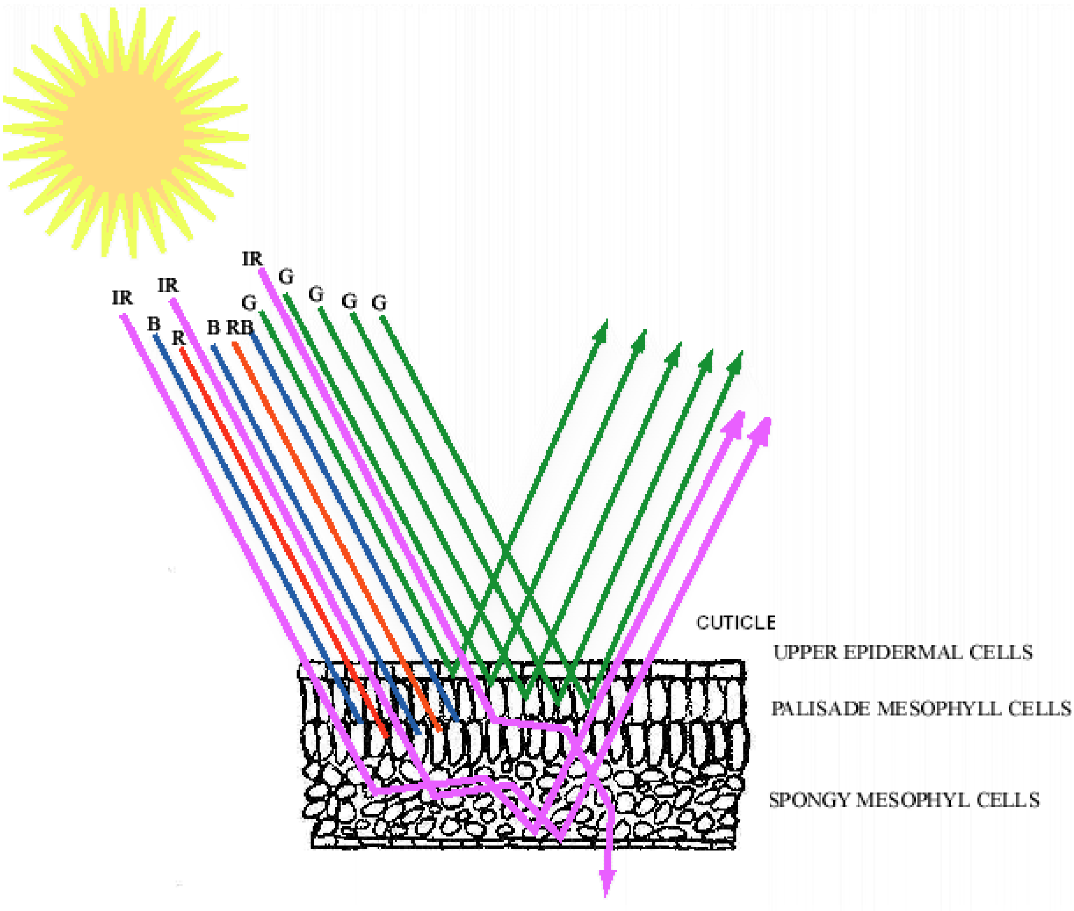


Figure 1.8 Cross section of a typical plant leaf

Spectral Response

Chlorophyll primarily absorbs light in the violet to blue and red wavelengths. Green light is not readily absorbed and is reflected thus giving the leaf a green color appearance. The internal cell wall structure of the mesophyll causes high reflectance of near infrared radiation. Chlorophyll is transparent to near infrared radiation. The sharp increase of reflected energy just beyond the red region of visible light into the near infrared region is referred to as the red edge. Figure 1.9 shows this sharp reflection increase located around the 0.7 µm wavelength. The location of the red edge is not static throughout the life of a leaf. As the leaf matures, chlorophyll will absorb slightly longer wavelengths in the visible red region. This change moves the red edge shown in figure 1.9 to the right and is referred to as the red shift (Campbell, 1996).

Environmental stress factors such as drought, disease, weed pressure, insect damage and others stress or injure plants. This stress will cause physiological changes in the plant. Stressed plants will have a spectral reflectance that is different from normal plants at the same growth stage. One example of a physiological change would be the change in the color of plant leaves due to chlorosis. The yellow color from chlorosis is caused by the breakdown of chlorophyll. Reflected green will be decreased, and reflected red will increase. The correlation of the different spectral responses observed with remote sensing equipment to the actual condition of the plants, is critical for the accurate interpretation and identification of crop injury and stress.

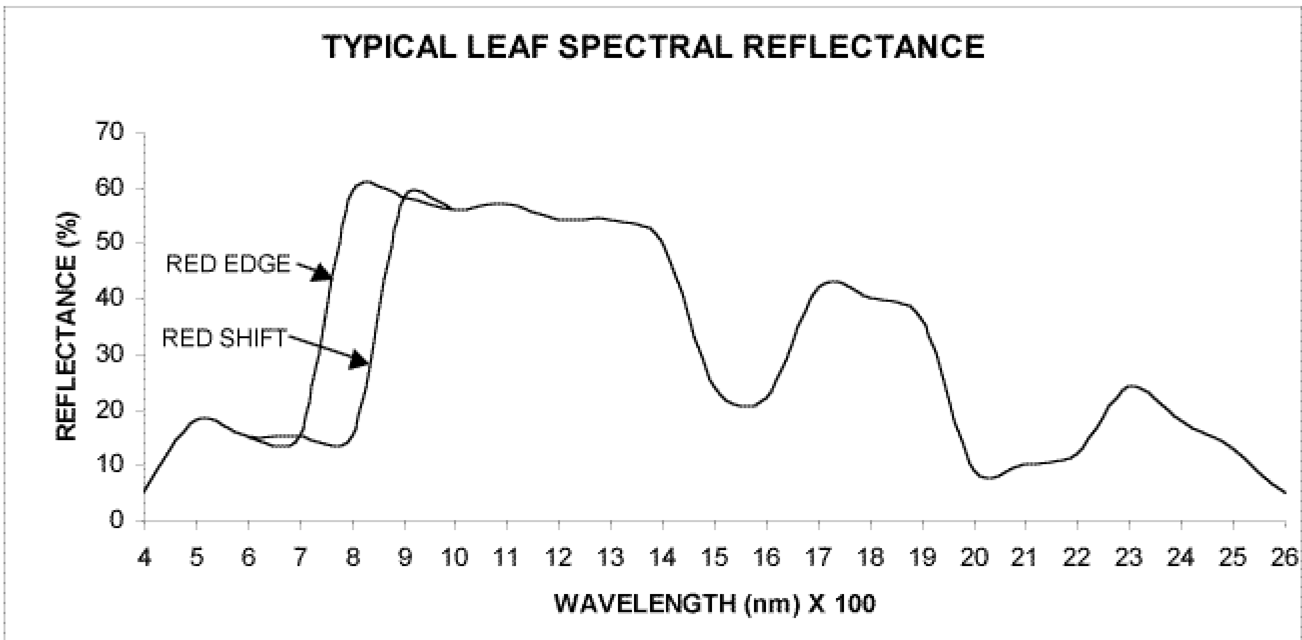


Figure 1.9

Sensor Types

Most remote sensors measure and record the magnitude and frequency of reflected radiation from an object. The recorded frequency spectrum data from the object is then compared and matched to the spectrum signatures of known objects thus allowing for the identification and classification of the object on the ground.

Remote sensing from aircraft and satellites use imaging sensors, which measure reflected energy from objects under surveillance. These imaging sensors fall into two general categories, active sensors and passive sensors. Passive sensors monitor only the natural solar reflected light or electromagnetic energy from an object. Passive sensors make up a majority of the sensors in use today. Active image sensors provide their own light or electromagnetic energy, which is transmitted to the object and then reflected back to the sensor. A common example of this type of sensor is radar. Cloud cover in the sky can often block passive sensors from receiving reflected energy from the ground but radar systems can penetrate cloud cover.

Early remote sensing history consisted of photographic images on film taken by cameras. Reflected light received by the camera exposes the film by reacting with the chemical emulsion on the film to create an image in analog format. The images produced are fixed and not subject to very much manipulation unless they are converted into an electronic digital format. Digital images have advantages over analog film images because computers can store, process, enhance, analyze, and render images on a computer screen.

Digital images are images reduced to numbers. The image is made up of numbers, which represent image attributes such as brightness, color or radiated energy frequency wavelength, and position location for each point or picture element in the image. The smallest size picture elements on a computer screen are called pixels. A digital image is made up of pixels arranged in rows and columns depicted in figures 1.6, 1.7, 1.8.

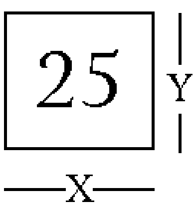


Figure 1.10 A single pixel

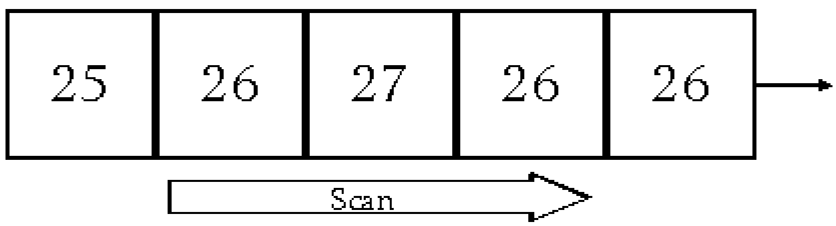


Figure 1.11 A row of pixels represents a scan line

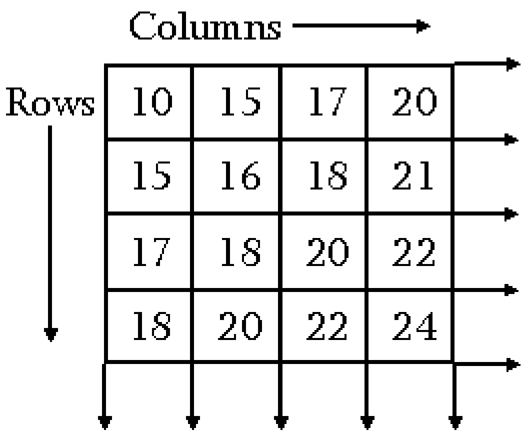


Figure 1.12 Rows and columns of pixels represent an image

Resolution

Remote sensors measure differences and variations of objects. There are four main resolutions, which affect the accuracy and usefulness of remote sensors.

Spatial resolution describes the ability of a sensor to identify the smallest size detail of a pattern on an image. The distance between distinguishable patterns or objects in an image that can be separated from each other is often expressed in meters.

Spectral resolution, is the sensitivity of a sensor to respond to a specific frequency range. The frequency ranges covered often include not only visible light but also non-visible light and electromagnetic radiation. The discrete range of frequency wavelengths that a sensor is able to detect and measure is called a Band. Features on the ground such as water and vegetation can be identified by the different wavelengths reflected. The sensor used must be able to detect these wavelengths in order to see these and other features.

Radiometric resolution is often called contrast. It describes the ability of the sensor to measure the signal strength or brightness of objects. The more sensitive a sensor is to the brightness of an object as compared to its surroundings, the smaller an object that can be detected and identified.

Temporal resolution, is the period of elapsed time between images taken of the same object at the same location. The more frequent a sensor is able to return to an exact specific location the greater the temporal resolution. Several observations over time reveal changes and variations in the object being observed. For satellite systems temporal resolution is described as the revisit period, which refers to the time it takes for a satellite to return to the same area on subsequent orbits.

Image processing

Once the raw remote sensing digital data has been acquired, it is then processed into usable information. Analog film photographs are chemically processed in a darkroom whereas digital images are processed within a computer. Processing digital data involves changing the data to correct for certain types of distortions. Whenever data is changed to correct for one type of distortion, the possibility of the creating another type of distortion exists. The changes made to remote sensing data involve two major operations: *preprocessing* and *postprocessing*.

Preprocessing

The preprocessing steps of a remotely sensed image generally are performed before the postprocessing enhancement, extraction and analysis of information from the image. Typically, it will be the data provider who will preprocess the image data before delivery of the data to the customer or user. Preprocessing of image data often will include *radiometric correction* and *geometric correction*.

Radiometric corrections are made to the raw digital image data to correct for brightness values, of the object on the ground, that have been distorted because of sensor calibration or sensor malfunction problems. The distortion of images is caused by the scattering of reflected electromagnetic light energy due to a constantly changing atmosphere. This is one source of sensor calibration error.

Geometric corrections are made to correct the inaccuracy between the location coordinates of the picture elements in the image data, and the actual location coordinates on the ground. Several types of geometric corrections include system, precision, and terrain corrections.

System correction uses a geographic reference point for a pixel element such as that provided by the global positioning system. Correction accuracy often varies depending upon the accuracy of the position given by the global positioning system. Aircraft platform system instability is shown in figure 1.13. Preprocessing correction removes the motion distortion as shown in figure 1.14.

Figure 1.13 Raw uncorrected aerial sensor data.

Figure 1.14 Preprocessed data corrected for aircraft motion.

Precision correction uses ground control points. Ground control points, which have accurate predetermined longitude and latitude geographic locations, are often used to measure the location error of the picture elements. Several mathematical models are available to estimate the actual position of each picture element based on its distance from the control ground point.

Terrain correction is similar to precision correction except that in addition to longitude and latitude a third dimension of elevation is referenced with the ground control point to correct for terrain induced distortion. This procedure is also referred to as ortho-corrected or orthorectified. For example the tall buildings appear to lean away from the center point of figure 1.15 while the buildings directly below the camera lens (nadir) have only their roofs visible. The relief distortion will be larger for objects further away from the center of the photo.

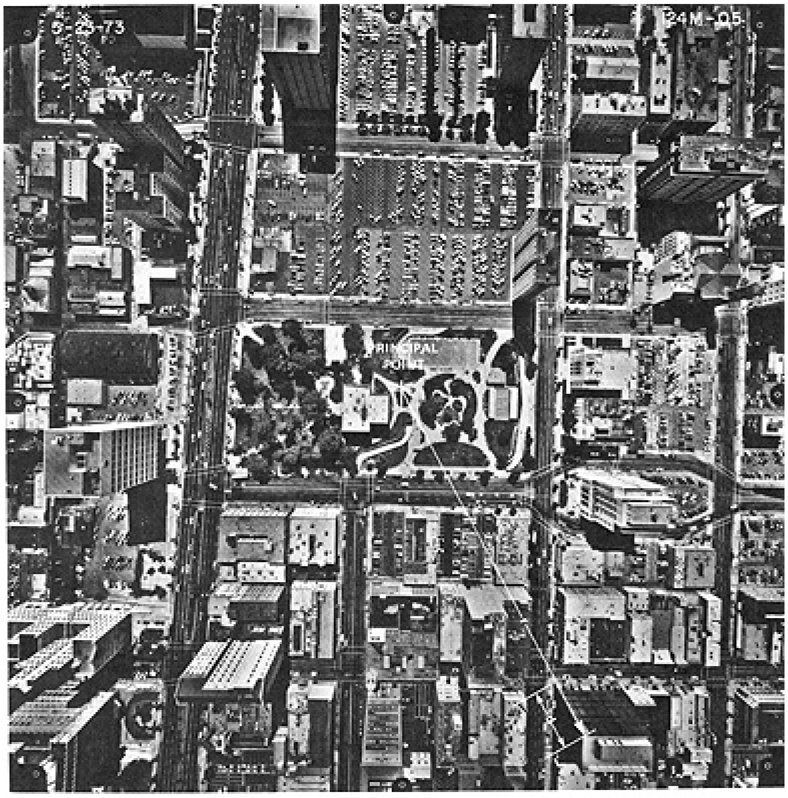


Figure 1.15 Example of terrain or relief displacement.

Postprocessing

Digital image postprocessing routines include *image enhancement, image classification*, and *change detection*. These computerized process routines improve the image scene quality and aid in the data interpretation.

Image enhancement techniques include contrast stretching, spatial filtering, and ratioing.

Contrast stretching changes the distribution and range of the digital numbers assigned to each pixel in an image. This is often done to accent image details that may be difficult for the human viewer to observe unaided.

Spatial filtering involves the use of algorithms called filters to either emphasize or de-emphasize brightness using a certain digital number range over an image. High pass filters improve image edge detail. Low pass filters smooth an image and reduce image noise.

Ratios are computed by taking the digital numbers for a frequency band and dividing them by the values of another band. The ratio range can be redistributed to highlight certain image features.

Image classification groups pixels into classes or categories. This image classification process may be unsupervised or supervised.

Unsupervised image classification is a computer-based system that assigns pixels to statistically separable clusters based on the pixel digital number values from several spectral bands. The resulting cluster patterns can be assigned different colors or symbols for viewing to produce a cluster map. The resulting map may not necessarily correspond to ground features that the user is interested in.

Supervised classification is a more comprehensive procedure which uses experienced human image analyst to recognize and group pixels into classes and categories of interest to the user. The analyst picks several samples of homogeneous pixel patterns on the image called training sites. Analysts identify these sites by actually visiting the ground location and making field observations (ground truthing) or by using past experience and skill. The remaining pixels outside the training sites are then matched to the training sites using statistical processing techniques.

Change detection is a process where two images at the same location taken on different dates are compared with each other to measure any changes in physical shape, location, or spectral properties. A third image is then produced which shows only the changes between the first and second image. Change detection lends itself to computer automation analysis. Pixel digital number values are compared pixel by pixel within each frequency band. Computer analysis is most useful when combined with the human analyst's experience and knowledge to interpret the image changes.

Section 2: Acquiring Remote Sensing Data

Sensors

Remote sensors can be grouped according to the number of bands and the frequency range of those bands that the sensor can detect. Common categories of remote sensors include *panchromatic*, *multispectral*, *hyperspectral*, and *ultraspectral* sensors.

Panchromatic sensors cover a wide band of wavelengths in the visible light or near infrared light spectrum. An example of a single band sensor of this type would be a black and white photographic film camera.

Multispectral sensors cover two or more spectral bands simultaneously typically from 0.3 m to 14 m wide.

Hyperspectral sensors cover spectral bands narrower than multispectral sensors. Image data from several hundred bands are recorded at the same time offering much greater spectral resolution than a sensor covering wider bands.

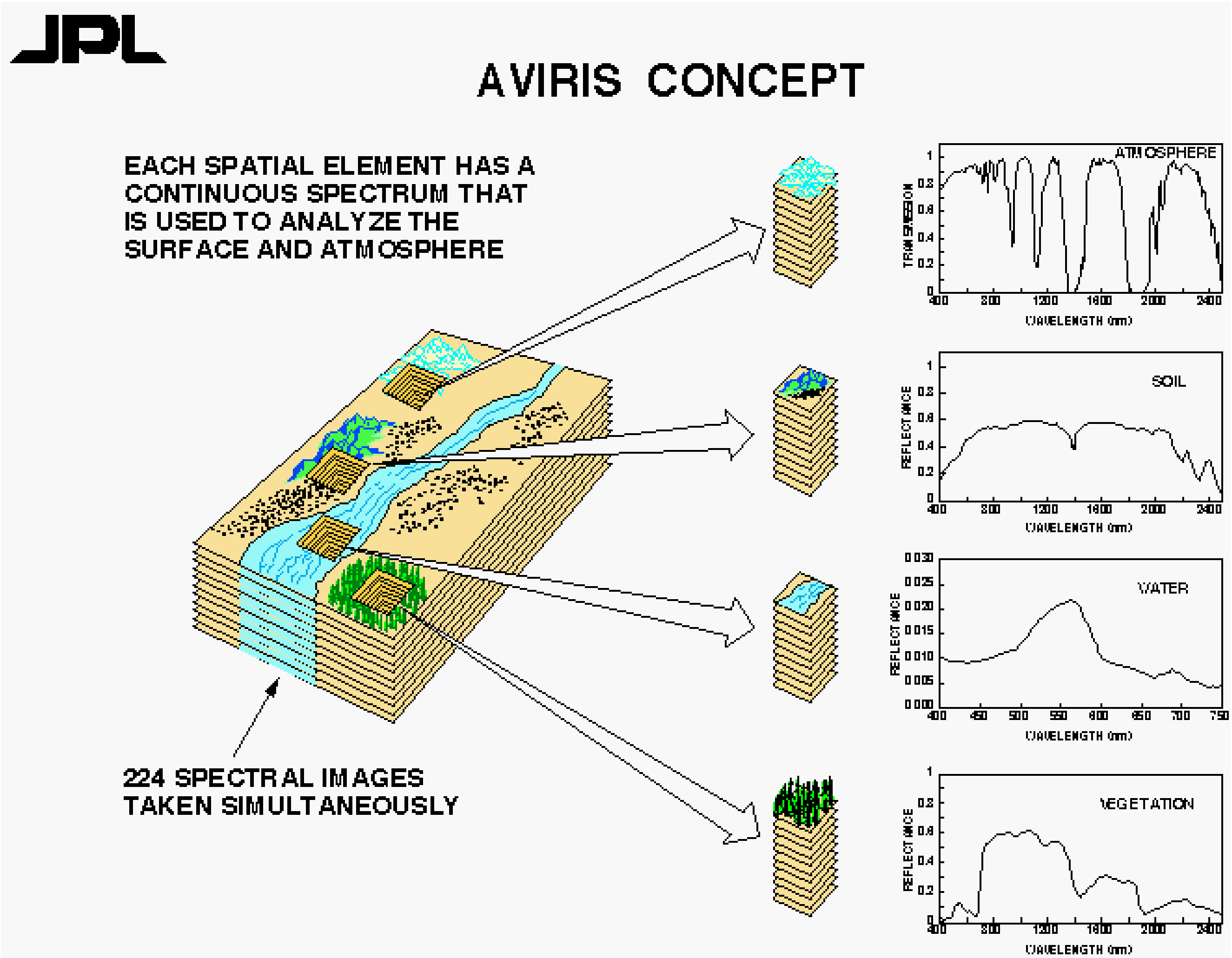


Figure 2.1 Diagram of a Hyperspectral image.

Ultrasprectral sensors are still under development and not yet in use. These sensors will cover thousands of bands with an even narrower bandwidth than hyperspectral sensors.

Digital Image Data Delivery Systems

Scanner Sensor Systems

Electro-optical and spectral imaging scanners produce digital images with the use of detectors that measure the brightness of reflected electromagnetic energy. Scanners consist of one or more sensor detectors depending on type of sensor system used.

One type of scanner is called a whiskbroom scanner also referred to as across-track scanners. It uses rotating mirrors to scan the landscape below from side to side perpendicular to the direction of the sensor platform, like a whiskbroom. The width of the sweep is referred to as the sensor swath. The rotating mirrors redirect the reflected light to a point where a single or just a few sensor detectors are grouped together. Whiskbroom scanners with their moving mirrors tend to be large and complex to build. The moving mirrors create spatial distortions that must be corrected with preprocessing by the data provider before image data is delivered to the user. An advantage of whiskbroom scanners is that they have fewer sensor detectors to keep calibrated as compared to other types of sensors.

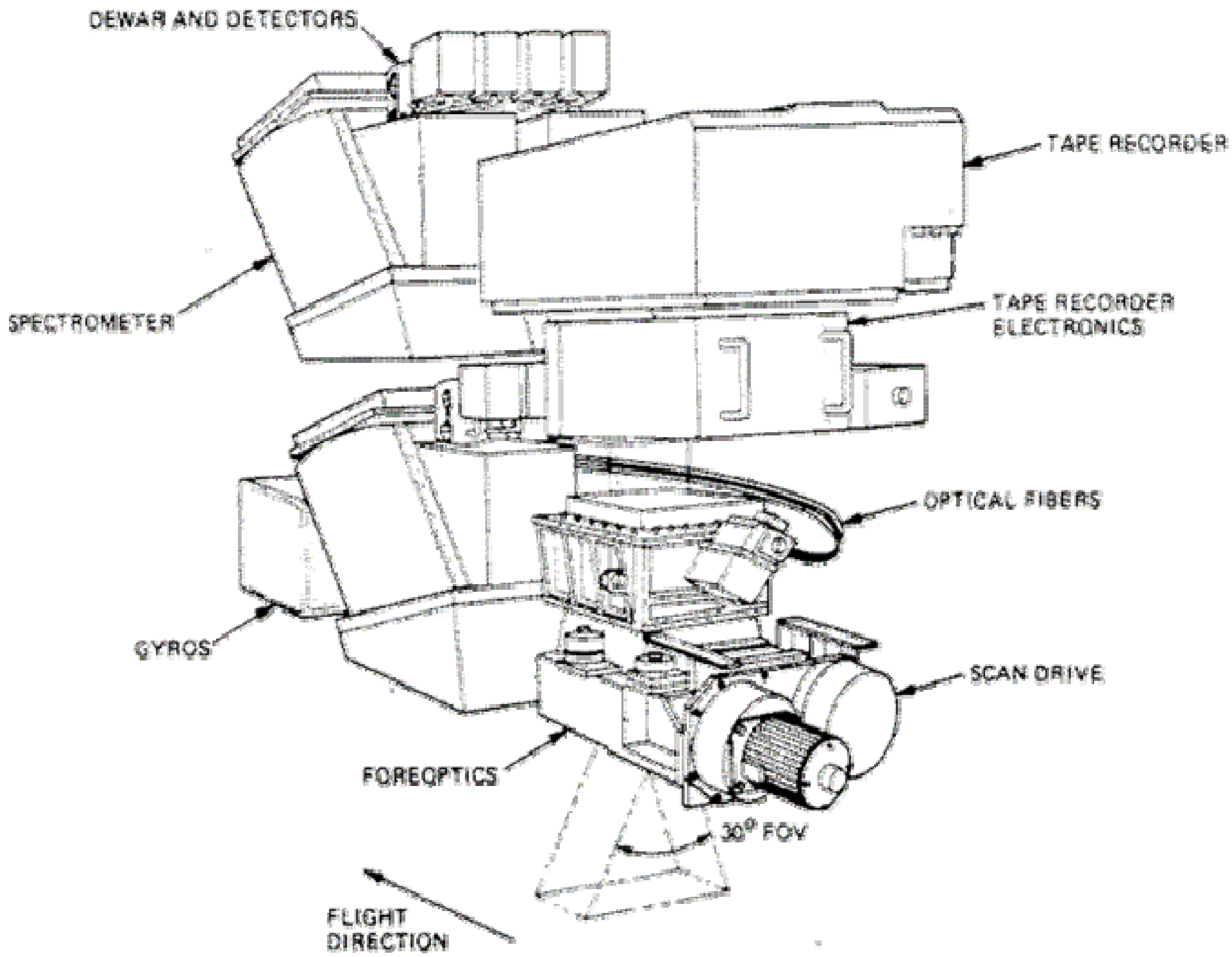


Figure 2.2 AVIRIS whiskbroom scanner

Another type of scanner, which does not use rotating mirrors, is the pushbroom scanner also referred to as an along-track scanner. The sensor detectors in a pushbroom scanner are lined up in a row called a linear array. Instead of sweeping from side to side as the sensor system moves forward, the one dimensional sensor array captures the entire scan line at once like a pushbroom would. Some recent scanners referred to as step stare scanners contain two-dimensional arrays in rows and columns for each band. Pushbroom scanners are lighter, smaller and less complex because of fewer moving parts than whiskbroom scanners. Also they have better radiometric and spatial resolution. A major disadvantage of pushbroom scanners is the calibration required for a large number of detectors that make up the sensor system.

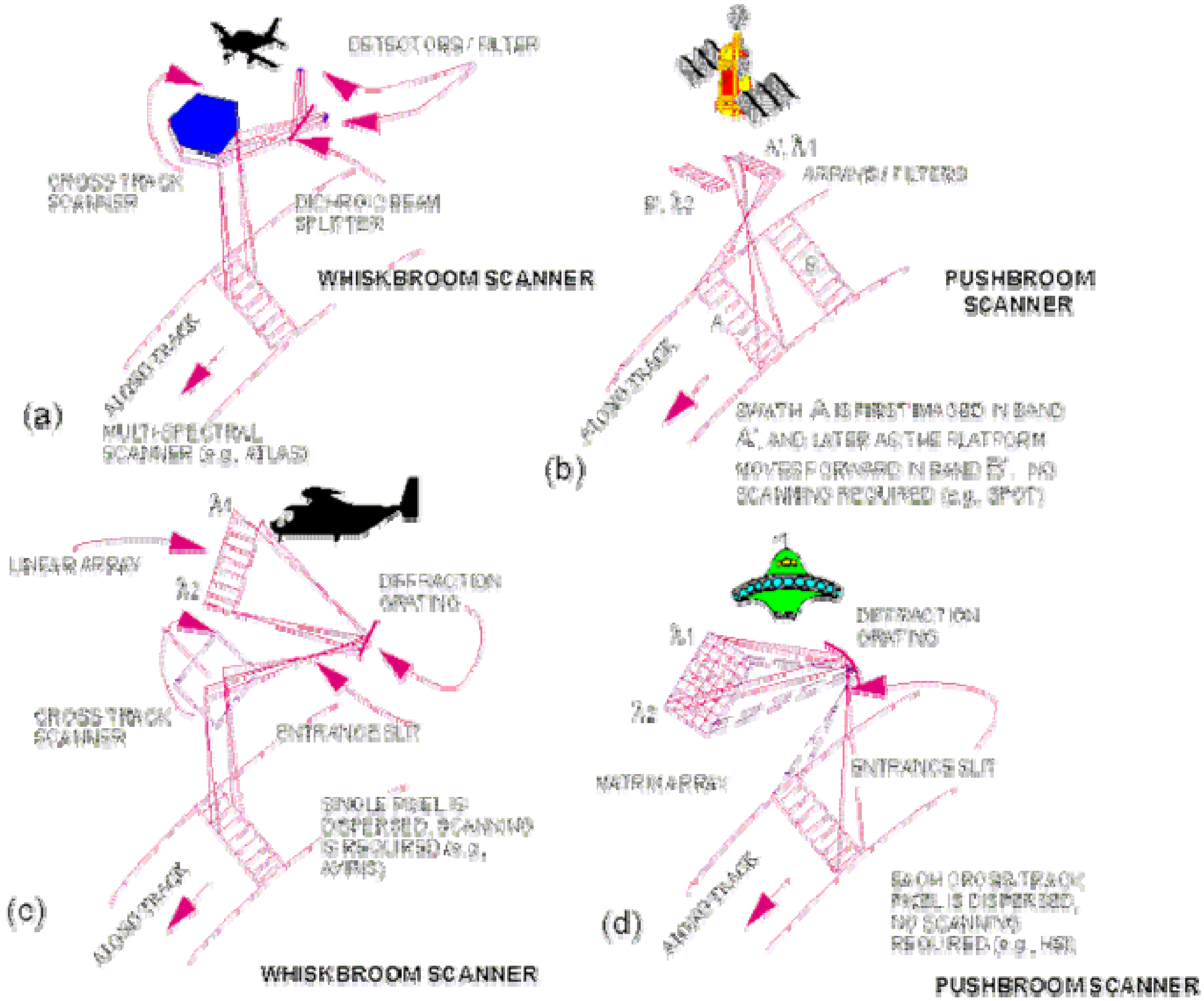


Figure 2.3 (a), (b), (c), (d)

Scanner Platform Systems

Aircraft Systems

Airplanes have served as remote sensing platforms starting with Wilber Wright carrying the first camera into the air. Aircraft have several useful advantages as platforms for remote sensing systems. Aircraft can fly at relatively low altitudes thus allowing for sub-meter sensor spatial resolution. Aircraft can easily change their schedule to avoid weather problems such as clouds, which may block a passive sensor's view of the ground. Last minute timing changes can be made to adjust for illumination from the sun, the location of the area to be visited and additional revisits to that location. Sensor maintenance, repair and configuration changes are easily made to aircraft platforms. Aircraft flight paths know no boundaries except political boundaries. Getting permission to intrude into foreign airspace can be a lengthy and frustrating process. The low altitude flown by aircraft narrows the field of view to the sensor requiring many passes to cover a large area on the ground. The turnaround time it takes to get the data to the user is delayed due to the necessity of returning the aircraft to the airport before transferring the raw image data to the data provider's facility for preprocessing.

Figure 2.4 40 band sensor installed inside an airplane.

Satellite Systems

Satellite platforms flown from space provide a very wide field of view for the sensor and regular systematic repetitive revisits. Resolution is limited due to the satellite's fixed altitude and orbital path flown. Satellites know no political boundaries allowing them to cover any corner of the globe unheeded by foreign government interference. Expensive ground support facilities are required to operate satellites. The satellites systems are capital intensive costing hundreds of millions of dollars and have relatively short operating life spans of usually five years or less.

Major Satellite Programs

Some major satellite programs delivering images used in agriculture today include the following:

Landsat 5 uses a thematic sensor ("TM") which operates in 7 bands with a resolution of 30 meters except thermal infrared with has a resolution of 120 meters. Space Imaging EOSAT of Thornton, Colorado is the exclusive distributor of Landsat images.

Spot 1,2,3, and 4 use high-resolution visible ("HRV") sensors that operate in 4 bands with a resolution of 10 m panchromatic and 20 m multispectral. Spot images are distributed by Spot Image headquartered in Toulouse, France.

IRS-1C uses three sensors: the LISS-III, with 23 meter resolution in four spectral bands, a panchromatic sensor, with 5.8 m resolution, and a Wide Field Sensor ("WiFS"), with 188 m resolution. IRS images are distributed by Space Imaging EOSAT of Thornton, Colorado under an exclusive license from ANTRIX Corp. Ltd. of India, the commercial marketing company of the Indian Space Research Organization.

Investing in commercial satellites can be a risky business. TRW's Lewis satellite with hyperspectral sensors was lost shortly after launch in August of 1997. EarthWatch also lost its EarlyBird satellite four days after launch in December of 1997.

Terrestrial Systems

Terrestrial remote sensing systems are ground-based sensor systems. Some research has been done using remote sensors attached to long hydraulic booms hoisted above the crop canopy from the ground. Images collected from such a close distance have resolutions that are much greater than images from aircraft or satellites. Other ground-based systems use vehicle-mounted sensors that control variable rate applicators in real time. For example, remote sensors that can distinguish weeds from the crop are mounted on sprayers that change the application rate of herbicides applied on the go (Figures 2.5 and 2.6). A form of remote sensing technology called *machine vision* is used to sense weeds in the crop and control the sprayer. (Steward and Tian, 1998).

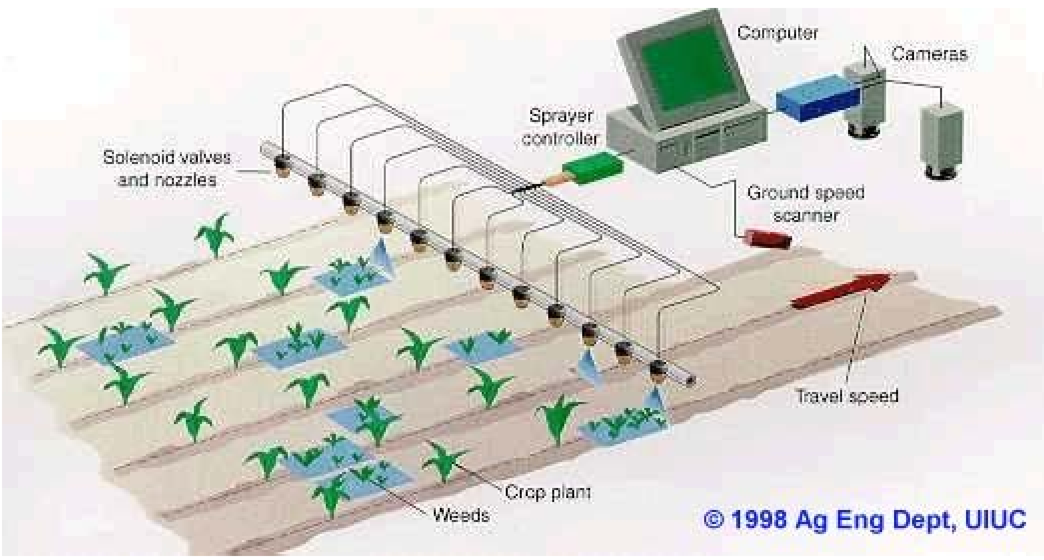


Figure 2.5 Machine vision Smart Sprayer concept developed at the University of Illinois at Urbana-Champaign

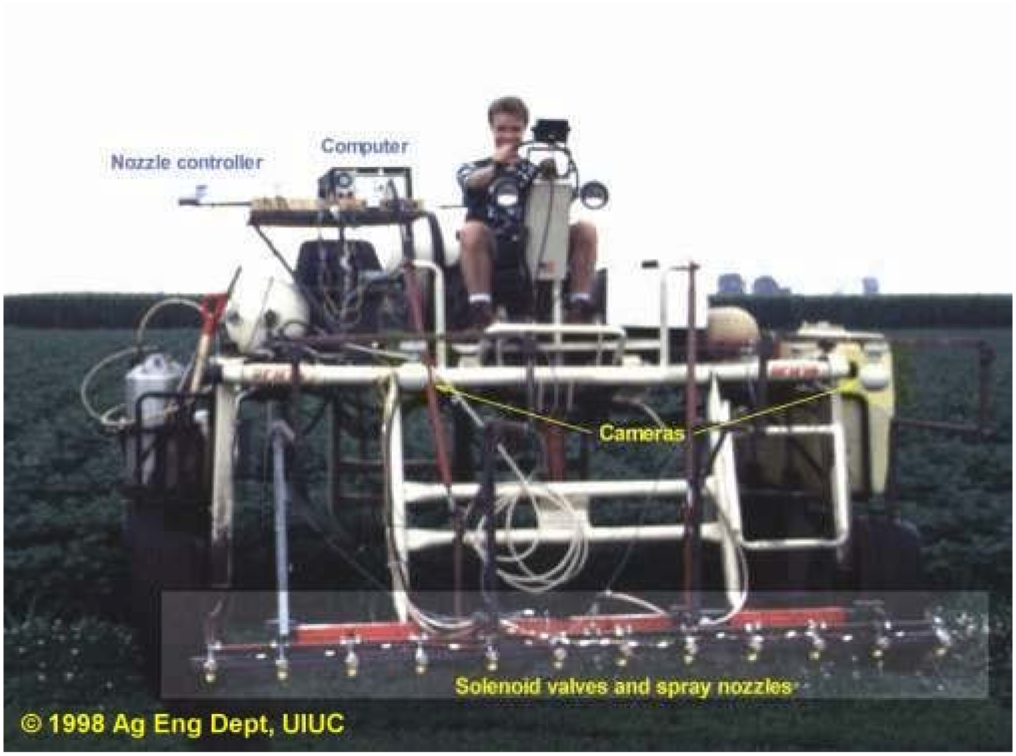


Figure 2.6 Sprayer prototype developed at the University of Illinois at Urbana-Champaign

Section 3: Basic Applications of Remote Sensing in Agriculture

Large Scale Government Users and Programs

The World Agricultural Outlook Board ("WAOB") is one of the U.S. Federal Government's largest users of remote sensing (USDA WAOB, 1998). The WAOB coordinates all remote sensing activities for the United States Department of Agriculture ("USDA") agencies. USDA agencies use remote sensing to assess crop conditions; monitor, manage and administer natural resources; and conduct remote sensing research.

The USDA provides statistical information about agriculture and rural communities through its agency the National Agricultural Statistics Service ("NASS"). The NASS conducts surveys and prepares estimates of U.S. agricultural crop production, supply inventories and agricultural production revenue and costs. Federal, State and Local governments use this information to help form public policy and legislation controlling agricultural commodity production, storage, marketing, and distribution.

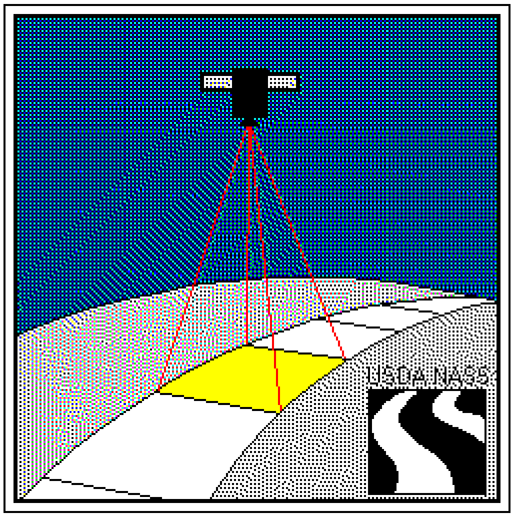


Figure 3.3

The NASS has had limited success using remote sensing to assist in estimating crop yields. NASS statisticians use Landsat satellites to identify patterns in crops in order to assess crop development and progress. Problems cited by the NASS for limiting its remote sensing to only one or two states include temporal availability that doesn't allow for an adequate number of revisits and cloud cover similar to that shown in figure 3.3 that has reduced or blocked the number of useful images (NASS, 1998).

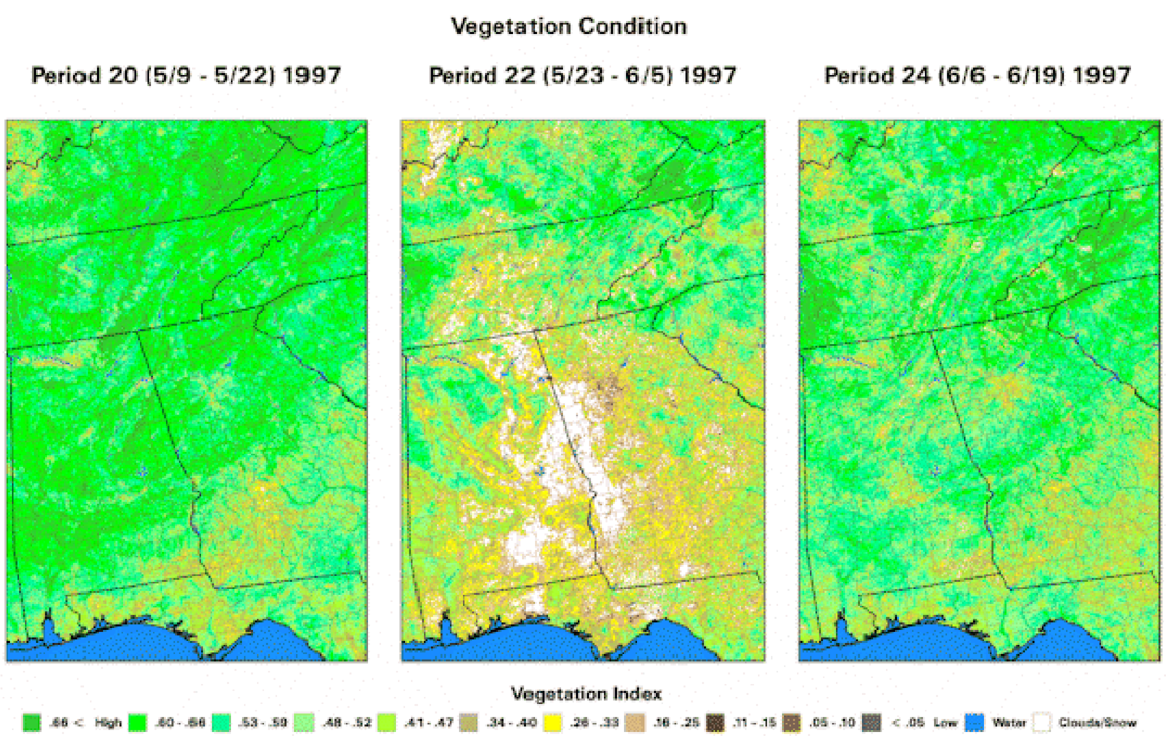


Figure 3.4 Cloud cover anomaly in center image

Every two weeks, NASS statisticians use remote sensing information from the National Oceanic and Atmospheric Administration ("NOAA") satellites and vegetation vigor indices from the U.S. Geological Survey ("USGS") to estimate crop condition. The USGS indices are based on the NOAA satellite remote sensor data. NASS compares the current year vigor indices with prior year images, using change detection postprocessing, to determine if crop development is lower, higher or the same as prior years as shown in figure 3.5. NASS has not yet been able to convert the vigor indices into specific crop yield data (NASS, 1998).

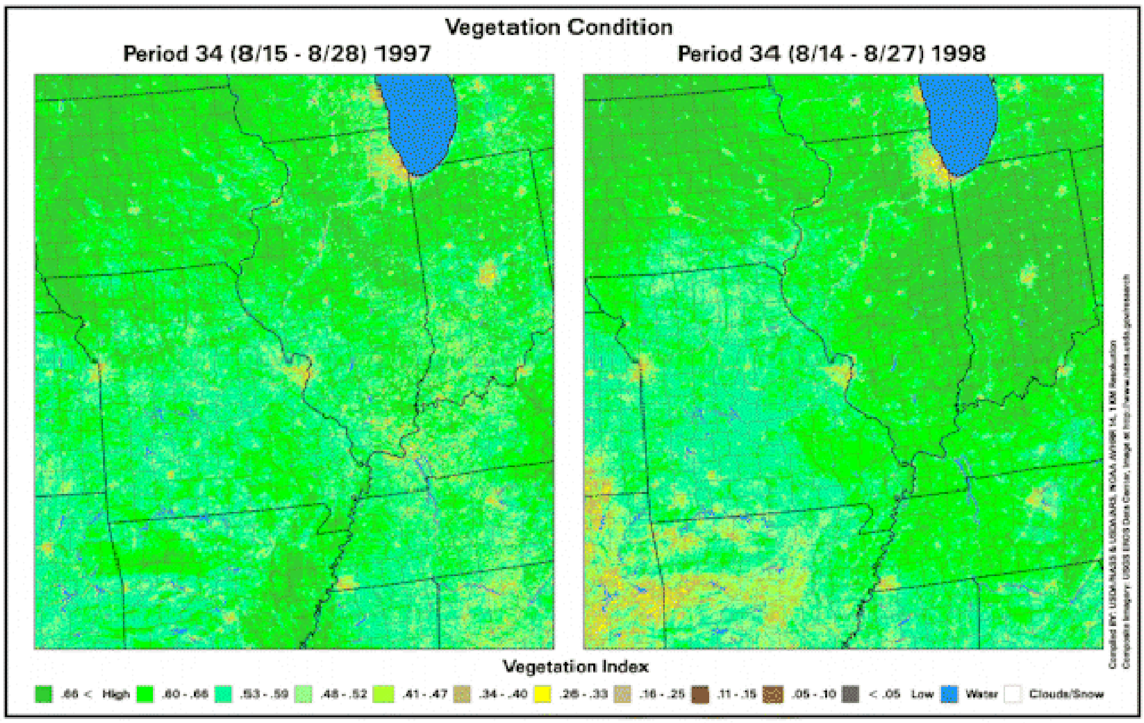


Figure 3.5 Normalized Difference Vegetation Index images.

The Foreign Agricultural Service ("FAS") collects and reports statistical information on global crop conditions and production. This USDA agency has developed crop models, which combine satellite images and weather data to estimate yield, plant growth stage, soil moisture and winterkill. The FAS analyzes over 9,500 multispectral satellite images per year (FAS, 1998).

European Commission

The European Commission ("EC") through its complex networks of associations and departments, under the EC's research affiliate the Joint Research Centre ("JRC"), controls the research activity for country members of the European Union ("EU"). The JRC program, Monitoring Agriculture with Remote Sensing ("MARS"), provides the necessary technical support and image data to EU organizations such as the Directorate General for Agriculture and the European Statistical Office. Satellite data is used to measure crop acreage, type and yield. The resulting agricultural statistical information assists the EU in monitoring member states' compliance with EU agricultural policies.

Section 4: Remote Sensing in Precision Agriculture

Definition of Precision Agriculture

"Precision Farming is the title given to a method of crop management by which areas of land/crop within a field may be managed with different levels of input depending upon the yield potential of the crop in that particular area of land. The benefits of so doing are two fold:

i. the cost of producing the crop in that area can be reduced and,
ii. the risk of environmental pollution from agrochemicals applied at levels greater than those required by the crop can be reduced" (Earl et al, 1996).

Precision farming is an integrated agricultural management system incorporating several technologies. The technological tools often include the *global positioning system, geographical information system, yield monitor, variable rate technology, and remote sensing*.

The *global positioning system* ("GPS") is a network of satellites developed for and managed by the U.S. Defense Department. The GPS constellation of 24 satellites orbiting the earth, transmit precise satellite time and location information to ground receivers. The ground receiving units are able to receive this location information from several satellites at a time for use in calculating a triangulation fix thus determining the exact location of the receiver.

Figure 4.1 Global Positioning System

A *geographical information system* ("GIS") consists of a computer software data base system used to input, store, retrieve, analyze, and display, in map like form, spatially referenced geographical information.

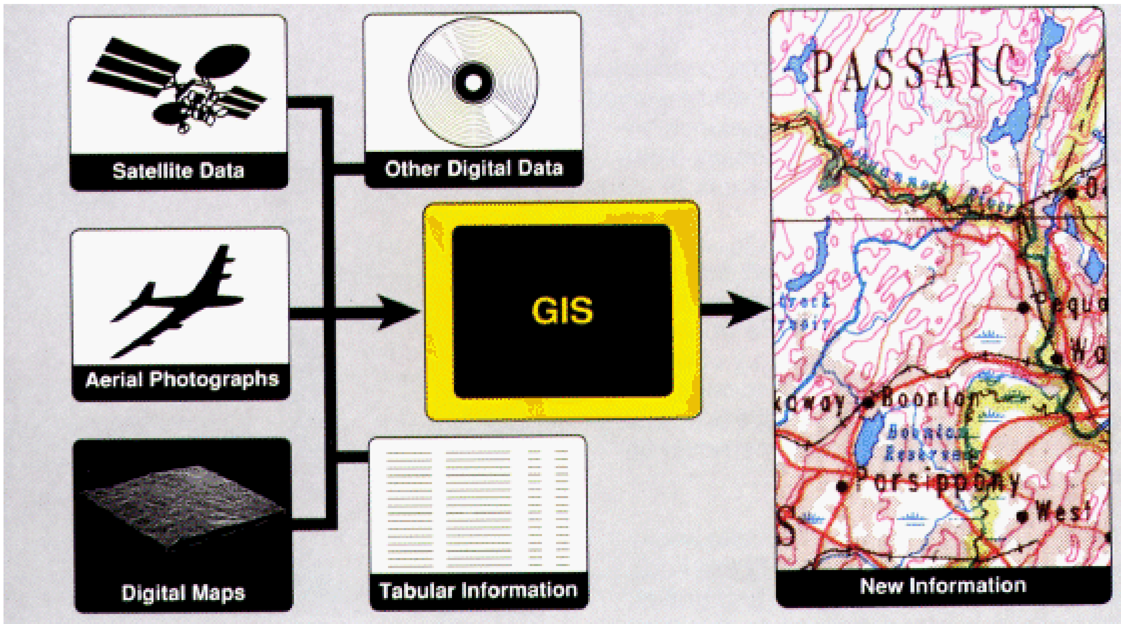


Figure 4.2 Data Integrated Through a Geographical Information System

Yield monitors are crop yield measuring devices installed on harvesting equipment. The yield data from the monitor is recorded and stored at regular intervals along with positional data received from the GPS unit. GIS software takes the yield data and produces yield maps.

Figure 4.3 Combine Yield Monitor

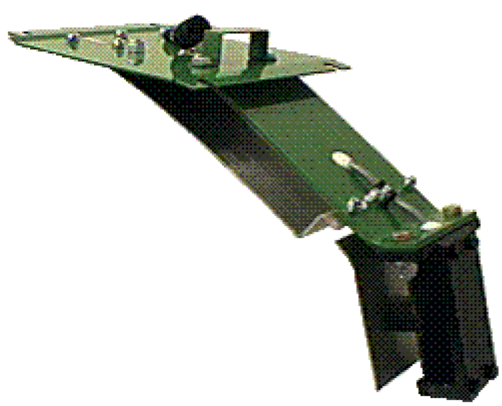


Figure 4.4 Combine Grain Tank Flow Sensor

Variable rate technology ("VRT") consists of farm field equipment with the ability to precisely control the rate of application of crop inputs and tillage operations.

Figure 4.5 VRT Spreader

Remote sensing image data from the soil and crops is processed and then added to the GIS database.

Figure 4.6 Normalized Vegetation Index Image of Farm Field

Goal of Precision Farming

The goal of precision farming is to gather and analyze information about the variability of soil and crop conditions in order to maximize the efficiency of crop inputs within small areas of the farm field. To meet this efficiency goal the variability within the field must be controllable.

Efficiency in the use of crop inputs means that fewer crop inputs such as fertilizer and chemicals will be used and placed where needed. The benefits from this efficiency will be both economical and environmental. Environmental costs are difficult to quantify in monetary terms. The reduction of soil and groundwater pollution from farming activities has a desirable benefit to the farmer and to society.

Research

Precision farming is an integration of several technologies. U.S. and foreign governments originally paid for the development and support of technologies such as GPS, Remote Sensing, and GIS, for military or other civilian purposes long before the emergence of precision farming.

Figure 4.7 GPS Survey Equipment

It is the use of these advanced technologies that has generated enormous amounts of data to process with computers. A very basic question that still needs to be answered by researchers is what does all of this data mean in order for farmers to make profitable management decisions? In other words we have the technology to gather the data from the field but we don't yet have the knowledge to transform the data into answers for agricultural management decisions.

Universities around the world, and foreign and U.S. government entities such as the Agricultural Research Stations of the USDA are conducting extensive research on precision farming. Research projects will apply technologies such as remote sensing, GPS, GIS, and VRT to create management decision support systems. A goal of many publicly funded research institutions is to promote technology transfer from government agencies to the private sector.

Application of Remote Sensing in Precision Agriculture

Soil and Drainage Maps

Management Zones and Soil Maps

Soil maps are also sometimes used to determine management zones. Soil maps are becoming part of the GIS database.

The grid sampling technique takes separate soil samples from uniform sized grids laid out over the field. A problem with this type of sampling is the variability that can exist in soil types with in each grid. This variability makes it much tougher to determine soil characteristics within the grid for crop input management purposes. To minimize this problem smaller grids are required which then requires many more soil samples to be take for a larger number of grids. Soil samples can become a major cost of precision farming.

An alternative to grid sampling is targeted or zone sampling. The soil samples are located in homogeneous management zones instead of uniformly spaced grids (Searcy, 1997). The zones are laid out using a process similar to computer based unsupervised image classification. Images obtained from multispectral remote sensors are taken of the vegetated areas of the field. The pixel digital numbers for each band are separated into statistically separable clusters that are classified into homogeneous zones. This cuts down on the soil, terrain, plant growth, and other variability within each area to be managed; thus fewer soil samples are needed for each area (Anderson et al, 1996).

Except for county soil surveys remote sensing has not gained wide acceptance as a mapping tool for soil characteristics. This is because "the reflectance characteristics of the desired soil properties (e.g., organic matter, texture, iron content) are often confused by variability in soil moisture content, surface roughness, climate factors, solar zenith angle, and view angle"(Moran et al, 1997).

Drainage Maps

Subsurface drainage tile lines that have been installed, as long as 50 or more years ago are still partially or totally functional today. Often the existence or location of older tile lines has been lost as landowners die or sell their property. Some states, including Iowa (Iowa Code, 1997), are now starting to require landowners to prepare and file drainage plats with county recorders when new tile lines are installed. It is desirable to have accurate drain tile maps for maintenance purposes or for the installation of new additional tile line systems. Installation of new tile lines may cut through old tile lines at unknown locations. Building livestock manure lagoons, which cut through old unknown and uncharted tile lines may cause environmental damage from manure leaking through the old tile lines.

Figure 4.8 Normal Color Photo of Dry Soil

Figure 4.9 Normal Color Photo of Soil After Rain

Color infrared ("CIR") aerial photographs have been shown to be an effective tool in locating unknown subsurface tile lines. The image data is digitized for preprocessing and then geo-referenced using ground control points. The CIR photographs show different tones of gray depending on soil type and moisture. By filtering out spectral reflectance differences due to soil type, soil moisture content in dry soils that have a higher reflectance can be identified from lower reflectance wet soils. The resulting image shows were the tile lines are located and whether they are working properly (Verma et al, 1997).

Normal color aerial photographs can also be used to locate tile lines. Simple color photographs offer tile line images similar to CIR but at a lower cost. If the soil is too dry such as that shown in Figure 4.8 the tile lines will not be visible in the image. The images similar to Figure 4.9 must be acquired when the soil is bare and within a few days after an adequate rain. High resolution and on demand temporal availability make images acquired from aircraft platforms ideal for acquiring this kind of image data.

Variable Rate Technology

One method of controlling variability within the field is VRT. VRT allows the grower to apply the quantity of crop inputs needed at a precise location in the field based on the individual characteristics of that location. Crop inputs that can be varied in their application commonly include tillage, fertilizer, weed control, insect control, plant variety, plant population, and irrigation.

Typical VRT system components include a computer controller, GPS receiver, and GIS map database. The computer controller adjusts the equipment application rate of the crop input applied. The computer controller is integrated with the GIS database, which contains the flow rate instructions for the application equipment. A GPS receiver is linked to the computer. The computer controller uses the location coordinates from the GPS unit to find the equipment location on the map provided by the GIS unit. The computer controller reads the instructions from the GIS system and varies the rate of the crop input being applied as the equipment crosses the field. The computer controller will record the actual rates applied at each location in the field and store the information in the GIS system, thus maintaining precise field maps of materials applied.

Although VRT can control inputs applied to crops, it cannot control factors such as soil type, weather climate, and topography that are fixed.

Monitor Crop Health

Remote sensing data and images provide farmers with the ability to monitor the health and condition of crops. Multispectral remote sensing can detect reflected light that is not visible to the naked eye. The chlorophyll in the plant leaf reflects green light while absorbing most of the blue and red lightwaves emitted from the sun. Stressed plants reflect various wavelengths of light that are different from healthy plants. Healthy plants reflect more infrared energy from the spongy mesophyll plant leaf tissue than stressed plants. By being able to detect areas of plant stress before its becomes visible, farmers will have additional time to analyze the problem area and apply a treatment.

Water Stress

The use of remote sensors to directly measure soil moisture has had very limited success. Synthetic Aperture Radar ("SAR") sensors are sensitive to soil moisture and they have been used to directly measure soil moisture. SAR data requires extensive use of processing to remove surface induced noise such as soil surface roughness, vegetation, and topography.

A crop evapotranspiration rate decrease is an indicator of crop water stress or other crop problems such as plant disease or insect infestation. Remote sensing images have been combined with a crop water stress index ("CWSI") model to measure field variations (Moran et al, 1997).

Simple panchromatic aerial photographs have been used to spot irrigation equipment problems. Strips in the vegetation images point to problems with water application rates from defective water nozzles (Univ. of Georgia, 1995).

Weed Management

One goal of precision farming is to cut crop production inputs, which result in cost and environmental savings. Conventional farming methods apply herbicides to the entire field. Site-specific variable-rate application puts the herbicide where the weeds are.

Aerial remote sensing has not yet proved to be very useful in monitoring and locating dispersed weed populations. Some difficulties encountered are that weeds often will be dispersed throughout a crop that is spectrally similar, and very large-scale high resolution images will be needed for detection and identification (Ryerson, Curran, P. and Stephens 1997).

The use of machine vision technology systems to detect and identify weeds places remote sensors directly on the sprayer equipment. Being close to the crop allows for very high spatial resolutions. Machine vision systems have the ability to be used in the field with the real-time capabilities that are necessary to control sprayer equipment (Steward and Tian, 1998).

Insect Detection

Aerial or satellite remote sensing has not been successfully used to identify and locate insects directly. Indirect detection of insects through the detection of plant stress has generally not been used in annual crops. The economic injury level for treatment is usually exceeded by the time plant stress is detected by remote sensing. Entomologists prefer to do direct in field scouting in order to detect insects in time for chemical treatments to be effective and economical.

Nutrient Stress

Plant nitrogen stress areas can be located in the field using high-resolution color infrared aerial images. The reflectance of near infrared, visible red and visible green wavelengths have a high correlation to the amount of applied nitrogen in the field. Canopy reflectance of red provides a good estimate of actual crop yields (GeopalaPillai, Tian, and Beal 1998).

Yield Forecasting

Plant tissue absorbs much of the red light band and is very reflective of energy in near infrared ("NIR") wavebands. The ratio of these two bands is referred to as the vegetation index ("VI"). The difference of red and NIR measurements divided by their sum is normalized difference VI ("NDVI").

For crops such as grain sorghum, production yields, leaf area index ("LAI"), crop height and biomass have been correlated with NDVI data obtained from multispectral images (Anderson et al, 1996). In order to get reasonably accurate yield predictions this data must be combined with input from weather models during the growing season (Moran et al, 1997).

Management Decision Support Systems

Just having information about variability within the field doesn't solve any problems unless there is some kind of decision support system ("DSS") in order to make VRT recommendations. Russo and Dantinne (Russo et al, 1997) have suggested the following steps for a DSS:

1. Identify environmental and biological states and processes in the field that can be monitored and manipulated for the betterment of crop production.
2. Choose sensors and supporting equipment to record data on these states and processes.
3. Collect, store and communicate the field-recorded data.
4. Process and manipulate the data into useful information and knowledge.
5. Present the information and knowledge in a form that can be interpreted to make decisions.

Choose an action associated with a decision to change the identified state or process in a way that makes it more favorable to profitable crop production.

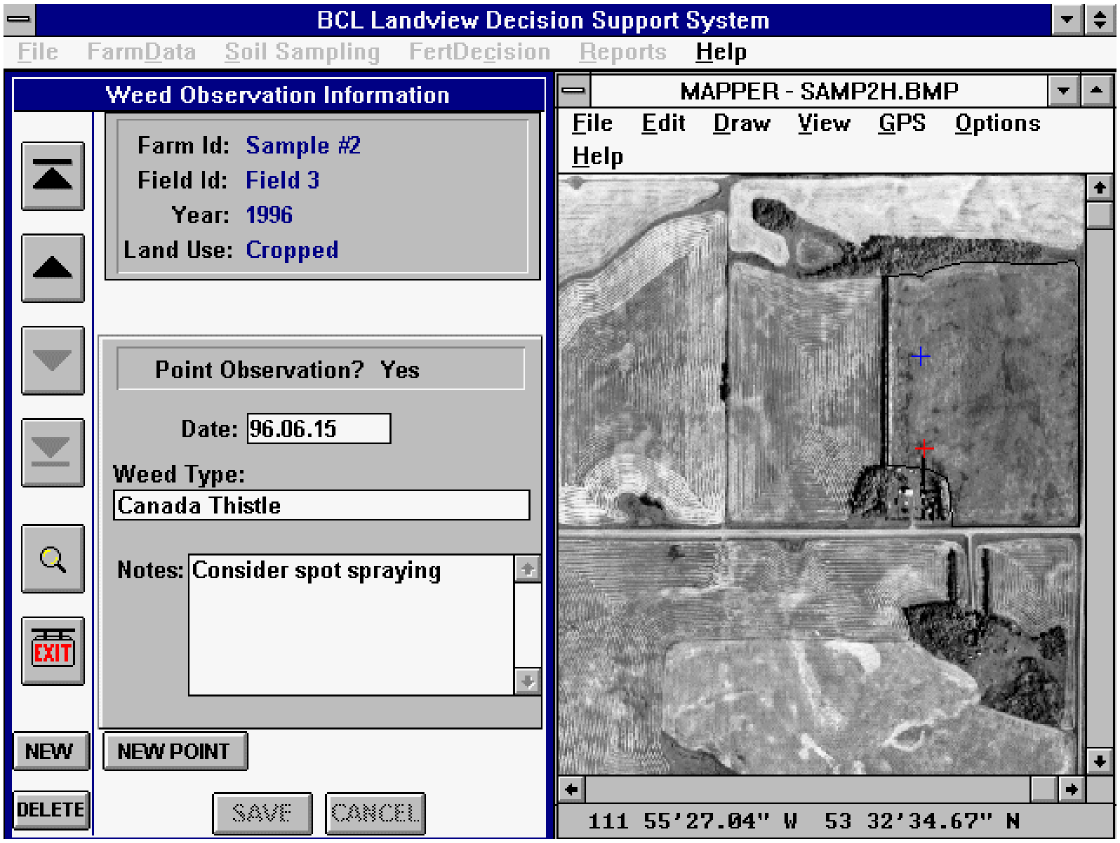


Figure 4.11 Decision Support System Software

Future Prospects and Developments

Future satellite systems to be launched within the next year such as Ball Corporation's Quickbird will have a four-band multispectral pushbroom sensor with a resolution of .8 m panchromatic and 4.5 m multispectral. EarthWatch Incorporated of Longmont, Colorado will distribute Quickbird images.

Future satellites will have better spatial and spectral resolutions. Launching more satellites will also improve temporal resolution.

The delivery time of remote sensing data to the customer will improve. We will someday have real-time satellite remote sensing systems.

University research will concentrate more on the cause of soil and crop variability verses just being able to measure that variability. A greater emphasis will be placed on technology transfer from universities to commercial agribusiness industry.

Decision support systems will become the main link to convert the spatial data collected into detailed management recommendations at the farmer level. Decision support systems is what will add the most value to remote sensing data for the farmer.

The future of remote sensing in precision agriculture will depend upon meeting the needs of the end user, the farmer. Right now remote sensing for agricultural use is still in an early stage of commercial development with unproven economic benefits to the farm producer.

The cost of remote sensing data and the other systems associated with precision agriculture will come down to be in line with the benefits received. This is likely to happen in the future as more agricultural information technology companies enter the marketplace.

Section 5: Cost Benefit Analysis

Precision Farming

Remote sensing is just one component of a much larger integrated technology known as precision farming. Precision farming is still an emerging technology with very limited economic success. Precision farming will first have to become an economical management system before the integration and use of remote sensing becomes widely used in agriculture. Early adopters of new farming technology will benefit the most when precision farming does become profitable (Cochrane, 1979).

Profit

The increase in net profits from precision farming come from a combination of revenue increases from higher yields and/or decreased input use and their associated costs.

Lowenberg-DeBoar and Swinton (1997) reviewed 17 published precision farming economic studies in an attempt to answer the question whether precision farming is more profitable than whole-field farming. Precision farming is not profitable in five studies, profitable in six studies, and mixed or inconclusive in six studies. Several problems with these studies exist. The studies are not very comparable because of various different assumptions and cost accounting methods. Twelve studies use actual crop yields while the remaining five studies use simulated yields. *Under accounting for true costs, assumed nitrogen response, and high product value* are three factors that are cited by Lowenberg-DeBoar in the group of studies that are profitable.

Under accounting for true costs omitted costs such as the cost of collecting and analyzing soil samples, map making, and input application.

Assumed nitrogen response assumes that the crop will yield will reach its targeted yield if nitrogen is not a limiting factor. Four profitable studies did not generate any data to prove this assumption.

High product value was a factor in two out of the six profitable studies. All of the inconclusive and unprofitable studies are low-value grain crops.

None of these studies attempted or considered the environmental costs and benefits of precise placement and reduced use of agricultural chemicals.

Some people assume that increased technology automatically increases pollution. Pollution is not the result of technology and the high level of inputs. It is the result of the inefficient use of those inputs that result in byproducts and waste material that is created in the production process (Khanna et al, 1996).

Pollution from farm chemicals to the environment does not yet have a significant cost directly charged to the farmer. All taxpayers, rural and urban, are still paying the cost of removing farm chemical runoff in public water supplies.

Risk and Uncertainty

Lowenberg-DeBoar and Aghib (1997) determined that the precision application of phosphorous ("P") and potassium ("K") using either grid or soil type management did not significantly increase net profit compared to whole field management. The data was collected from six farms located in Northeastern Indiana, Northwestern Ohio and Southern Michigan. The average net return per acre was $146.93 for whole field management, $136.99 for grid soil sampling management, and $147.80 for management areas based on soil type.

The study also found that although precision application of P and K did not significantly increase net profits, it did reduce the risk of poor profit results by decreasing the variability of net profits for each type of crop management used.

The variability of net profit per acre was significant for the three management types. For example:

> Whole field management had a profit spread of $276.93, varying from a minimum of $35.15 to a maximum of $312.08.
>
> Grid area management had a profit spread of $209.80, varying from a minimum of $65.14 to a maximum of $274.94.
>
> Soil type management had a profit spread of $180.48, varying from a minimum of $57.23 to a maximum of $237.71.

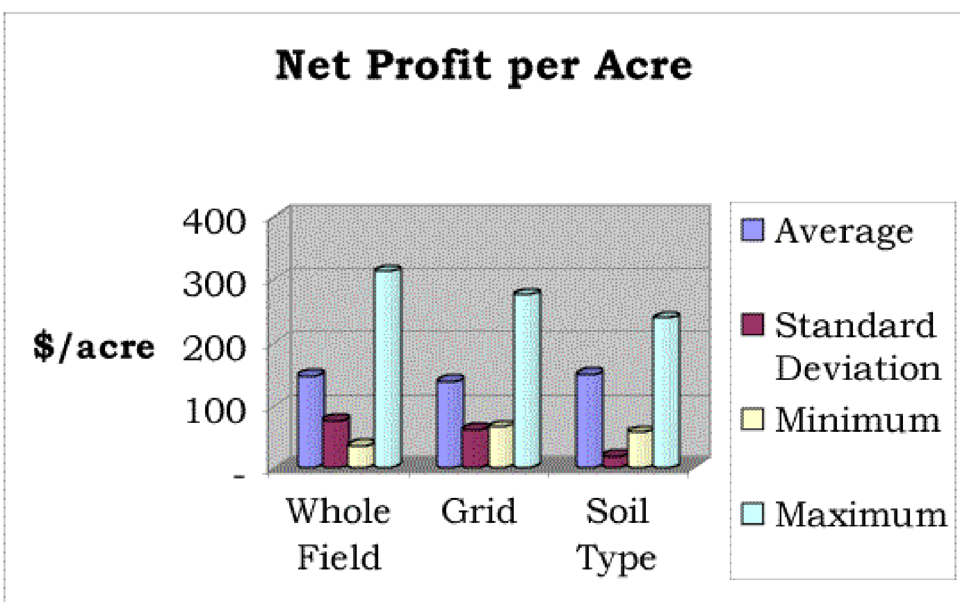


Figure 5.1 Data from Lowenberg-DeBoar and Aghib (1997)

Precision farming using soil type management showed only a very slight increase in profit verses whole field or grid type management. This study shows that the greatest benefit for the farmer using precision farming, will be the risk reduction of incurring low profits.

Remote Sensing Ecomonics

Remote sensing will not be a commonly used technology until precision farming is profitable. Farmers just aren't going to be willing to pay for remote sensing images if its not going to add value to their crop growing operation. Remote sensing can be a very expensive component of precision farming. The cost of a remote sensing images has very little meaning unless it becomes part of a precision farming decision support system.

The following are some examples of the cost of remote sensing images from data providers specializing in agricultural images and decision systems.

Satellite Image Cost

Many satellite companies will not normally deliver remote sensing images directly to the retail customer. Images are sold through authorized retailers. These retailers will take the satellite images and perform post processing steps to make the classified image more useful to the customer. For example, a Canadian company, Prairie Geomatics, will create NDVI vegetation maps derived from India IRS-1D, French SPOT, or U.S. Landsat satellite photos for approximately 47¢ per acre.

Aerial Image Cost

Commercial aerial images tend to be higher in cost than satellite images. Multispectral classified images with a resolution of 2 meters are available from DTN, a Nebraska company, for approximately 75¢ per acre. DTN advertises a 48-hour turnaround from image acquisition to customer delivery.

Farmers are finding inexpensive ways to acquire aerial images with the use of aircraft platforms such as the powered parachute shown in figure 5.2. Figures 5.3 and 5.4 were taken from the powered parachute with a hand held camera in the visible red and near-infrared bands.

Figure 5.2 Powered Parachute

Figure 5.3

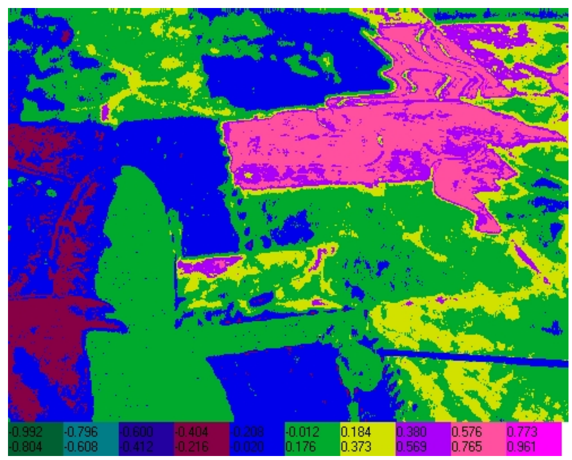


Figure 5.4

Section 6: Conclusion

Remote sensing has a long history as a useful tool for military applications. The end of the cold war has driven defense contractors to look for and promote civilian uses of remote sensing technology. The agriculture industry is seen as one additional market for remote sensing data providers.

Remote sensing sensors collect data on energy reflected from the surface of plants and soil. The physics used in remote sensing technology is very complicated. Farm operators will be dependent upon professional engineers and precision farming consultants to process the raw image data into useable information for making management decisions. There is an abundance of remote sensing technology available to measure variability in plants and soils. Also, there is a shortage of information about the causes of plant condition variability and the management solutions needed manage variability to improve crop production. The lack of knowledge needed to answer these variability questions is restricting the development of precision farming management decision support systems.

Remote sensing is just one component of the emerging technology called precision farming. Precision farming has not yet developed into a practical and profitable management tool for agriculture.

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Farms Appendix II - Quiz

Fill in the blanks.

1. ___________________ ______________________ refers to the process of gathering information about an object, at a distance, without touching the object itself.

2. Three major components of electromagnetic radiation are ____________________________, ____________________________, and _______________________________.

3. A major difference between the human eye and remote sensors is the ____________________________ range of light in the electromagnetic spectrum that they are sensitive to.

4. The electromagnetic spectrum can be sliced up into discrete segments of wavelength ranges called __________, also sometimes referred to as a channel.

5. The frequency of visible light ranges from a high of _____ µm to a low of _____µm.

6. The three primary colors reflected from an object known as additive primaries are the ____________, _______________, and _________ wavelengths.

7. Remote sensors operating in the thermal infrared wavelength range measure an object's __________________________________.

8. The sharp increase of reflected energy just beyond the red region of visible light into the near infrared region is referred to as the _________ ____________.

9. ______________________ sensors monitor only the natural solar reflected light or electromagnetic energy from an object.

10. The smallest size picture elements on a computer screen are called ___________________.

11. _________________________ resolution, is the sensitivity of a sensor to respond to a specific frequency range.

12. ______________________ ____________________________ is a process where two images at the same location taken on different dates are compared with each other to measure any changes in physical shape, location, or spectral properties.

13. The sensor detectors in a ____________________________ scanner are lined up in a row called a linear array.

14. _______________________________ remote sensing systems are ground-based sensor systems.

15. The goal of precision farming is to gather and analyze information about the _________________________________ of soil and crop conditions in order to maximize the efficiency of crop inputs within small areas of the farm field.

Appendix III - Quiz Answers

Fill in the blanks.

1. **Remote sensing** refers to the process of gathering information about an object, at a distance, without touching the object itself.

2. Three major components of electromagnetic radiation are **frequency**, **amplitude**, and **wavelength**.

3. A major difference between the human eye and remote sensors is the **frequency** range of light in the electromagnetic spectrum that they are sensitive to.

4. The electromagnetic spectrum can be sliced up into discrete segments of wavelength ranges called **bands**, also sometimes referred to as a channel.

5. The frequency of visible light ranges from a high of **.4** µm to a low of **.7** µm.

6. The three primary colors reflected from an object known as additive primaries are the **blue**, **green**, and **red** wavelengths.

7. Remote sensors operating in the thermal infrared wavelength range measure an object's **temperature**.

8. The sharp increase of reflected energy just beyond the red region of visible light into the near infrared region is referred to as the **red edge**.

9. **Passive** sensors monitor only the natural solar reflected light or electromagnetic energy from an object.

10. The smallest size picture elements on a computer screen are called **pixels**.

11. **Spectral** resolution, is the sensitivity of a sensor to respond to a specific frequency range.

12. **Change detection** is a process where two images at the same location taken on different dates are compared with each other to measure any changes in physical shape, location, or spectral properties.

13. The sensor detectors in a **pushbroom** scanner are lined up in a row called a linear array.

14. **Terrestrial** remote sensing systems are ground-based sensor systems.

15. The goal of precision farming is to gather and analyze information about the **variability** of soil and crop conditions in order to maximize the efficiency of crop inputs within small areas of the farm field.