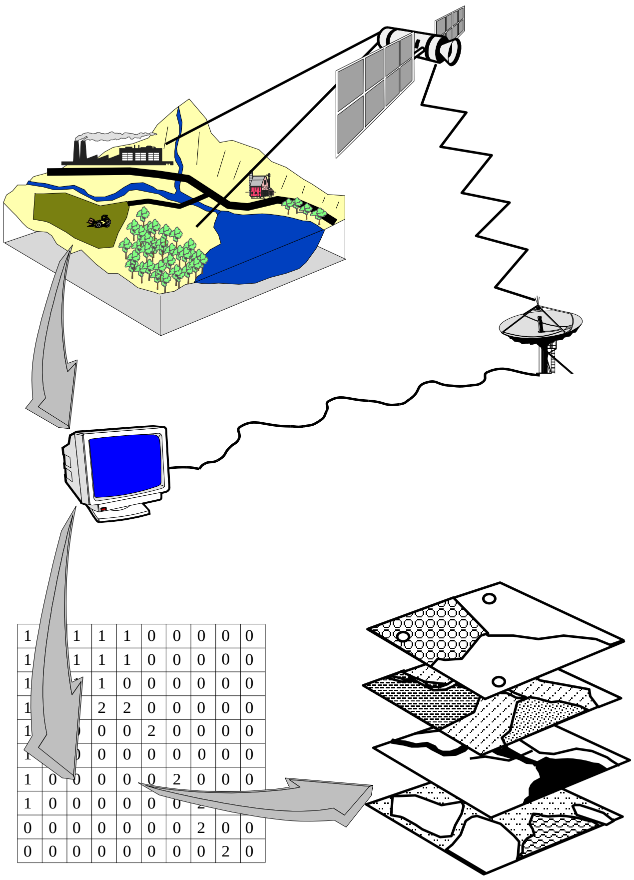
Department of Physical Geography and Ecosystems Sciences
Lund University

Introduction to Remote Sensing and Geographical Information Systems



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Preface

The fields of Remote Sensing and Geographical Information Systems (GIS) are expanding very fast and the methods are constantly adapted to new fields of application. This paper aims to introduce the concepts to the beginner. Since a complete review of applications where these methods might be useful is far beyond the scope of this paper the cited examples are mainly restricted to applications within the field of Geography. All illustrations have been prepared by the author.

After reading the paper it is presumed that the reader will be fairly familiar with basic theoretical foundation and terminology of both Remote Sensing and GIS. In order to expand your knowledge it is recommended to read some of the titles recommended in the ”Further Reading” section at the end of the paper.

This paper has been used on undergraduate courses at the Dept. of Physical Geography and Ecosystems Sciences at Lund University and Department of Geography at Ohio State University as well as on preparatory ”on the job” training courses in different countries in the world in co-operation with Swedish and foreign consultants and governmental agencies.

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INTRODUCTION TO REMOTE SENSING AND GEOGRAPHICAL INFORMATION SYSTEMS

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1. Introduction

The term remote sensing is often wrongly applied to satellite-borne imaging of the earth's surface only. *Remote sensing is the common name for all methods used to collect data at a distance from the object under study by some kind of recording device.* The use of remote sensing techniques is increasing rapidly, finding new fields of application as technology advances in developing the remote sensing systems. The aim with this paper is not to fully review existing remote sensing methods but rather to introduce the concept of remote sensing to the reader. It will provide a foundation to the understanding of the principles of remote sensing needed when working with applications of this technique. The emphasis will be on satellite sensor remote sensing but some aspects of traditional photographic remote sensing and aerial photography using digital aerial cameras will also be treated.

2. Brief history of remote sensing

According to the definition above a pair of binoculars or an ordinary camera are simple remote sensing systems. The camera was used already during the end of the 19th century for e.g. military reconnaissance, having the obvious advantage over simple visual inspection in the fact that it produced an image that could be studied and reproduced in several copies. Since the late 1920s, aerial photography has been an important tool in all kinds of mapping and planning work.

During World War II, two new remote sensing methods were developed, the sonar and the radar. After World War II, several systems have been developed for different types of electromagnetic radiation. Remote sensing systems based on electronic radiation detectors are not obviously image generating systems, that is, the result is not an image, but rather a set of numbers stored in a computer compatible format. The stored data can often be transformed into an image by a computer using dedicated software.

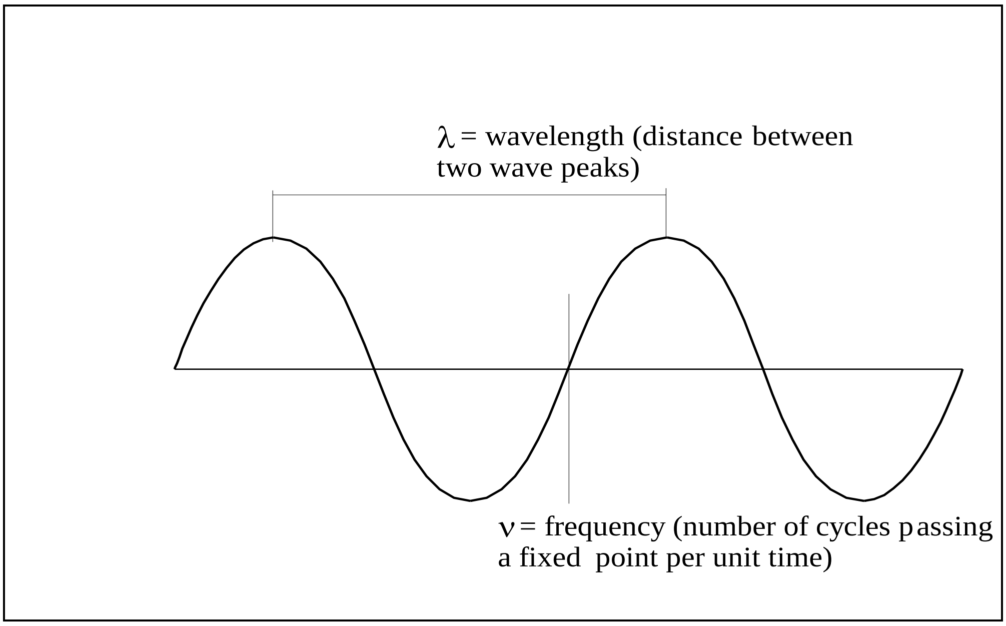


Figure 1: Definition of wavelength and frequency

Remote sensing systems are divided into two groups based on separate technical solutions. **Passive remote sensing systems** measure existing radiation such as the reflected solar radiation from the earth's surface. **Active remote sensing systems** emit radiation on the study object and measure the reflected amount of radiation.

An ordinary camera is an example of a passive remote sensing system using existing light as input, and forms an image on the film. If a flash is added to the camera it becomes an active remote sensing system since it then provides the necessary radiation without considering the existing radiation sources.

Examples of remote sensing systems of the active type are: Radar, Sonar, and Echo-sounder and the more recently added Lidar which use laser technology to emit and then collect reflections from the surface of the earth. Examples of remote sensing systems of the passive type are: Photography, Digital photography, Scanning Mirror (MSS), and Push broom Scanner.

Radar is currently being employed more frequently in different resource inventories, the use of radar remote sensing is particularly useful in areas that often have a thick cover, since radar waves penetrate clouds and even to certain extent vegetation cover. So radar images has been used e.g. to map landscape and soils in the Amazonas. Lidar is a technology that is becoming more and more frequent in use, often in order to generate topographic maps and digital elevation models of high resolution. Another trend in the current development is the use of so called hyperspectral satellite sensors that instead of recording in 3-7 wavebands records in several hundreds of narrow wavebands. But still, the most widespread remote sensing systems are aerial photography and satellite multispectral scanning. This review will treat these two systems with special emphasis on satellite multispectral sensors.

3. The physical foundation of remote sensing

Electromagnetic energy is treated by two principal theories, the theory of waves and the theory of particles. According to the theory of waves, electromagnetic energy travels in sinusoidal waves by the ”speed of light”, c. The distance from one wave peak to the next is the wavelength (λ), and the number of peaks passing a point per unit time is the frequency (ν) (Figure 1). The relation between speed, wavelength and frequency is given by the basic physical expression:

$$c = \nu \cdot \lambda \qquad (1)$$

As c is fairly constant (around 3 x 10^8 m/s) the frequency and wavelength are related inversely. In remote sensing applications, the electromagnetic energy is normally classified according to its location in the electromagnetic spectrum, that is, by its wavelength (Figure 2). At the lower end (shorter wavelengths) of the spectrum is X-rays, and at the higher end different communication wavelengths (television and radio).

While the wavelength of radio and television broadcasting can be measured in metres, the most common measuring units when speaking of the electromagnetic spectrum in remote sensing applications is the micrometer, μm, which is 10^{-6} m, but the ISO unit is Nano-meter, which is 10^{-9} m.

In natural resources assessment applications of remote sensing the radiation in the visible and near visible regions of the spectrum are the most frequently used data sources. Visible light is divided into three basic intervals, the blue, green and red **wavelength bands** (an interval in the electromagnetic spectrum having similar characteristics is normally called wavelength band or simply band, e.g. the red band) or sometimes also **channel**, in this case red channel.

To the shorter side of visible light is the **Ultra-Violet** (UV) and to the longer wavelength side is the **Near InfraRed** (NIR) wavelengths followed by **Thermal InfraRed** (TIR). It is important to separate the NIR-band, sometimes also called reflected infrared since it consists of reflected radiation from the sun, from the TIR-band consisting of emitted radiation associated with the sensation of heat. The divide between reflected and emitted infrared is around 3 μm. Wavelengths below consists of reflected energy (from the sun), while the longer wavelengths are emitted from various sources (as heat). Farther away to the longer wave length's side of the electromagnetic spectrum are microwaves (radar).

This paper will mainly focus on the portion of radiation in the approximate range from 0.3 to 3 μm which is reflected incident solar energy. It is not by chance that the human eye is sensitive to radiation in this part of spectrum, since it is where the sun emission is strongest as will be shown in the following section.

According to the theory of particles, all matter with a temperature above the absolute zero (0º K or -273º C) emits energy. The total energy increases rapidly as the temperature increases, following the **Stefan-Boltzmann's Law**:

$$M = \sigma \cdot T^4 \qquad (2)$$

where M is the total amount of radiated energy from the surface of an object (W/m^2), σ is the Stefan-Boltzmann constant ($5.6697 \cdot 10^{-8}$ W/m^2/°K) and T is the absolute temperature (°K). Figure 3 illustrates the Stefan-Boltzmann's Law, showing the distribution of emitted energy in different wavelength bands. Equation (2) is valid for a blackbody which is an ideal radiator that totally absorbs and re-emits all incident energy.

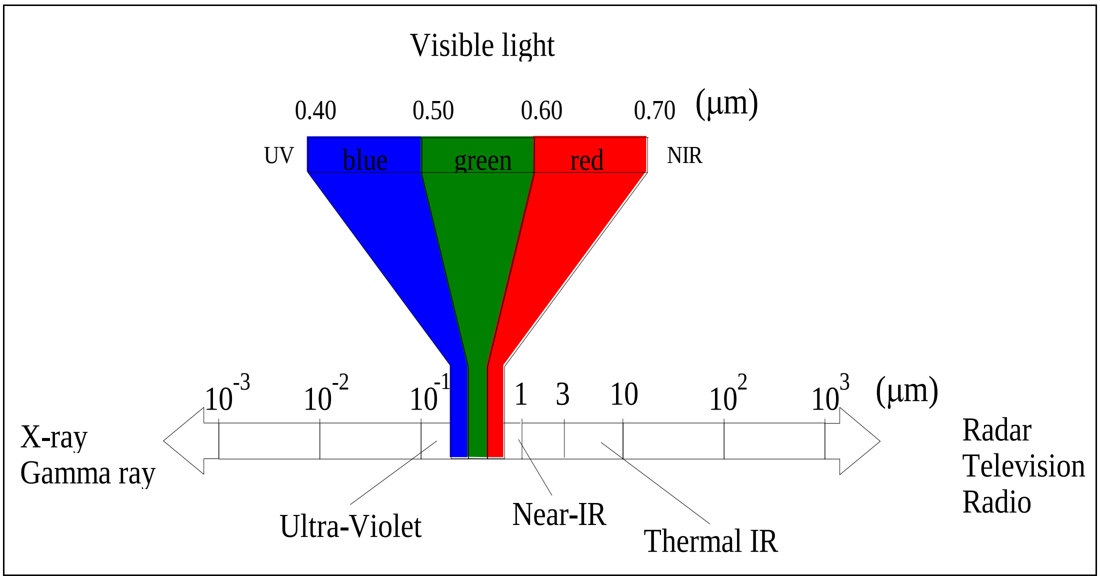


Figure 2: The spectrum of electromagnetic radiation.

Natural objects are not blackbodies and may be either greybodies, having a constant emissivity at all wavelengths that is less than the blackbody radiation, or selective radiators, having different emissivity in different parts of the spectrum. In the case of a greybody, an emissivity factor (ε, ranging from around 0.50 to 0.95) is added to the equation (2) to obtain the emitted energy. The selective radiator is more difficult to treat since the emissivity factor is not identical for different wavelengths or range of wavelengths. Knowledge of the emissivity of different objects is important particularly in thermal remote sensing since these sensors operate on the emitted energy part of spectrum.

Figure 3 shows that the sun's maximum energy output is in the visible part of the spectrum, as can be calculated by **Wien's Displacement Law**:

$$\lambda_m = \frac{A}{T} \qquad (3)$$

where λ_m is the wavelength with maximum radiation, A is a constant 2898 µm ºK) and T is the absolute temperature (ºK) of the object.

The equation permits the calculation of the wavelength where an object has its maximum radiation at any given temperature. If the equation is applied on the radiation emitted from the sun, having a temperature of about 6000° K, the result gives a maximum radiation at a wavelength of 0.48 µm. The earth has a mean temperature of around 300° K (27° C) and maximum emittance at 9.7 µm.

Between these two radiators are several other light sources, such as ordinary light bulbs having a temperature of 3200°-3600° K. Integrating the spectral radiant emittance over the whole spectrum gives the total emitted energy from an object at a given temperature. The total energy from the sun is much higher than the energy emitted from the earth since the temperature of the sun is higher. Human eyes and normal photographic film are sensitive to wavelengths ranging from about 0.4 µm to 0.7 µm, using the energy from the sun as ”illumination”. The energy emitted from the earth can not be seen nor recorded by any photographic film, but it is possibly measure it with electronic radiation detectors constructed to record emitted energy in the wavelengths around 10 µm. This wavelength is in the TIR range of the spectrum.

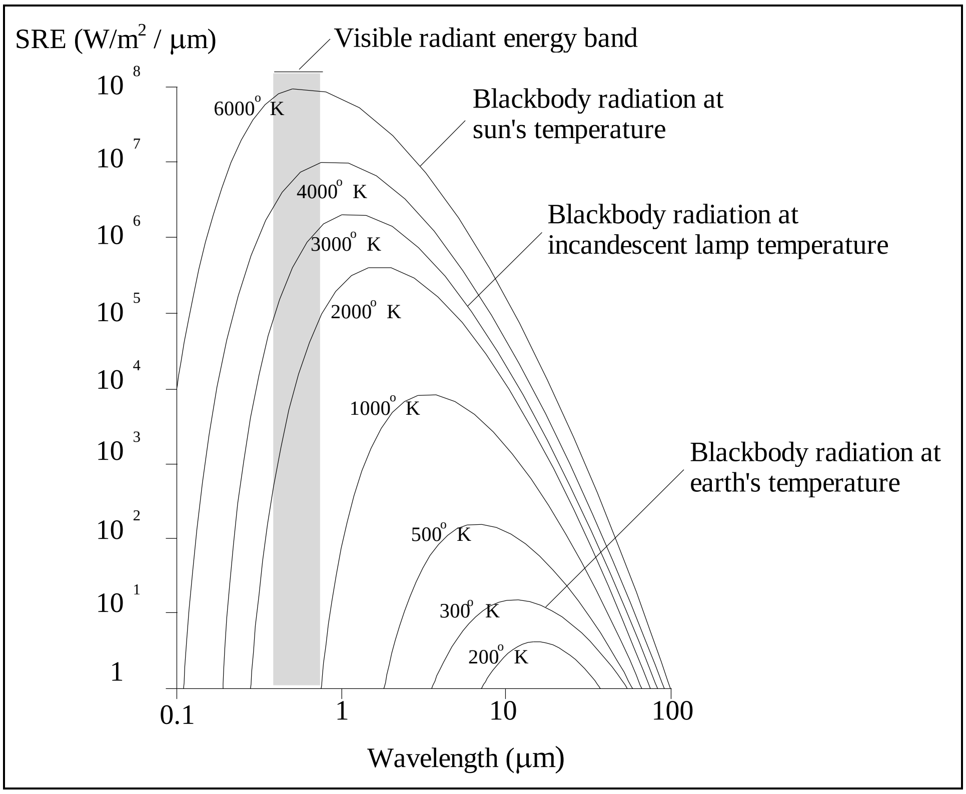


Figure 3: Spectral Radiant Emittance (SRE), the spectral distribution of energy radiated from blackbodies of different temperatures, for different wavelength bands. The total energy emitted from a blackbody is the area under the curve for the different temperatures.

4. Radiation in the atmosphere

The atmosphere influences the incoming radiation by **atmospheric scattering** and **atmospheric absorption**. Scattering is a process of diffusion, caused by redirecting of the radiation by particles of different sizes that are present in the atmosphere. Absorption consumes part of the incoming energy, and some of it will eventually be re-emitted from the atmosphere as heat. Both processes are governed mainly by the sizes of the present atmospheric particles, that is, the prevailing atmospheric conditions and the nature of the incoming radiation, mainly its wavelength.

Rayleigh scattering occurs when the wavelength of the radiation is larger than the diameter of the particles it interacts with. The magnitude of scattering increases as the wavelength decreases. The blue colour of the sky is a result of Rayleigh scattering, since the shorter blue wavelength in the visible part of spectrum are diffused all over the sky, making the blue dominating over other colours. In the early morning and late evening the sun is close to the horizon.

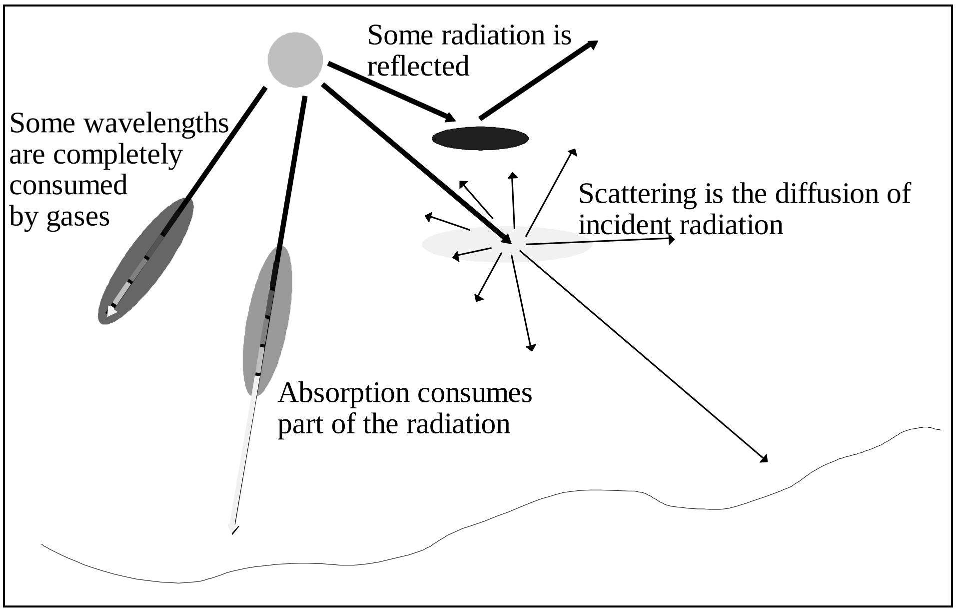


Figure 4: Scattering and absorption in the atmosphere.

This makes the path of the radiation through the atmosphere longer, resulting in a complete diffusion of blue, and the longer waves in the yellow-orange-red band predominating in the radiation reaching the earth’s surface. Rayleigh scattering is important enough to be a problem even in ordinary photography, making long distance shots look hazy and without contrast, particularly when using telephoto lenses. This may be corrected by a brownish or tobacco tinted filter, blocking the shortest wavelengths in the upper UV and lower blue bands.

The same type of filtering is needed in aerial photography to assure maximum sharpness and contrast in the images. Sometimes even stronger blocking of scattered radiation is needed in that case a yellow or red filter is used.

Mie scattering occur when the sizes of the particles matches the wavelength of the radiation, examples are water vapour and small dust particles. Mie scattering is not as obvious as the Rayleigh scattering. It diffuses the longer waves and is particularly significant during days with slight overcast. Since such days normally are considered as unsuitable for recording of remote sensing data, Mie scattering is a minor problem in remote sensing.

Non-selective scattering is when the particles are essentially larger than the wavelengths they scatter. This scatter does not affect any particular wavelength more than others; it is a process which evenly scatters all wavebands from visible light up to the reflected infrared portion of the spectrum.

Absorption is when different gases in the atmosphere absorb the radiation energy. Absorption is also wavelength selective, depending on what atoms the gases are built of.

The most important absorbers of the incoming solar radiation in atmosphere are water vapour, carbon dioxide and ozone (Figure 5).

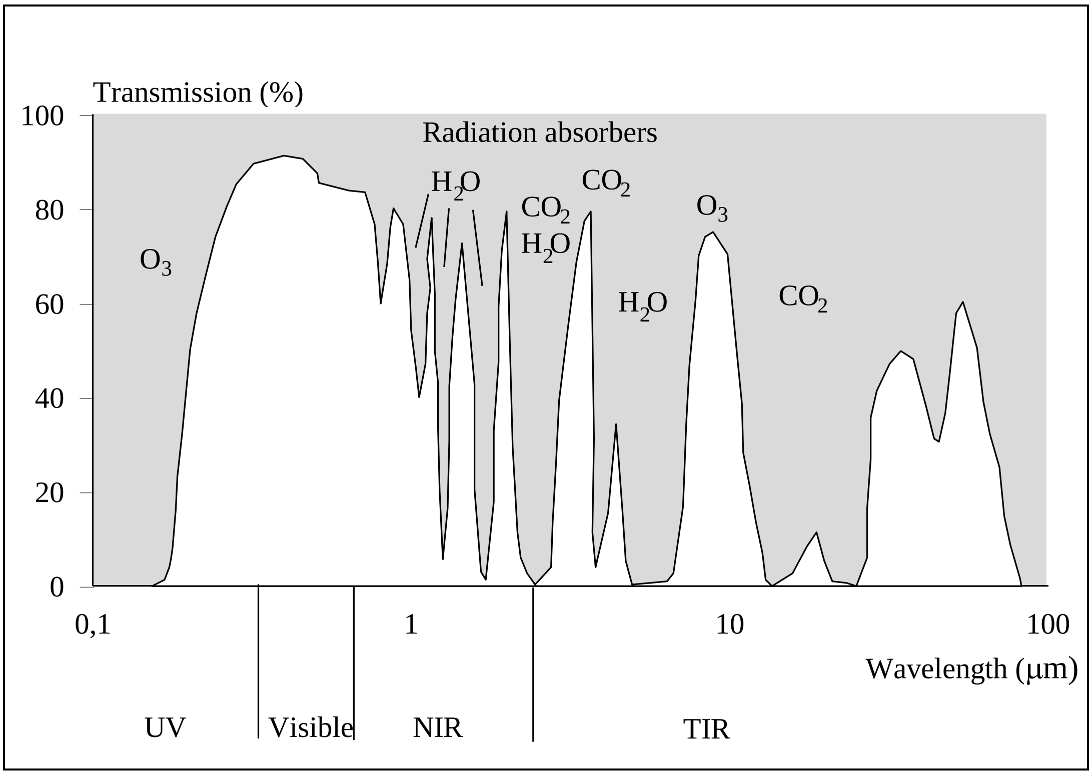


Figure 5: Transmission of radiation in different wavelengths. The atmosphere is almost opaque for incident radiation in several parts of spectrum. Most remote sensing systems sense radiation in the visual and NIR band because of the high transmission of radiation. The UV-band is submitted to heavy scattering, besides the absorption by ozone.

The absorption causes a loss of energy, diminishing the energy arriving at the surface of the earth. In some cases the atmospheric absorption is essential for the existence of biological activities, as the ozone-absorption of dangerous UV-radiation. The effect of absorption is so important that the atmosphere is virtually opaque for radiation at certain wavelengths.

The wavelength bands where the atmosphere transmits radiation are called **atmospheric windows**. From 0.25 µm to roughly 100 µm the atmosphere is fairly transparent to radiation. Then it is opaque all the way up to 1000 ❍m (1 mm) where the micro-wave window permits the use of radar systems.

5. Reflection from the earth's surface

Incident radiation on the earth's surface is either absorbed or reflected (very long wavelengths may also be transmitted). The characteristics of the surface features and the wavelength of the incident radiation decide if the radiation is reflected or absorbed. The **albedo** is the ratio between the reflected part of incident radiation and the total incident radiation. The albedo varies between objects and between wavelength bands for the same object. Snow is a classical example with a very high albedo in the visible part of spectrum (above 90 %) but due to absorption by water the albedo is much lower in the NIR-band (above 1.40 μm).

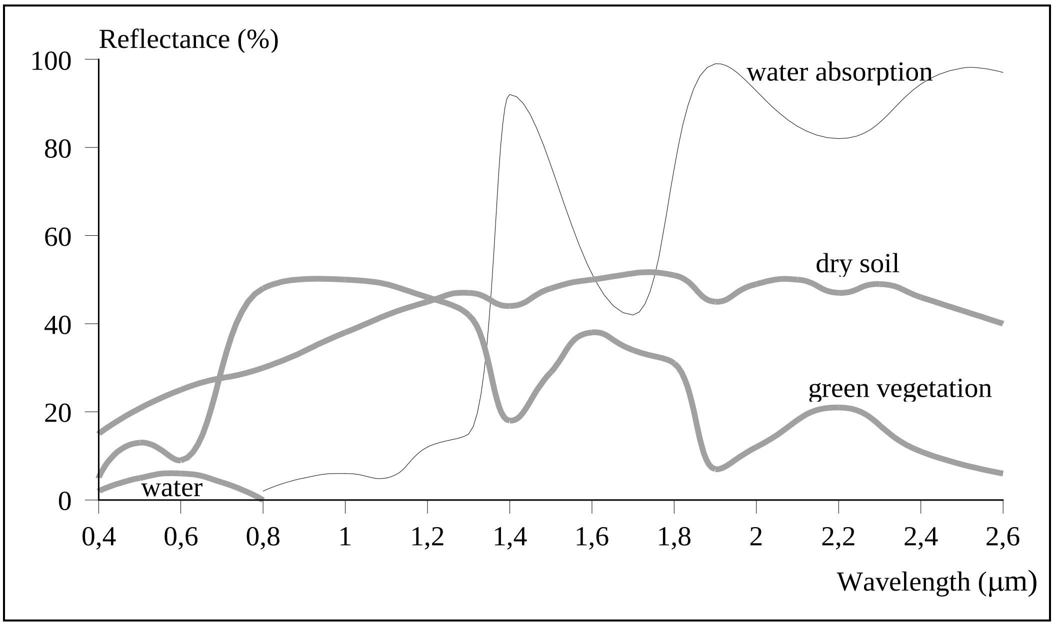


Figure 6: Reflection from dry soil, water and vegetation. The thicker line is the water absorption in different wavelengths. Note the inverse correlation between the absorption curve and the reflection of vegetation. Although dry, the soil reflection curve shows that the soil contains some water.

Our perception of colours is also based on the selective reflection of different objects. A green leaf has its maximum reflection in the green part of the visible wavelength band and absorbs in the blue and red parts. A red object reflects in the red band and absorbs in the other bands.

The difference in albedo between objects is fundamental to all image interpretation. In the visual part of the spectrum, interpretation is fairly easy and intuitive, vegetation appears green, a tarmac road is black, water is blue, etc. Many features can easily be identified by their reflected radiation in the visible band. In the invisible part of spectrum, object identification is less obvious to the inexperienced interpreter. Training is needed to adapt to the difference in appearance between different wavelength bands. It is far beyond the aim of this paper to give a complete review of the spectral reflectance of different objects. In environmental mapping applications, the basic objects under investigation are often vegetation (species, cover, status, etc.), soils and geology (type of geological structure, soil type, etc.) and water (availability, quality, etc.). Knowing the basic principles of how these reflect in different wavelength bands will help an interpreter in the mapping work. Figure 6 shows the spectral reflectance curve for green vegetation, soil and water.

Vegetation has a small peak in reflection in the green band making it appear green to the human eye, but as seen, the maximum reflectance of vegetation is in the NIR band, in the range 0.7 to 1.4 μm. The simple explanation is that vegetation uses the sun radiation in its photosynthesis and has adapted to use the part of spectrum where radiation is highest, which is in the visible band. Chlorophyll absorbs very much of the radiation in the range 0.45 - 0.67 μm. Plants under stress ceases to produce chlorophyll, which changes the balance in reflected energy. Reflection from the red band increases and the mixture of red and green will make the plant look yellow. The spectral reflectance curve has several dips, at 1.4, 1.9 and 2.6 μm. This caused by water absorption, beginning at about 0.7 μm. The water absorption curve is important to keep in mind, since water will influence the reflected radiation from any object containing water. Soils will consequently also be influenced by water absorption. In living green vegetation the reflection is about inversely related to water content.

Soil and vegetation may have very similar reflectance in the NIR-band but will in most cases be possible to separate by using some kind of manipulation of the digital information in the red and NIR-bands.

The soil curve in Figure 6 shows much less variation than the vegetation curve. If it had been a humid soil it would have had pronounced dips in reflectance similar to the vegetation curve. But soil reflectance is also affected by texture, colour (presence of different oxides, etc.) and the content of organic matter. These factors are all interrelated; a clay soil has higher water retention than a sandy soil and low content of organic matter also has a negative influence on the water holding capacity of a soil.

Water absorption will affect the reflection making dry soils reflect more radiation than humid and coarse textured soils more than fine textured under normal humidity conditions. If the soils are extremely dry, a coarse grained soil will cause a more diffuse reflection which lowers the reflected radiation from such a soil. The influence of water is present already in the visible part of spectrum but it gets even more accentuated in the NIR-band.

Water itself does not reflect much energy at all. On the contrary, water is a good absorber of energy, and is also emitting radiation in the longer TIR-band. At wavelengths over 0.6 μm most of the incident radiation is absorbed. To distinguish water bodies from other features radiation in the NIR band should be used since water will appear as almost black in this range of spectrum. Reflection is highest towards the blue band and into the UV-band.

The reflectance of water is influenced by water quality, that is, by the presence of particles in the water. Increasing concentration of particles will decrease the transmissivity. Water absorbs energy in all bands and consequently it is only the surface water that is penetrated and from which reflections may be recorded by photographic or passive sensor remote sensing systems. Underwater remote sensing is applying other methods, using active systems such as the echo sounder and side looking sonar.

6. Aerial photography

Aerial photography is the most wide-spread remote sensing method but it has been submitted to competition from satellite sensors since data from the latter became generally introduced in 1972. Recently the digital camera revolution has also reached into professional surveying aerial photography and many mapping and surveying agencies around the world has invested in digital aerial cameras in order to record digital images instead of using photographic film. The shift started around the year 2000 and by today, 2011, the standard product for mapping is a digital aerial photograph in many countries.

Generally available historical aerial photographs are **panchromatic**, that is black and white, and **colour** photographs being sensitive to radiation in the visible part of spectrum. By the use of special film emulsions sensitive also to radiation in the lower end of the NIR band, **IR-panchromatic** and **IR-colour** photography may record radiation up to around 0.9 µm.

Digital aerial cameras normally operate in four wave bands, blue, green, red and near infrared. Since the delivery of these images is in digital format, the initiated user can assemble either a standard colour product (using the blue, green and red bands) or a colour infrared (CIR) product using the green, red and near infrared bands. More about this is to be found in the section on Multispectral images (section 9).

The sensitivity of ordinary film emulsions is close to the sensitivity of human eyes, making objects on the photographs look very similar to the way humans see them. The advantage is that interpretation of photographs is quite easy and intuitive, since the objects look familiar even to the non-experienced interpreter.

IR-emulsions give a different result since ordinary objects may have very different reflection coefficients in the visible and NIR bands, e.g. rendering an object that is dark in the visible wavelength band very bright when using IR-film.

As the name indicates, aerial photography uses an aeroplane as the camera platform, taking vertical or oblique photographs. Vertical photographs are exposed with the lens axis as vertical as possible (slight deviations from the absolute vertical is always present, since the aircraft is not a stable platform). Oblique photographs are taken with an intentional deviation from the vertical axis, giving panoramic views.

The camera uses a lens (or rather a complex combination of several lenses with different convexity and concavity assembled in a ”tube”, referred to as lens) to gather and concentrate the radiation on the film. This will influence the geometrical properties of photographs; cameras produce images that are called **central projections** (Figure 7). This projection owe its name to the fact that all radiation passes through a central point within the lens, normally where the diaphragm is located, and then fans out on the film. This gives rise to a radial displacement of objects reproduced in the image.

It is impossible to use an aerial photograph for geometric correct mapping without applying correction measures. This could be done by using instruments of the ”Zoom transfer scope”-family, designed to allow a certain amount of rotation and stretch, as well as scale transformation, making it possible to adjust a photograph to a map projection.

By the introduction of digital photography for aerial imaging the handling systems have also shifted towards computerised operations. In a contemporary mapping project, the images are handled by a computer and dedicated software is assisting in deriving different types of information from the images. The images are geometrically corrected and registered to a known map projection and coordinate system using the computer. Mapping is normally done on screen and different objects are digitised using a GIS or Remote Sensing software. The advantage is that the resulting maps are produced with a corrected geometry that fits directly to existing maps.

If two photographs overlapping on the same area were taken with a certain distance between the camera positions as is the case in aerial photography objects would be reproduced from slightly different angles. Putting the two images together as they were photographed will create a three-dimensional image, a **stereo-pair**.

In the stereo-pair an apparent change in relative positions of stationary objects caused by the change of viewing position will be present, often referred to as **parallax**. The change in relative positions will be more apparent in object close to the camera (mountain peaks, buildings, trees, etc.) than in objects far away. As parallax increases when the distance between camera and object decreases, and the geometrical laws controlling parallax are known, it is possible to obtain measures of different.

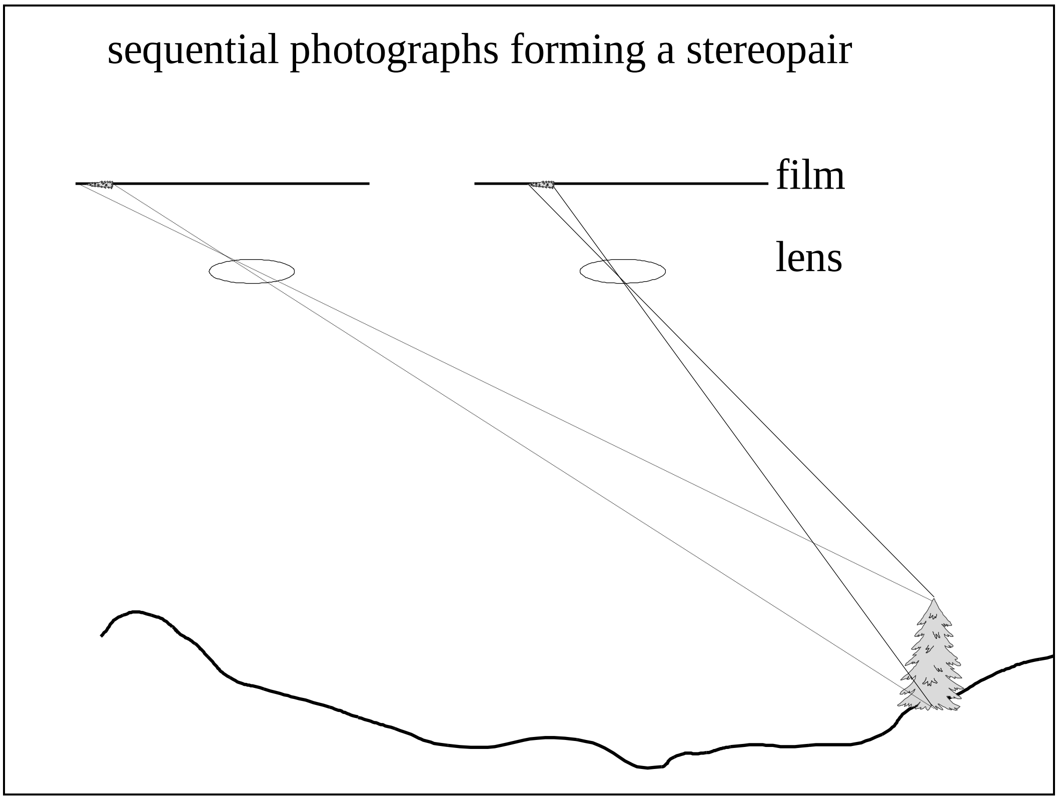


Figure 7: In the central projection the image generating radiation is recorded by a lens. The geometrical distortion makes imaged objects that have a vertical extension radially displaced. The two trees have their trunk and crown placed on a vertical line. In the recorded image, the crown is radially displaced so it seems to be at another location than the trunk.

This property of the aerial photography is the basis of **Photogrammetry**, the science for quantitative image analysis mainly working with the production of topographic maps. The stereo-pair will also be relatively free from geometric distortion if appropriate restitution measures are applied permitting the mapping of features ”where they are” from the photographs to produce topographic and other thematic maps. This demands the use of special precision instruments called stereo-plotters and skilled operators. These have to a large extent been replaced by computer algorithms that make the same operations on digital images.

The aerial photograph has a geometrical resolution that was determined by the silver oxide grains that was used as the radiation sensitive medium on the photographic film, and today, when using digital cameras, by the number of pixels used to capture the reflected radiation. Depending on the airplane flying altitude this translates to a ground resolution that indicates the smallest possible detectable object in the image. The ground resolution has evolved over time due to development of higher resolution film emulsions starting at around 1 m in older images from the time around World War II and ending presently at about 15-25 cm for images taken at a standard altitude of about 4500 metres. The image examples below (figure 8 a-e) illustrate and try to give an impression of what this translates to when it comes to information content in the image. It also illustrates the difference between Black and white, colour and NIR colour images.


Figure 8 a: Aerial photograph 1940, 4600 m flying altitude, ground resolution approximately 1 metre


Figure 8 b: Aerial photograph 1989, 4600 m flying altitude, ground resolution approximately 1 metre


Figure 8 c: Colour aerial photograph 2007, 4600 m flying altitude, ground resolution approximately 1 metre

Figure 8 d: Colour digital aerial photograph 2010, 4600 m flying altitude, ground resolution approximately 0.25 metre

Figure 8 e: Infrared (NIR) digital colour aerial photograph 2010, 4600 m flying altitude, ground resolution approximately 0.25 metre

Besides the qualitative and quantitative advantages with aerial photography described above the high resolution on the ground permits the identification and mapping of very small objects, and gives them an obvious advantage over satellite imagery for local surveys.

The main difference between photographic and sensor based remote sensing systems is that the photographic medium (the film emulsion) collects data over a broad range of wavelengths and sensors are normally tuned to collect data from only a limited wavelength range.

Photographic remote sensing systems reproduce an average image of the reflected energy from a surface without considering the differences that might occur in reflectance in different wavelengths bands. This is a disadvantage since many objects are impossible to separate when studying only the average reflection.

One way to overcome this is to use several cameras simultaneously loaded with different kinds of film and with filters permitting only selected parts of the spectrum to pass and be recorded on the film.

With the introduction of digital aerial photography, this disadvantage disappear, and as stated above, digital photographical systems normally records in four wave bands, blue, green, red and NIR. It is important to be aware and understand this difference between analogue and digital imaging systems.

To summarise it is appropriate to use aerial photography when the area of interest is small or relatively small, the area of interest is heterogeneous, objects of interest are tiny or the mapping units small, the objects of interest can easily be identified in the visible wavelengths, and when stereo-pairs and 3D interpretation will improve the results.

7. Satellite sensor systems

Satellite sensors have with very few exceptions always been based on digital technology. To understand the difference between photographic remote sensing and sensor remote sensing it is important to understand the fundamental difference between **analogue** and **digital** data. Analogue data can be described as if recording data on a ruler where the data can be assigned to any value on the ruler (e.g. recorded in real numbers).

A panchromatic photograph has a successive transition of different shades of grey between ”absolute” white and ”absolute” black and the photograph can theoretically contain an indefinite number shades of grey. The actual number of shades is controlled by the capabilities of the photographic mediums (film and paper) and the processing (development, etc.). In digital imaging data can only be assigned to selected number of different values on the ruler (normally recorded as integers). A digital image can thus contain only a definite number of shades of grey.

The number of shades (levels) is determined by the system capacity handling the data. The normal case for satellite sensor data is a 256 (8-bit) level resolution recorded in integers ranging from 0 to 255 where 0 is no reflection (black) and 255 is maximum reflection (white). However, with the reduction in size of electronic components and devices some recent satellites are using 16 or 32 bit pixel values, improving the number of “shades” significantly. Actually it is exactly the same development that is on-going for ordinary digital cameras, improving image quality significantly.

Sensor data acquisition

A sensor is composed of several **radiation detectors**, an electronic device that is sensible to radiation very much similar to the CCD-sensor in an ordinary digital camera. By using different construction materials, by incorporating a filter, or by splitting the incoming radiation with a prism or other device, it is possible to record radiation only in a selected wavelength interval. The analogy to digital cameras is still strong; an ordinary digital photograph can normally be split into three separate black and white pictures, representing the blue, green and red wavebands of spectrum.

Assembling a set of radiation detectors (with different wavelength band sensitivity) and adding the necessary hardware will result in a **multispectral** sensor. The recording of image generating data by multispectral sensors is often performed by **multispectral scanning**. Multispectral since data is recorded in several discrete wavelength bands, scanning since the data acquisition involves data recording along a **scan line** perpendicular to the flight direction of the recording platform (aircraft or satellite). A set of sequential scan lines will eventually build an image (Figure 9).

The smallest element to be detected by a sensor is called the **geometric resolution** of the system, and is determined by the sensor construction. Some aspects of ground resolution are mentioned below. Incident radiation on the radiation detector is the reflection from an area on the ground that has the size of the ground resolution.

The detector will measure the average reflection in a selected wavelength band. The result will be recorded as an image element on the scan line called a **pixel**. A pixel is normally a square and when speaking of the ground resolution of a certain sensor system it is the pixel size that is cited, e.g. 80 m pixel size means that the smallest image element records the average reflection from an area of 80 by 80 m (6400 m^2). In some cases it is possible to identify objects smaller than one pixel.

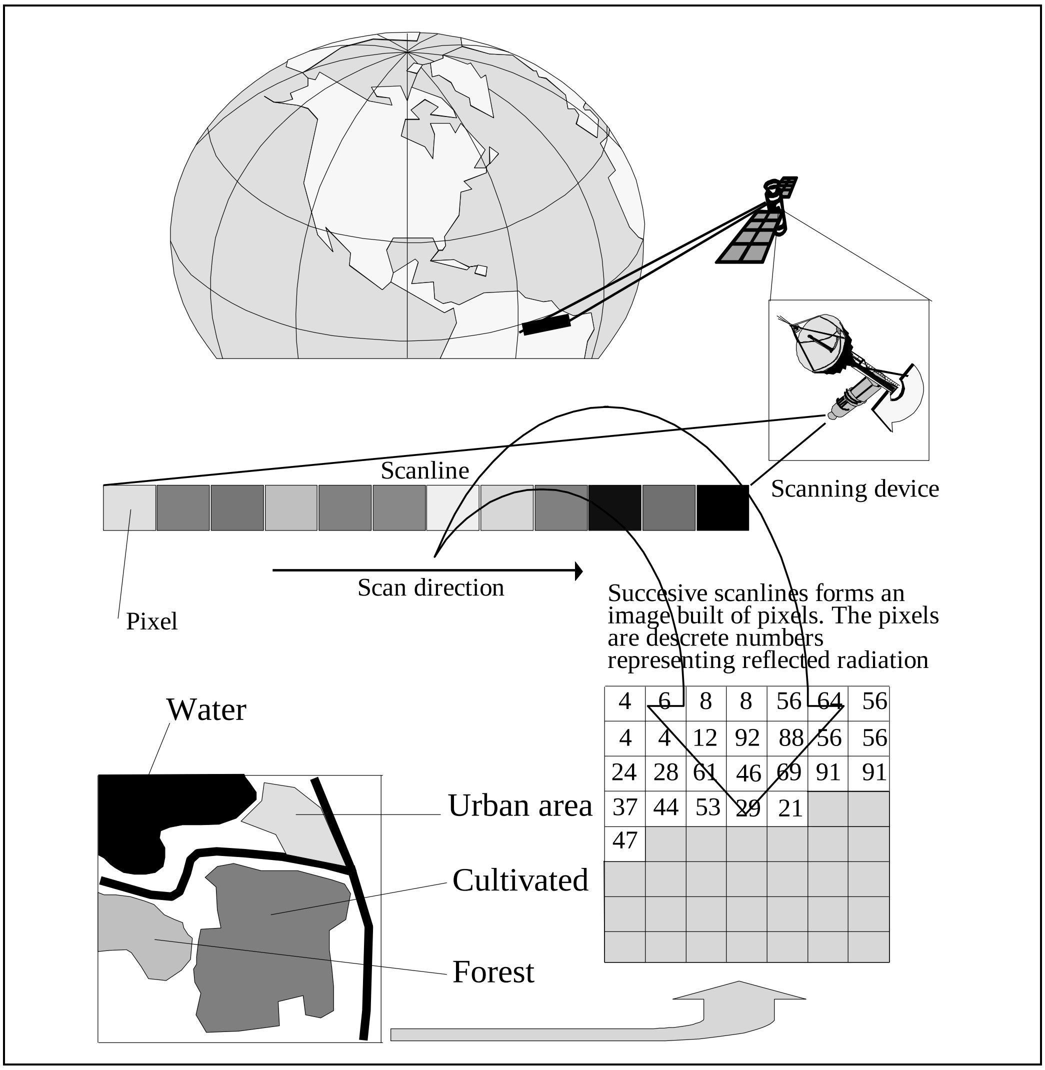


Figure 9: The chain of satellite data acquisition. The scanning device records data, pixel by pixel, along a scan line. Assembling the scan lines gives an image. The radiation is recorded in grey levels, most satellite sensors have an 8-bit resolution that permits 256 levels.

Consider a dry water course passing through an irrigated agriculture area. The reflectance from the river will differ very much from the surroundings since it lacks vegetation and has a bed of coarse sand and gravels with a high reflectance. The radiation detector will take an average reading from every pixel in the area. Pixels containing only irrigated fields will have a low reflection and appears dark on an image. Although the river is only 20 m wide it will significantly influence the average reading of the reflectance from all pixels it passes through. This will render these pixels brighter than the surroundings and on an image a series of pixels, following the river bed will get significantly different radiation readings, making the river appearing as a line on the image.

To summarise a satellite (sensor) image is built by pixels (the smallest element in the image). A number of pixels are forming a line (scan line), recorded perpendicular to the flight direction of the sensor platform. When arranged properly using dedicated software the lines form an image.

Multispectral scanning systems are mainly of two different types, **scanning mirror systems** and **push-broom scanning systems**. The scanning mirror systems uses a rotating scanning mirror that collects data along a line perpendicular to the direction of satellite movement as illustrated in figure 9.

This system may theoretically use only one radiation detector for each wavelength band, sampling and transmitting the radiation measure, pixel by pixel, to a recorder as the mirror sweeps along the scan line. The ground resolution or spatial resolution of a scanning mirror system is determined by the scanning speed of the mirror, the sampling frequency of the radiation detector, and by the ground speed of the platform.

Push-broom scanners use arrays of radiation detectors. Every array has a number of radiation detectors assembled in a line that has as many detector elements as the scan line has pixels. This means that all pixels in the scan line is recorded simultaneously. The advantage of this construction is that it has no moving parts, making it less sensitive. The disadvantage is that if one detector element ceases to function, the scan line will lack data in the pixel recorded by this detector until it is repaired.

Radiometric resolution of a sensor system is the number of wavelength bands that are recorded and the width of each band. Different satellites records in different bands and with different bandwidth. The number and width is determined by the application that the satellite sensor is intended for. Normally a satellite recording of multispectral data has one or more channels in the visible band (but not in the blue part) and at least one in the NIR-band.

Satellites constructed for resources monitoring normally follows an orbit that passes over the North and South Pole. They are sun-synchronous which means that they pass over the equator at the same local time during every lap of the orbit and at about the same local sun-time at any other point on the orbit.

This is to assure as similar conditions as possible during the recording of subsequent images of the same area. If images of the same area were recorded during different times of the day the incident solar radiation would vary heavily causing the radiometric properties of the images to be very different.

The recording of an image is completed during a time laps of less than one minute. Even during such short time the rotation of the earth will introduce some geometric errors causing the images to be slightly skewed. This will be further discussed in the next section.

8. Pre-processing of satellite images

Before using the satellite images it is necessary to compensate for different inherent errors. The common name for techniques applied to compensate and correct errors and distortions in the images is **pre-processing**. Corrections are divided into two categories, **geometric correction** aiming to correct geometric errors in the data acquisition system and to register the satellite image to a map projection.

Radiometric correction is the correction of radiometric errors due to sensor specific errors and to the atmospheric condition during recording. For many applications the corrected image is also treated by different **image enhancement** techniques to improve the quality and facilitate the analysis.

Geometric correction

Geometric distortions in the raw satellite image are so apparent that the images may not be used without applying some correction algorithms. Errors in the geometry of the image originate from many different sources. Variation in altitude, ground speed of the satellite, attitude, difference in the scan speed of a scanning mirror, rotation of the earth during the registration of an image, earth curvature, and relief displacement all needs to be compensated for.

Many distortions are systematic which means that they follow a known pattern and can thus easily be corrected. Other distortions are random or unique for each image and needs supplementary information to be corrected. The satellites ground speed, attitude, altitude, etc. are monitored during flight, and corrections for variations are normally applied before commercialisation of the images. Registration of the satellite image to a map projection is carried out only on request or can be done by the advanced user having access to necessary hard and software, and possessing enough knowledge of the area to be resampled.

The resampling process is illustrated in Figure 10. A regular map grid is superimposed on the skewed satellite image. To do this it is necessary to have a certain number of **ground control points** (GCP) with known x and y co-ordinates in the desired map projection that can be identified on the satellite image. Good GCP's are located on distinct features in the images, a road crossing, river bend, etc. Assigning values to the new pixels may be done using several different resampling algorithms.

The **nearest neighbour** resampling simply takes the value from the closest pixel in the original image. The original values are kept, but the image will suffer from a certain displacement error.

Bilinear interpolation uses the weighted average of the four closest pixels. This alters the original measurements of reflected radiation generating an image that will look smoother than the original.

Cubic convulution resampling uses the 16 surrounding pixels to assign new values to the pixels in the resampled image. Since both bilinear interpolation and cubic convolution transforms the original radiation measurements they are preferably applied after the image has been analysed.

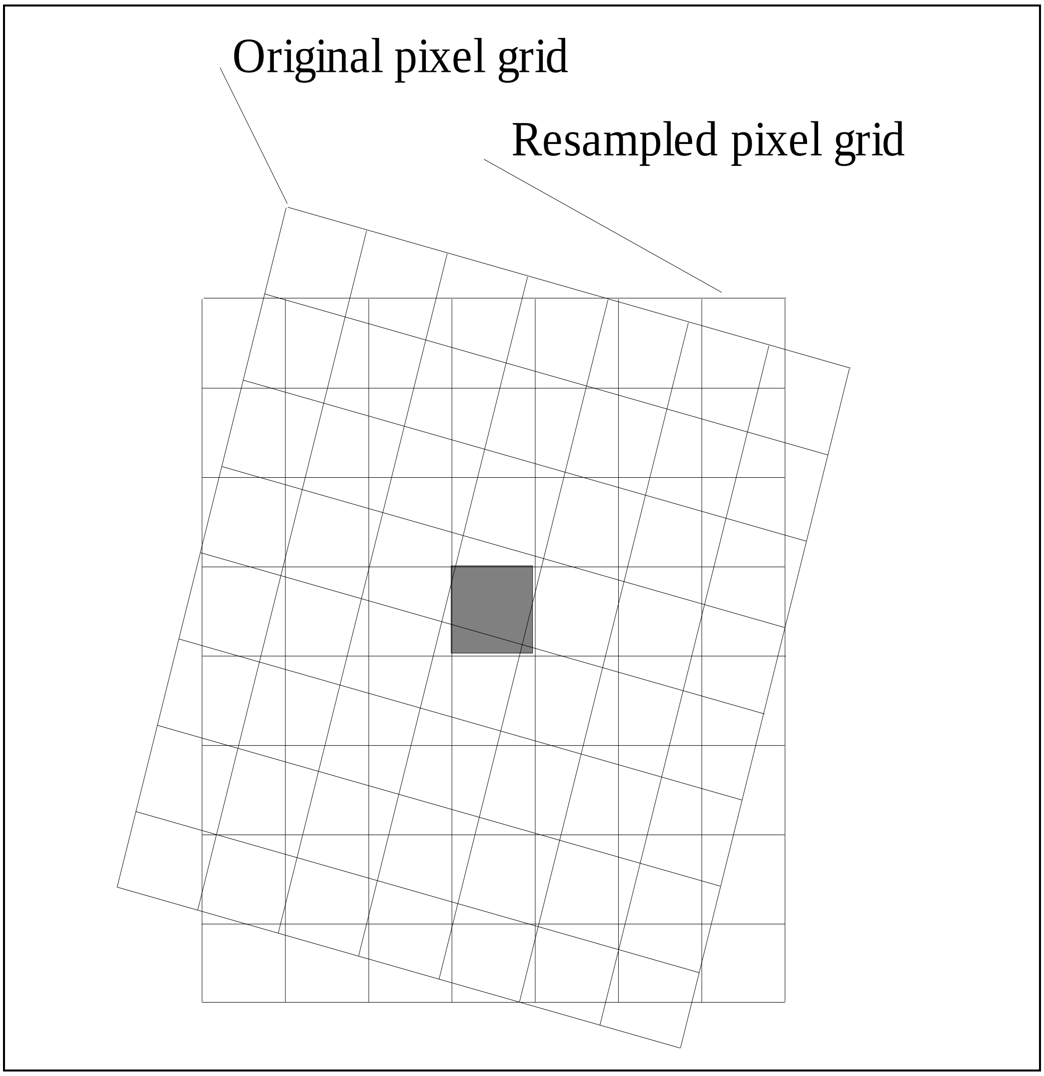


Figure 10: Geometric resampling of the inclined original pixels to a map-grid. During this procedure, the original pixel values are affected. This will result in a lower spatial resolution.

Resampling will also influence the spatial resolution. A satellite registration with an original pixel size of 20 m can be resampled to virtually any output pixel size. But as shown in Figure 10 the resampling processes uses the information on reflected radiation from a larger area than just one pixel which reduces the spatial resolution.

Images that are destined for manual interpretation on hardcopy or on screen are often resampled to a smaller pixel size than the original image. This gives an apparent improvement of the image sharpness removing some of its pixel inherent characteristics and rendering it closer to the aerial photography in appearance. The smaller pixel sizes are however only an apparent increase in spatial resolution as the actual resolution can never be higher than the original pixel sizes, and in most cases it is lower than in the raw image.

Radiometric correction

Radiance measurements are influenced by the construction of the sensor and of the prevailing conditions when the measurement was made. Sensor specific variation needs to be corrected when data recorded by different sensors are to be used as when monitoring changes over time. The normal procedure when applying corrections for this type of variation is to transform the digital numbers (DN) normally ranging from 0-255 in an image to absolute radiance values. The relation between sensor response and absolute spectral radiance is normally linear. The transformation into absolute radiance is performed by using this knowledge of the sensitivity of the sensor over a given wavelength band. Normally this type of information can be obtained from the organisations distributing satellite images.

Correction for the prevailing atmospheric conditions during recording is needed if more than one scene is to be treated in the same study. Haze is often present and its influence needs to be compensated for by applying some kind of haze correction. The most obvious way to do this is to use GCP's with an expected zero reflectance such as water in the NIR-bands. Reflections recorded over water should be due to the scattering in the atmosphere and may be subtracted from all pixels in that band.

This assumes that the haze effect is evenly distributed over the scene which is not obviously true. In very delicate studies involving absolute measurements of the reflected radiation from different objects, the DN needs to be transformed to absolute radiance <u>and</u> radiometric measurements of different objects on the ground during the passage of the satellite is needed for calibration of the satellite data.

Topography also influences the radiation recorded by the satellite sensor as well as the angle of incident energy (the sun angle). Some pixels have angles and aspects accentuating the reflection towards the satellite sensor while others will reflect the radiation away from the sensor. Thus the same object will look differently depending on its topographical location. Radiometric corrections normalising the radiance to a predetermined incident and reflection angle will help overcome this problem.

Noise is unwanted signals caused by limitations in the sensing process, either during recording, transmitting or storing image data. This can be due to malfunction of the sensor, electronic interference between different components in the sensor, or similar problems during transmitting or storing the data. Normally the systematic sources are known and corrections are applied automatically before any customer gets in contact with the data.

In many applications it is not necessary to make precise corrections. Mapping accuracy will of course benefit if corrections are applied but it is only absolutely necessary when studying changes over time or space involving several sensor images. Basic radiometric corrections to compensate for sensor specific variations might be requested when ordering satellite data.

Contrast stretching is a frequently applied method of image enhancement, particularly when the images should be used in manual interpretation on hard copies. This process is similar to contrast manipulations applied on ordinary photographs using different processing of film and print or by using photographic paper with different contrast grades. The total recording capability of shades of grey in satellite sensor images is normally 256, where zero represents ”black” and 255 ”white”. The actual range of a typical image seldom spans the 256 levels. A normal scene might have reflection levels ranging from 60 to 180. This means that levels 0 to 59 and 181 to 255 are empty, that is, no pixels have theses values.

Contrast stretch aims to make use of the total range of grey levels by assigning the lowest value in the scene to zero and the highest recorded value to 255. In the simplest form of linear contrast stretch 60 in the example above will be assigned to the level zero and 180 will be assigned to the level 255. The other values in the scene will be evenly or linear distributed in between. The resulting image will have a larger spacing between the recorded pixel values than the original image where the pixel values were crowded in the range 60 - 180.

Several other techniques for image enhancement are available all aims to produce images that are better than the originals for a specific application. Some of them involves quite advanced algorithms while others are simple grouping of data in different ways. A complete review of these methods is outside the scope of this paper. The section of selected reading contains textbooks and papers treating the subject more thoroughly.

9. Multispectral images

Digital photography and satellite sensors generate data files that are stored in different ways depending on how the software engineers have designed the software handling the images. In the early days of satellite imaging the data formats where differing from one satellite to another but later the development has seen a certain amount of standardisation and most satellite images and digital aerial photographs of today are stored in TIFF-format, that, after the image has been geometrically corrected and registered to a proper coordinate system are called GEO-TIFF.

As both types of sensor systems generates multispectral data, recorded in separate wavebands or channels, at least four different bands, a problem arises when displaying the data on a computer screen or making a hard copy print-out of an image. Our computer systems are designed to generate colours using only three “channels” but the image contains at least four so one of the bands could not be displayed. When generating a “True colour image” the blue, green and red wavebands are mapped to the colours blue, green and red in the computers visualisation system. However, following the discussion on reflectance from different objects in the section 5 above, we are often interested to use at least the NIR information that is recorded.

In order to solve this problem, a **False Colour Composition** (FCC) image is generated. Figure 11 tries to illustrate how an FCC is generated. As seen, the reflection from the blue part of the spectrum is omitted in the FCC. The main reason to this is because Rayleigh scattering is highly influencing this part of the spectrum and this generates quite high levels of noise. Thus the image quality in the blue band is quite low and actually many standard satellite sensors is not even designed to record radiation from that band. Instead the reflected radiation in the green band is mapped to the colour blue, reflection in the red band to the colour green and the NIR reflection mapped to the colour red. The FCC, or as it sometimes is called when the image is a digital air photo, the CIR, generated in this way will exhibit colouring that differs from how we normally percept the world around us. This makes a displayed satellite image look unfamiliar to the non-experienced user. Bedrock that is greenish, as many shale rocks will look blue, the strong reflection from vegetation in the NIR band will render it red or reddish in colour etc.

When data from earth observation satellites first became commercially available the mapping potential of satellite images and the possibilities to classify the images into useful classes that relate to real world objects where severely overestimated by the user community. In the beginning manual interpretation prevailed but as computers became generally available digital image processing gained ground and manual interpretation was considered inferior in all aspects. After a while the users became aware of the limitations with computer classification and the interest of manual interpretation was restored. In many applications the digital images are in a first step treated by computers to produce images that have the specific properties needed to achieve an application. The actual interpretation and mapping are made on the computer screen or sometimes on print outs. In the final step the result from manual interpretation is converted to digital format and the final treatment is made by computers.

However, the computer classification software is constantly developed and improved and particularly when it comes to classifications that involve more than three spectral bands, computer classification is more efficient than human interpretation. This is particularly true for the so called hyperspectral satellite data, when more than 100 wavebands are used to distinguish different types of objects from each other. However, even given this, image classification by computers is still very much something for a limited user community of experts, quite often in research or research-like environments. For most everyday tasks in public service or private industry, manual interpretation is a more straightforward approach where you do not really have to bother about classification algorithms, accuracy statistics, ground truth sample sizes, etc. Using a true colour printout most people are able to make out the general and most important features in the area covered by the image.

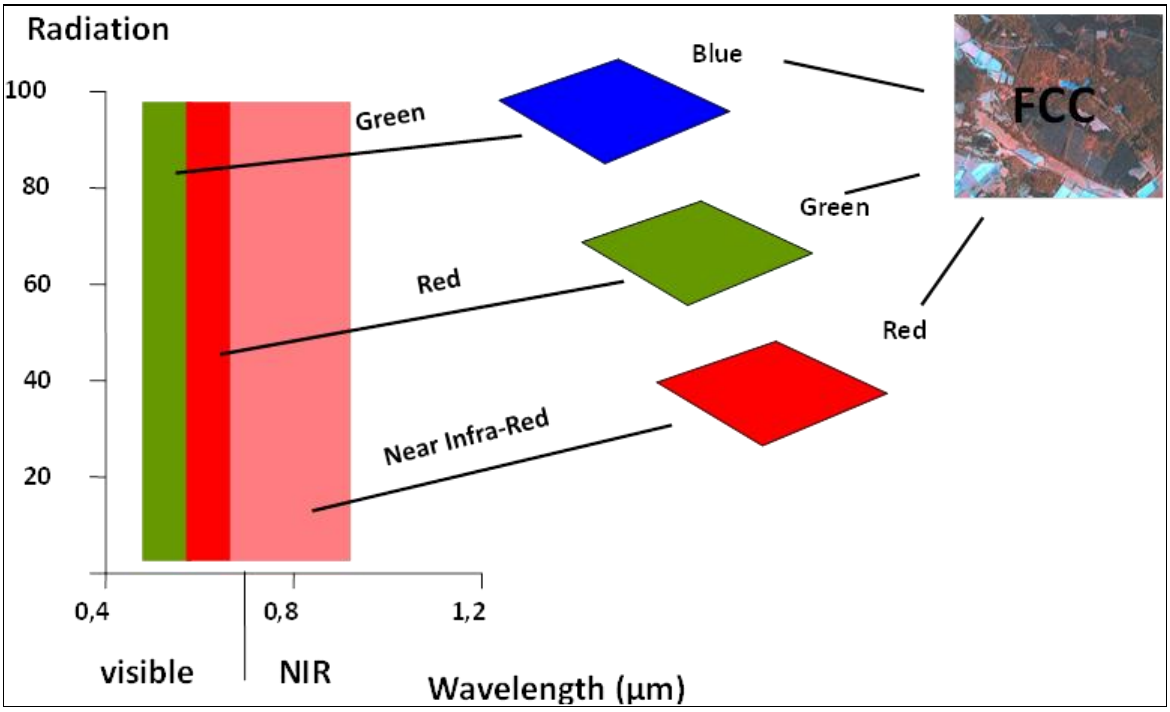


Figure 11: The recordings of radiation in the green, red and near infra-red parts of spectrum are re-mapped to the colours blue, green and red when printed or displayed on a computer screen. The colouring of known objects will differ from what we normally see - one example is vegetation that is reproduced as red, since the reflection from healthy vegetation is important in the near infra-red radiation band.

Recently efforts have been made to combine the advantages of computers and human interpreters in so called expert systems. These are computerised systems that used the experience of humans as input in the image classification process. They contain algorithms able to consider the results of a previous classification and introduce the experience acquired during other interpretation sessions to improve the results of the study at hand. These systems are however still on a very experimental stage, and will not become operational before undergoing more development.

Digital data processing

It is recognised that computers are efficient for pre-processing and pixel by pixel processing of digital images; geometric correction, radiometric correction, and to create different ratios between wavelength bands, etc. The advancing computer technology makes image processing systems more readily available for any user. The advantage is that the user with a certain amount of knowledge can perform image corrections and manipulation aiming to improve the image for a specific application purpose. In many studies it is necessary to combine image data with data from other sources to improve the interpretation results and this is only possible by using digital data and computer assisted processing.

A main advantage working with digital multispectral data recorded in several distinguished wavelength bands is that many natural objects have different reflection properties in different wavelength bands, and only the processing of the bands in different combinations allows them to be identified and separated. Reflectance for a given pair of objects may be very similar in one part of the spectrum and very different in another part. The constructors of the current satellites have considered this when deciding on the radiometric resolution of the sensors.

Vegetation mapping is an example of digital treatment of satellite data enhancing the interpretation results. Mapping vegetation proved to be quite difficult. The reflectance from vegetation resembled the reflection from many other surface features. By using digital data permitting virtually all kinds of manipulations of the pixel values the recorded reflection from the NIR-band and the red-band was used to create a ratio forming a new image that emphasis the vegetation and decreases the influence of other objects. This ratio is called the **Normalised Density Vegetation Index** (NDVI) and has become a standard in the mapping of living green biomass. The creation of this index would not be possible if photographic data was used.

Manual interpretation

A human interpreter is superior to the computer when it comes to identifying patterns and objects in the images. The main disadvantage with a human interpreter is the relative subjectivity that is impossible to avoid. If multi temporal comparisons (comparisons over time) are to be made it is wiser to use some kind of index or absolute physical measurement of the objects of interest to avoid the influence of subjective interpreters. Image interpretation is performed on FCC's in the same way as ordinary aerial photograph interpretation. Besides what was discussed in the previous sections the properties of a FCC differs from an aerial photograph in that the FCC is built of three discrete wavelength bands. A photograph is the reproduction of the average reflection over a broader wavelength interval. On normal colour photography any person will be able to discriminate between basic objects, such as forest, cultivated fields, grazing land, roads, building, etc. An FCC shows these features in a different way because it is made of radiation from a different part of spectrum. Normally an FCC don't contain any radiation from the blue band. It is a combination of green, red and NIR radiation, with the three bands mapped to different colours. Radiation from the green band is mapped to the colour blue, red to the colour green and NIR to the colour red. This gives an image with roughly the same appearance as a colour-IR photograph. The resulting image will show vegetation as red, with an increasing saturation as the vegetation cover increases.

10. Satellite examples

The LANDSAT-satellite family uses a scanning mirror system for data acquisition. The LANDSAT, launched by the USA in 1972, was the first satellite having generally available high resolution data. Geometric resolution of the first generation of Multi Spectral Scanning (MSS) data was 80 by 80 m and the sensors on board was recording radiation in four wavelength bands (Figure 12).

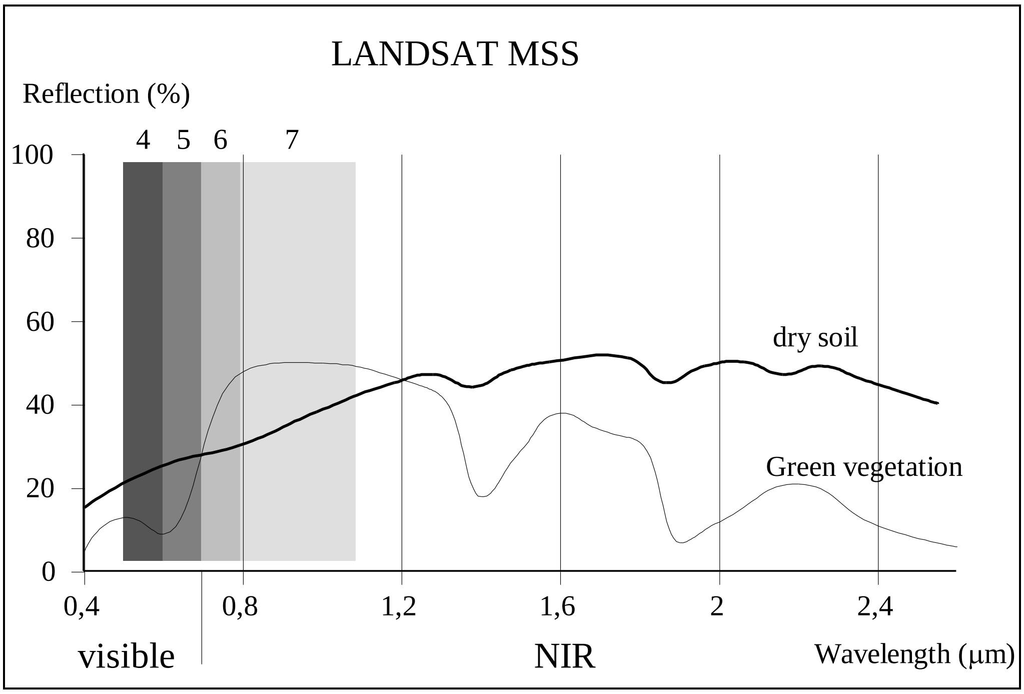


Figure 12: The LANDSAT MSS sensor was one of the first commercially available satellite data sources. The first satellite was launched in 1972. The pixel size is 80 m. One LANDSAT scene covers 185 by 185 km. The satellite registers radiation in four wavelength bands (in µm); the MSS4=0.50-0.60, MSS5=0.60-0.70, MSS6=0.70-0.80, MSS7=0.80-1.10.

A second generation of LANDSAT satellites that became operational in 1984 contains two sensors; the MSS and the Thematic Mapper (TM) that records the radiation in seven bands (Figure 13) being an improvement of the radiometric resolution derived from experiences gained with the MSS-data. The spatial resolution of the TM-data is also higher - the pixel size is 30 by 30 m. The coverage of one LANDSAT scene is 185 by 185 km on the ground for both sensors. The current version of the Landsat satellite is Landsat 7 that carries the ETM+ (Enhanced Thematic Mapper) was launched in 1999 and capable of generating 15 by 15 m resolution images.

The LANDSAT programme is the longest continuous programme for recording data of the surface of the Earth since it started already 1972. Currently the NASA and other US interests are planning the Landsat Data Continuity Mission (LDCM) that will take over after the LANDSAT 7. It will probably be launched late 2012 and contains a sensor that is very similar to the ETM/ETM+, with a maximum geometrical resolution of 15 m except for the thermal band that has a 100 m resolution. It will also expand the radiometric resolution by the addition of several new channels in order to cover not only terrestrial applications and improve its use for marine applications.

The temporal resolution (time between sequential images) of most of the Landsat family sensors is 15 days.

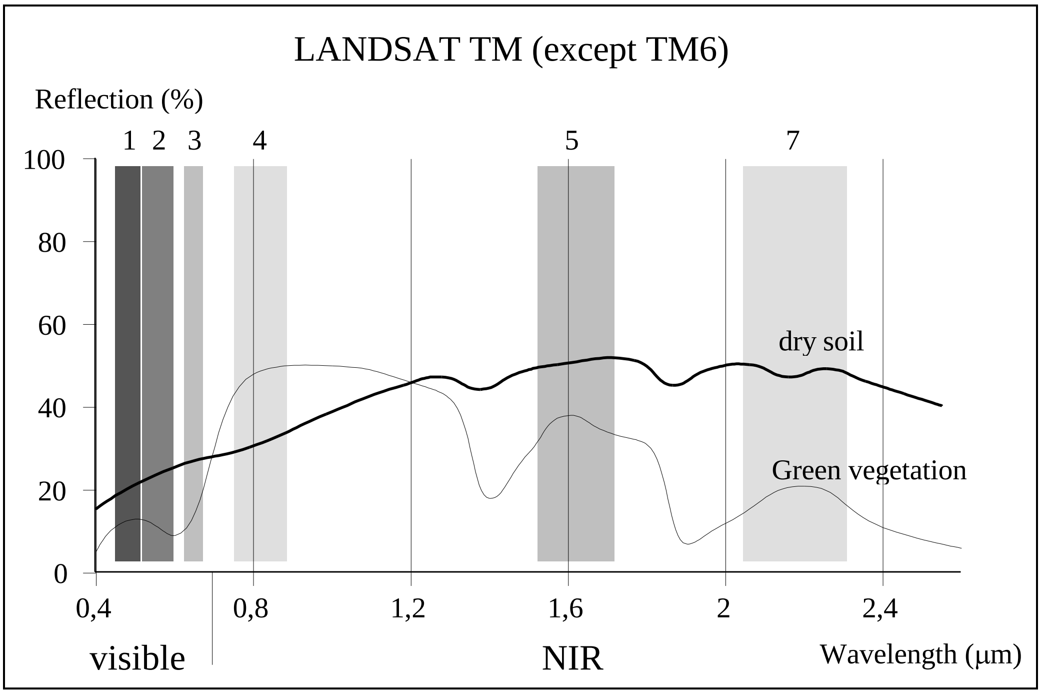


Figure 13: The wavelength bands of the LANDSAT TM, ETM and ETM+ sensors. This satellite has a very good radiometric resolution, recording seven bands. Note that band 6 (TM6) records radiation in the 10.4 - 12.5 μm band (Thermal Infrared) and is not shown in the figure. The other wavelength bands are recording (in μm) TM1=0.45-0.52; TM2=0.52-0.60; TM3=0.63-0.69; TM4=0.76-0.90; TM5=1.55-1.75 and TM7=2.08-2.35. The spatial resolution is 30 m for the TM and 15 m for the later ETM and ETM+ sensors, except for band 6 that has a 120 m pixel size.

The SPOT-satellite family was launched in 1986 and is based on the push-broom sensor technology. The sensor is called High Resolution Visible (HRV) and the satellite actually carries two parallel sensors capable of recording radiation either in panchromatic mode or in a three band multispectral mode (Figure 14). In the construction of the satellite sensors special attention was made to ground resolution. The pixel size in panchromatic mode is 10 by 10 m and 20 by 20 m in multispectral mode. The HRV sensors are movable, having the ability of recording data both vertically under the satellite, and oblique. The temporal resolution is 15 days.

The oblique option of the sensor makes it possible to get very frequent recordings from the same area and to assemble stereo pairs. Using photographic prints of the satellite images makes it possible to make topographic maps with the same instruments that are used in aerial photography photogrammetry. Lately the process of topographical mapping has been automated by using dedicated software on the digital satellite data. Obviously the

LANDSAT satellite data has a much higher radiometric resolution, which often is more important than spatial resolution in remote sensing applications.

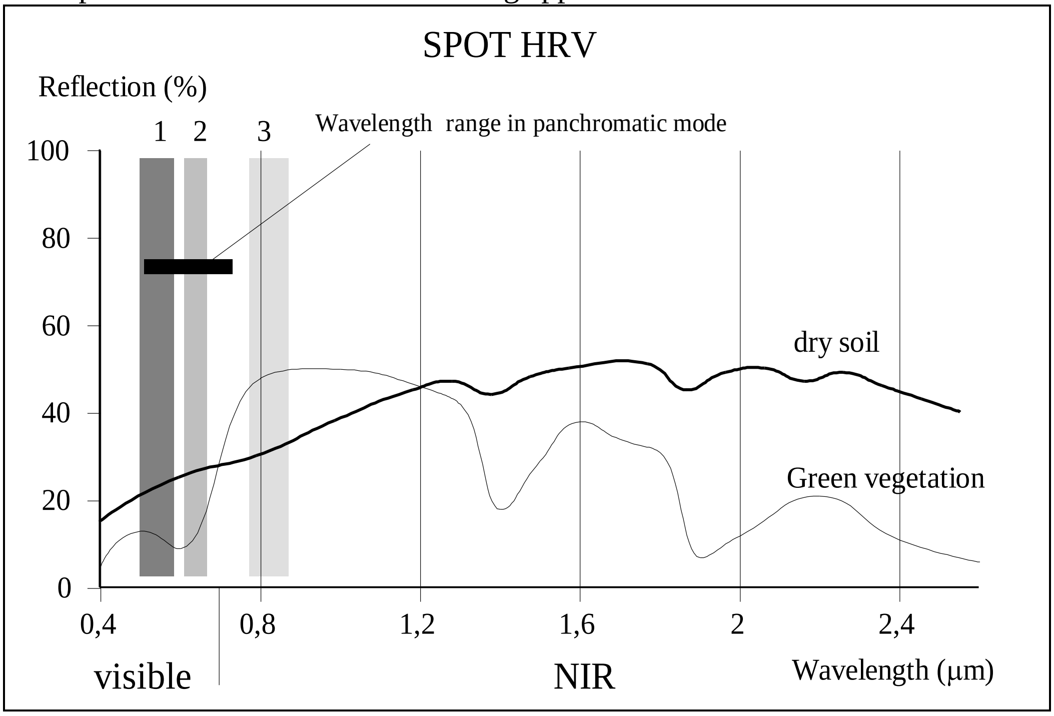


Figure 14: The HRV sensor onboard the SPOT satellites has two recording modes, panchromatic (P), recording from 0.51 to 0.73 µm and multispectral (XS) mode recording in three bands, 0.50-0.59, 0.61-0.68 and 0.79-0.89 µm. Ground resolution was 10 m in P-mode and 20 m in XS-mode for the first generations of this sensor that was improved in the later versions to 5 m in P-mode and 10 m in XS-mode.

The Hyperion provides a high resolution hyperspectral imager capable of resolving 220 spectral bands (from 0.4 to 2.5 µm) with a 30-meter resolution. The instrument can image a 7.5 km by 100 km land area per image, and provide detailed spectral mapping across all 220 channels with high radiometric accuracy. The coverage from this satellite is not world-wide it has a database of scattered recordings all over the world. It is more of a research satellite than actually providing operational data for civil service and private industry.

The ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is a Mainly Japanese funded multi-purpose satellite the records 14 wavebands from the visible to thermal IR with a ground resolution of 15 to 90 metres depending on waveband. It has stereo image capabilities and is intended for many different uses. It was launched in 1999. The temporal resolution is 16 days.

IKONOS is a high resolution satellite recording blue, green, red and NIR band data that has a pixel size of 1 m panchromatic mode and 4 m multispectral mode. The satellite has a stereo option and data can be used to create topographical maps with quite high resolution. It was launched in 1999 and has a temporal resolution of 3-5 days.

GeoEye 1 currently the top of the line of satellites when it comes to geometrical resolution. Its high technology instrumentations yield a resolution of 0.4 m in panchromatic mode and

1.6 m in multispectral mode. It records as most high resolution satellites, blue, green, red and NIR data and has a revisit period of 2-8 days. It also has stereo capabilities making it possible to derive topographic data from its sensors. The satellite was launched in 2008.

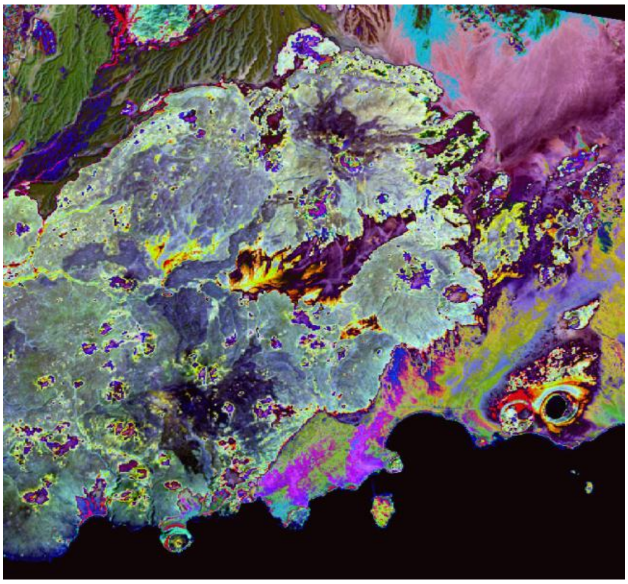
QuickBird is another of the modern satellite family members, recording blue, green, red and NIR data with a maximum resolution of 0.6 m (panchromatic) and 2.5-3 m multispectral. The satellite revisits the same area approximately every 3.5 days. It was launched in 2001.

World View 2 is a panchromatic and 8 multispectral (4 standard colours: red, blue, green, near-IR), 4 new wavebands: red edge, coastal, yellow, near-IR2 satellite with a 0.5 m ground resolution that has stereo capabilities and that could collect data from an area of 1 million square kilometres per day. The return period is about 3 days. This satellite was launched in 2009.

Future satellites will have an even higher radiometric resolution based on experiences from data available today. Many objects look very much alike when examined using data recorded over quite broad wavebands but if studied in the appropriate wavelength intervals it is often possible to separate them. Increasing geometrical resolution of satellite images is already at the same level as aerial photographs and most likely satellite images will replace the airborne systems for many applications. The space borne imaging instruments are relatively cheaper and generates continuous data, while the airborne instruments do not. So it is likely that satellite data will eventually be the main source of data for all types of inventories and mapping projects.

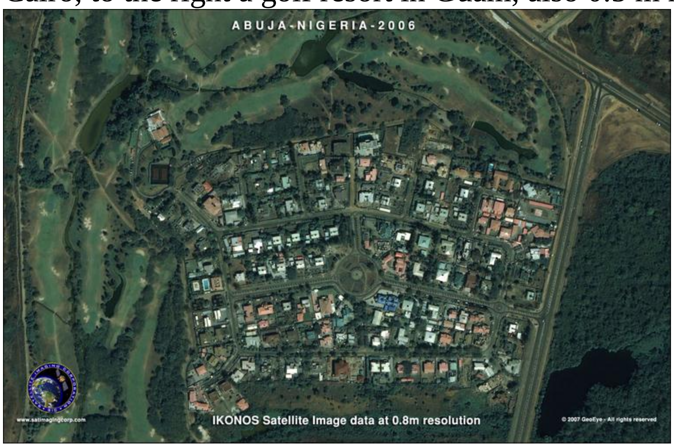
Satellite image examples (free downloads available from Satellite Image Corporation, http://www.satimagingcorp.com/about.html):

To the left a LANDSAT 7 image of Philadelphia, USA, 15 m resolution, and to the right 2.5 m High resolution SPOT 5 image of the airport in Tripoli, Libya.



Aster images, the left showing the great wall in China, the right is a different band combination assembled to detect geological strata in Yemen.

To the left a GeoEye 1 image with 0.5 m resolution showing the Tahir Square and central Cairo, to the right a golf resort in Guam, also 0.5 m resolution



To the left an IKONOS image of the Nigerian capital Abuja, to the right a Worldview 2image from Bangkok, Thailand, 0.5 m resolution.

11. Introduction to Geographical Information System (GIS)

As an option to a more traditional approach for different kinds of planning work and studies Geographical Information Systems (GIS) has become more frequently applied. This is due to the increasing capacity of modern computers and the development of specialised and user friendly software. Over the years since it first appeared, GIS has been associated with several different names, so sometimes you encounter Geographical Information Science (GIS), Geographical Information Technology (GIT), Geospatial Information Studies or Technology (GIS/GIT) and other denominations for what is basically the same thing.

In its essence, a GIS has capacity to handle spatial components of map data and non-spatial components. The basic idea is that every piece of information what so ever is connected to a certain location, that is, it has its geographic co-ordinates, and that is normally representing a specific phenomena in real life, having a specific shape and extent – this is the spatial component of map data. A GIS must also be able to handle the non-spatial characteristics (referred to as **attributes**) that describe the spatial components of map data.

So, map data is composed by two components. On one hand we have geometrical data, which is the actual map objects, the features on the map that represent objects in real life. This could be a point representing a water source, or a line representing a river, or an area representing a lake, actually most objects around us can be represented by these three type of geometrical shapes. The point might as well be an elevation point on the maps, a telecom tower, navigation beacon, etc. – the line could be a road, a power line or a shipping route – the area a forest, the outline of a city or a restricted area zone around a sensitive object. The essential with the geometrical objects are that we know where they are, we have information of their location. This is normally recorded as coordinates, could be longitude and latitude or some other of the existing coordinate systems that we use.

However, as noted, the line could be either a river or a road or a power line or shipping route. So besides having the geometry, the line itself, we also need to know what feature the line is supposed to represent, often this is called the attribute of the line. When we have the geometry and the attribute and we are able to link the correct attribute to the correct geometry, then we have the basics of a GIS. On this rudimentary GIS we add functions that allow us to overlay two or more maps on top of each other, multiply the attribute of one map with that of another, measure distance between point, line or area, etc., etc. – then we are approaching a full-fledged GIS.

To be more formal regarding GIS, it is a set of tools that permit us to input, store, edit, analyze and output map data. GIS could be considered as equivalent to any information system, that is, it is based on database technology for handling the data, but it goes beyond a traditional database in the respect that it also contains aspects of Cartography and handles geographical coordinates. It offers all the flexibility found in an ordinary database, including possibilities to make queries to select only interesting parts of the total amount of data, and it also contains tools for conducting statistical analysis and perform measurements of spatial characteristics, e.g. length, area and distance.

Since the structure of data storing is based on database technology, the amount of attributes that can be connected to each spatial data is virtually unlimited; in the well example above attributes could be information about water quality, the permeability of the aquifer, age of the well, area irrigated from the well, etc.

GIS operates on two conceptually different data models, **Raster model** and **Vector model**. These two models are based on different concepts with inherent advantages and disadvantages. In the following two sections we will examine these in order to better understand when to use them. Chapter 16 outlines the major advantages and disadvantages of the two models.

13. Vector GIS

In the vector model the location (spatial data) is represented by coordinate pairs, (x) and (y). If we examine the world around us and think about how they could be represented on a map, we will probably arrive at the conclusion that real world objects in most cases could be represented by three different types of geometrical shapes:

1. **Points** are used for representing objects without any area extent such as wells, rainfall stations, drilling sites, etc. These objects can be regarded as 0-dimensional and their location is described with one pair of coordinates.
2. **Lines** are used for representing linear objects such as roads, rivers, telephone lines, etc. Linear objects are described by vectors, in the simplest form a line having a start and an end point. These points are referred to as **nodes**. More complex lines have start point, end point and a number of breakpoints in between that define a change in direction of the line. The more complex the shape of the linear feature, the more breakpoints are needed to describe its shape. Such breakpoint is often referred to as a **vertex** and the location is described by a coordinate pair for each vertex.
3. **Polygons** (areas) are used for representing areas such as land cover classes, soil classes, etc. The pair of coordinates for the line that defines the limit or border of the area are stored in the same way as for a line object, with the fundamental difference that the coordinates for the start and end nodes are the same (the line delimiting the area must make a complete closure of the area, hence the coordinates must be the same).

Vector data have no scale in this respect and the resolution of the geographic co-ordinates is basically determined by computer limitations for storing decimals and the accuracy and precision that was used to measure the x and y coordinates. In most applications the resolution can be considered as mathematically exact.

The vector model uses the pair of coordinates to describe the geometry of different objects. In order to make it possible to link attributes to the geometry each geometrical object is assigned a unique ID-number. In its simplest form the data structure of a map data file differs if the objects are of point, line or polygon type. This means that normally these objects are stored in separate data files, in GIS often referred to as layers. Figure XX illustrates the storing for these.

Point data			Line data			Polygon data	
ID=1			ID=1			ID=1	
x=5	y=17		x=78	y=19		x=14	y=41
ID=2			x=91	y=37		x=25	y=21
x=78	y=7		x=131	y=14		x=39	y=12
ID=3			x=140	y=138		x=14	y=41
x=5	y=95		x=151	y=222		ID=2	
ID=4			x=178	y=251		x=140	y=338
x=5	y=12		ID=2			x=119	y=350
Etc…			x=140	y=338		x=98	y=267
			x=119	y=350		x=82	y=121
			x=98	y=267		x=89	y=191
			x=82	y=121		x=97	y=293
			x=78	y=19		x=140	y=338
			ID=3			ID=3	
			x=14	y=41		x=140	y=138
			x=25	y=21		x=151	y=222
			x=39	y=12		x=178	y=251
			Etc…			…	…
						Etc…	

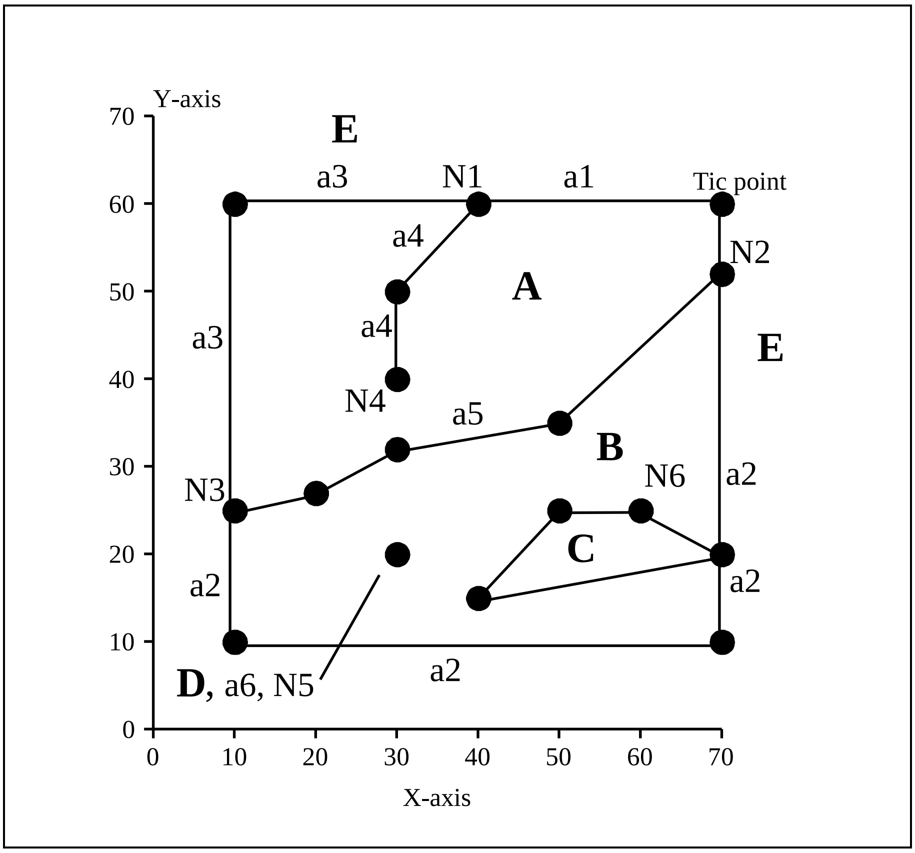
The smallest components in a vector GIS are co-ordinates which make up each single vector which can be combined and joined by lines to describe larger and more complex objects. Each vector has a unique Id-number. This allows for complex data structures since the Id-number can be used to link the geographical co-ordinates to one or more attributes in a data base. The linking in a vector model is often more complex than in the raster model and also involves the relationship between different objects. This operation is called **topology building**.

The topology will be stored in attribute tables in which different objects are linked to the attributes via their Id-number. Figure 21 shows an example of the topology in a vector GIS. Polygons, nodes and vectors are stored separately. The polygon table contain the vectors defining their limits, the node table which vector each node is connected to, and the vector table contains start and end node as well as left and right polygon information. Finally topology includes the co-ordinates of all nodes and break points. In the topology tables it is easy to add attribute information and link it to a specific object with data base software.

Topology gives information on the neighbours of a given object (contiguity) and on the linking between objects (connectivity). Contiguity describes if two different polygons have a common border, information that may be interesting e.g. for studies on urban expansion on the expense of arable land. Connectivity describes whether two river segments are connected which may be important in run-off modelling. The information on connectivity is stored in the node connecting i.e. the main stream with a tributary.

When the relationship is established between all objects in the data base search operations will perform faster and it will be possible to set complex queries to isolate a desired phenomenon or object such as all rivers running through cultivated areas or how many electricity plants existing in an area.

It is important that all polygons are closed with no loose ends between the vectors defining the polygon limits. In most GIS software automatic or semi-automatic editing are supported to avoid this problem. The vector model is very often utilised in the final map making stage of a study since it generates more attractive plots than does the raster model.



TOPOLOGY (Spatial data encoding)

POLYGON TOPOLOGY	
POLYGON	VECTOR
A	a1, a5, a3
B	a2, a5, 0, a6, 0 ,a7
C	a7
D	a6
E	area outside map coverage

NODE TOPOLOGY	
NODE	VECTOR
N1	a1, a3, a4
N2	a1, a2, a5
N3	a2, a3, a5
N4	a4
N5	a6
N6	a7

VECTOR TOPOLOGY				
VECTOR	START NODE	END NODE	LEFT POLYGON	RIGHT POLYGON
a1	N1	N2	E	A
a2	N2	N3	E	B
a3	N3	N1	E	A
a4	N4	N1	A	A
a5	N3	N2	A	B
a6	N5	N5	B	B
a7	N6	N6	B	C

ARC CO-ORDINATE DATA			
VECTOR	START X, Y	INTERMEDIATE X, Y	END X, Y
a1	40, 60	70, 60	70, 52
a2	70, 52	70, 20; 70,10; 10, 10	10, 25
a3	10, 25	10, 60	40, 60
a4	30, 40	30, 50	40, 60
a5	10, 25	20, 27; 30,32; 50, 35	70, 52
a6	30, 20		30, 20
a7	60, 25	70, 20; 40, 15; 50, 25	60, 25

Figure 21: A vector GIS containing point features, line features and polygon features. Four corner points are used to establish the transformation between digitising table and map co-ordinate systems. The relationship and linking is illustrated in the topology tables. Lines are named a(n), nodes N(n).

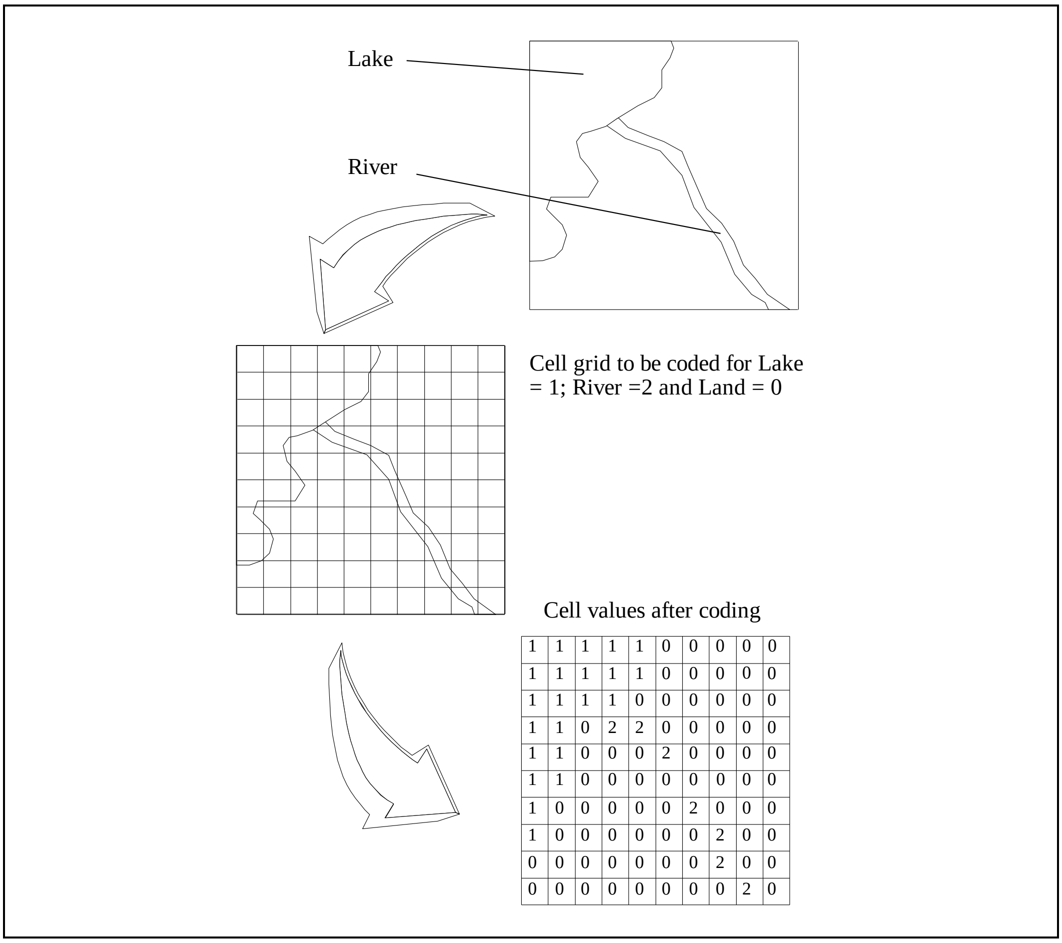


Figure 16: Data capture in a raster GIS is done by overlaying a fixed grid on the study area and then coding the objects of interest according to a predetermined coding key. The resolution of the data set is determined by the size of the grid cells. Note that in this case the cells are coded according to the dominating class. This introduces certain errors in the area extent of each class and even causes the river to disappear in the central right part of the area.

12. Raster GIS

Raster format is when an area is divided into a grid containing a number of uniform grid cells. Each grid cell has a fixed size that decides the resolution of the information, a given position in the grid is expressed as geographic co-ordinates or row and column number, and a value telling which type of cell it is. This value may be of virtually any desired type, and is derived from the area the cell represents. It can be the arithmetic mean of revenue for the population in the area, the most important vegetation cover class or the mid-point elevation of the cell.

Satellite images and computer assisted classifications made from satellite images are examples of raster format data suitable to store in a GIS. An example of the steps to create a raster data file is illustrated in figure 16.

The simplest way data in a raster format file is stored is sequentially in a predetermined order in which the position in the grid can be identified for each cell. Each row in the raster data file may represent one row in the grid, or each cell can be stored on a new row in the data file, or the number of cell values stored on a row in the data file may be fixed to a certain number. The latter way of storing data is a common way to store digital satellite data.

One obvious disadvantage of raster format is that the size of the grid cells determines the maximum geometric resolution of the stored data. Many cells will not be of uniform class assignment in reality. Imagine a raster data set showing different vegetation cover classes. Borders between different cover classes will not coincide with the cell borders causing many cells to be a mixture of several classes.

One solution to this problem is to assign the cell value to the class dominating the cell. But it is easily understood that area computations and similar operations are affected by such generalisations.

Another solution might be to increase the geographic resolution by decreasing the grid cell size but then it is important to keep in mind that the amount of data increases with a factor of four with the reduction of the grid size to half the original size. This imposes practical limitations on the resolution of a raster data set.

16. Summary of advantages and disadvantages of Raster and Vector GIS

The conceptual difference between vector data and raster data is illustrated in figure 20. Note the differences in area representation.

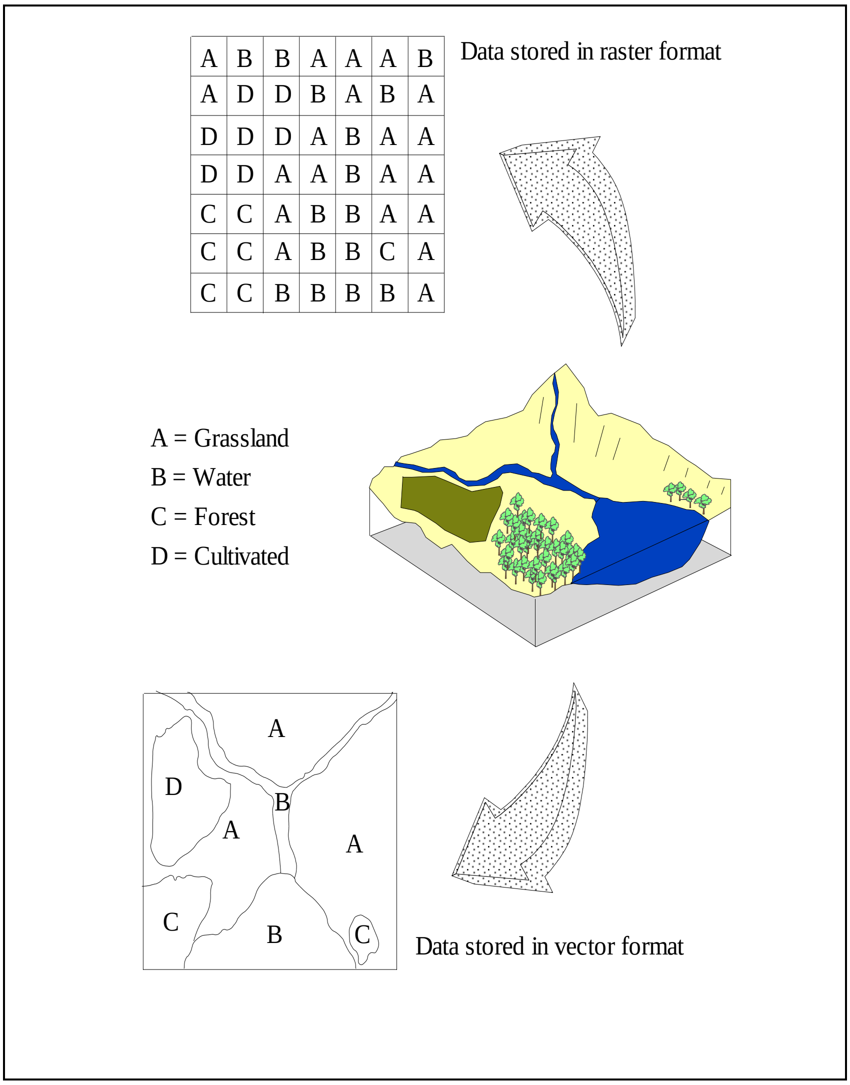


Figure 20: The basic difference between raster and vector data format. The raster image will yield a much lower resolution and will produce less attractive printouts. Note the differences in area representation.

Raster GIS has the advantage of simple data structure, all kinds of spatial analysis and modelling fairly fast and easy. The representation of continuously changing surfaces is good. Simulation is easy due to the uniform grid size. Data is also easy to combine with remote sensing data, since both are in raster format. The available software is generally fairly cheap. The main disadvantages are large data volumes, fixed (and often low) resolution, projection transformations are difficult to perform, advanced topology is difficult to establish, and finally the output is less beautiful than drawn line maps.

Vector models have good representation of complex topology making queries on attribute easy, the geographic precision is higher, updating is easier, and output is compatible to hand drawn line maps. Disadvantages are the complex data structure, overlaying and simulation is difficult to understand, spatial analysis and filtering within polygons are impossible, and the vector technology is more expensive, both regarding software and hardware.

In many contemporary software systems both models are co-existing. Vector models are used for digitising and topology building. Handling and analysis of attribute data is also done on data stored in vector format. Raster models are used for overlaying and similar analysis. The result is often converted to vector format for presentation since the output from raster models is less attractive. Most software's contain modules that convert between the two models.

14. Data capture and editing

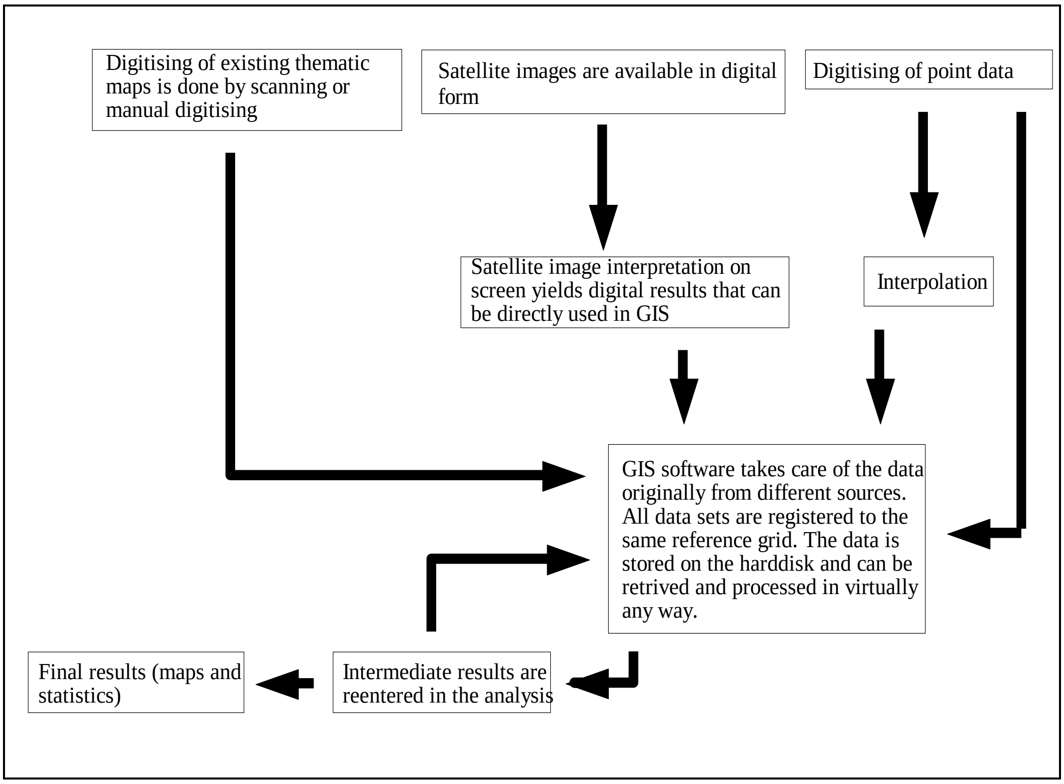


Figure 15 Data acquisition procedure and storing in a Geographical Information System (GIS). Data can be of different origin; from available maps information is digitised by scanning or manual digitising, from point data sources such as rainfall stations the information may need to be interpolated in order to cover the area of interest, satellite data is already available in digital form if the interpretation is done on screen.

The data capture procedure is subdivided in three major steps. In the first step geographic information is collected and introduced in the computer.

This may be done by manual digitising of existing maps, automatic scanning or by importing co-ordinates from other sources, i.e. digital map data bases or GPS co-ordinates (Global Positioning System, satellite navigation system).

Often some kind of reformatting of the existing digital data is necessary to make it fit the GIS-software. Co-ordinates could also be manually typed into the system.

The second step is to introduce the attribute data which is often done by typing data to an attribute file. This file could also be imported from an existing digital data base. The third step is to connect attributes and spatial information. This is done using the GIS-software.

The digitised information is considered as a generalised model of the real world and in a computer data can be stored either as a

The first operation is collection of data into the computer system. The most frequently used method for spatial data capture is digitising of existing maps. Digitising is done on a digitising table. Usually all digitised data is stored in vector format. All objects are allocated unique Id's and in a second step linked to attributes. Digitising starts with the definition of a number of **control points** with known co-ordinates in a known projection and co-ordinate system. Control points are used to establish the transformation between table and map co-ordinate systems.

An alternative way of data capture is automatic scanning. Instead of manually pointing to the objects to be converted to digital form, a machine sensible to shades of grey (or even colour) is utilised to capture the map of interest. Scanned maps are stored in raster format. Scanning is a quicker way to input data but with the exception of simple line/point maps, editing is often very time-consuming. A third method for data conversion is automatic line following, but this method is not yet in common use.

When digitising is completed attributes should be attached. The most efficient way to do this is to type the desired information in an attribute file keeping the same order as in the digitised spatial data file. Then topology is created by applying a GIS software module that links attributes to location.

In many GIS software point data and linear/polygon data are saved in different information layers. The main reason is the different requirements in topology. Consider figure 21 where the nodes only needs geographic co-ordinates, ID's and then attributes, while the lines (arcs) needs a more complex topological structure involving start and end nodes, break points, etc. It will also be easier to analyse data when separated into different information layers.

A major problem in the process of data capture is joining adjacent map sheets. Normally the match between two sheets is not perfect due to small digitising errors, errors during the draw and print process or variations in paper size caused by heat or humidity. Most GIS software have an **edge matching** or "**rubber sheet**" function which allows for a certain degree of relocation of objects along the border of the digitised map sheet. In some cases automatic or semi-automatic rubber sheeting is performed to assure a perfect match between maps.

It is not evident that input data is in a format that is desired for an application. The digitised information may be in a different co-ordinate system or projection. A professional GIS should, however, be able to cope with this kind of problem, and some kind of transformation function handling frequently used co-ordinate systems, projections and ellipsoids should be included.

Another example of data which needs special attention is topography. On most maps topography is represented by iso-lines with a given equidistance. Contours is a graphic representation of elevation and not suitable for input to a GIS. Elevation values will cluster on contours and in between no information is available. Normally elevation models are constructed by interpolation. If interpolation is performed on contours the empty spaces between them will create errors in the final output. Instead it is advised to digitise point elevation information by superposing a grid on the map and digitise elevation at each intersection. To increase detail and capture topographic breakpoints additional elevation points can be selected along ridges and water courses, etc. An appropriate interpolation method is then used to estimate the elevation of each cell in the raster model data set to derive a **Digital Elevation Model** (DEM).

15. Data analysis in a GIS

In a manual Geographical Information System the information is drawn on maps, every map presenting one **information layer**, i.e. soil, population density, roads, etc. Figure 22 outlines the GIS-concept with information layers compiled from different sources, each containing information on a specific topic.

Consider to make i.e. a study to localise arable land in the area on figure 22. In this example rainfall data, information on soils and geology, roads and drainage pattern, and the actual land use is judged sufficient for the task. In order to derive a arable land map from these four layers several operation are necessary.

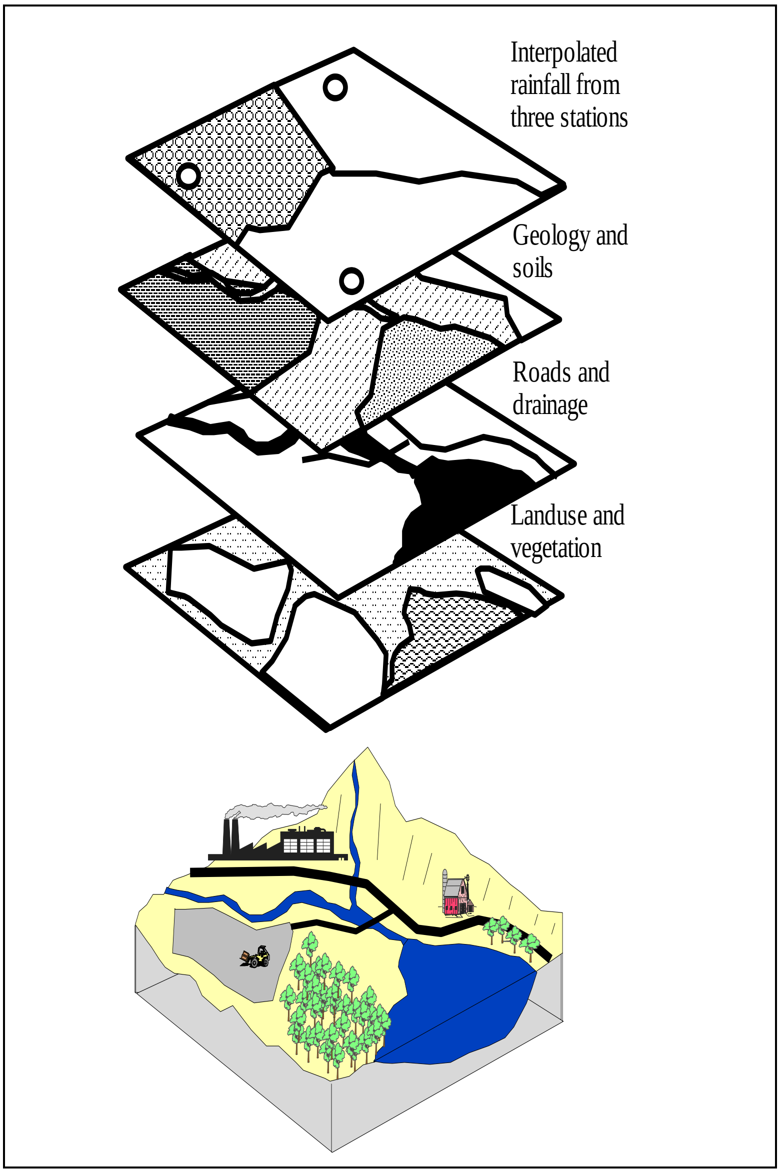


Figure 22: Multiple layers of information from various sources are combined in the GIS to derive new information on the study area. Virtually any type of information that is geographically distributed can be used as input in the analysis. Data only available as point information can be interpolated to cover the whole map extent.

Overlaying of the maps can be done manually but this is both labour intense and time consuming. New maps would have to be traced and up dating the model utilised to derive the result as well as the input data is difficult. In the GIS overlaying and all other operations are performed by a computer and updating can readily be done. The result of any operation is stored as a new layer in the data set and can easily be printed or used as input in the next operation.

In a raster GIS it is easy to understand that overlaying is an operation that is done on cells with the same position in each layer. Vector data operations are more complex to understand and to perform since the grid is absent.

While overlaying involves more than one information layer, many other GIS operations can applied on multiple layer, single layer or on the attribute data. GIS operations can be divided in the following groups:

The most evident operations to perform on geocoded objects are **measurements** of distance, area and perimeter. This involves many applications as the extent of land use classes, the length of the rail way network in a country, etc. but could also be combined with e.g. logical operations to measure only a certain type of object.

Another type of operations are **Spread functions** which involves cost-distance and friction surface functions. This could be the arrival time for an ambulance coming from a nearby hospital with 10 km of heavy city traffic to cross with the arrival time of an ambulance coming from a hospital 50 km outside the city with a high way connection. Transportation costs, energy consumption, offer & demand models, etc. often requires these kinds of operations.

Neighbourhood operations assume that the value changes according to its relations to neighbouring cells. Interpolation was briefly described in the previous section, is the main method for transforming point data to surface data by applying different interpolation algorithms (Averaging, Inverse distance, Spline interpolation, Krieging, etc) but it is also an example of neighbourhood operations. Spatial filtering using a window of *n* by *n* cells to recalculate the value of the centre cell is a very common technique in remote sensing to enhance image quality or smooth the results of digital classifications (see chapters 8 and 9).

Point in polygon, line in polygon and polygon in polygon are operations used to identify e.g. how many houses are built on a certain soil type, what land use classes a river flows through before reaching the outlet, what type of soil almonds are cultivated on, etc.

Many applications in terrain and topography analysis uses neighbourhood operations applied on DEM’s. Examples are analysis of topography when valleys and mountains can be detected by inspecting the relation between a cell’s elevation and the elevation of it’s neighbours. Computation of slope and aspect are other examples. Such information can be used to compute the water divide between catchments and their size. Visibility from a certain point in the landscape is used by landscape architects to show the effect of urbanisation or deforestation from an aesthetic point of view.

Functional operations are when the value changes according to a function, which can be arithmetic functions applied on several layers or with-in a layer, e.g. two layers can be multiplied or a layer can be divided by 10. Virtually any expression can be used, e.g. from simple rescaling of a layer by a factor of 10 to complex computations involving multiple layers and complex arithmetic expressions as layer one raised to the power of layer two divided by layer three, multiplied by the cosine of layer four, etc. that allows modelling of complex processes. An example of modelling is estimations of erosion intensity, when land characteristics, rain fall data, cultivation practise, land cover, etc. are translated into numbers according to their influence on erosion processes. All layers are multiplied and the results will indicate the annual soil loss in tons/hectare.

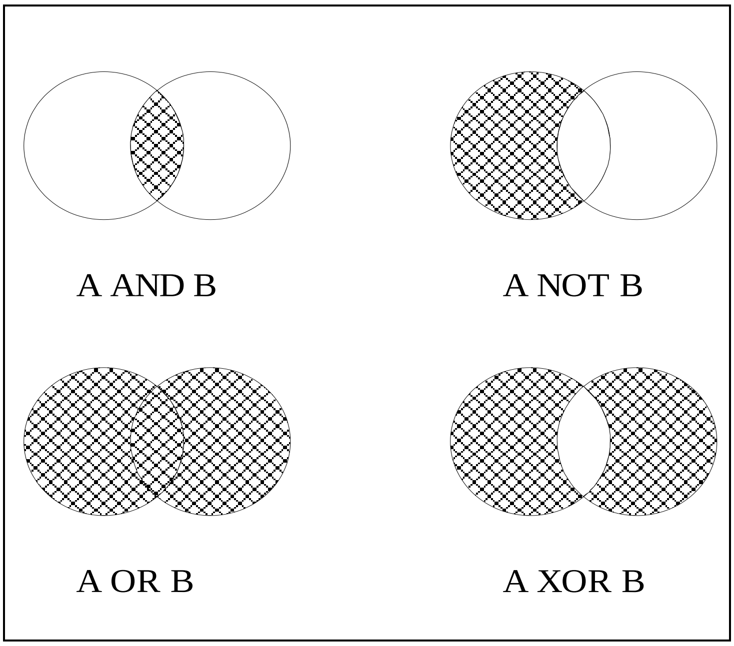


Figure 23: Venn diagrams showing the results of Bolean operations on the intersection of two information layers. A is the circle to the left, B to the right. The shaded area is represents the ”truth”, when the condition is fulfilled.

Logical operations are when the value changes according to the result of a logical expression applied to one or more layers. In logical operations (Boolean logic) the operators are ”**AND**”, ”**OR**”, ”**XOR**” and ”**NOT**”. Figure 23 shows a Venn diagram of the results of some Boolean operations applied on different layer combinations. The result from such operations is often a new layer containing only ”1” and ”0”, where 1 stands for cells fulfilling the criteria and 0 for cells not fulfilling the selection criteria.
Figure 24 shows an example of a Boolean ”**AND**” operation on the rain fall and the reclassified soil layers in the land use planning example. The resulting raster contains only ”1” and ”0”, where 1 represents areas fulfilling the requirements for cultivation while the 0 areas should be utilised for other land uses. Note that in layer B a fourth soil class has been added. This is the lake which is useless for any other land use than the present one. The area of the lake was added from the land use and vegetation cover.

Buffering or proximity operations is when the surroundings of an object (point, line or polygon) is ”buffered” in the context that the value changes depending on if the object is covered or not covered by the buffer zone.

If applied on the arable land example buffering can be used to add additional restrictions on the data set. When the potentially arable land is identified it should also be within a certain distance from the water courses in order facilitate irrigation and not to close to any major road due to toxic effects from the traffic. The buffering operations are often used to impose such restrictions on the data set.

The GIS software allows the operator to decide on a buffer zone surrounding an object (point, line or polygon). In a raster GIS the buffer is set in number of cells while in a vector GIS it can be set to any value in the coordinate system. Simple buffering is illustrated in figure 25.

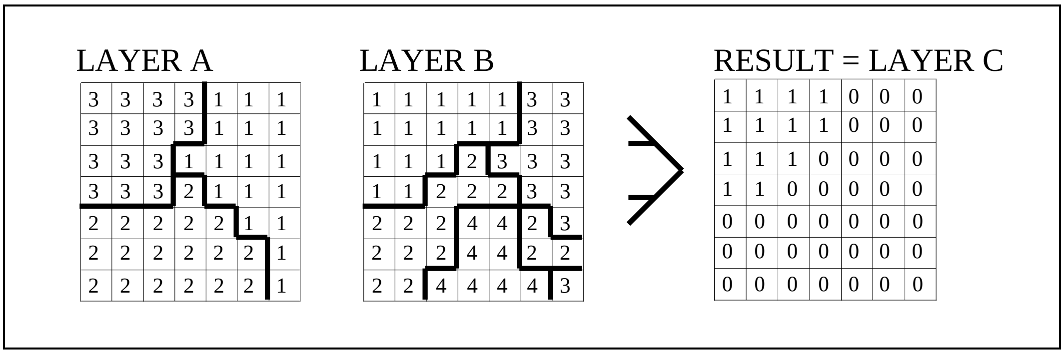


Figure 24: A logic ”AND” operation applied on layer A (rain fall) and B (soils). The conditional condition was ”if the value in layer A=3 <u>AND</u> the value in layer B=1 then =>true (yields 1 in layer C).

Attribute data operations are the same as in any data base. Search and select operands (**queries**) can be used to identify and isolate objects, Boolean logic operations, arithmetic functions, etc. are all possible to use.

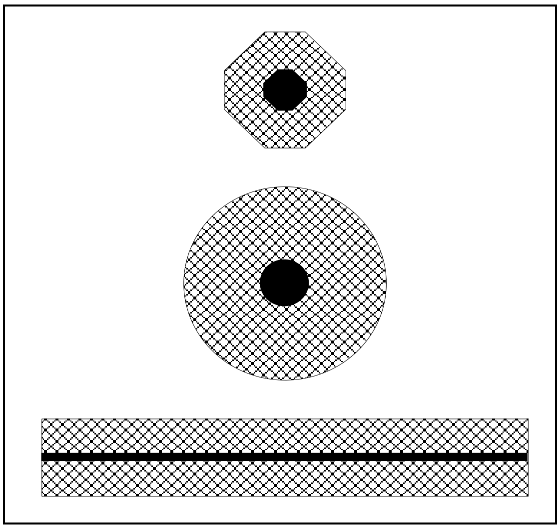


Figure 25: Examples of buffering around different objects.

All the described operations can be performed using both vector and raster model data but vector data will normally yield results with higher geometric accuracy.

17. Outline of a possible Remote Sensing and GIS mapping methodology

A general flow chart for a GIS and remote sensing based inventory is presented in figure 26. Before the actual interpretation of satellite images starts it is important to assure that the team responsible for interpretation has the same level of interpretation skills. It is also necessary to make an interpretation key that contains a description of the features to map and how they are recognised in the imageries.

The interpretation work is by preference initialised by a training course in remote sensing and the application of remote sensing in the field of interest. The first part should treat some of the theoretical foundation of satellite remote sensing and contain several interpretation exercises. The main goal should be to assure a uniform interpretation result.

The second part of the course should be devoted to on the job training and construction of interpretation keys, listing features to be mapped and their identification criteria. All participants should try to contribute with aspects from their particular fields of experience. If the team is judged to have little or no field experience from the study area, a short field trip is preferable to familiarise the team members with the environment to be mapped.

Then the actual interpretation may start, following the key and it is advisable that no major changes in the key is made during the interpretation in order to avoid confusion or inconsistencies in the interpretation results. When a large part of the interpretation is completed a second and more extensive field work should be performed. During this field work the interpretations made so far should be field checked and all questions about the identification of different objects should be settled.

After the field visits some minor changes may be introduced and in a few cases they may result in a complete revision of the interpretation.

Delineation of mapped features is made on clear plastic sheet film. This is the easiest way to do interpretation on images made available as photographic products. For practical reasons, it is advisable to separate the interpretation in two layers, one containing linear and point features, such as roads, faults, ponds, quarries, and one containing polygon features such as cultivated areas and rock types.

During the interpretation the major problem is always to obtain a uniform interpretation of features when different persons interpret the same features. Special attention should be paid to assure a uniform interpretation result. Every interpreted map sheet is thoroughly discussed between the members of the interpretation team before passed on to retracing.

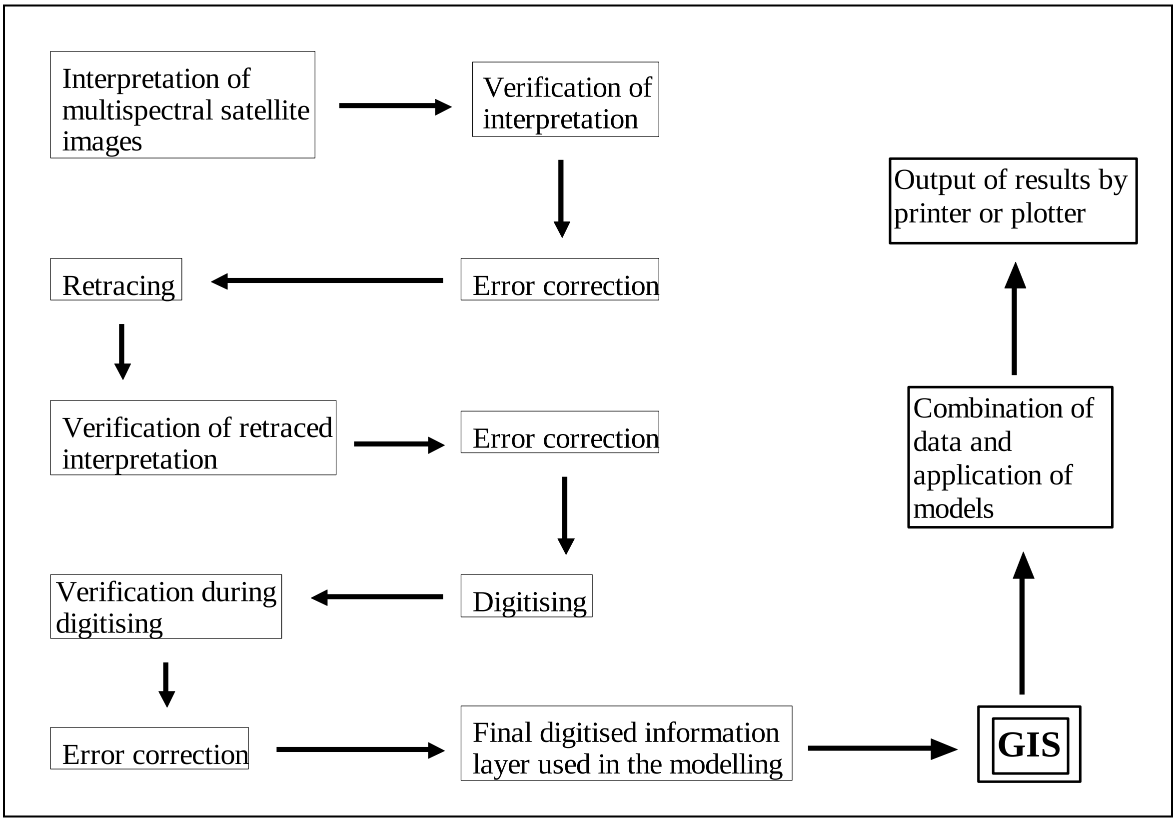


Figure 26: Flow chart of the working procedure in a project based on interpretation of satellite images and modelling in a GIS.

Conflicts are settled by the supervisors and during the field trips. Once the interpretation is considered terminated for a map sheet the result is retraced by a draughtsman to a suitable map grid size on opaque drawing film.

After retracing the map should once again be verified by the responsible interpreter and then passed on to be digitised. During digitising error detection should also be kept in mind to avoid errors in the final product. One possibility is to plot the digitised raw data and compare it with the original interpretation. It is important to understand that the quality of the final results from the GIS is very sensitive to errors in the preceding steps in the production chain. All possible efforts should therefore be made to assure maximum precision and error detection during these operations. Once in the GIS and attached to a map grid, the source of errors are likely to be much reduced.

A main source of error in the process of interpretation and digitising is difficulty in line following. This means that someone that should follow a line, a boarder line between two polygons or a line feature such as a road, does this with a certain degree of precision.

Once all data is available in digital form necessary operations in order to derive the desired final product are performed. The output from different operations often needs to be reclassified which is particularly easy done in the data base handler of a vector GIS by recoding the attributes or adding new attributes containing the new class assignment.

Output in map or tabular form can often be generated directly using the GIS software. In some cases it may be desirable to export data to a graphics program or a statistics program in order to enhance output quality or to perform advanced statistical analysis.

Further reading

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Useful links to free Internet resources regarding remote Sensing and GIS

http://www.usgs.gov/pubprod/aerial.html
http://landsat.gsfc.nasa.gov/

Landsat Satellite applications (from NASA homepage)

Agriculture, Forestry and Range Resources	**Land Use and Mapping**	**Geology**	**Hydrology**	**Coastal Resources**	**Environmental Monitoring**
Discriminating vegetative, crop and timber types	Classifying land uses	Mapping major geologic features	Determining water boundaries and surface water areas	Determining patterns and extent of turbidity	Monitoring deforestation
Measuring crop and timber	Cartographic mapping and	Revising	Mapping floods and flood plain	Mapping shoreline	Monitoring volcanic flow

acreage	map updating	geologic maps	characteristics	changes	activity
Precision farming land management	Categorizing land capabilities	Recognizing and classifying certain rock types	Determining area extent of snow and ice coverage	Mapping shoals, reefs and shallow areas	Mapping and monitoring water pollution
Monitoring crop and forest harvests	Monitoring urban growth	Delineating unconsolidated rocks and soils	Measuring changes and extent of glacial features	Mapping and monitoring sea ice in shipping lanes	Determining effects of natural disasters
Determining range readiness, biomass and health	Aiding regional planning	Mapping volcanic surface deposits	Measuring turbidity and sediment patterns	Tracking beach erosion and flooding	Assessing drought impact
Determining soil conditions and associations	Mapping transportation networks	Mapping geologic landforms	Delineating irrigated fields	Monitoring coral reef health	Tracking oil spills
Monitoring desert blooms	Mapping land-water boundaries	Identifying indicators of mineral and petroleum resources	Monitoring lake inventories and health	Determining coastal circulation patterns	Assessing and monitoring grass and forest fires
Assessing wildlife habitat	Citing transportation and power transmission routes	Determining regional geologic structures	Estimating snow melt runoff	Measuring sea surface temperature	Mapping and monitoring lake eutrophication
Characterizing forest range vegetation	Planning solid waste disposal sites, power plants and other industries	Producing geomorphic maps	Characterizing tropical rainfall	Monitoring and tracking 'red' tides	Monitoring mine waste pollution
Monitoring and mapping insect infestations	Mapping and managing flood plains	Mapping impact craters	Mapping watersheds	Coral reef health assessment	Monitoring volcanic ash plumes

Monitoring irrigation practices	Tracking socioeconomic impacts on land use	Chevron discovery	Mapping closed-basin ponds	Global coral reef mapping	Assessing carbon stocks
Bison management	Online mapping	Mega-lake discovery	Monitoring wetlands	Chesapeake Bay restoration	Cancer research
Crop production estimates	Cartographic discoveries	Soil carbon flux	Water management	Monitoring coastal erosion	Atmospheric modeling
Quantifying burn severity	Mapping Antarctica		Wetland restoration	Coastal Studies	Mapping Rift Valley Fever risk areas
Fighting crop insurance fraud	Fighting hunger		Monitoring dam construction	Chesapeake Bay management	Assessing clear-cutting impacts
Forest trends in Madagascar	Urban sprawl and climate change		Groundwater discharge		Assessing impacts of industrial logging
Forest protection in Peru	Caribbean Island mapping		Bushfire impact on water yields		Mapping urban heat islands
Better Estimate of Boreal Forest Loss	Tropical forest clearing for development				Landsat, Potholes, and Climate Change
Crop water stress	Exploring ancient Mexico				Disaster aftermath
Crop water demand	Landsat Image Mosaic of Antarctica				African environmental change

Rice production monitoring	Kansas Map				Cyclone Nargis' impact on Burma
Demise of Papua New Guinea forests					Fire prevention in Spain
Monitoring conservation tillage					Surveying mangroves
North American forest disturbance					Greek fires
Sumatran deforestation					Algea monitoring
Forest damage caused by Hurricane Katrina					Glacier monitoring

Return to Landsat Program Applications page.