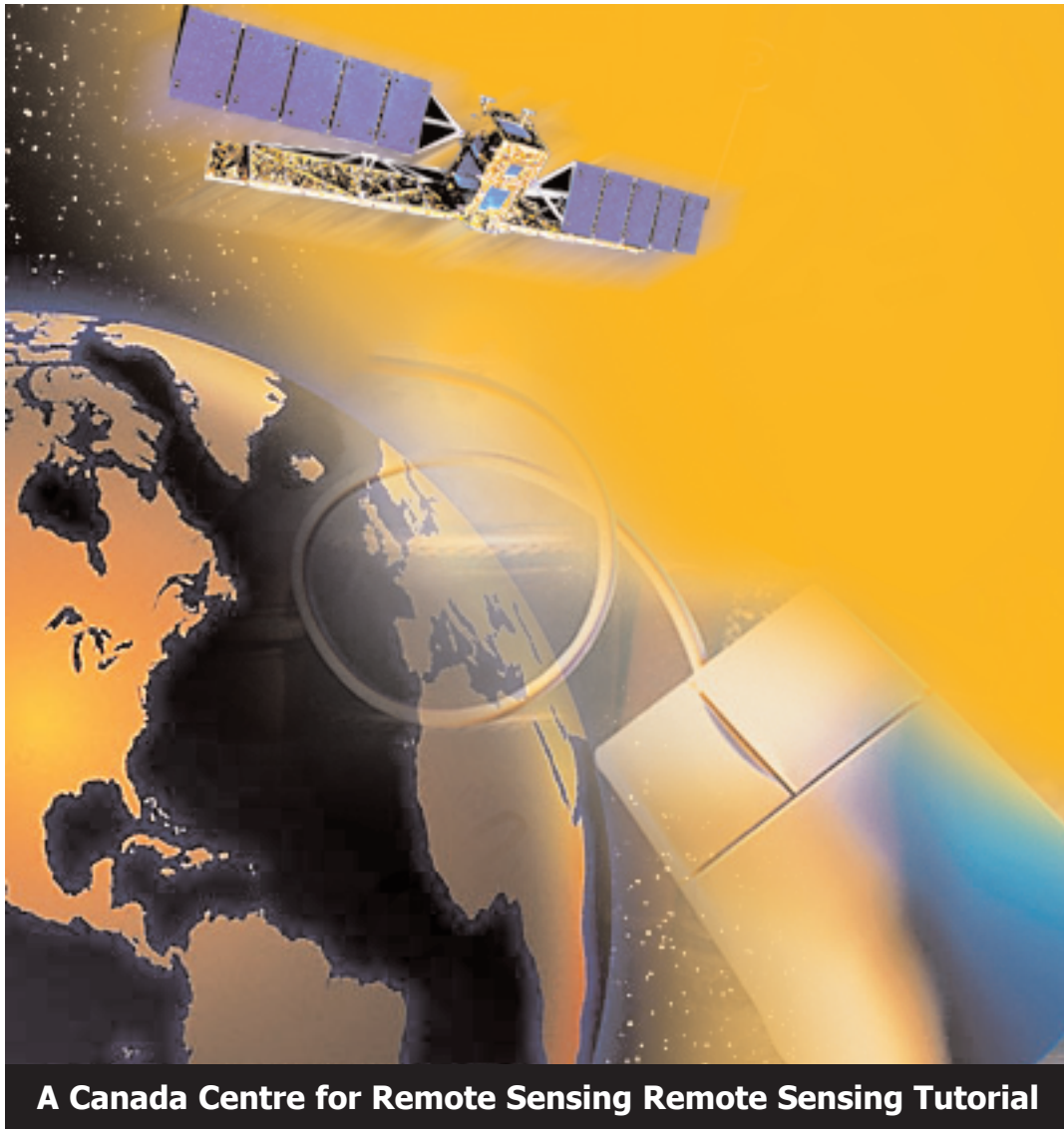


Fundamentals of Remote Sensing



A Canada Centre for Remote Sensing Remote Sensing Tutorial



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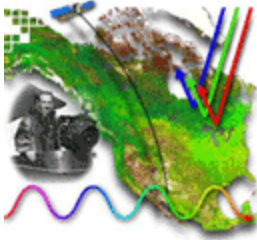


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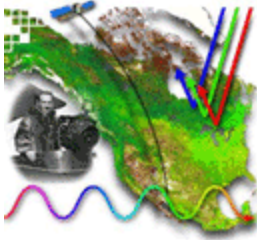
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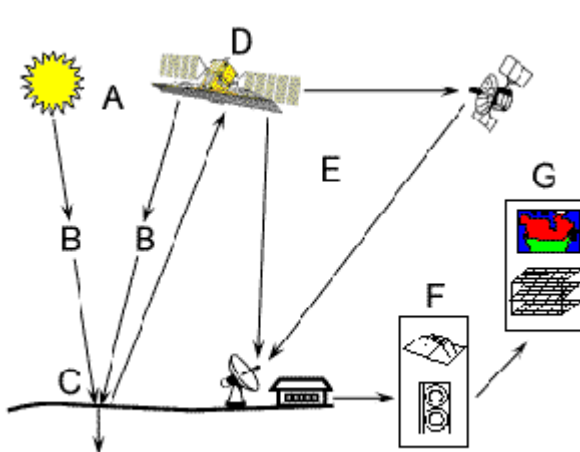
1. Introduction to Fundamentals

1.1 What is Remote Sensing?

So, what exactly is **remote sensing**? For the purposes of this tutorial, we will use the following definition:

"Remote sensing is the science (and to some extent, art) of acquiring information about the Earth's surface without actually being in contact with it. This is done by sensing and recording reflected or emitted energy and processing, analyzing, and applying that information."

In much of remote sensing, **the process** involves an interaction between incident radiation and the targets of interest. This is exemplified by the use of imaging systems where the following seven elements are involved. Note, however that remote sensing also involves the sensing of emitted energy and the use of non-imaging sensors.



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1. Energy Source or Illumination (A) - the first requirement for remote sensing is to have an energy source which illuminates or provides electromagnetic energy to the target of interest.

2. Radiation and the Atmosphere (B) - as the energy travels from its source to the target, it will come in contact with and interact with the atmosphere it passes through. This interaction may take place a second time as the energy travels from the target to the sensor.

3. Interaction with the Target (C) - once the energy makes its way to the target through the atmosphere, it interacts with the target depending on the properties of both the target and the radiation.

4. Recording of Energy by the Sensor (D) - after the energy has been scattered by, or emitted from the target, we require a sensor (remote - not in contact with the target) to collect and record the electromagnetic radiation.

5. Transmission, Reception, and Processing (E) - the energy recorded by the sensor has to be transmitted, often in electronic form, to a receiving and processing station where the data are processed into an image (hardcopy and/or digital).

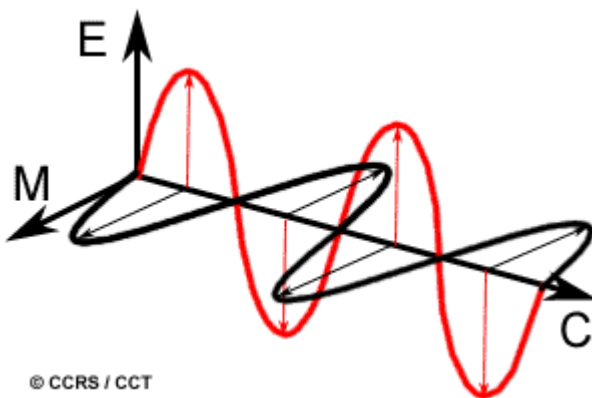
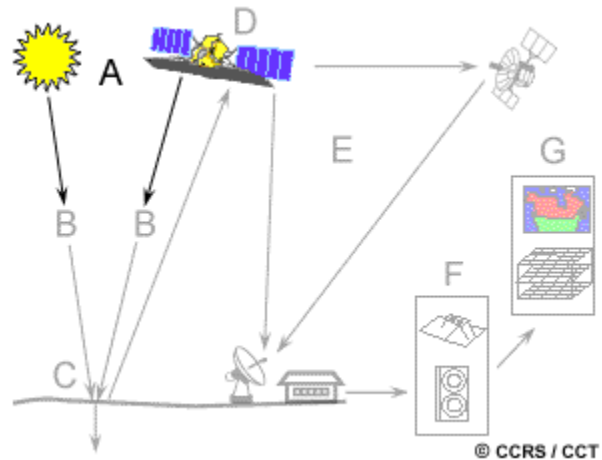
6. Interpretation and Analysis (F) - the processed image is interpreted, visually and/or digitally or electronically, to extract information about the target which was illuminated.

7. Application (G) - the final element of the remote sensing process is achieved when we apply the information we have been able to extract from the imagery about the target in order to better understand it, reveal some new information, or assist in solving a particular problem.

These seven elements comprise the remote sensing process from beginning to end. We will be covering all of these in sequential order throughout the five chapters of this tutorial, building upon the information learned as we go. Enjoy the journey!

1.2 Electromagnetic Radiation

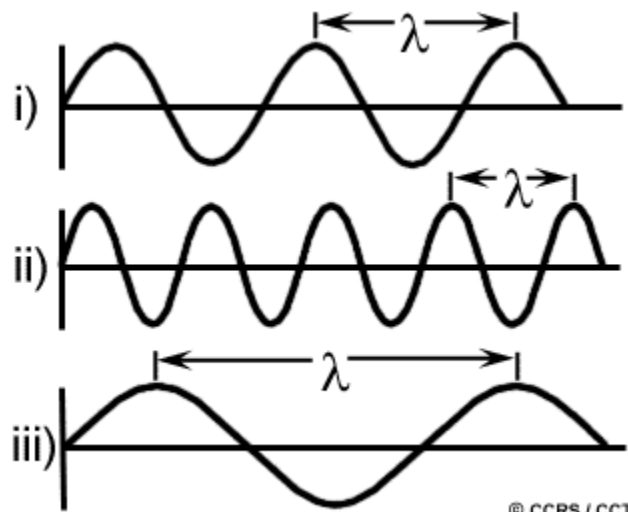
As was noted in the previous section, the first requirement for remote sensing is to have an **energy source to illuminate the target** (unless the sensed energy is being emitted by the target). This energy is in the form of electromagnetic radiation.



All electromagnetic radiation has fundamental properties and behaves in predictable ways according to the basics of wave theory.

Electromagnetic radiation consists of an electrical field (E) which varies in magnitude in a direction perpendicular to the direction in which the radiation is traveling, and a magnetic field (M) oriented at right angles to the electrical field. Both these fields travel at the speed of light (c).

Two characteristics of electromagnetic radiation are particularly important for understanding remote sensing. These are the **wavelength and frequency**.



The wavelength is the length of one wave cycle, which can be measured as the distance between successive wave crests. Wavelength is usually represented by the Greek letter lambda (λ). Wavelength is measured in metres (m) or some factor of metres such as **nanometres** (nm, 10^{-9} metres), **micrometres** (μm , 10^{-6} metres) (μm , 10^{-6} metres) or centimetres (cm, 10^{-2} metres). Frequency refers to the number of cycles of a wave passing a fixed point per unit of time. Frequency is normally measured in **hertz** (Hz), equivalent to one cycle per second, and various multiples of hertz.

Wavelength and frequency are related by the following formula:

$$c = \lambda \nu$$

where:

λ = wavelength (m)

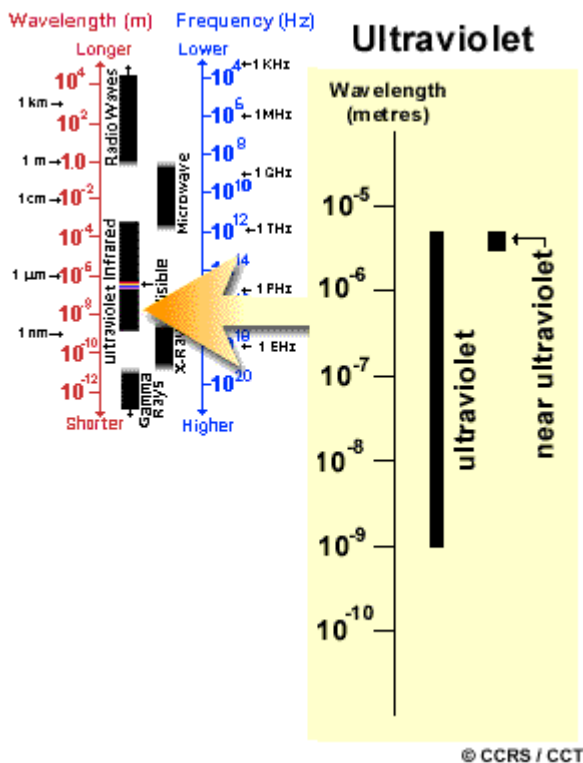
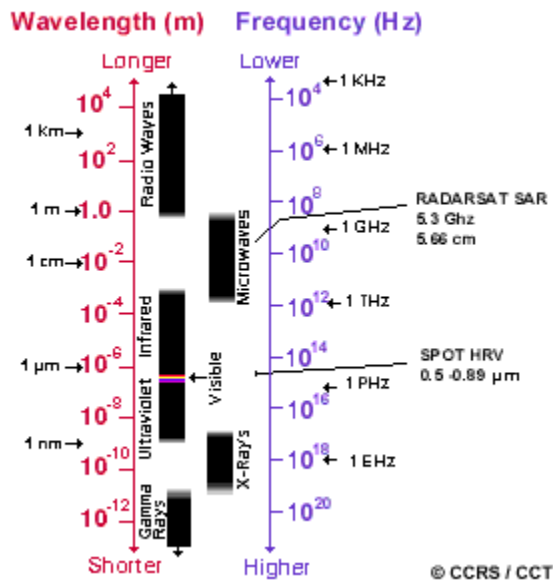
ν = frequency (cycles per second, Hz)

c = speed of light (3×10^8 m/s)

Therefore, the two are inversely related to each other. The shorter the wavelength, the higher the frequency. The longer the wavelength, the lower the frequency. Understanding the characteristics of electromagnetic radiation in terms of their wavelength and frequency is crucial to understanding the information to be extracted from remote sensing data. Next we will be examining the way in which we categorize electromagnetic radiation for just that purpose.

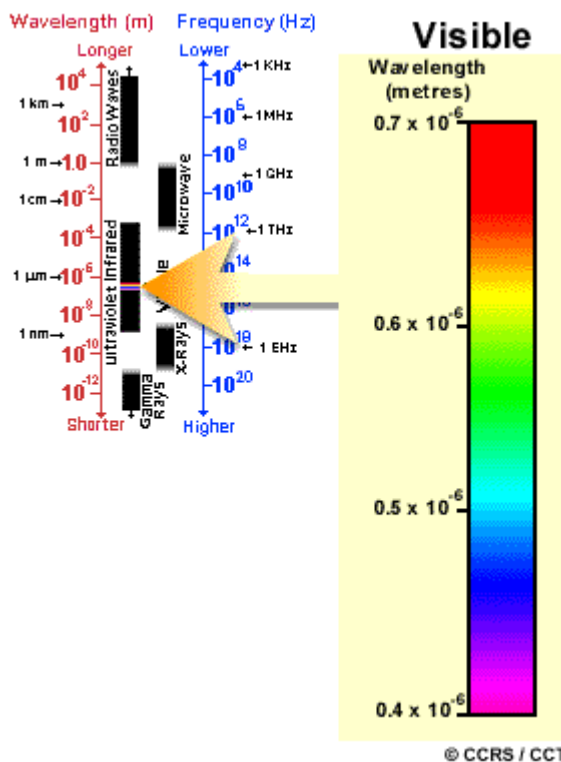
1.3 The Electromagnetic Spectrum

The **electromagnetic spectrum** ranges from the shorter wavelengths (including gamma and x-rays) to the longer wavelengths (including microwaves and broadcast radio waves). There are several regions of the electromagnetic spectrum which are useful for remote sensing.



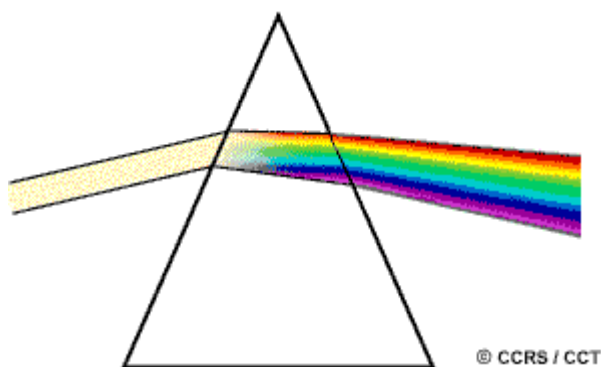
For most purposes, the **ultraviolet or UV** portion of the spectrum has the shortest wavelengths which are practical for remote sensing. This radiation is just beyond the violet portion of the visible wavelengths, hence its name. Some Earth surface materials, primarily rocks and minerals, fluoresce or emit visible light when illuminated by UV radiation.

The light which our eyes - our "remote sensors" - can detect is part of the **visible spectrum**. It is important to recognize how small the visible portion is relative to the rest of the spectrum. There is a lot of radiation around us which is "invisible" to our eyes, but can be detected by other remote sensing instruments and used to our advantage. The visible wavelengths cover a range from approximately 0.4 to 0.7 μm . The longest visible wavelength is red and the shortest is violet. Common wavelengths of what we perceive as particular colours from the visible portion of the spectrum are listed below. It is important to note that this is the only portion of the spectrum we can associate with the concept of **colours**.

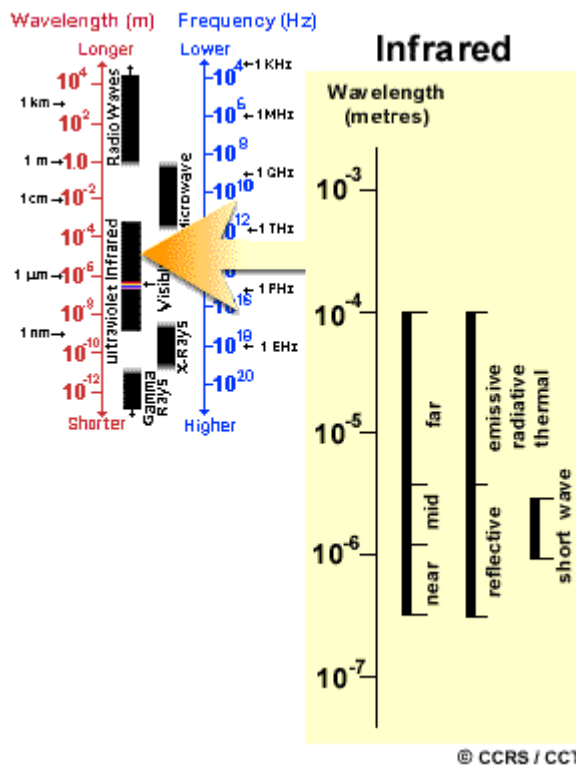


- **Violet:** 0.4 - 0.446 μm
- **Blue:** 0.446 - 0.500 μm
- **Green:** 0.500 - 0.578 μm
- **Yellow:** 0.578 - 0.592 μm
- **Orange:** 0.592 - 0.620 μm
- **Red:** 0.620 - 0.7 μm

Blue, green, and red are the **primary colours** or wavelengths of the visible spectrum. They are defined as such because no single primary colour can be created from the other two, but all other colours can be formed by combining blue, green, and red in various proportions. Although we see sunlight as a uniform or homogeneous colour, it is actually composed of various wavelengths of radiation in primarily the ultraviolet, visible and infrared portions of the spectrum. The visible portion of this radiation can be shown in its

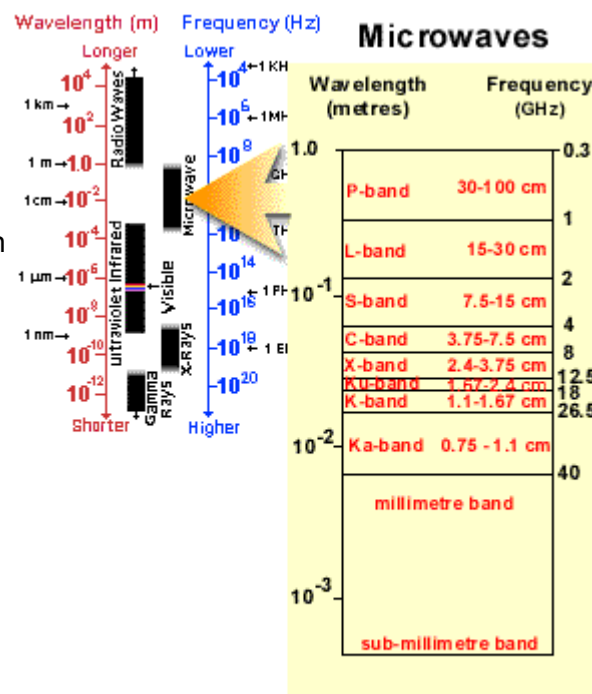


component colours when sunlight is passed through a **prism**, which bends the light in differing amounts according to wavelength.



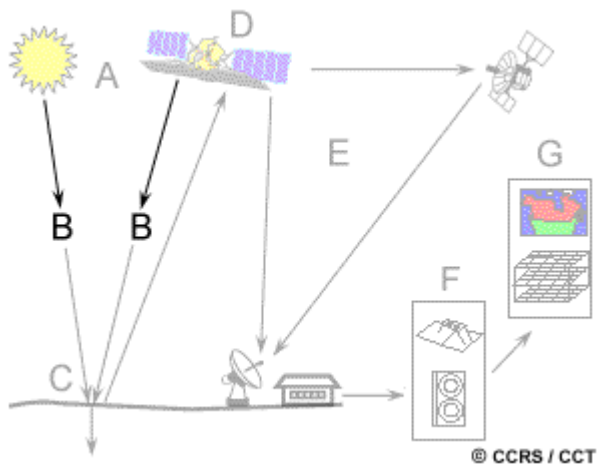
The next portion of the spectrum of interest is the infrared (IR) region which covers the wavelength range from approximately 0.7 μm to 100 μm - more than 100 times as wide as the visible portion! The infrared region can be divided into two categories based on their radiation properties - the **reflected IR**, and the emitted or **thermal IR**. Radiation in the reflected IR region is used for remote sensing purposes in ways very similar to radiation in the visible portion. The reflected IR covers wavelengths from approximately 0.7 μm to 3.0 μm . The thermal IR region is quite different than the visible and reflected IR portions, as this energy is essentially the radiation that is emitted from the Earth's surface in the form of heat. The thermal IR covers wavelengths from approximately 3.0 μm to 100 μm .

The portion of the spectrum of more recent interest to remote sensing is the **microwave region** from about 1 mm to 1 m. This covers the longest wavelengths used for remote sensing. The shorter wavelengths have properties similar to the thermal infrared region while the longer wavelengths approach the wavelengths used for radio broadcasts. Because of the special nature of this region and its importance to remote sensing in Canada, an entire chapter (Chapter 3) of the tutorial is dedicated to microwave sensing.

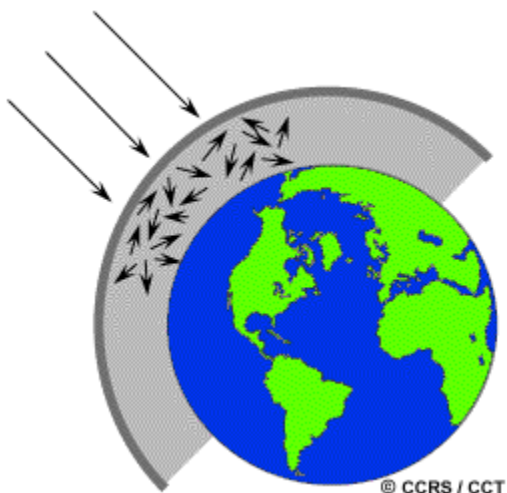


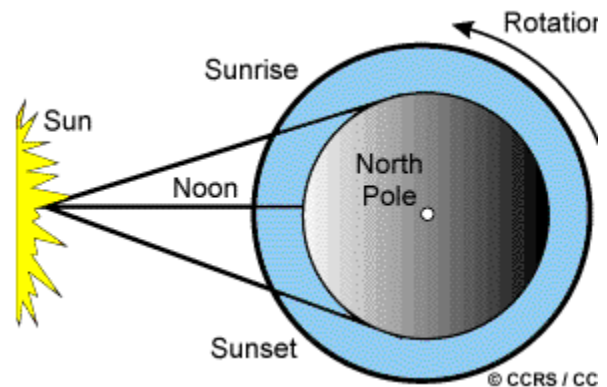
1.4 Interactions with the Atmosphere

Before radiation used for remote sensing reaches the Earth's surface it has to travel through some distance of the Earth's atmosphere. Particles and gases in the atmosphere can affect the incoming light and radiation. These effects are caused by the mechanisms of **scattering** and **absorption**.



Scattering occurs when particles or large gas molecules present in the atmosphere interact with and cause the electromagnetic radiation to be redirected from its original path. How much scattering takes place depends on several factors including the wavelength of the radiation, the abundance of particles or gases, and the distance the radiation travels through the atmosphere. There are three (3) types of scattering which take place.





Rayleigh scattering occurs when particles are very small compared to the wavelength of the radiation. These could be particles such as small specks of dust or nitrogen and oxygen molecules. Rayleigh scattering causes shorter wavelengths of energy to be scattered much more than longer wavelengths. Rayleigh scattering is the dominant scattering mechanism in the upper atmosphere. The fact that the sky appears "blue" during the day is because of this phenomenon. As sunlight passes through the atmosphere, the shorter wavelengths (i.e. blue) of the visible spectrum are scattered more than the other (longer) visible wavelengths. At **sunrise and sunset** the light has to travel farther through the atmosphere than at midday and the scattering of the shorter wavelengths is more complete; this leaves a greater proportion of the longer wavelengths to penetrate the atmosphere.

Mie scattering occurs when the particles are just about the same size as the wavelength of the radiation. Dust, pollen, smoke and water vapour are common causes of Mie scattering which tends to affect longer wavelengths than those affected by Rayleigh scattering. Mie scattering occurs mostly in the lower portions of the atmosphere where larger particles are more abundant, and dominates when cloud conditions are overcast.

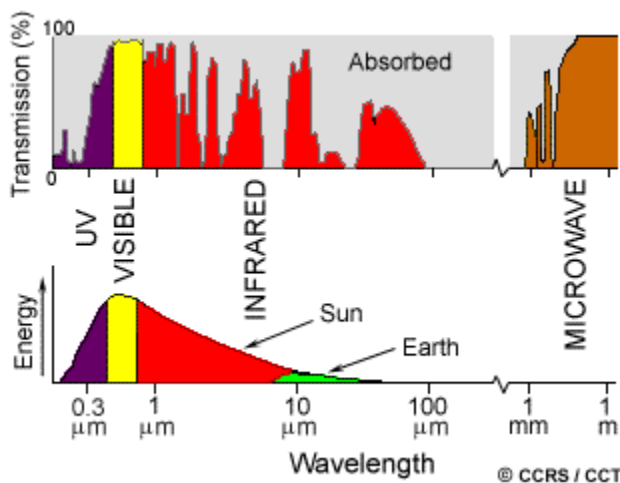
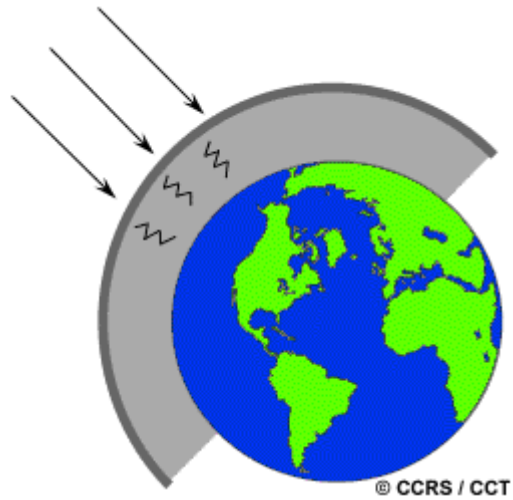


The final scattering mechanism of importance is called **nonselective scattering**. This occurs when the particles are much larger than the wavelength of the radiation. Water droplets and large dust particles can cause this type of scattering. Nonselective scattering gets its name from the fact that all wavelengths are scattered about equally. This type of scattering causes fog and clouds to appear white to our eyes because blue, green, and red light are all scattered in approximately equal quantities (blue+green+red light = white light).

Absorption is the other main mechanism at work when electromagnetic radiation interacts with the atmosphere. In contrast to scattering, this phenomenon causes molecules in the atmosphere to absorb energy at various wavelengths. Ozone, carbon dioxide, and water vapour are the three main atmospheric constituents which absorb radiation.

Ozone serves to absorb the harmful (to most living things) ultraviolet radiation from the sun. Without this protective layer in the atmosphere our skin would burn when exposed to sunlight.

You may have heard **carbon dioxide** referred to as a greenhouse gas. This is because it tends to absorb radiation strongly in the far infrared portion of the spectrum - that area associated with thermal heating - which serves to trap this heat inside the atmosphere. Water vapour in the atmosphere absorbs much of the incoming longwave infrared and shortwave microwave radiation (between $22\mu\text{m}$ and 1m). The presence of water vapour in the lower atmosphere varies greatly from location to location and at different times of the year. For example, the air mass above a desert would have very little water vapour to absorb energy, while the tropics would have high concentrations of water vapour (i.e. high humidity).



Because these gases absorb electromagnetic energy in very specific regions of the spectrum, they influence where (in the spectrum) we can "look" for remote sensing purposes. Those areas of the spectrum which are not severely influenced by atmospheric absorption and thus, are useful to remote sensors, are called **atmospheric windows**. By comparing the characteristics of the two most common energy/radiation sources (the sun and the earth) with the

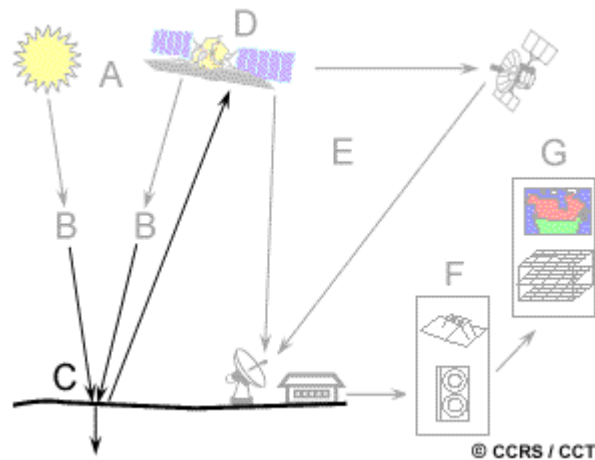
atmospheric windows available to us, we can define those wavelengths that we can use **most effectively** for remote sensing. The visible portion of the spectrum, to which our eyes are most sensitive, corresponds to both an atmospheric window and the peak energy level of the sun. Note also that heat energy emitted by the Earth corresponds to a window around $10\mu\text{m}$ in the thermal IR portion of the spectrum, while the large window at wavelengths beyond 1mm is associated with the

microwave region.

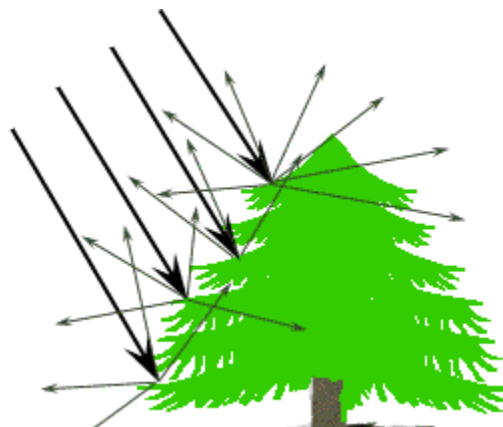
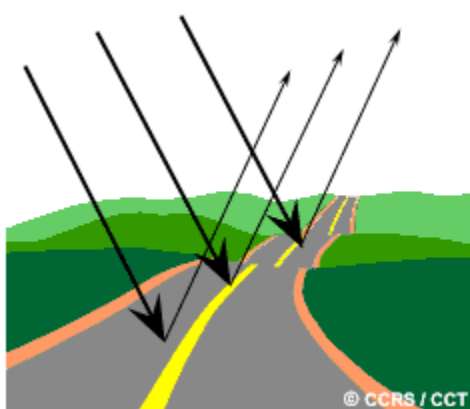
Now that we understand how electromagnetic energy makes its journey from its source to the surface (and it is a difficult journey, as you can see) we will next examine what happens to that radiation when it does arrive at the Earth's surface.

1.5 Radiation - Target Interactions

Radiation that is not absorbed or scattered in the atmosphere can reach and interact with the Earth's surface. There are three (3) forms of interaction that can take place when energy strikes, or is **incident (I)** upon the surface. These are: **absorption (A)**; **transmission (T)**; and **reflection (R)**. The total incident energy will interact with the surface in one or more of these three ways. The proportions of each will depend on the wavelength of the energy and the material and condition of the feature.

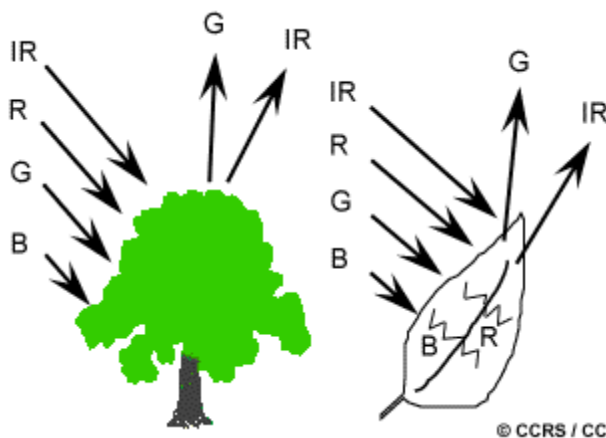


Absorption (A) occurs when radiation (energy) is absorbed into the target while transmission (T) occurs when radiation passes through a target. Reflection (R) occurs when radiation "bounces" off the target and is redirected. In remote sensing, we are most interested in measuring the radiation reflected from targets. We refer to two types of reflection, which represent the two extreme ends of the way in which energy is reflected from a target: **specular reflection** and **diffuse reflection**.



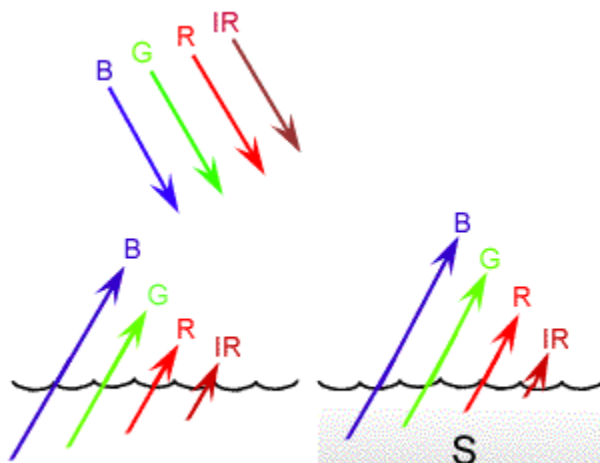
When a surface is smooth we get **specular** or mirror-like reflection where all (or almost all) of the energy is directed away from the surface in a single direction. **Diffuse** reflection occurs when the surface is rough and the energy is reflected almost uniformly in all directions. Most earth surface features lie somewhere between perfectly specular or perfectly diffuse reflectors. Whether a particular target reflects specularly or diffusely, or somewhere in between, depends on the surface roughness of the feature in comparison to the wavelength of the incoming radiation. If the wavelengths are much smaller than the surface variations or the particle sizes that make up the surface, diffuse reflection will dominate. For example, fine-grained sand would appear fairly smooth to long wavelength microwaves but would appear quite rough to the visible wavelengths.

Let's take a look at a couple of examples of targets at the Earth's surface and how energy at the visible and infrared wavelengths interacts with them.



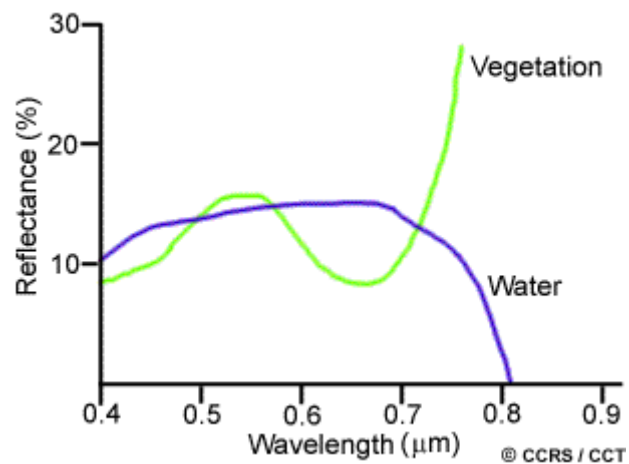
Leaves: A chemical compound in leaves called chlorophyll strongly absorbs radiation in the red and blue wavelengths but reflects green wavelengths. Leaves appear "greenest" to us in the summer, when chlorophyll content is at its maximum. In autumn, there is less chlorophyll in the leaves, so there is less absorption and proportionately more reflection of the red wavelengths, making the leaves appear red or yellow (yellow is a combination of red and green wavelengths). The

internal structure of healthy leaves act as excellent diffuse reflectors of near-infrared wavelengths. If our eyes were sensitive to near-infrared, trees would appear extremely bright to us at these wavelengths. In fact, measuring and monitoring the near-IR reflectance is one way that scientists can determine how healthy (or unhealthy) vegetation may be.



Water: Longer wavelength visible and near infrared radiation is absorbed more by water than shorter visible wavelengths. Thus water typically looks blue or blue-green due to stronger reflectance at these shorter wavelengths, and darker if viewed at red or near infrared wavelengths. If there is suspended sediment present in the upper layers of the water body, then this will allow better reflectivity and a brighter appearance of the water. The apparent colour of the water will show a slight shift to longer

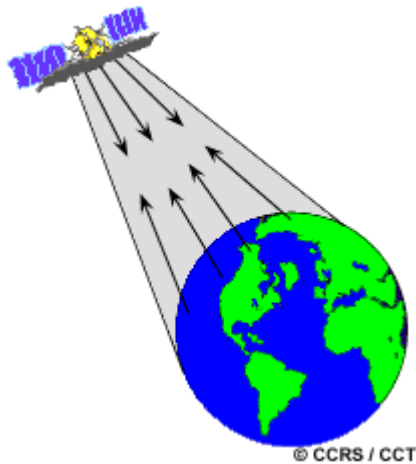
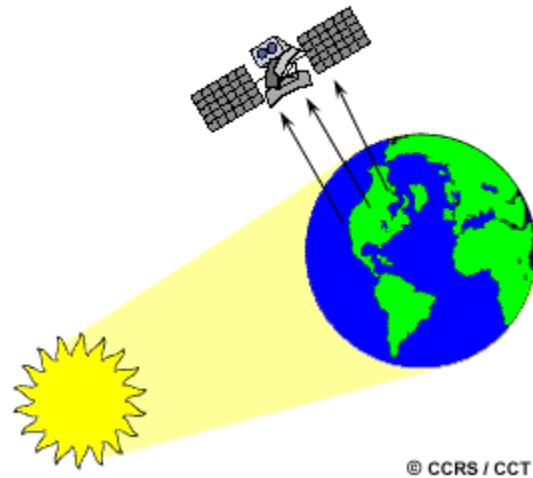
wavelengths. Suspended sediment (S) can be easily confused with shallow (but clear) water, since these two phenomena appear very similar. Chlorophyll in algae absorbs more of the blue wavelengths and reflects the green, making the water appear more green in colour when algae is present. The topography of the water surface (rough, smooth, floating materials, etc.) can also lead to complications for water-related interpretation due to potential problems of specular reflection and other influences on colour and brightness.



We can see from these examples that, depending on the complex make-up of the target that is being looked at, and the wavelengths of radiation involved, we can observe very different responses to the mechanisms of absorption, transmission, and reflection. By measuring the energy that is reflected (or emitted) by targets on the Earth's surface over a variety of different wavelengths, we can build up a **spectral response** for that object. By comparing the response patterns of different features we may be able to distinguish between them, where we might not be able to, if we only compared them at one wavelength. For example, water and vegetation may reflect somewhat similarly in the visible wavelengths but are almost always separable in the infrared. Spectral response can be quite variable, even for the same target type, and can also vary with time (e.g. "green-ness" of leaves) and location. Knowing where to "look" spectrally and understanding the factors which influence the spectral response of the features of interest are critical to correctly interpreting the interaction of electromagnetic radiation with the surface.

1.6 Passive vs. Active Sensing

So far, throughout this chapter, we have made various references to the sun as a source of energy or radiation. The sun provides a very convenient source of energy for remote sensing. The sun's energy is either **reflected**, as it is for visible wavelengths, or absorbed and then **re-emitted**, as it is for thermal infrared wavelengths. Remote sensing systems which measure energy that is naturally available are called **passive sensors**. Passive sensors can only be used to detect energy when the naturally occurring energy is available. For all reflected energy, this can only take place during the time when the sun is illuminating the Earth. There is no reflected energy available from the sun at night. Energy that is naturally emitted (such as thermal infrared) can be detected day or night, as long as the amount of energy is large enough to be recorded.



aperture radar (SAR).

Active sensors, on the other hand, provide their own energy source for illumination. The sensor emits radiation which is directed toward the target to be investigated. The radiation reflected from that target is detected and measured by the sensor. Advantages for active sensors include the ability to obtain measurements anytime, regardless of the time of day or season. Active sensors can be used for examining wavelengths that are not sufficiently provided by the sun, such as microwaves, or to better control the way a target is illuminated. However, active systems require the generation of a fairly large amount of energy to adequately illuminate targets. Some examples of active sensors are a laser fluorosensor and a synthetic

1.7 Characteristics of Images

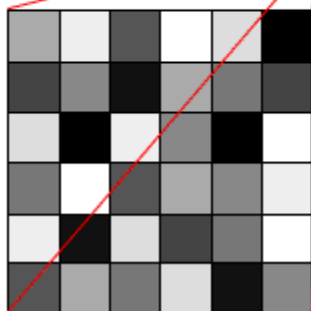
Before we go on to the next chapter, which looks in more detail at sensors and their characteristics, we need to define and understand a few fundamental terms and concepts associated with remote sensing images.



Electromagnetic energy may be detected either photographically or electronically. The photographic process uses chemical reactions on the surface of light-sensitive film to detect and record energy variations. It is important to distinguish between the terms **images** and **photographs** in remote sensing. An image refers to any pictorial representation, regardless of what wavelengths or remote sensing device has been used to detect and record the electromagnetic energy. A **photograph** refers

specifically to images that have been detected as well as recorded on photographic film. The black and white photo to the left, of part of the city of Ottawa, Canada was taken in the visible part of the spectrum. Photos are normally recorded over the wavelength range from $0.3 \mu\text{m}$ to $0.9 \mu\text{m}$ - the visible and reflected infrared. Based on these definitions, we can say that all photographs are images, but not all images are photographs. Therefore, unless we are talking specifically about an image recorded photographically, we use the term image.

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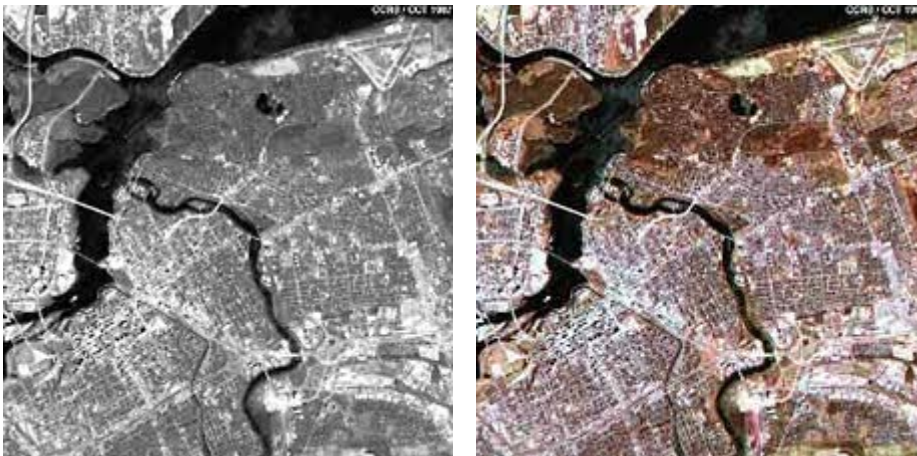
170	238	85	255	221	0
68	136	17	170	119	68
221	0	238	136	0	255
119	255	85	170	136	238
238	17	221	68	119	255
85	170	119	221	17	136

A photograph could also be represented and displayed in a **digital** format by subdividing the image into small equal-sized and shaped areas, called picture elements or **pixels**, and representing the brightness of each area with a numeric value or **digital number**. Indeed, that is exactly what has been done to the photo to the left. In fact, using the definitions we have just discussed, this is actually a **digital image** of the

original photograph! The photograph was scanned and subdivided into pixels with each pixel assigned a digital number representing its relative brightness. The computer displays each digital value as different brightness levels. Sensors that

record electromagnetic energy, electronically record the energy as an array of numbers in digital format right from the start. These two different ways of representing and displaying remote sensing data, either pictorially or digitally, are interchangeable as they convey the same information (although some detail may be lost when converting back and forth).

In previous sections we described the visible portion of the spectrum and the concept of colours. We see colour because our eyes detect the entire visible range of wavelengths and our brains process the information into separate colours. Can you imagine what the world would look like if we could only see very narrow ranges of wavelengths or colours? That is how many sensors work. The information from a narrow wavelength range is gathered and stored in a **channel**, also sometimes referred to as a **band**. We can combine and display channels of information digitally using the three primary colours (blue, green, and red). The data from each channel is represented as one of the primary colours and, depending on the relative brightness (i.e. the digital value) of each pixel in each channel, the primary colours combine in different proportions to represent different colours.



When we use this method to display a single channel or range of wavelengths, we are actually displaying that channel through all three primary colours. Because the brightness level of each pixel is the same for each primary colour, they combine to form a **black and white image**, showing various shades of gray from black to white. When we display more than one channel each as a different primary colour, then the brightness levels may be different for each channel/primary colour combination and they will combine to form a **colour image**.

1.8 Endnotes

You have just completed **Chapter 1 - Fundamentals of Remote Sensing**. You can continue to Chapter 2 - Satellites and Sensors or first browse the [CCRS Web site](#)¹ for other articles related to remote sensing fundamentals.

For instance, you may want to look at some [conventional](#)² or [unconventional definitions](#)³ of "remote sensing" developed by experts and other rif-raf from around the world.

We have an explanation and calculation on just how much [you need to worry about the effect of radiation](#)⁴ from Canada's first remote sensing satellite: RADARSAT.

The knowledge of how radiation interacts with the atmospheric is used by scientists in the Environmental Monitoring Section of CCRS to develop various ["radiation products"](#)⁵. Check them out!

Learn more on how various targets like [water](#)⁶, [rocks](#)⁷, [ice](#)⁸, [man-made features](#)⁹, and [oil slicks](#)¹⁰ interact with microwave energy.

Our [Remote Sensing Glossary](#)¹¹ can help fill out your knowledge of remote sensing fundamentals. Try searching for specific terms of interest or review the terms in the "phenomena" category.

¹<http://www.ccrs.nrcan.gc.ca/>

²http://www.ccrs.nrcan.gc.ca/ccrs/learn/terms/definition/convdef_e.html

³http://www.ccrs.nrcan.gc.ca/ccrs/learn/terms/definition/unconvdef_e.html

⁴http://www.ccrs.nrcan.gc.ca/ccrs/learn/fun/radiation/radiation_e.html

⁵http://www.ccrs.nrcan.gc.ca/ccrs/rd/apps/landcov/rad/emrad_e.html

⁶http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/images/man/rman01_e.html

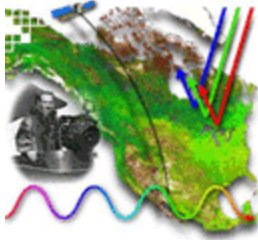
⁷http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/images/nwt/rnwt01_e.html

⁸http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/images/pei/rpei01_e.html

⁹http://www.ccrs.nrcan.gc.ca/ccrs/rd/ana/cnfdbrig/confed_e.html

¹⁰http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/images/uk/ruk01_e.html

¹¹http://www.ccrs.nrcan.gc.ca/ccrs/learn/terms/glossary/glossary_e.html



1. Did You Know

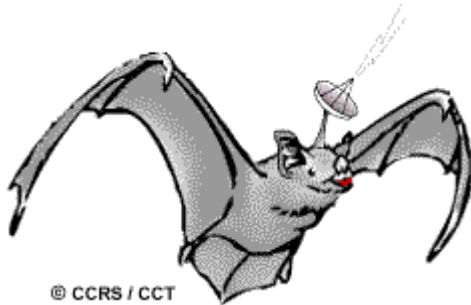
1.1 Did You Know?



Of our five senses (sight, hearing, taste, smell, touch), three may be considered forms of "remote sensing", where the source of information is at some distance. The other two rely on direct contact with the source of information - which are they?

1.2 Did You Know?

"I've Gone Batty!"

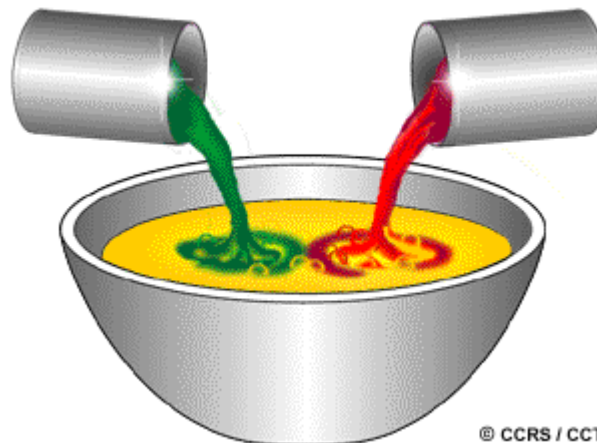


...that remote sensing, in its broadest definition, includes ultrasounds, satellite weather maps, speed radar, graduation photos, and sonar - both for ships and for bats!. Hospitals use imaging technology, including CAT scans, magnetic resonance imaging (3-D imaging of soft tissue), and x-rays for examining our bodies. These are all examples of non-intrusive remote sensing methods.

...you can use an oscilloscope, a special electronic device which displays waves similar to the electromagnetic radiation waves you have seen here, to look at the wavelength and frequency patterns of your voice. High-pitched sounds have short wavelengths and high frequencies. Low sounds are the opposite. Scientists say that the Earth itself vibrates at a very low frequency, making a sound far below the human hearing range.

...that the concept of wavelength and frequency is an important principle behind something called the Doppler Shift, which explains how sound and light waves are perceived to be compressed or expanded if the object producing them is moving relative to the sensor. As a train or race car advances towards us, our ears tend to hear progressively lower sounds or frequencies (shorter wavelengths) until it reaches us, the original frequency of the object when it is broadside, then even lower frequencies as it moves further away. This same principle (applied to light) is used by astronomers to see how quickly stars are moving away from us (the Red shift).

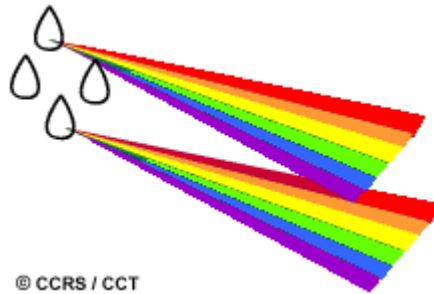
1.3 Did You Know?



Hue and **saturation** are independent characteristics of colour. Hue refers to the wavelength of light, which we commonly call "colour", while saturation indicates how pure the colour is, or how much white is mixed in with it. For instance, "pink" can be considered a less saturated version of "red".

1.4 Did You Know?

"...sorry, no pot of gold at the end of this rainbow..."



...water droplets act as tiny, individual prisms. When sunlight passes through them, the constituent wavelengths are bent in varying amounts according to wavelength. Individual colours in the sunlight are made visible and a rainbow is the result, with shorter wavelengths (violet, blue) in the inner part of the arc, and longer wavelengths (orange, red) along the outer arc.

...if scattering of radiation in the atmosphere did not take place, then shadows would appear as jet black instead of being various degrees of darkness. Scattering causes the atmosphere to have its own brightness (from the light scattered by particles in the path of sunlight) which helps to illuminate the objects in the shadows.

1.5 Did You Know?

"...now, here's something to 'reflect' on..."



... the colours we perceive are a combination of these radiation interactions (absorption, transmission, reflection), and represent the wavelengths being reflected. If all visible wavelengths are reflected from an object, it will appear white, while an object absorbing all visible wavelengths will appear colourless, or black.

1.6 Did You Know?

"...say 'Cheese!'..."

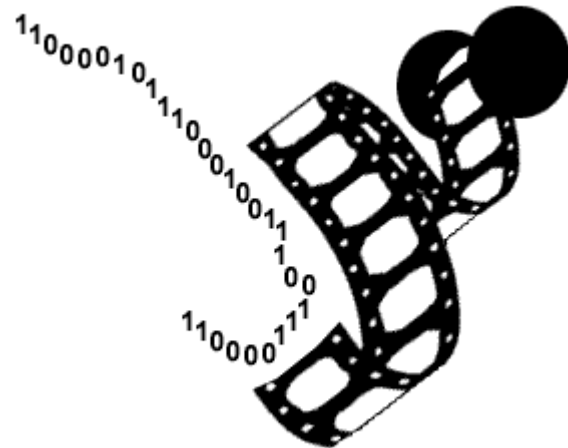
...a camera provides an excellent example of both passive and active sensors. During a bright sunny day, enough sunlight is illuminating the targets and then reflecting toward the camera lens, that the camera simply records the radiation provided (passive mode). On a cloudy day or inside a room, there is often not enough sunlight for the camera to record the targets adequately. Instead, it uses its own energy source - a flash - to illuminate the targets and record the radiation reflected from them (active mode).

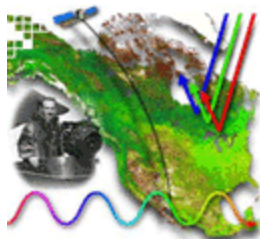
... radar used by police to measure the speed of traveling vehicles is a use of active remote sensing. The radar device is pointed at a vehicle, pulses of radiation are emitted, and the reflection of that radiation from the vehicle is detected and timed. The speed of the vehicle is determined by calculating time delays between the repeated emissions and reception of the pulses. This can be calculated very accurately because the speed of the radiation is moving much, much faster than most vehicles...unless you're driving at the speed of light!



1.7 Did You Know?

Photographic film has the clear advantage of recording extremely fine spatial detail, since individual silver halide molecules can record light sensitivity differently than their neighbouring molecules. But when it comes to spectral and radiometric qualities, digital sensors outperform film, by being able to use extremely fine spectral bands (for spectral 'fingerprinting' of targets), and recording up to many thousands of levels of brightness.





1. Whiz Quiz and Answers

1.1 Whiz Quiz



Can "remote sensing" employ anything other than electromagnetic radiation?

1.1 Whiz Quiz - Answer

While the term 'remote sensing' typically assumes the use of electromagnetic radiation, the more general definition of 'acquiring information at a distance', does not preclude other forms of energy. The use of sound is an obvious alternative; thus you can claim that your telephone conversation is indeed 'remote sensing'.

1.2 Whiz Quiz

The first requirement for remote sensing is an energy source which can illuminate a target. What is the obvious source of electromagnetic energy that you can think of? What "remote sensing device" do you personally use to detect this energy?



Assume the speed of light to be 3×10^8 m/s. If the frequency of an electromagnetic wave is 500,000 GHz (GHz = gigahertz = 10^9 m/s), what is the wavelength of that radiation? Express your answer in micrometres (μm).

1.2 Whiz Quiz - Answers

Answer 1: The most obvious source of electromagnetic energy and radiation is the sun. The sun provides the initial energy source for much of the remote sensing of the Earth surface. The remote sensing device that we humans use to detect radiation from the sun is our eyes. Yes, they can be considered remote sensors - and very good ones - as they detect the visible light from the sun, which allows us to see. There are other types of light which are invisible to us...but more about that later.

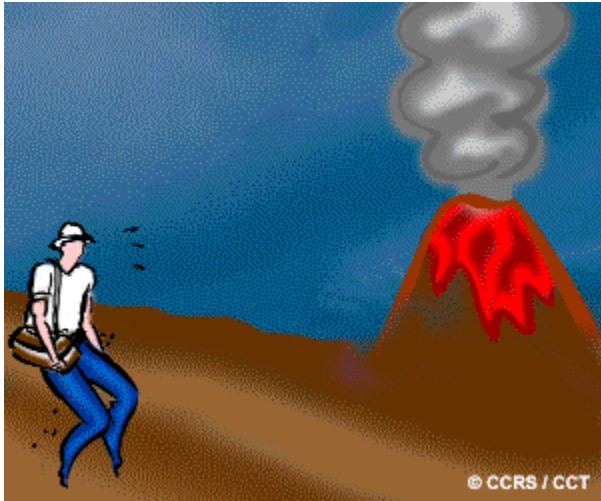
Answer 2: Using the equation for the relationship between wavelength and frequency, let's calculate the wavelength of radiation of a frequency of 500,000 GHz.



$$\begin{aligned}
 c &= \lambda \nu \\
 3 \times 10^8 &= \lambda (500,000 \times 10^9) \\
 3 \times 10^8 &= \lambda (5 \times 10^{14}) \\
 3 \times 10^8 / 5 \times 10^{14} &= \lambda \\
 6 \times 10^{-7} \text{ metres} &= \lambda
 \end{aligned}$$

1.3 Whiz Quiz

The infrared portion of the electromagnetic spectrum has two parts: the reflective and the emissive. Can you take photographs in these wavelength ranges?



1.3 Whiz Quiz - Answer

Yes and no. There are photographic films in black and white as well as colour emulsions, which are sensitive to the reflective portion of the infrared band and these are used for scientific and artistic purposes too. But no photographic films exist to directly record emissive infrared (heat). If they did, then they would have to be cooled (and kept very cold during use), which would be very impractical. However there are a number of electronic devices which detect and record thermal infrared images.

1.4 Whiz Quiz



© CCRS / CCT

1. Most remote sensing systems avoid detecting and recording wavelengths in the ultraviolet and blue portions of the spectrum. Explain why this would be the case.

is ...

2. What do you think would be some of the best atmospheric conditions for remote sensing in the visible portion of the spectrum?

1.4 Whiz Quiz - Answer



© CCRS / CCT

1. Detecting and recording the ultraviolet and blue wavelengths of radiation is difficult because of scattering and absorption in the atmosphere. Ozone gas in the upper atmosphere absorbs most of the ultraviolet radiation of wavelengths shorter than about 0.25 μm . This is actually a positive thing for us and most other living things, because of the harmful nature of ultraviolet radiation below these wavelengths. Rayleigh scattering, which affects the shorter wavelengths more severely than longer wavelengths, causes the remaining UV radiation and the shorter visible wavelengths (i.e. blue) to be scattered much more than longer wavelengths, so that very little of this energy is able to reach and interact with the Earth's surface. In fact, blue light is scattered about 4 times as much as red light, while UV light is scattered 16 times as much as red light!

2. Around noon on a sunny, dry day with no clouds and no pollution would be very good for remote sensing in the visible wavelengths. At noon the sun would be at its most directly overhead point, which would reduce the distance the radiation has to travel and therefore the effects of scattering, to a minimum. Cloud-free conditions would ensure that there will be uniform illumination and that there will be no shadows from clouds. Dry, pollutant-free conditions would minimize the scattering and absorption that would take place due to water droplets and other particles in the atmosphere.

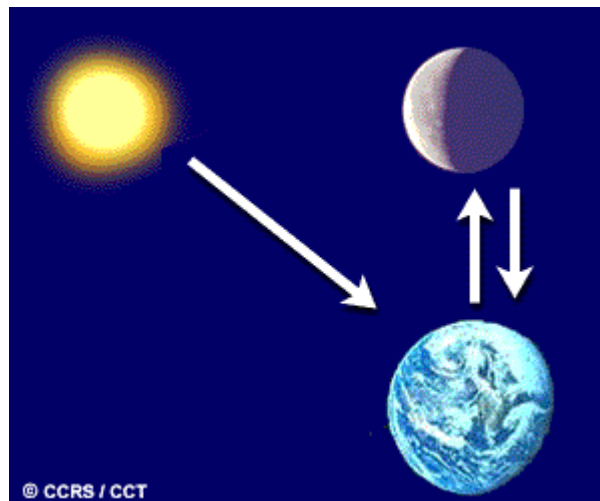


1.5 Whiz Quiz



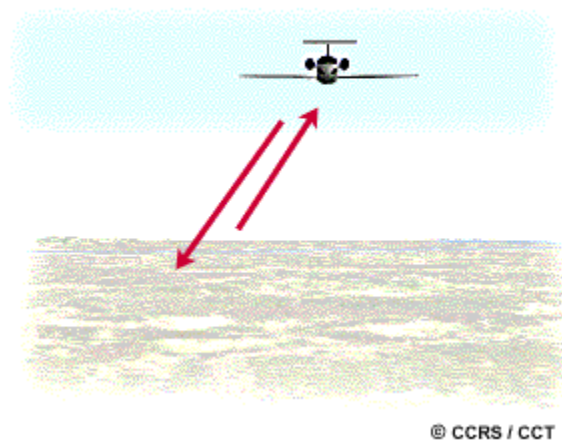
On a clear night with the crescent or half moon showing, it is possible to see the outline and perhaps very slight detail of the dark portion of the moon. Where is the light coming from, that illuminates the dark side of the moon?

1.5 Whiz Quiz - Answer



The light originates from the sun (of course), hits the earth, bounces up to the (dark side of the) moon and then comes back to the earth and into your eye. A long way around - isn't it?

1.6 Whiz Quiz

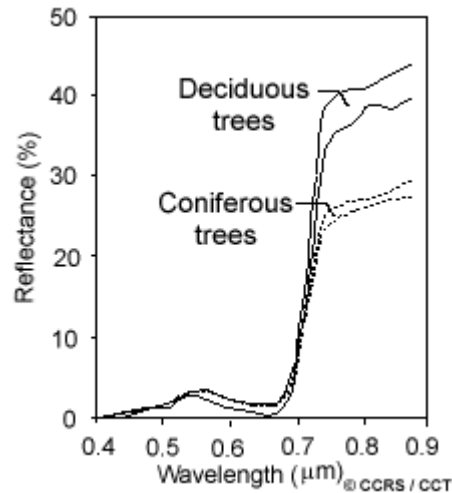


Is there a passive equivalent to the radar sensor?

1.6 Whiz Quiz - Answer

Indeed. The passive microwave radiometer, for instance, does not carry an illumination source, relying instead on detecting naturally emitted microwave energy. Such an instrument can be used for detecting, identifying and measuring marine oil slicks, for instance.

1.7 Whiz Quiz



1. If you wanted to map the deciduous (e.g. maple, birch) and the coniferous (e.g. pine, fir, spruce) trees in a forest in summer using remote sensing data, what would be the best way to go about this and why? Use the reflectance curves illustrating the spectral response patterns of these two categories to help explain your answer.

2. What would be the advantage of displaying various wavelength ranges, or channels, in combination as colour images as opposed to examining each of the images individually?

1.7 Whiz Quiz - Answer

1. Because both types of trees will appear as similar shades of green to the naked eye, imagery (or photography) using the visible portion of the spectrum may not be useful. Trying to distinguish the different types from aerial photographs based on tree crown shape or size might also be difficult, particularly when the tree types are intermixed. Looking at the reflectance curves for the two types, it is clear that they would be difficult to distinguish using any of the visible wavelengths. However, in the near-infrared, although both types reflect a significant portion of the incident radiation, they are clearly separable. Thus, a remote sensing system, such as black and white infrared film, which detects the infrared reflectance around 0.8 mm wavelength would be ideal for this purpose.

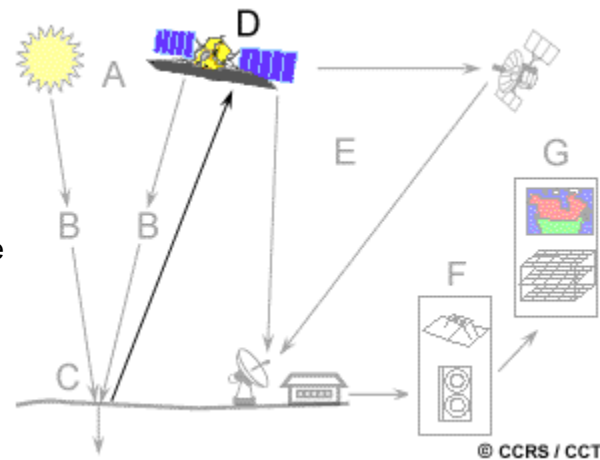
2. By combining different channels of imagery representing different wavelengths, we may be able to identify combinations of reflectance between the different channels which highlight features that we would not otherwise be able to see, if we examine only one channel at a time. Additionally, these combinations may manifest themselves as subtle variations in colour (which our eyes are more sensitive to), rather than variations in gray tone, as would be seen when examining only one image at a time.



2. Satellites and Sensors

2.1 On the Ground, In the Air, In Space

In Chapter 1 we learned some of the fundamental concepts required to understand the process that encompasses remote sensing. We covered in some detail the first three components of this process: the energy source, interaction of energy with the atmosphere, and interaction of energy with the surface. We touched briefly on the fourth component - **recording of energy by the sensor** - when we discussed passive vs. active sensors and characteristics of images. In this chapter, we will take a closer look at this component of the remote sensing process by examining in greater detail, the characteristics of remote sensing platforms and sensors and the data they collect. We will also touch briefly on how those data are processed once they have been recorded by the sensor.



In order for a sensor to collect and record energy reflected or emitted from a target or surface, it must reside on a stable **platform** removed from the target or surface being observed. Platforms for remote sensors may be situated on the ground, on an aircraft or balloon (or some other platform within the Earth's atmosphere), or on a spacecraft or satellite outside of the Earth's atmosphere.

Ground-based sensors are often used to record detailed information about the surface which is compared with information collected from aircraft or satellite sensors. In some cases,

this can be used to better characterize the target which is being imaged by these other sensors, making it possible to better understand the information in the imagery.



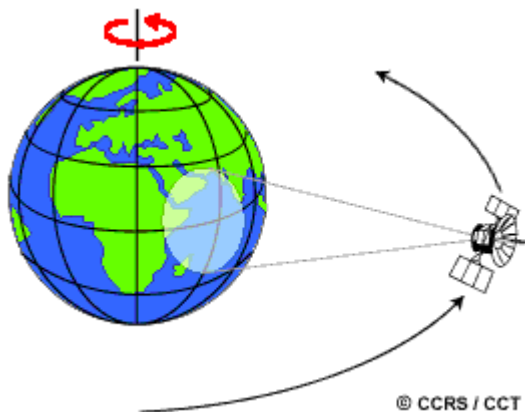
Sensors may be placed on a ladder, scaffolding, tall building, cherry-picker, crane, etc. Aerial platforms are primarily stable wing **aircraft**, although helicopters are occasionally used. Aircraft are often used to collect very detailed images and facilitate the collection of data over virtually any portion of the Earth's surface at any time.

In space, remote sensing is sometimes conducted from the **space shuttle** or, more commonly, from satellites. **Satellites** are objects which revolve around another object - in this case, the Earth. For example, the moon is a natural satellite, whereas man-made satellites include those platforms launched for remote sensing, communication, and telemetry (location and navigation) purposes. Because of their orbits, satellites permit repetitive coverage of the Earth's surface on a continuing basis. Cost is often a significant factor in choosing among the various platform options.



2.2 Satellite Characteristics: Orbits and Swaths

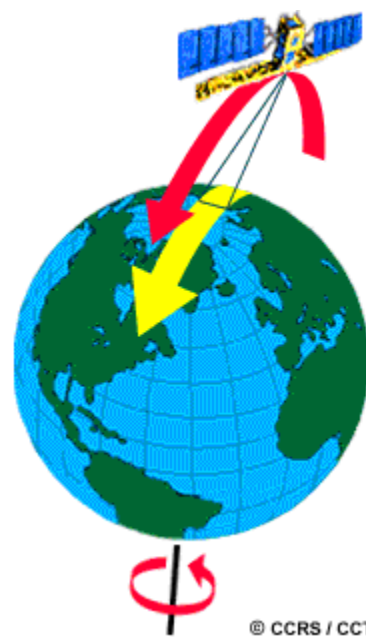
We learned in the previous section that remote sensing instruments can be placed on a variety of platforms to view and image targets. Although ground-based and aircraft platforms may be used, satellites provide a great deal of the remote sensing imagery commonly used today. Satellites have several unique characteristics which make them particularly useful for remote sensing of the Earth's surface.

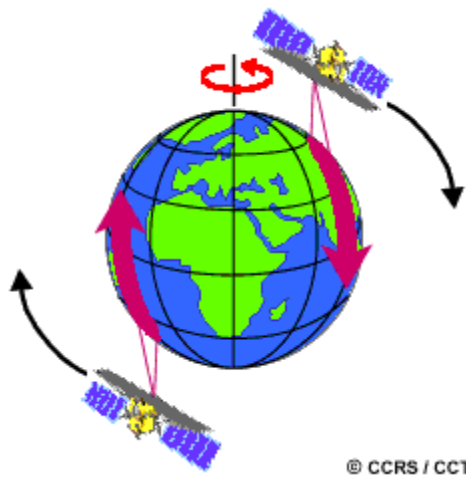


The path followed by a satellite is referred to as its **orbit**. Satellite orbits are matched to the capability and objective of the sensor(s) they carry. Orbit selection can vary in terms of altitude (their height above the Earth's surface) and their orientation and rotation relative to the Earth. Satellites at very high altitudes, which view the same portion of the Earth's surface at all times have **geostationary orbits**. These geostationary satellites, at altitudes of approximately 36,000 kilometres, revolve at speeds which match the rotation of the Earth so they seem stationary, relative to the Earth's

surface. This allows the satellites to observe and collect information continuously over specific areas. Weather and communications satellites commonly have these types of orbits. Due to their high altitude, some geostationary weather satellites can monitor weather and cloud patterns covering an entire hemisphere of the Earth.

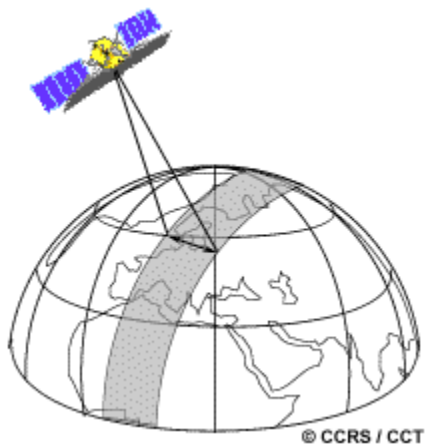
Many remote sensing platforms are designed to follow an orbit (basically north-south) which, in conjunction with the Earth's rotation (west-east), allows them to cover most of the Earth's surface over a certain period of time. These are **near-polar orbits**, so named for the inclination of the orbit relative to a line running between the North and South poles. Many of these satellite orbits are also **sun-synchronous** such that they cover each area of the world at a constant local time of day called **local sun time**. At any given latitude, the position of the sun in the sky as the satellite passes overhead will be the same within the same season. This ensures consistent illumination conditions when acquiring images in a specific season over successive years, or over a particular area over a series of days. This is an important factor for monitoring changes between images or for mosaicking adjacent images together, as they do not have to be corrected for different illumination conditions.





Most of the remote sensing satellite platforms today are in near-polar orbits, which means that the satellite travels northwards on one side of the Earth and then toward the southern pole on the second half of its orbit. These are called **ascending and descending passes**, respectively. If the orbit is also sun-synchronous, the ascending pass is most likely on the shadowed side of the Earth while the descending pass is on the sunlit side. Sensors recording reflected solar energy only image the surface on a descending pass, when solar illumination is available. Active sensors which provide their own illumination or passive sensors that record emitted (e.g. thermal) radiation can also image the surface on ascending

passes.

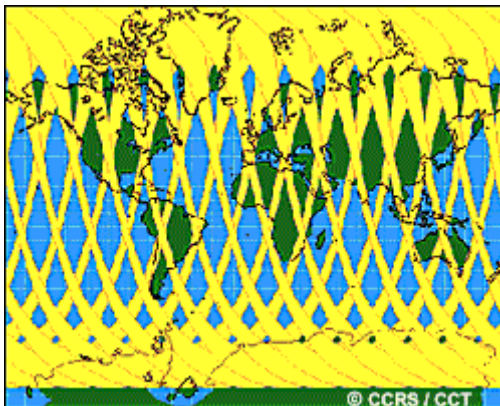
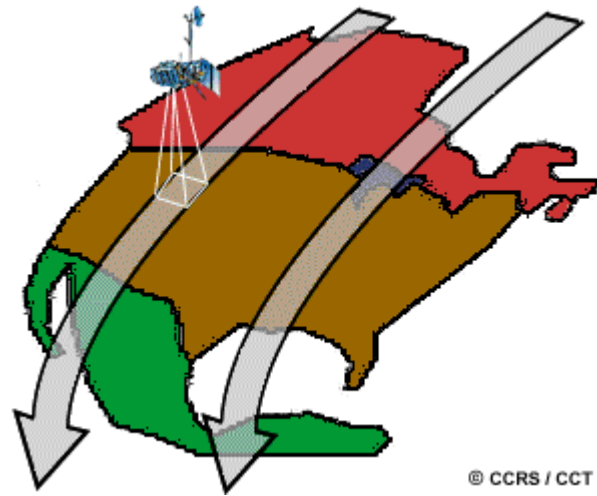


As a satellite revolves around the Earth, the sensor "sees" a certain portion of the Earth's surface. The area imaged on the surface, is referred to as the **swath**. Imaging swaths for spaceborne sensors generally vary between tens and hundreds of kilometres wide. As the satellite orbits the Earth from pole to pole, its east-west position wouldn't change if the Earth didn't rotate. However, as seen from the Earth, it seems that the satellite is shifting westward because the Earth is rotating (from west to east) beneath it. This apparent movement allows the satellite swath to cover a **new area with each consecutive pass**. The satellite's orbit and the rotation of the Earth work together to allow complete coverage of

the Earth's surface, after it has completed one complete cycle of orbits.

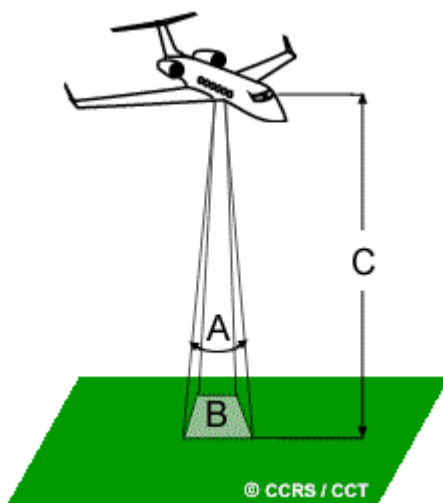
If we start with any randomly selected pass in a satellite's orbit, an orbit cycle will be completed when the satellite retraces its path, passing over the same point on the Earth's surface directly below the satellite (called the **nadir** point) for a second time. The exact length of time of the orbital cycle will vary with each satellite. The interval of time required for the satellite to complete its orbit cycle is not the same as the "**revisit period**". Using steerable sensors, an

satellite-borne instrument can view an area (off-nadir) before and after the orbit passes over a target, thus making the 'revisit' time less than the orbit cycle time. The revisit period is an important consideration for a number of monitoring applications, especially when frequent imaging is required (for example, to monitor the spread of an oil spill, or the extent of flooding). In near-polar orbits, areas at high latitudes will be imaged more frequently than the equatorial zone due to the increasing **overlap in adjacent swaths** as the orbit paths come closer together near the poles.



2.3 Spatial Resolution, Pixel Size, and Scale

For some remote sensing instruments, the distance between the target being imaged and the platform, plays a large role in determining the detail of information obtained and the total area imaged by the sensor. Sensors onboard platforms far away from their targets, typically view a larger area, but cannot provide great detail. Compare what an astronaut onboard the space shuttle sees of the Earth to what you can see from an airplane. The astronaut might see your whole province or country in one glance, but couldn't distinguish individual houses. Flying over a city or town, you would be able to see individual buildings and cars, but you would be viewing a much smaller area than the astronaut. There is a similar difference between satellite images and airphotos.



The detail discernible in an image is dependent on the **spatial resolution** of the sensor and refers to the size of the smallest possible feature that can be detected. Spatial resolution of passive sensors (we will look at the special case of active microwave sensors later) depends primarily on their **Instantaneous Field of View (IFOV)**. The IFOV is the angular cone of visibility of the sensor (A) and determines the area on the Earth's surface which is "seen" from a given altitude at one particular moment in time (B). The size of the area viewed is determined by multiplying the IFOV by the distance from the ground to the sensor (C). This area on the ground is called the **resolution cell** and determines a sensor's maximum spatial resolution. For a homogeneous feature to be

detected, its size generally has to be equal to or larger than the resolution cell. If the feature is smaller than this, it may not be detectable as the average brightness of all features in that resolution cell will be recorded. However, smaller features may sometimes be detectable if their reflectance dominates within a particular resolution cell allowing sub-pixel or resolution cell detection.

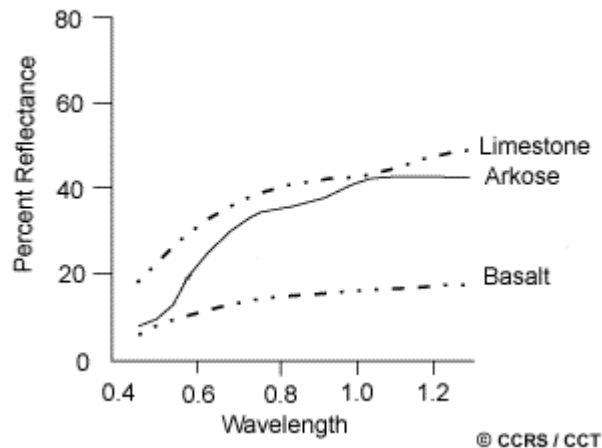
As we mentioned in Chapter 1, most remote sensing images are composed of a matrix of picture elements, or **pixels**, which are the smallest units of an image. Image pixels are normally square and represent a certain area on an image. It is important to distinguish between pixel size and spatial resolution - they are not interchangeable. If a sensor has a spatial resolution of 20 metres and an image from that sensor is displayed at full resolution, each pixel represents an area of 20m x 20m on the ground. In this case the pixel size and resolution are the same. However, it is possible to display an image with a pixel size different than the resolution. Many posters of satellite images of the Earth have their pixels averaged to represent larger areas, although the original spatial resolution of the sensor that collected the imagery remains the same.



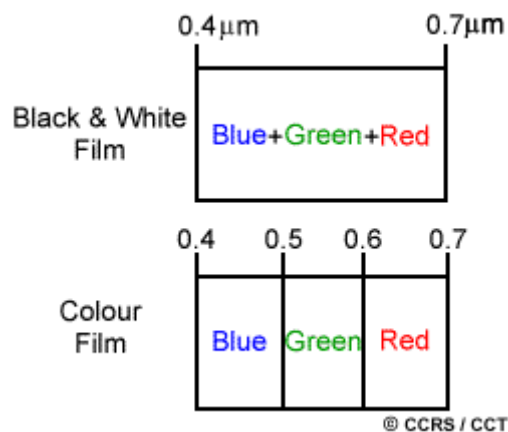
Images where only large features are visible are said to have **coarse or low resolution**. In **fine or high resolution** images, small objects can be detected. Military sensors for example, are designed to view as much detail as possible, and therefore have very fine resolution. Commercial satellites provide imagery with resolutions varying from a few metres to several kilometres. Generally speaking, the finer the resolution, the less total ground area can be seen.

The ratio of distance on an image or map, to actual ground distance is referred to as scale. If you had a map with a scale of 1:100,000, an object of 1cm length on the map would actually be an object 100,000cm (1km) long on the ground. Maps or images with small "map-to-ground ratios" are referred to as small scale (e.g. 1:100,000), and those with larger ratios (e.g. 1:5,000) are called large scale.

2.4 Spectral Resolution



In Chapter 1, we learned about **spectral response** and **spectral emissivity curves** which characterize the reflectance and/or emittance of a feature or target over a variety of wavelengths. Different classes of features and details in an image can often be distinguished by comparing their responses over distinct wavelength ranges. Broad classes, such as water and vegetation, can usually be separated using very broad wavelength ranges - the visible and near infrared - as we learned in section 1.5. Other more specific classes, such as **different rock types**, may not be easily distinguishable using either of these broad wavelength ranges and would require comparison at much finer wavelength ranges to separate them. Thus, we would require a sensor with higher **spectral resolution**. Spectral resolution describes the ability of a sensor to define fine wavelength intervals. The finer the spectral resolution, the narrower the wavelength range for a particular channel or band.



Black and white film records wavelengths extending over much, or all of the visible portion of the electromagnetic spectrum. Its **spectral resolution** is fairly coarse, as the various wavelengths of the visible spectrum are not individually distinguished and the overall

reflectance in the entire visible portion is recorded. Colour film is also sensitive to the reflected energy over the visible portion of the spectrum, but has higher spectral resolution, as it is individually sensitive to the reflected energy at the blue, green, and red wavelengths of the spectrum. Thus, it can represent features of various colours based on their reflectance in each of these distinct wavelength ranges.

Many remote sensing systems record energy over several separate wavelength ranges at various spectral resolutions. These are referred to as **multi-spectral sensors** and will be described in some detail in following sections. Advanced multi-spectral sensors called **hyperspectral** sensors, detect hundreds of very narrow spectral bands throughout the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum. Their very high spectral resolution facilitates fine discrimination between different targets based on their spectral response in each of the narrow bands.

2.5 Radiometric Resolution

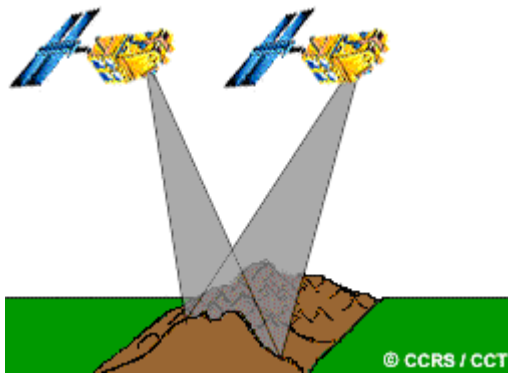
While the arrangement of pixels describes the spatial structure of an image, the radiometric characteristics describe the actual information content in an image. Every time an image is acquired on film or by a sensor, its sensitivity to the magnitude of the electromagnetic energy determines the **radiometric resolution**. The radiometric resolution of an imaging system describes its ability to discriminate very slight differences in energy. The finer the radiometric resolution of a sensor, the more sensitive it is to detecting small differences in reflected or emitted energy.



Imagery data are represented by positive digital numbers which vary from 0 to (one less than) a selected power of 2. This range corresponds to the number of bits used for coding numbers in binary format. Each bit records an exponent of power 2 (e.g. 1 bit = $2^1 = 2$). The maximum number of brightness levels available depends on the number of bits used in representing the energy recorded. Thus, if a sensor used 8 bits to record the data, there would be $2^8 = 256$ digital values available, ranging from 0 to 255. However, if only 4 bits were used, then only $2^4 = 16$ values ranging from 0 to 15 would be available. Thus, the radiometric resolution would be much less. Image data are generally displayed in a range of grey tones, with black representing a digital number of 0 and white representing the maximum value (for example, 255 in 8-bit data). By **comparing a 2-bit image with an 8-bit image**, we can see that there is a large difference in the level of detail discernible depending on their radiometric resolutions.

2.6 Temporal Resolution

In addition to spatial, spectral, and radiometric resolution, the concept of **temporal resolution** is also important to consider in a remote sensing system. We alluded to this idea in section 2.2 when we discussed the concept of revisit period, which refers to the length of time it takes for a satellite to complete one entire orbit cycle. The revisit period of a satellite sensor is usually several days. Therefore the absolute temporal resolution of a remote sensing system to image the exact same area at the same viewing angle a second time is equal to this period. However, because of some degree of overlap in the imaging swaths of adjacent orbits for most satellites and the increase in this overlap with increasing latitude, some areas of the Earth tend to be re-imaged more frequently. Also, some satellite systems are able to **point their sensors to image the same area** between different satellite passes separated by periods from one to five days. Thus, the actual temporal resolution of a sensor depends on a variety of factors, including the satellite/sensor capabilities, the swath overlap, and latitude.

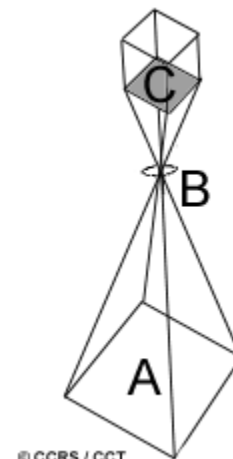


The ability to collect imagery of the same area of the Earth's surface at different periods of time is one of the most important elements for applying remote sensing data. Spectral characteristics of features may change over time and these changes can be detected by collecting and comparing **multi-temporal** imagery. For example, during the growing season, most species of vegetation are in a continual state of change and our ability to monitor those subtle changes using remote sensing is dependent on when and how frequently we collect imagery. By imaging on a continuing basis at different times we are able to monitor the changes that take place on the Earth's surface, whether they are naturally occurring (such as changes in natural vegetation cover or flooding) or induced by humans (such as urban development or deforestation). The time factor in imaging is important when:

- persistent clouds offer limited clear views of the Earth's surface (often in the tropics)
- short-lived phenomena (floods, oil slicks, etc.) need to be imaged
- multi-temporal comparisons are required (e.g. the spread of a forest disease from one year to the next)
- the changing appearance of a feature over time can be used to distinguish it from near-similar features (wheat / maize)

2.7 Cameras and Aerial Photography

Cameras and their use for aerial photography are the simplest and oldest of sensors used for remote sensing of the Earth's surface. Cameras are **framing systems** which acquire a near-instantaneous "snapshot" of an **area (A)**, of the surface. Camera systems are passive optical sensors that use a **lens (B)** (or system of lenses collectively referred to as the optics) to form an image at the focal plane (C), the plane at which an image is sharply defined.



Photographic films are sensitive to light from 0.3 μm to 0.9 μm in wavelength covering the ultraviolet (UV), visible, and near-infrared (NIR). **Panchromatic** films are sensitive to the UV and the visible portions of the spectrum. Panchromatic film produces black and white images and is the most common type of film used for aerial photography. UV photography also uses panchromatic film, but a filter is used with the camera to absorb and block the visible energy from reaching the film. As a result, only the UV reflectance from targets is recorded. UV photography is not widely used, because of the atmospheric scattering and absorption that occurs in this region of the spectrum. Black and white infrared photography uses film sensitive to the entire 0.3 to 0.9 μm wavelength range and is useful for detecting differences in vegetation cover, due to its sensitivity to IR reflectance.



Colour and false colour (or colour infrared, CIR) photography involves the use of a three layer film with each layer sensitive to different ranges of light. For a **normal colour photograph**, the layers are sensitive to blue, green, and red light - the same as our eyes. These photos appear to us the same way that our eyes see the environment, as the colours resemble those which would appear to us as "normal" (i.e. trees appear green, etc.). In colour infrared (CIR) photography, the three emulsion layers are sensitive to green, red, and the photographic portion of near-infrared radiation, which are processed to appear as blue, green, and red,

respectively. In a **false colour photograph**, targets with high near-infrared reflectance appear red, those with a high red reflectance appear green, and those with a high green reflectance appear blue, thus giving us a "false" presentation of the targets relative to the colour we normally perceive them to be.

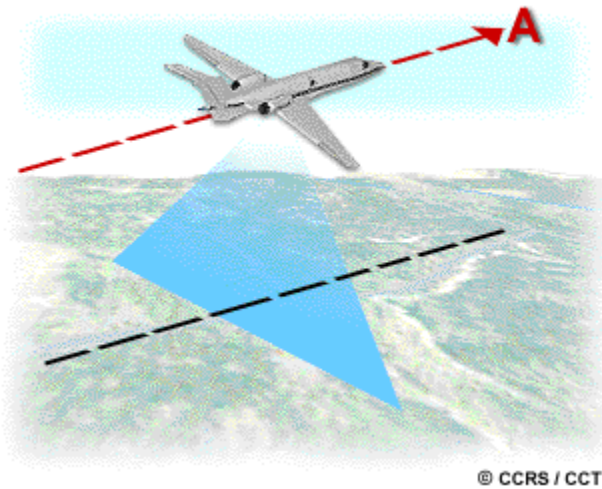
Cameras can be used on a variety of platforms including ground-based stages, helicopters, aircraft, and spacecraft. Very detailed photographs taken from aircraft are useful for many applications where identification of detail or small targets is required. The ground coverage of a photo depends on several factors, including the focal length of the lens, the platform altitude, and the format and size of the film. The focal length effectively controls the **angular field of view** of the lens (similar to the concept of instantaneous field of view discussed in section 2.3) and determines the area "seen" by the camera. Typical focal lengths used are 90mm, 210mm, and most commonly, 152mm. The longer the focal length, the smaller the area covered on the ground, but with greater detail (i.e. larger scale). The area covered also depends on the altitude of the platform. At high altitudes, a camera will "see" a larger area on the ground than at lower altitudes, but with reduced detail (i.e. smaller scale). Aerial photos can provide fine detail down to spatial resolutions of less than 50 cm. A photo's exact spatial resolution varies as a complex function of many factors which vary with each acquisition of data.



Most aerial photographs are classified as either **oblique** or **vertical**, depending on the orientation of the camera relative to the ground during acquisition. **Oblique aerial photographs** are taken with the camera pointed to the side of the aircraft. High oblique photographs usually include the horizon while low oblique photographs do not. Oblique photographs can be useful for covering very large areas in a single image and for depicting terrain relief and scale. However, they are not widely used for mapping as distortions in scale from the foreground to the background preclude easy measurements of distance, area, and elevation.

Vertical photographs taken with a single-lens frame camera is the most common use of aerial photography for remote sensing and mapping purposes. These cameras are specifically built for capturing a rapid sequence of photographs while limiting geometric distortion. They are often linked with navigation systems onboard the aircraft platform, to allow for accurate geographic coordinates to be instantly assigned to each photograph. Most camera systems also include mechanisms which compensate for the effect of the aircraft motion relative to the ground, in order to limit distortion as much as possible.

When obtaining vertical aerial photographs, the aircraft normally flies in a series of lines, each called a **flight line**. Photos are taken in rapid succession looking straight down at the ground, often with a 50-60 percent overlap (A) between successive photos. The overlap ensures total coverage along a flight line and also facilitates **stereoscopic viewing**. Successive photo pairs display the overlap region from different perspectives and can be viewed through a device called a **stereoscope** to see a three-dimensional view of the area, called a **stereo model**. Many applications of aerial photography use stereoscopic coverage and stereo viewing.



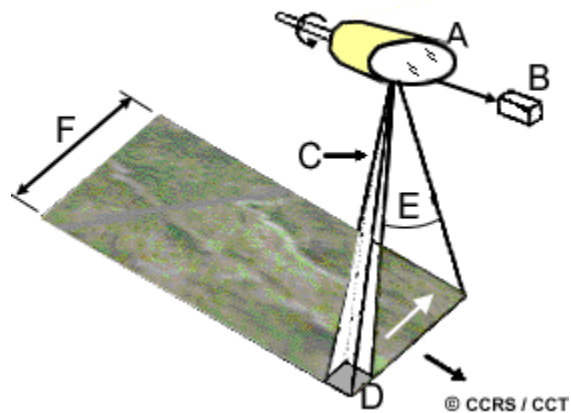
Aerial photographs are most useful when fine spatial detail is more critical than spectral information, as their spectral resolution is generally coarse when compared to data captured with electronic sensing devices. The geometry of vertical photographs is well understood and it is possible to make very accurate measurements from them, for a variety of different applications (geology, forestry, mapping, etc.). The science of making measurements from photographs is called **photogrammetry** and has been performed extensively since the very beginnings of aerial photography. Photos are most often interpreted manually by a human analyst (often viewed stereoscopically). They can also be scanned to create a digital image and then analyzed in a digital computer environment. In Chapter 4, we will discuss in greater detail, various methods (manually and by computer) for interpreting different types of remote sensing images.

Multiband photography uses multi-lens systems with different film-filter combinations to acquire photos simultaneously in a number of different spectral ranges. The advantage of these types of cameras is their ability to record reflected energy separately in discrete wavelength ranges, thus providing potentially better separation and identification of various features. However, simultaneous analysis of these multiple photographs can be problematic. **Digital cameras**, which record electromagnetic radiation electronically, differ significantly from their counterparts which use film. Instead of using film, digital cameras use a gridded array of silicon coated CCDs (charge-coupled devices) that individually respond to electromagnetic radiation. Energy reaching the surface of the CCDs causes the generation of an electronic charge which is proportional in magnitude to the "brightness" of the ground area. A digital number for each spectral band is assigned to each pixel based on the magnitude of the electronic charge. The digital format of the output image is amenable to digital analysis and archiving in a computer environment, as well as output as a hardcopy product similar to regular photos. Digital cameras also provide quicker turn-around for acquisition and retrieval of data and allow greater control of the spectral resolution. Although parameters vary, digital imaging systems are capable of collecting data with a spatial resolution of 0.3m, and with a spectral resolution of 0.012 mm to 0.3 mm. The size of the pixel arrays varies between systems, but typically ranges between 512 x 512 to 2048 x 2048.

2.8 Multispectral Scanning

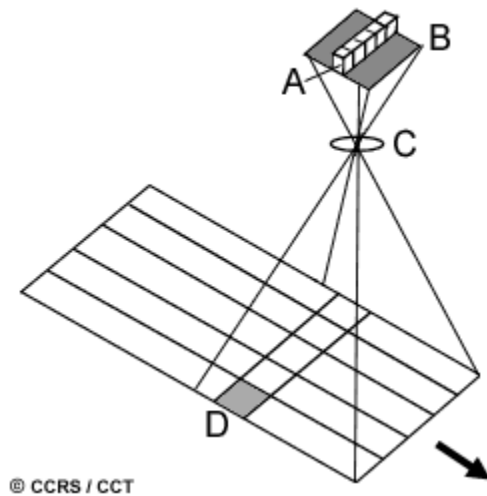
Many electronic (as opposed to photographic) remote sensors acquire data using **scanning systems**, which employ a sensor with a narrow field of view (i.e. IFOV) that sweeps over the terrain to build up and produce a two-dimensional image of the surface. Scanning systems can be used on both aircraft and satellite platforms and have essentially the same operating principles. A scanning system used to collect data over a variety of different wavelength ranges is called a **multispectral scanner (MSS)**, and is the most commonly used scanning system. There are two main modes or methods of scanning employed to acquire multispectral image data - **across-track scanning**, and **along-track scanning**.

Across-track scanners scan the Earth in a series of lines. The lines are oriented perpendicular to the direction of motion of the sensor platform (i.e. across the swath). Each line is scanned from one side of the sensor to the other, using a **rotating mirror (A)**. As the platform moves forward over the Earth, successive scans build up a two-dimensional image of the Earth's surface. The incoming reflected or emitted radiation is separated into several spectral components that are detected independently. The UV, visible, near-infrared, and thermal radiation are dispersed into their constituent wavelengths. A bank of internal **detectors (B)**, each sensitive to a specific range of wavelengths, detects and measures the energy for each spectral band and then, as an electrical signal, they are converted to digital data and recorded for subsequent computer processing.



The **IFOV (C)** of the sensor and the altitude of the platform determine the **ground resolution cell viewed (D)**, and thus the spatial resolution. The **angular field of view (E)** is the sweep of the mirror, measured in degrees, used to record a scan line, and determines the width of the imaged **swath (F)**. Airborne scanners typically sweep large angles (between 90° and 120°), while satellites, because of their higher altitude need only to sweep fairly small angles (10-20°) to cover a broad region. Because the distance from the sensor to the target increases towards the edges of the swath, the ground resolution cells also become larger and introduce geometric distortions to the images. Also, the length of time the IFOV "sees" a ground resolution cell as the rotating mirror scans (called the **dwelt time**), is generally quite short and influences the design of the spatial, spectral, and radiometric resolution of the sensor.

Along-track scanners also use the forward motion of the platform to record successive scan lines and build up a two-dimensional image, perpendicular to the flight direction. However, instead of a scanning mirror, they use a linear array of detectors (A) located at the focal plane of the image (B) formed by lens systems (C), which are "pushed" along in the flight track direction (i.e. along track). These systems are also referred to as **pushbroom scanners**, as the motion of the detector array is analogous to the bristles of a broom being pushed along a floor. Each individual detector measures the energy for a single ground resolution cell (D) and thus the size and IFOV of the detectors determines the spatial resolution of the system. A separate linear array is required to measure each spectral band or channel. For each scan line, the energy detected by each detector of each linear array is sampled electronically and digitally recorded.

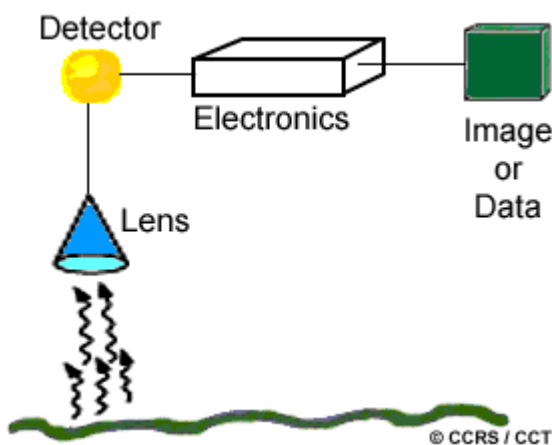


Along-track scanners with linear arrays have several advantages over across-track mirror scanners. The array of detectors combined with the pushbroom motion allows each detector to "see" and measure the energy from each ground resolution cell for a longer period of time (dwell time). This allows more energy to be detected and improves the radiometric resolution. The increased dwell time also facilitates smaller IFOVs and narrower bandwidths for each detector. Thus, finer spatial and spectral resolution can be achieved without impacting radiometric resolution. Because detectors are usually solid-state microelectronic devices, they are generally smaller, lighter, require less power, and are more reliable and last longer because they have no moving parts. On the other hand, cross-calibrating thousands of detectors to achieve uniform sensitivity across the array is necessary and complicated.

Regardless of whether the scanning system used is either of these two types, it has several advantages over photographic systems. The spectral range of photographic systems is restricted to the visible and near-infrared regions while MSS systems can extend this range into the thermal infrared. They are also capable of much higher spectral resolution than photographic systems. Multi-band or multispectral photographic systems use separate lens systems to acquire each spectral band. This may cause problems in ensuring that the different bands are comparable both spatially and radiometrically and with registration of the multiple images. MSS systems acquire all spectral bands simultaneously through the same optical system to alleviate these problems. Photographic systems record the energy detected by means of a photochemical process which is difficult to measure and to make consistent. Because MSS data are recorded electronically, it is easier to determine the specific amount of energy measured, and they can record over a greater range of values in a digital format. Photographic systems require a continuous supply of film and processing on the ground after the photos have been taken. The digital recording in MSS systems facilitates transmission of data to receiving stations on the ground and immediate processing of data in a computer environment.

2.9 Thermal Imaging

Many multispectral (MSS) systems sense radiation in the thermal infrared as well as the visible and reflected infrared portions of the spectrum. However, remote sensing of energy emitted from the Earth's surface in the thermal infrared ($3\ \mu\text{m}$ to $15\ \mu\text{m}$) is different than the sensing of reflected energy. **Thermal sensors** use photo detectors sensitive to the direct contact of photons on their surface, to detect emitted thermal radiation. The detectors are cooled to temperatures close to absolute zero in order to limit their own thermal emissions. Thermal sensors essentially measure the surface temperature and thermal properties of targets.



Thermal imagers are typically across-track scanners (like those described in the previous section) that detect emitted radiation in only the thermal portion of the spectrum. Thermal sensors employ one or more internal temperature references for comparison with the detected radiation, so they can be related to absolute radiant temperature. The data are generally recorded on film and/or magnetic tape and the temperature resolution of current sensors can reach $0.1\ ^\circ\text{C}$. For analysis, an image of relative radiant temperatures

(a **thermogram**) is depicted in grey levels, with warmer temperatures shown in light tones, and cooler temperatures in dark tones. Imagery which portrays relative temperature differences in their relative spatial locations are sufficient for most applications. Absolute temperature measurements may be calculated but require accurate calibration and measurement of the temperature references and detailed knowledge of the thermal properties of the target, geometric distortions, and radiometric effects.

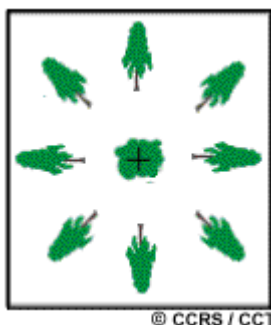
Because of the relatively long wavelength of thermal radiation (compared to visible radiation), atmospheric scattering is minimal. However, absorption by atmospheric gases normally

restricts thermal sensing to two specific regions - 3 to 5 μm and 8 to 14 μm . Because energy decreases as the wavelength increases, thermal sensors generally have large IFOVs to ensure that enough energy reaches the detector in order to make a reliable measurement. Therefore the spatial resolution of thermal sensors is usually fairly coarse, relative to the spatial resolution possible in the visible and reflected infrared. Thermal imagery can be acquired during the day or night (because the radiation is emitted not reflected) and is used for a variety of applications such as military reconnaissance, disaster management (forest fire mapping), and heat loss monitoring.

2.10 Geometric Distortion in Imagery

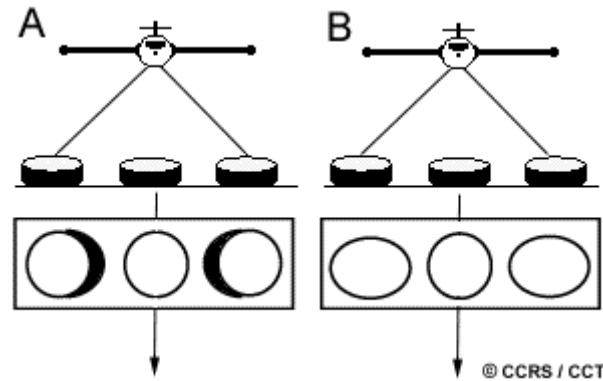
Any remote sensing image, regardless of whether it is acquired by a multispectral scanner on board a satellite, a photographic system in an aircraft, or any other platform/sensor combination, will have various geometric distortions. This problem is inherent in remote sensing, as we attempt to accurately represent the three-dimensional surface of the Earth as a two-dimensional image. All remote sensing images are subject to some form of geometric distortions, depending on the manner in which the data are acquired. These errors may be due to a variety of factors, including one or more of the following, to name only a few:

- the perspective of the sensor optics,
- the motion of the scanning system,
- the motion and (in)stability of the platform,
- the platform altitude, attitude, and velocity,
- the terrain relief, and
- the curvature and rotation of the Earth.



Framing systems, such as cameras used for aerial photography, provide an instantaneous "snapshot" view of the Earth from directly overhead. The primary geometric distortion in vertical aerial photographs is due to **relief displacement**. Objects directly below the centre of the camera lens (i.e. at the **nadir**) will have only their tops visible, while all other objects will appear to lean away from the centre of the photo such that their tops and sides are visible. If the objects are tall or are far away from the centre of the photo, the distortion and positional error will be larger.

The geometry of along-track scanner imagery is similar to that of an aerial photograph for each scan line as each detector essentially takes a "snapshot" of each ground resolution cell. Geometric variations between lines are caused by random variations in platform altitude and attitude along the direction of flight.



Images from across-track scanning systems exhibit two main types of **geometric distortion**. They too exhibit relief displacement (A), similar to aerial photographs, but in only one direction parallel to the direction of scan. There is no displacement directly below the sensor, at nadir. As the sensor scans across the swath, the top and side of objects are imaged and appear to lean away from the nadir point in each scan line. Again, the displacement increases, moving towards the edges of the swath. Another distortion (B) occurs due to the rotation of the scanning optics. As the sensor scans across each line, the distance from the sensor to the ground increases further away from the centre of the swath. Although the scanning mirror rotates at a constant speed, the IFOV of the sensor moves faster (relative to the ground) and scans a larger area as it moves closer to the edges. This effect results in the compression of image features at points away from the nadir and is called **tangential scale distortion**. All images are susceptible to geometric distortions caused by variations in platform stability including changes in their speed, altitude, and attitude (angular orientation with respect to the ground) during data acquisition. These effects are most pronounced when using aircraft platforms and are alleviated to a large degree with the use of satellite platforms, as their orbits are relatively stable, particularly in relation to their distance from the Earth. However, the eastward rotation of the Earth, during a satellite orbit causes the sweep of scanning systems to cover an area slightly to the west of each previous scan. The resultant imagery is thus skewed across the image. This is known as **skew distortion** and is common in imagery obtained from satellite multispectral scanners.

The sources of geometric distortion and positional error vary with each specific situation, but are inherent in remote sensing imagery. In most instances, we may be able to remove, or at least reduce these errors but they must be taken into account in each instance before attempting to make measurements or extract further information.

Now that we have learned about some of the general characteristics of platforms and sensors, in the next sections we will look at some specific sensors (primarily satellite systems) operating in the visible and infrared portions of the spectrum.

2.11 Weather Satellites/Sensors



Weather monitoring and forecasting was one of the first civilian (as opposed to military) applications of satellite remote sensing, dating back to the first true weather satellite, TIROS-1 (Television and Infrared Observation Satellite - 1), launched in 1960 by the United States. Several other weather satellites were launched over the next five years, in near-polar orbits, providing repetitive coverage of global weather patterns. In 1966, NASA (the U.S. National Aeronautics and Space Administration) launched the geostationary Applications Technology Satellite (ATS-1) which provided **hemispheric images** of the Earth's surface and cloud cover every half hour.

For the first time, the development and movement of weather systems could be routinely monitored. Today, several countries operate weather, or meteorological satellites to monitor weather conditions around the globe. Generally speaking, these satellites use sensors which have fairly coarse spatial resolution (when compared to systems for observing land) and provide large areal coverage.

Their temporal resolutions are generally quite high, providing frequent observations of the Earth's surface, atmospheric moisture, and cloud cover, which allows for near-continuous monitoring of global weather conditions, and hence - forecasting. Here we review a few of the representative satellites/sensors used for meteorological applications.

GOES



The GOES (Geostationary Operational Environmental Satellite) System is the follow-up to the ATS series. They were designed by NASA for the National Oceanic and Atmospheric Administration (NOAA) to provide the United States National Weather Service with frequent, small-scale imaging of the Earth's surface and cloud cover. The GOES series of satellites have been used extensively by meteorologists for weather monitoring and forecasting for over 20 years. These satellites are part of a global network of meteorological

satellites spaced at approximately 70° longitude intervals around the Earth in order to provide near-global coverage. Two GOES satellites, placed in **geostationary orbits** 36000 km above the equator, each view approximately one-third of the Earth. One is situated at 75°W longitude and monitors North and South America and most of the Atlantic Ocean. The other is situated at 135°W longitude and monitors North America and the Pacific Ocean basin. Together they

cover from 20°W to 165°E longitude. This GOES image covers a portion of the southeastern United States, and the adjacent ocean areas where many severe storms originate and develop. This image shows Hurricane Fran approaching the southeastern United States and the Bahamas in September of 1996.

Two generations of GOES satellites have been launched, each measuring emitted and reflected radiation from which atmospheric temperature, winds, moisture, and cloud cover can be derived. The first generation of satellites consisted of GOES-1 (launched 1975) through GOES-7 (launched 1992). Due to their design, these satellites were capable of viewing the Earth only a small percentage of the time (approximately five per cent). The second generation of satellites began with GOES-8 (launched 1994) and has numerous technological improvements over the first series. They provide near-continuous observation of the Earth allowing more frequent imaging (as often as every 15 minutes). This increase in temporal resolution coupled with improvements in the spatial and radiometric resolution of the sensors provides timelier information and improved data quality for forecasting meteorological conditions.

GOES-8 and the other second generation GOES satellites have separate **imaging** and **sounding** instruments. The **imager** has five channels sensing visible and infrared reflected and emitted solar radiation. The infrared capability allows for day and night imaging. Sensor pointing and scan selection capability enable imaging of an entire hemisphere, or small-scale imaging of selected areas. The latter allows meteorologists to monitor specific weather trouble spots to assist in improved short-term forecasting. The imager data are 10-bit radiometric resolution, and can be transmitted directly to local user terminals on the Earth's surface. The accompanying table describes the individual bands, their spatial resolution, and their meteorological applications.

GOES Bands

Band	Wavelength Range (> μm)	Spatial Resolution	Application
1	0.52 - 0.72 (visible)	1 km	cloud, pollution, and haze detection; severe storm identification
2	3.78 - 4.03 (shortwave IR)	4 km	identification of fog at night; discriminating water clouds and snow or ice clouds during daytime; detecting fires and volcanoes; night time determination of sea surface temperatures
3	6.47 - 7.02 (upper level water vapour)	4 km	estimating regions of mid-level moisture content and advection; tracking mid-level atmospheric motion
4	10.2 - 11.2 (longwave IR)	4 km	identifying cloud-drift winds, severe storms, and heavy rainfall
5	11.5 - 12.5 (IR window sensitive to water vapour)	4 km	identification of low-level moisture; determination of sea surface temperature; detection of airborne dust and volcanic ash

The 19 channel **sounder** measures emitted radiation in 18 thermal infrared bands and reflected radiation in one visible band. These data have a spatial resolution of 8 km and 13-bit radiometric resolution. Sounder data are used for surface and cloud-top temperatures, multi-level moisture profiling in the atmosphere, and ozone distribution analysis.

NOAA AVHRR

NOAA is also responsible for another series of satellites which are useful for meteorological, as well as other, applications. These satellites, in **sun-synchronous, near-polar orbits** (830-870 km above the Earth), are part of the Advanced TIROS series (originally dating back to 1960) and provide complementary information to the geostationary meteorological satellites (such as GOES). Two satellites, each providing global coverage, work together to ensure that data for any region of the Earth is no more than six hours old. One satellite crosses the equator in the early morning from north-to-south while the other crosses in the afternoon.

The primary sensor on board the NOAA satellites, used for both meteorology and small-scale Earth observation and reconnaissance, is the **Advanced Very High Resolution Radiometer (AVHRR)**. The AVHRR sensor detects radiation in the visible, near and mid infrared, and thermal infrared portions of the electromagnetic spectrum, over a swath width of 3000 km. The accompanying table, outlines the AVHRR bands, their wavelengths and spatial resolution (at swath nadir), and general applications of each.

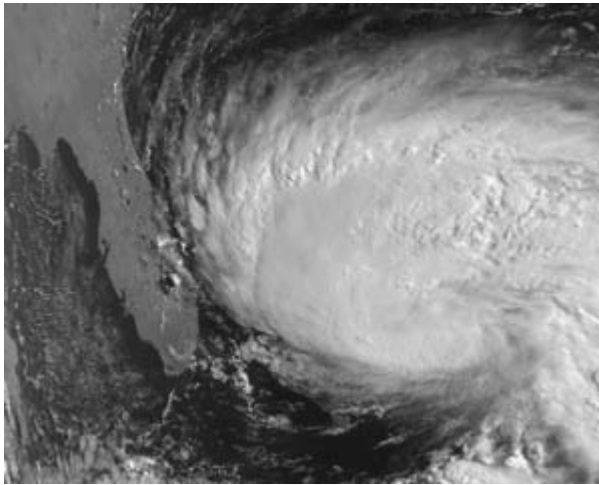
NOAA AVHRR Bands

Band	Wavelength Range (μm)	Spatial Resolution	Application
1	0.58 - 0.68 (red)	1.1 km	cloud, snow, and ice monitoring
2	0.725 - 1.1 (near IR)	1.1 km	water, vegetation, and agriculture surveys
3	3.55 - 3.93 (mid IR)	1.1 km	sea surface temperature, volcanoes, and forest fire activity
4	10.3 - 11.3 (thermal IR)	1.1 km	sea surface temperature, soil moisture
5	11.5 - 12.5 (thermal IR)	1.1 km	sea surface temperature, soil moisture

AVHRR data can be acquired and formatted in four operational modes, differing in resolution and method of transmission. Data can be transmitted directly to the ground and viewed as data are collected, or recorded on board the satellite for later transmission and processing. The accompanying table describes the various data formats and their characteristics.

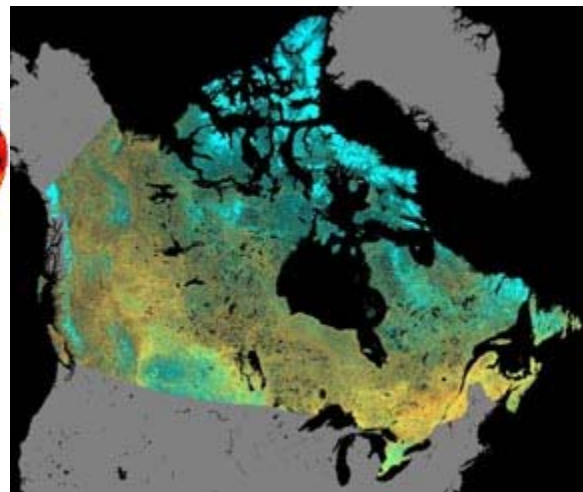
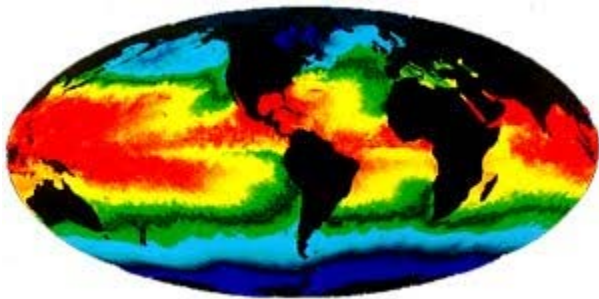
AVHRR Data Formats

Format	Spatial Resolution	Transmission and Processing
APT (Automatic Picture Transmission)	4 km	low-resolution direct transmission and display
HRPT (High Resolution Picture Transmission)	1.1 km	full-resolution direct transmission and display
GAC (Global Area Coverage)	4 km	low-resolution coverage from recorded data
LAC (Local Area Coverage)	1.1 km	selected full-resolution local area data from recorded data



Although AVHRR data are widely used for **weather system** forecasting and analysis, the sensor is also well-suited to observation and monitoring of land features. AVHRR has much coarser spatial resolution than other typical land observations sensors (discussed in the next section), but is used extensively for monitoring regional, small-scale phenomena, including mapping of **sea surface temperature**, and natural vegetation and crop conditions. **Mosaics** covering large areas can be created from several AVHRR data sets allowing small scale analysis and mapping of broad vegetation cover. In

Canada, AVHRR data received at the Prince Albert Receiving Station Saskatchewan, are used as part of a crop information system, monitoring the health of grain crops in the Prairies throughout the growing season.



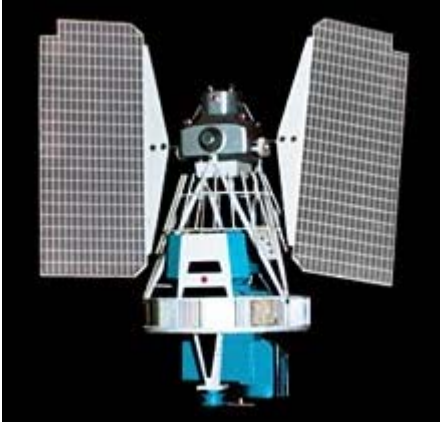
Other Weather Satellites

The United States operates the **DMSP** (Defense Meteorological Satellite Program) series of satellites which are also used for weather monitoring. These are near-polar orbiting satellites whose Operational Linescan System (OLS) sensor provides twice daily coverage with a swath width of 3000 km at a spatial resolution of 2.7 km. It has two fairly broad wavelength bands: a visible and near infrared band (0.4 to 1.1 μm) and a thermal infrared band (10.0 to 13.4 μm). An interesting feature of the sensor is its ability to acquire visible band night time imagery under very low illumination conditions. With this sensor, it is possible to collect striking images of the Earth showing (typically) the night time lights of large urban centres.

There are several other meteorological satellites in orbit, launched and operated by other countries, or groups of countries. These include Japan, with the **GMS** satellite series, and the consortium of European communities, with the **Meteosat** satellites. Both are geostationary satellites situated above the equator over Japan and Europe, respectively. Both provide half-hourly imaging of the Earth similar to GOES. **GMS** has two bands: 0.5 to 0.75 μm (1.25 km resolution), and 10.5 to 12.5 μm (5 km resolution). **Meteosat** has three bands: visible band (0.4 to 1.1 μm ; 2.5 km resolution), mid-IR (5.7 to 7.1 μm ; 5 km resolution), and thermal IR (10.5 to 12.5 μm ; 5 km resolution).

2.12 Land Observation Satellites/Sensors

Landsat



Although many of the weather satellite systems (such as those described in the previous section) are also used for monitoring the Earth's surface, they are not optimized for detailed mapping of the land surface. Driven by the exciting views from, and great success of the early meteorological satellites in the 1960's, as well as from images taken during manned spacecraft missions, the first satellite designed specifically to monitor the Earth's surface, Landsat-1, was launched by NASA in 1972. Initially referred to as ERTS-1, (Earth Resources Technology Satellite), **Landsat** was designed as an experiment to test the feasibility of collecting multi-spectral Earth observation data from an unmanned satellite platform. Since that time, this highly successful program has collected an abundance of data from around the world from several Landsat satellites. Originally managed by NASA, responsibility for the Landsat program was transferred to NOAA in 1983. In 1985, the program became commercialized, providing data to civilian and applications users.

Landsat's success is due to several factors, including: a combination of sensors with spectral bands tailored to Earth observation; functional spatial resolution; and good areal coverage (swath width and revisit period). The long lifespan of the program has provided a voluminous archive of Earth resource data facilitating long term monitoring and historical records and research. All Landsat satellites are placed in near-polar, sun-synchronous orbits. The first three satellites (Landsats 1-3) are at altitudes around 900 km and have revisit periods of 18 days while the later satellites are at around 700 km and have revisit periods of 16 days. All Landsat satellites have equator crossing times in the morning to optimize illumination conditions.

A number of sensors have been on board the Landsat series of satellites, including the **Return Beam Vidicon (RBV)** camera systems, the **MultiSpectral Scanner (MSS)** systems, and the **Thematic Mapper (TM)**. The most popular instrument in the early days of Landsat was the MultiSpectral Scanner (MSS) and later the Thematic Mapper (TM). Each of these sensors collected data over a swath width of 185 km, with a full scene being defined as 185 km x 185 km.

The MSS senses the electromagnetic radiation from the Earth's surface in four spectral bands. Each band has a spatial resolution of approximately 60 x 80 metres and a radiometric resolution of 6 bits, or 64 digital numbers. Sensing is accomplished with a line scanning device using an oscillating mirror. Six scan lines are collected simultaneously with each west-to-east sweep of the scanning mirror. The accompanying table outlines the spectral wavelength ranges for the MSS.

MSS Bands

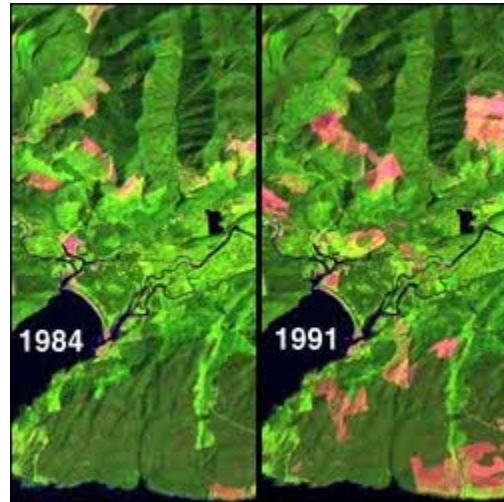
Channel		Wavelength Range (μm)
Landsat 1,2,3	Landsat 4,5	
MSS 4	MSS 1	0.5 - 0.6 (green)
MSS 5	MSS 2	0.6 - 0.7 (red)
MSS 6	MSS 3	0.7 - 0.8 (near infrared)
MSS 7	MSS 4	0.8 - 1.1 (near infrared)

Routine collection of MSS data ceased in 1992, as the use of TM data, starting on Landsat 4, superseded the MSS. The **TM** sensor provides several improvements over the MSS sensor including: higher spatial and radiometric resolution; finer spectral bands; seven as opposed to four spectral bands; and an increase in the number of detectors per band (16 for the non-thermal channels versus six for MSS). Sixteen scan lines are captured simultaneously for each non-thermal spectral band (four for thermal band), using an oscillating mirror which scans during both the forward (west-to-east) and reverse (east-to-west) sweeps of the scanning mirror. This difference from the MSS increases the **dwel time** (see section 2.8) and improves the geometric and radiometric integrity of the data. Spatial resolution of TM is 30 m for all but the thermal infrared band which is 120 m. All channels are recorded over a range of 256 digital numbers (8 bits). The accompanying table outlines the spectral resolution of the individual TM bands and some useful applications of each.

TM Bands

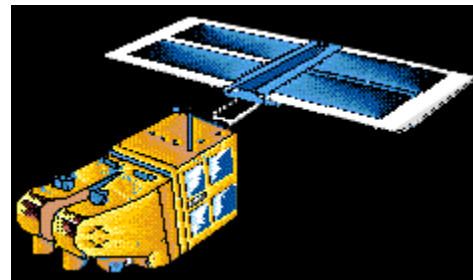
Channel	Wavelength Range (μm)	Application
TM 1	0.45 - 0.52 (blue)	soil/vegetation discrimination; bathymetry/coastal mapping; cultural/urban feature identification
TM 2	0.52 - 0.60 (green)	green vegetation mapping (measures reflectance peak); cultural/urban feature identification
TM 3	0.63 - 0.69 (red)	vegetated vs. non-vegetated and plant species discrimination (plant chlorophyll absorption); cultural/urban feature identification
TM 4	0.76 - 0.90 (near IR)	identification of plant/vegetation types, health, and biomass content; water body delineation; soil moisture
TM 5	1.55 - 1.75 (short wave IR)	sensitive to moisture in soil and vegetation; discriminating snow and cloud-covered areas
TM 6	10.4 - 12.5 (thermal IR)	vegetation stress and soil moisture discrimination related to thermal radiation; thermal mapping (urban, water)
TM 7	2.08 - 2.35 (short wave IR)	discrimination of mineral and rock types; sensitive to vegetation moisture content

Data from both the TM and MSS sensors are used for a wide variety of applications, including resource management, mapping, environmental monitoring, and change detection (e.g. **monitoring forest clearcutting**). The archives of Canadian imagery include over 350,000 scenes of MSS and over 200,000 scenes of TM, managed by the licensed distributor in Canada: RSI Inc. Many more scenes are held by foreign facilities around the world.



SPOT

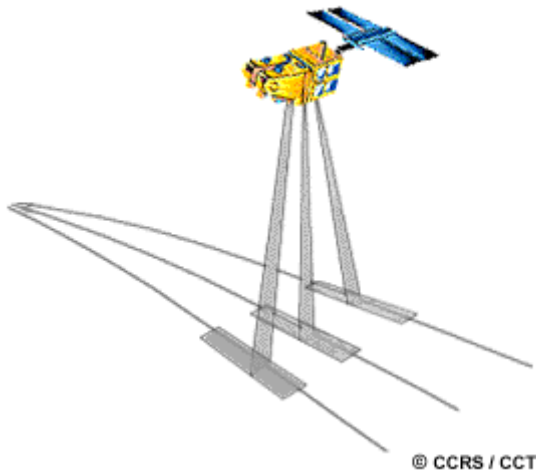
SPOT (Système Pour l'Observation de la Terre) is a series of Earth observation imaging satellites designed and launched by CNES (Centre National d'Études Spatiales) of France, with support from Sweden and Belgium. SPOT-1 was launched in 1986, with successors following every three or four years. All satellites are in sun-synchronous, near-polar orbits at altitudes around 830 km above the Earth, which results in orbit repetition every 26 days. They have equator crossing times around 10:30 AM local solar time. SPOT was designed to be a commercial provider of Earth observation data, and was the first satellite to use along-track, or pushbroom scanning technology.



The SPOT satellites each have twin **high resolution visible (HRV)** imaging systems, which can be operated independently and simultaneously. Each HRV is capable of sensing either in a high spatial resolution single-channel **panchromatic (PLA)** mode, or a coarser spatial resolution three-channel **multispectral (MLA)** mode. Each along-track scanning HRV sensor consists of four linear arrays of detectors: one 6000 element array for the panchromatic mode recording at a spatial resolution of 10 m, and one 3000 element array for each of the three multispectral bands, recording at 20 m spatial resolution. The swath width for both modes is 60 km at nadir. The accompanying table illustrates the spectral characteristics of the two different modes.

HRV Mode Spectral Ranges

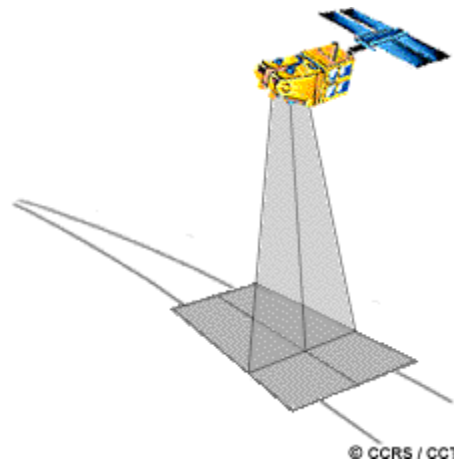
Mode/Band	Wavelength Range (µm)
Panchromatic (PLA)	0.51 - 0.73 (blue-green-red)
Multispectral (MLA)	
Band 1	0.50 - 0.59 (green)
Band 2	0.61 - 0.68 (red)
Band 3	0.79 - 0.89 (near infrared)



The viewing angle of the sensors can be adjusted to look to either side of the satellite's vertical (nadir) track, allowing **off-nadir viewing** which increases the satellite's revisit capability. This ability to point the sensors up to 27° from nadir, allows SPOT to view within a 950 km swath and to revisit any location several times per week. As the sensors point away from nadir, the swath varies from 60 to 80 km in width. This not only improves the ability to monitor specific locations and increases the chances of obtaining cloud free scenes, but the off-nadir viewing also provides the

capability of acquiring imagery for stereoscopic coverage. By recording the same area from two different angles, the imagery can be viewed and analyzed as a three dimensional model, a technique of tremendous value for terrain interpretation, mapping, and visual terrain simulations.

This oblique viewing capability increases the revisit frequency of equatorial regions to three days (seven times during the 26 day orbital cycle). Areas at a latitude of 45° can be imaged more frequently (11 times in 26 days) due to the convergence of orbit paths towards the poles. By pointing both HRV sensors to cover **adjacent ground swaths** at nadir, a swath of 117 km (3 km overlap between the two swaths) can be imaged. In this mode of operation, either panchromatic or multispectral data can be collected, but not both simultaneously.



SPOT has a number of benefits over other spaceborne optical sensors. Its fine spatial resolution and pointable sensors are the primary reasons for its popularity. The three-band multispectral data are well suited to displaying as false-colour images and the panchromatic band can also be used to "sharpen" the spatial detail in the multispectral data. SPOT allows applications requiring fine spatial detail (such as **urban mapping**) to be addressed while retaining the cost and timeliness advantage of satellite data. The potential applications of SPOT data are numerous. Applications requiring frequent monitoring (agriculture, forestry) are well served by the SPOT sensors. The acquisition of stereoscopic imagery from SPOT has played an important role in mapping applications and in the derivation of topographic information (Digital Elevation Models - DEMs) from satellite data.



IRS

The Indian Remote Sensing (IRS) satellite series, combines features from both the Landsat MSS/TM sensors and the SPOT HRV sensor. The third satellite in the series, IRS-1C, launched in December, 1995 has three sensors: a single-channel panchromatic (PAN) high resolution camera, a medium resolution four-channel Linear Imaging Self-scanning Sensor (LISS-III), and a coarse resolution two-channel Wide Field Sensor (WiFS). The accompanying table outlines the specific characteristics of each sensor.

IRS Sensors

Sensor	Wavelength Range (µm)	Spatial Resolution	Swath Width	Revisit Period (at equator)
PAN	0.5 - 0.75	5.8 m	70 km	24 days
LISS-II				
Green	0.52 - 0.59	23 m	142 km	24 days
Red	0.62 - 0.68	23 m	142 km	24 days
Near IR	0.77 - 0.86	23 m	142 km	24 days
Shortwave IR	1.55 - 1.70	70 m	148 km	24 days
WiFS				
Red	0.62 - 0.68	188 m	774 km	5 days
Near IR	0.77 - 0.86	188 m	774 km	5 days

In addition to its high spatial resolution, the panchromatic sensor can be steered up to 26° across-track, enabling stereoscopic imaging and increased revisit capabilities (as few as five days), similar to SPOT. This high resolution data is useful for urban planning and mapping applications. The four LISS-III multispectral bands are similar to Landsat's TM bands 1 to 4 and are excellent for vegetation discrimination, land-cover mapping, and natural resource planning. The WiFS sensor is similar to NOAA AVHRR bands and the spatial resolution and coverage is useful for regional scale vegetation monitoring.

MEIS-II and CASI

Although this tutorial concentrates on satellite-borne sensors, it is worth mentioning a couple of Canadian airborne sensors which have been used for various remote sensing applications, as these systems (and others like them) have influenced the design and development of satellite systems. The first is the MEIS-II (**Multispectral Electro-optical Imaging Scanner**) sensor developed for the Canada Centre for Remote Sensing. Although no longer active, MEIS was the first operational use of pushbroom, or along-track scanning technology in an airborne platform. The sensor collected 8-bit data (256 digital numbers) in eight spectral bands ranging from 0.39 to 1.1 µm, using linear arrays of 1728 detectors per band. The specific wavelength ranges were selectable, allowing different band combinations to be used for different applications. Stereo imaging from a single flight line was also possible, with channels aimed ahead of and behind nadir, supplementing the other nadir facing sensors. Both the stereo mapping and the selectable band capabilities were useful in research and development which was applied to development of other satellite (and airborne) sensor systems.

CASI, the **Compact Airborne Spectrographic Imager**, is a leader in airborne imaging, being the first commercial imaging spectrometer. This hyperspectral sensor detects a vast array of narrow spectral bands in the visible and infrared wavelengths, using along-track scanning. The spectral range covered by the 288 channels is between 0.4 and 0.9 μm . Each band covers a wavelength range of 0.018 μm . While spatial resolution depends on the altitude of the aircraft, the spectral bands measured and the bandwidths used are all programmable to meet the user's specifications and requirements. Hyperspectral sensors such as this can be important sources of diagnostic information about specific targets' absorption and reflection characteristics, in effect providing a spectral 'fingerprint'. Experimentation with CASI and other airborne imaging spectrometers has helped guide the development of hyperspectral sensor systems for advanced satellite systems.

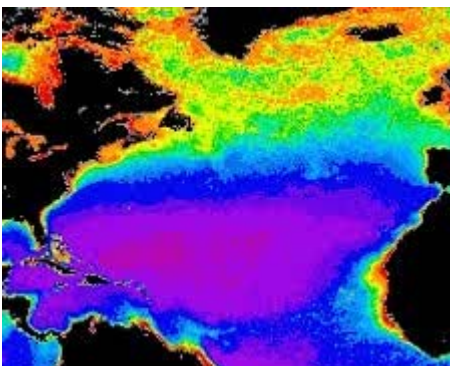
2.13 Marine Observation Satellites/Sensors

The Earth's oceans cover more than two-thirds of the Earth's surface and play an important role in the global climate system. They also contain an abundance of living organisms and natural resources which are susceptible to pollution and other man-induced hazards. The meteorological and land observations satellites/sensors we discussed in the previous two sections can be used for monitoring the oceans of the planet, but there are other satellite/sensor systems which have been designed specifically for this purpose.

The Nimbus-7 satellite, launched in 1978, carried the first sensor, the **Coastal Zone Colour Scanner (CZCS)**, specifically intended for monitoring the Earth's oceans and water bodies. The primary objective of this sensor was to observe ocean colour and temperature, particularly in coastal zones, with sufficient spatial and spectral resolution to detect pollutants in the upper levels of the ocean and to determine the nature of materials suspended in the water column. The Nimbus satellite was placed in a sun-synchronous, near-polar orbit at an altitude of 955 km. Equator crossing times were local noon for ascending passes and local midnight for descending passes. The repeat cycle of the satellite allowed for global coverage every six days, or every 83 orbits. The CZCS sensor consisted of six spectral bands in the visible, near-IR, and thermal portions of the spectrum each collecting data at a spatial resolution of 825 m at nadir over a 1566 km swath width. The accompanying table outlines the spectral ranges of each band and the primary parameter measured by each.

CZCS Spectral Bands

Channel	Wavelength Range (μm)	Primary Measured Parameter
1	0.43 - 0.45	Chlorophyll absorption
2	0.51 - 0.53	Chlorophyll absorption
3	0.54 - 0.56	Gelbstoffe (yellow substance)
4	0.66 - 0.68	Chlorophyll concentration
5	0.70 - 0.80	Surface vegetation
6	10.5 - 12.50	Surface temperature



As can be seen from the table, the first four bands of the CZCS sensor are very narrow. They were optimized to allow detailed discrimination of differences in water reflectance due to **phytoplankton concentrations** and other suspended particulates in the water. In addition to detecting surface vegetation on the water, band 5 was used to discriminate water from land prior to processing the other bands of information. The CZCS sensor ceased operation in 1986.

MOS

The first Marine Observation Satellite (MOS-1) was launched by Japan in February, 1987 and was followed by its successor, MOS-1b, in February of 1990. These satellites carry three different sensors: a four-channel Multispectral Electronic Self-Scanning Radiometer (MESSR), a four-channel Visible and Thermal Infrared Radiometer (VTIR), and a two-channel Microwave Scanning Radiometer (MSR), in the microwave portion of the spectrum. The characteristics of the two sensors in the visible/infrared are described in the accompanying table.

MOS Visible/Infrared Instruments

Sensor	Wavelength Ranges (μm)	Spatial Resolution	Swath Width
MESSR	0.51 - 0.59	50 m	100 km
	0.61 - 0.69	50 m	100 km
	0.72 - 0.80	50 m	100 km
	0.80 - 1.10	50 m	100 km
VTIR	0.50 - 0.70	900 m	1500 km
	6.0 - 7.0	2700 m	1500 km
	10.5 - 11.5	2700 m	1500 km
	11.5 - 12.5	2700 m	1500 km

The MESSR bands are quite similar in spectral range to the Landsat MSS sensor and are thus useful for land applications in addition to observations of marine environments. The MOS systems orbit at altitudes around 900 km and have revisit periods of 17 days.

SeaWiFS

The SeaWiFS (Sea-viewing Wide-Field-of View Sensor) on board the SeaStar spacecraft is an advanced sensor designed for ocean monitoring. It consists of eight spectral bands of very narrow wavelength ranges (see accompanying table) tailored for very specific detection and monitoring of various ocean phenomena including: ocean primary production and phytoplankton processes, ocean influences on climate processes (heat storage and aerosol formation), and monitoring of the cycles of carbon, sulfur, and nitrogen. The orbit altitude is 705 km with a local equatorial crossing time of 12 PM. Two combinations of spatial resolution and swath width are available for each band: a higher resolution mode of 1.1 km (at nadir) over a swath of 2800 km, and a lower resolution mode of 4.5 km (at nadir) over a swath of 1500 km.

SeaWiFS Spectral Bands

Channel	Wavelength Ranges (μm)
1	0.402 - 0.422
2	0.433 - 0.453
3	0.480 - 0.500
4	0.500 - 0.520
5	0.545 - 0.565
6	0.660 - 0.680
7	0.745 - 0.785
8	0.845 - 0.885

These ocean-observing satellite systems are important for global and regional scale monitoring of ocean pollution and health, and assist scientists in understanding the influence and impact of the oceans on the global climate system.

2.14 Other Sensors



The three previous sections provide a representative overview of specific systems available for remote sensing in the (predominantly) optical portions of the electromagnetic spectrum. However, there are many **other types of less common sensors** which are used for remote sensing purposes. We briefly touch on a few of these other types of sensors. The information is not considered comprehensive but serves as an introduction to alternative imagery sources and imaging concepts.

Video

Although coarser in spatial resolution than traditional photography or digital imaging, video cameras provide a useful means of acquiring timely and inexpensive data and vocally annotated imagery. Applications with these requirements include natural disaster management, (fires, flooding), crop and disease assessment, environmental hazard control, and police surveillance. Cameras used for video recording measure radiation in the visible, near infrared, and sometimes mid-infrared portions of the EM spectrum. The image data are recorded onto cassette, and can be viewed immediately.

FLIR

Forward Looking InfraRed (FLIR) systems operate in a similar manner to across-track thermal imaging sensors, but provide an oblique rather than nadir perspective of the Earth's surface. Typically positioned on aircraft or helicopters, and imaging the area ahead of the platform, FLIR systems provide relatively high spatial resolution imaging that can be used for military applications, search and rescue operations, law enforcement, and forest fire monitoring.

Laser fluorosensor

Some targets fluoresce, or emit energy, upon receiving incident energy. This is not a simple reflection of the incident radiation, but rather an absorption of the initial energy, excitation of the molecular components of the target materials, and emission of longer wavelength radiation which is then measured by the sensor. Laser fluorosensors illuminate the target with a specific wavelength of radiation and are capable of detecting multiple wavelengths of fluoresced radiation. This technology has been proven for ocean applications, such as chlorophyll mapping, and pollutant detection, particularly for naturally occurring and accidental oil slicks.

Lidar

Lidar is an acronym for LIght Detection And Ranging, an active imaging technology very similar to RADAR (see next paragraph). Pulses of laser light are emitted from the sensor and

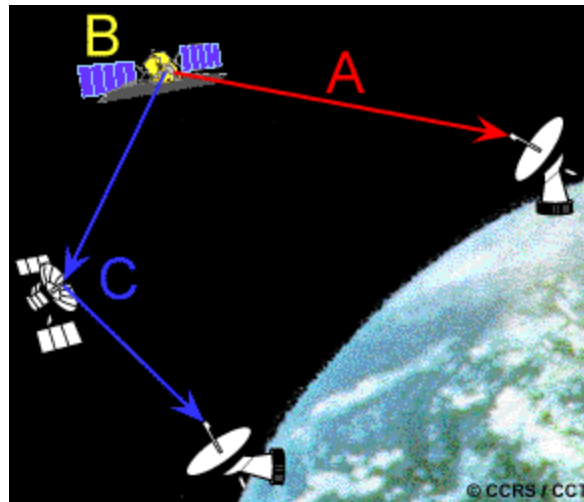
energy reflected from a target is detected. The time required for the energy to reach the target and return to the sensor determines the distance between the two. Lidar is used effectively for measuring heights of features, such as forest canopy height relative to the ground surface, and water depth relative to the water surface (laser profilometer). Lidar is also used in atmospheric studies to examine the particle content of various layers of the Earth's atmosphere and acquire air density readings and monitor air currents.

RADAR

RADAR stands for RAdio Detection And Ranging. RADAR systems are active sensors which provide their own source of electromagnetic energy. Active radar sensors, whether airborne or spaceborne, emit microwave radiation in a series of pulses from an antenna, looking obliquely at the surface perpendicular to the direction of motion. When the energy reaches the target, some of the energy is reflected back towards the sensor. This backscattered microwave radiation is detected, measured, and timed. The time required for the energy to travel to the target and return back to the sensor determines the distance or range to the target. By recording the range and magnitude of the energy reflected from all targets as the system passes by, a two-dimensional image of the surface can be produced. Because RADAR provides its own energy source, images can be acquired day or night. Also, microwave energy is able to penetrate through clouds and most rain, making it an all-weather sensor. Because of the unique characteristics and applications of microwave remote sensing, Chapter 3 covers this topic in detail, concentrating on RADAR remote sensing.

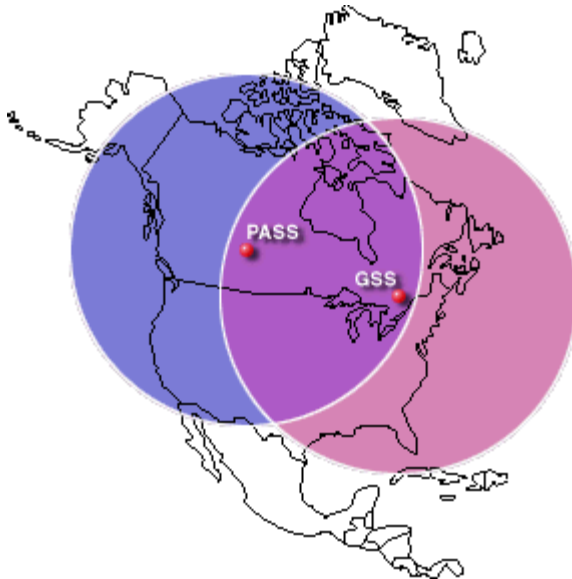
2.15 Data Reception, Transmission, and Processing

Data obtained during airborne remote sensing missions can be retrieved once the aircraft lands. It can then be processed and delivered to the end user. However, data acquired from satellite platforms need to be electronically transmitted to Earth, since the satellite continues to stay in orbit during its operational lifetime. The technologies designed to accomplish this can also be used by an aerial platform if the data are urgently needed on the surface.



There are three main options for **transmitting data** acquired by satellites to the surface. The data can be directly transmitted to Earth if a Ground Receiving Station (GRS) is in the line of sight of the satellite (A). If this is not the case, the data can be recorded on board the satellite (B) for transmission to a GRS at a later time. Data can also be relayed to the GRS through the Tracking and Data Relay Satellite System (TDRSS) (C), which consists of a series of communications satellites in geosynchronous orbit. The data are transmitted from one satellite to another until they reach the appropriate GRS.

In Canada, CCRS operates two **ground receiving stations** - one at Cantley, Québec (GSS), just outside of Ottawa, and another one at Prince Albert, Saskatchewan (PASS). The combined coverage circles for these Canadian ground stations enable the potential for reception of real-time or recorded data from satellites passing over almost any part of Canada's land mass, and much of the continental United States as well. Other ground stations have been set up around the world to capture data from a variety of satellites.



The data are received at the GRS in a raw digital format. They may then, if required, be processed to correct systematic, geometric and atmospheric distortions to the imagery, and be translated into a standardized format. The data are written to some form of storage medium such as tape, disk or CD. The data are typically archived at most receiving and processing stations, and full libraries of data are managed by government agencies as well as commercial companies responsible for each sensor's archives.

For many sensors it is possible to provide customers with **quick-turnaround** imagery when they need data as quickly as possible after it is collected. Near real-time processing systems are used to produce low resolution imagery in hard copy or soft copy (digital) format within hours of data acquisition. Such imagery can then be faxed or transmitted digitally to end users. One application of this type of fast data processing is to provide imagery to ships sailing in the Arctic, as it allows them to assess current ice conditions quickly in order to make navigation decisions about the easiest/safest routes through the ice. Real-time processing of imagery in airborne systems has been used, for example, to pass thermal infrared imagery to forest fire fighters right at the scene.

Low resolution quick-look imagery is used to preview archived imagery prior to purchase. The spatial and radiometric quality of these types of data products is degraded, but they are useful for ensuring that the overall quality, coverage and cloud cover of the data is appropriate.

2.16 Endnotes

You have just completed **Chapter 2 - Satellites and Sensors**. You can continue to Chapter 3 - Microwave Sensing or first browse the CCRS Web site for other articles related to platforms and sensors.

For instance, the [Remote Sensing Glossary](#)¹ has platform and sensor categories that contain more information about various platforms and sensors and their use around the world. The glossary also has optical and radar categories of terms, to allow you to focus on these aspects of remote sensing technology.

Our receiving stations at [Prince Albert](#)², Saskatchewan and [Gatineau](#)³, Quebec receive data from a number of satellites. See which satellites are received and what data reception [coverage](#)⁴ and [services](#)⁵ they provide.

If you are curious about detecting targets which are smaller than a pixel, see a [detailed discussion](#)⁶ in one of our "Images of Canada".

Until 1997, CCRS owned and operated a [Convair 580](#)⁷ aircraft which carried a number of research instruments including a [Synthetic Aperture Radar](#)⁸ (SAR) sensor. There are a number of images from this instrument on our Web site, one of which is of the [Confederation Bridge](#)⁹ between PEI and New Brunswick taken while it was under construction.

¹http://www.ccrs.nrcan.gc.ca/ccrs/learn/terms/glossary/glossary_e.html

²http://www.ccrs.nrcan.gc.ca/ccrs/data/stations/pass_e.html

³http://www.ccrs.nrcan.gc.ca/ccrs/data/stations/gss_e.html

⁴http://www.ccrs.nrcan.gc.ca/ccrs/data/stations/cc_e.html

⁵http://www.ccrs.nrcan.gc.ca/ccrs/data/stations/grss_e.html

⁶http://www.ccrs.nrcan.gc.ca/ccrs/learn/tour/16/16ns_e.html

⁷http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/airborne/sarbro/sbc580_e.html

⁸http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/airborne/sarbro/sbmain_e.html

⁹http://www.ccrs.nrcan.gc.ca/ccrs/rd/apps/marine/pei_link/bridge_e.html



2. Did You Know?

2.1 Did You Know?



© CCRS / CCT

- High wing aircraft are preferable to low wing aircraft for hand-held aerial photography.
- The 'drop hatch' in aircraft such as the DeHavilland "Beaver" and "Otter" are convenient to use for vertical aerial photography without performing aircraft structural modifications.
- Oblique aerial photography can preferably be done through an open window rather than through window glass/plastic.
- Photography through the aircraft door opening (having removed the door prior to flight) is also frequently done.
- Tethered balloons provide an inexpensive photography platform for long-term monitoring of a specific site.

2.2 Did You Know?

"...the forecast calls for scattered clouds with the possibility of rain..."

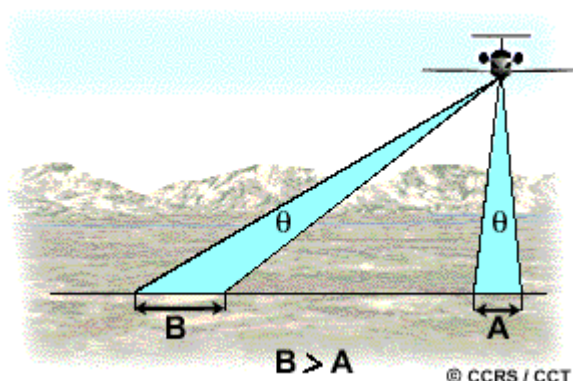
...most of the images you see on television weather forecasts are from geostationary satellites. This is because they provide broad coverage of the weather and cloud patterns on continental scales. Meteorologists (weather forecasters) use these images to help them determine in which direction the weather patterns are likely to go. The high repeat coverage capability of satellites with geostationary orbits allows them to collect several images daily to allow these patterns to be closely monitored.



...satellites occasionally require their orbits to be corrected. Because of atmospheric drag and other forces that occur when a satellite is in orbit, they may deviate from their initial orbital path. In order to maintain the planned orbit, a control center on the ground will issue commands to the satellite to place it back in the proper orbit. Most satellites and their sensors have a finite life-span ranging from a few to several years. Either the sensor will cease to function adequately or the satellite will suffer severe orbit decay such that the system is no longer useable.

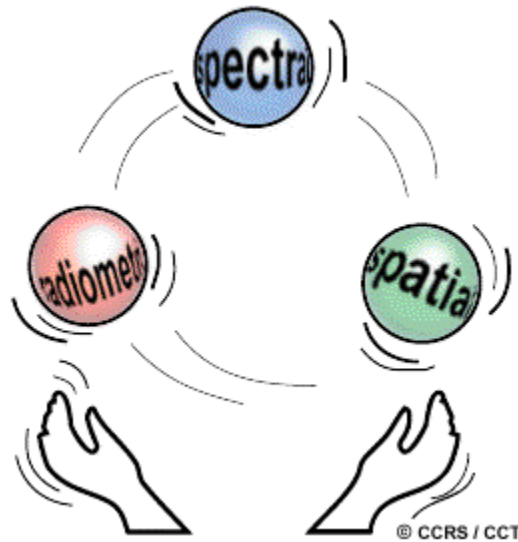
2.3 Did You Know?

If the IFOV for all pixels of a scanner stays constant (which is often the case), then the ground area represented by pixels at the nadir will have a larger scale than those pixels which are off-nadir. This means that spatial resolution will vary from the image centre to the swath edge.



2.5 Did You Know?

"...you just can't have it all!"



...that there are trade-offs between spatial, spectral, and radiometric resolution which must be taken into consideration when engineers design a sensor. For high spatial resolution, the sensor has to have a small IFOV (Instantaneous Field of View). However, this reduces the amount of energy that can be detected as the area of the ground resolution cell within the IFOV becomes smaller. This leads to reduced radiometric resolution - the ability to detect fine energy differences. To increase the amount of energy detected (and thus, the radiometric resolution) without reducing spatial resolution, we would have to broaden the wavelength range detected for a particular channel or band. Unfortunately, this would reduce the spectral resolution of the sensor. Conversely, coarser spatial resolution would allow improved radiometric and/or spectral resolution. Thus, these three types of resolution must be balanced against the desired capabilities and objectives of the sensor.

2.7 Did You Know?

"...let's take a look at the **BIG PICTURE**..."

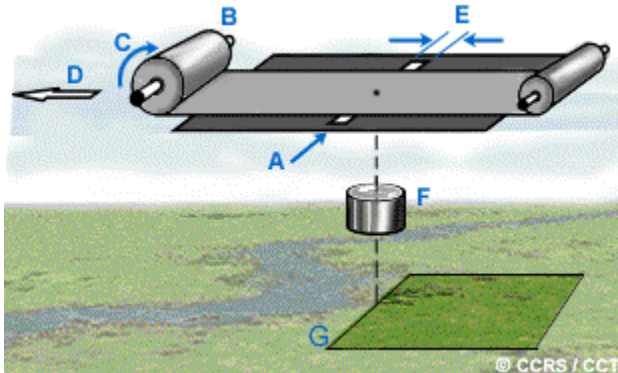


...that the U.S. Space Shuttles have been used to take photographs from space. The astronauts onboard the shuttle have taken many photographs using hand-held cameras, similar to the type you would use for taking family photos. They have also used much larger and more sophisticated cameras mounted in the shuttle's cargo bay, called Large Format Cameras (LFCs). LFCs have long focal lengths (305 mm) and take high quality photographs covering several hundreds of kilometres in both dimensions. The exact dimensions depend (of course) on the height of the shuttle above the Earth. Photos from these passive sensors need to be taken when the Earth's surface is being illuminated by the sun and are subject to cloud cover and other attenuation from the atmosphere. The shuttle has also been used several times to image many regions of the Earth using a special active microwave sensor called a RADAR. The RADAR sensor can collect detailed imagery during the night or day, as it provides its own energy source, and is able to penetrate and "see" through cloud cover due to the long wavelength of the electromagnetic radiation. We will learn more about RADAR in Chapter 3.

... although taking photographs in the UV portion of the spectrum is problematic due to atmospheric scattering and absorption, it can be very useful where other types of photography are not. An interesting example in wildlife research and management has used UV photography for detecting and counting harp seals on snow and ice. Adult harp seals have dark coats while their young have white coats. In normal panchromatic imagery, the dark coats of the adult seals are readily visible against the snow and ice background but the white coats of the young seals are not. However, the coats of both the adult and infant seals are strong absorbers of UV energy. Thus, both adult and young appear very dark in a UV image and can be easily detected. This allows simple and reliable monitoring of seal population changes over very large areas.

2.8 Did You Know?

"...backfield in motion..."

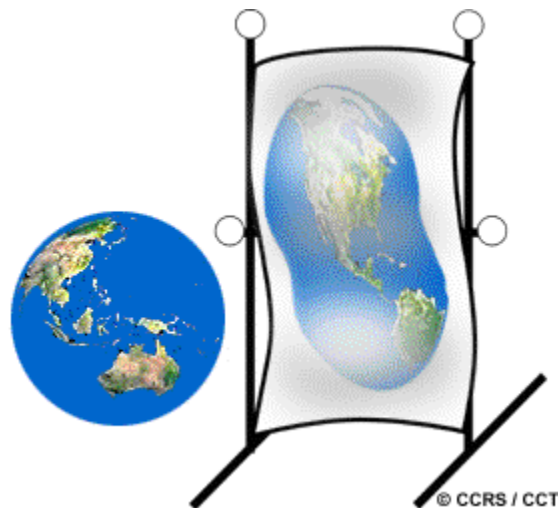


There is a photographic parallel to the push-broom scanner. It is based on the "slit camera". This camera does not have a shutter per se, but a slit (A) running in the across-track direction, which exposes film (B) which is being moved continuously (C) past the slit. The speed of motion of the film has to be proportional to the ground speed (D) of the aircraft. Thus the film speed has to be adjusted for the flying circumstances of the moment. The slit width (E) in the along-track direction is also adjustable so as to control exposure time. There are no individual photo 'frames' produced, but a continuous strip of imagery. Stereo slit photography is also possible, using a twin-lens system aimed slightly apart from parallel and each exposing one half of the film width.

2.10 Did You Know?

"...scanning for warm-bodied life forms, captain... "

...that, just as in aerial photography, some thermal scanner systems view the surface **obliquely**. Forward-Looking Infrared (**FLIR**) systems point ahead of the aircraft and scan across the scene. FLIR systems produce images very similar in appearance to oblique aerial photographs and are used for applications ranging from forest fire detection to law enforcement.



...many **systematic**, or predictable, geometric distortions can be accounted for in real-time (i.e. during image acquisition). As an example, skew distortion in across-track scanner imagery due to the Earth's rotation can be accurately modeled and easily corrected. Other random variations causing distortion cannot be as easily modeled and require **geometric correction** in a digital environment after the data have been collected. We will discuss this topic in more detail in Chapter 4.

2.12 Did You Know?

"...Land, Ho, matey!..."

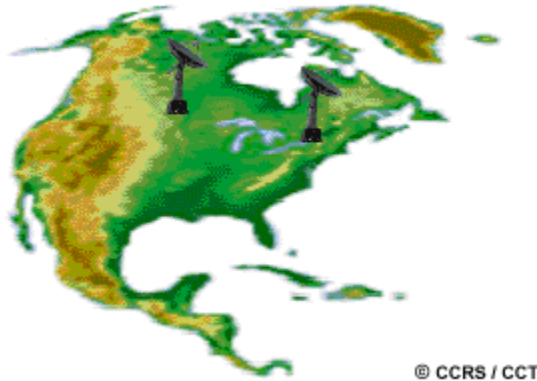
...the ERTS (Earth Resources Technology Satellite) program was renamed to Landsat just prior to the launch of the second satellite in the series. The Landsat title was used to distinguish the program from another satellite program in the planning stages, called Seasat, intended primarily for oceanographic applications. The first (and only) Seasat satellite was successfully launched in 1978, but unfortunately was only operational for 99 days. Even though the satellite was short-lived and the Seasat program was discontinued, it collected some of the first RADAR images from space which helped heighten the interest in satellite RADAR remote sensing. Today, several RADAR satellites are operational or planned. We will learn more about RADAR and these satellites in the next chapter.



...originally the MSS sensor numbering scheme (bands 4, 5, 6, and 7) came from their numerical sequence after the three bands of the RBV (Return Beam Vidicon) sensors. However, due to technical malfunctions with the RBV sensor and the fact that it was dropped from the satellite sensor payload with the launch of Landsat-4, the MSS bands were renumbered from 1 to 4. For the TM sensor, if we look at the wavelength ranges for each of the bands, we see that TM6 and TM7 are out of order in terms of increasing wavelength. This was because the TM7 channel was added as an afterthought late in the original system design process.

2.15 Did You Know?

"...I'm receiving you loud and clear..."



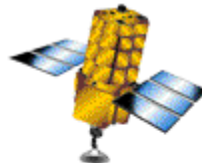
... Canada's ground receiving stations have been in operation since 1972 in Prince Albert, Saskatchewan and 1985 in Gatineau, Quebec. These two stations receive and process image data from several different satellites (NOAA, Landsat, RADARSAT, J-ERS, MOS, SPOT, and ERS) from five different countries or group of countries (USA, Canada, Japan, France, and Europe).



2. Whiz Quiz and Answers

2.2 Whiz Quiz

What advantages do sensors carried on board satellites have over those carried on aircraft?
Are there any disadvantages that you can think of?



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As a satellite in a near-polar sun-synchronous orbit revolves around the Earth, the satellite crosses the equator at approximately the same local sun time every day. Because of the orbital velocity, all other points on the globe are passed either slightly before or after this time. For a sensor in the visible portion of the spectrum, what would be the advantages and disadvantages of crossing times (local sun time) a) in the early morning, b) around noon, and c) in the mid afternoon?

2.2 Whiz Quiz - Answers

Answer 1: Sensors on board satellites generally can "see" a much larger area of the Earth's surface than would be possible from a sensor onboard an aircraft. Also, because they are continually orbiting the Earth, it is relatively easy to collect imagery on a systematic and repetitive basis in order to monitor changes over time. The geometry of orbiting satellites with respect to the Earth can be calculated quite accurately and facilitates correction of remote sensing images to their proper geographic orientation and position. However, aircraft sensors can collect data at any time and over any portion of the Earth's surface (as long as conditions allow it) while satellite sensors are restricted to collecting data over only those areas and during specific times dictated by their particular orbits. It is also much more difficult to fix a sensor in space if a problem or malfunction develops!



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Answer 2: An early morning crossing time would have the sun at a very low angle in the sky and would be good for emphasizing topographic effects but would result in a lot of shadow in areas of high relief. A crossing time around noon would have the sun at its highest point in the sky and would provide the maximum and most uniform illumination conditions. This would be useful for surfaces of low reflectance but might cause saturation of the sensor over high reflectance surfaces, such as ice. Also, under such illumination, 'specular reflection' from smooth surfaces may be a problem for interpreters. In the mid afternoon, the illumination conditions would be more moderate. However, a phenomenon called solar heating (due to the sun heating the surface), which causes difficulties for recording reflected energy, will be near maximum at this time of day. In order to minimize between these effects, most satellites which image in the visible, reflected, and emitted infrared regions use crossing times around mid-morning as a compromise.

2.3 Whiz Quiz

1. Look at the detail apparent in each of these two images. Which of the two images is of a smaller scale? What clues did you use to determine this? Would the imaging platform for the smaller scale image most likely have been a satellite or an aircraft?



2. If you wanted to monitor the general health of all vegetation cover over the Canadian Prairie provinces for several months, what type of platform and sensor characteristics (spatial, spectral, and temporal resolution) would be best for this and why?

2.3 Whiz Quiz - Answers

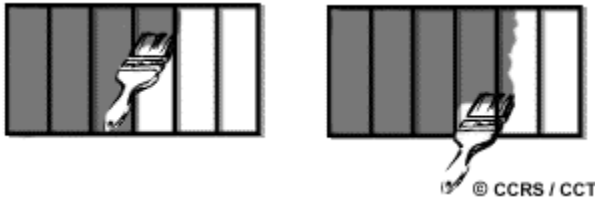
Answer 1: The image on the left is from a satellite while the image on the right is a photograph taken from an aircraft. The area covered in the image on the right is also covered in the image on the left, but this may be difficult to determine because the scales of the two images are much different. We are able to identify relatively small features (i.e. individual buildings) in the image on the right that are not discernible in the image on the left. Only general features such as street patterns, waterways, and bridges can be identified in the left-hand image. Because features appear larger in the image on the right and a particular measurement (eg. 1 cm) on the image represents a smaller true distance on the ground, this image is at a larger scale. It is an aerial photograph of the Parliament Buildings in Ottawa, Canada. The left-hand image is a satellite image of the city of Ottawa.



Answer 2: A satellite sensor with large area coverage and fairly coarse spatial resolution would be excellent for monitoring the general state of vegetation health over Alberta, Saskatchewan, and Manitoba. The large east-to-west expanse would be best covered by a sensor with a wide swath and broad coverage. This would also imply that the spatial resolution of the sensor would be fairly coarse. However, fine detail would not really be necessary for monitoring a broad class including all vegetation cover. With broad area coverage the revisit period would be shorter, increasing the opportunity for repeat coverage necessary for monitoring change. The frequent coverage would also allow for areas covered by clouds on one date, to be filled in by data collected from another date, reasonably close in time. The sensor would not necessarily require high spectral resolution, but would at a minimum, require channels in the visible and near-infrared regions of the spectrum. Vegetation generally has a low reflectance in the visible and a high reflectance in the near-infrared. The contrast in reflectance between these two regions assists in identifying vegetation cover. The magnitude of the reflected infrared energy is also an indication of vegetation health. A sensor on board the U.S. NOAA (National Oceanographic and Atmospheric Administration) series of satellites with exactly these types of characteristics is actually used for this type of monitoring over the entire surface of the Earth!

2.4 Whiz Quiz

1. Hyperspectral scanners (mentioned in Chapter 2.4) are special multispectral sensors which detect and record radiation in several (perhaps hundreds) of very narrow spectral bands. What would be some of the advantages of these types of sensors? What would be some of the disadvantages?



2. If the spectral range of the 288 channels of the CASI (Compact Airborne Spectrographic Imager) is exactly $0.40 \mu\text{m}$ to $0.90 \mu\text{m}$ and each band covers a wavelength of 1.8 nm (nanometres, 10^{-9} m), will there be any overlap between the bands?

2.4 Whiz Quiz - Answers

Answer 1: Hyperspectral scanners have very high spectral resolution because of their narrow bandwidths. By measuring radiation over several small wavelength ranges, we are able to effectively build up a continuous spectrum of the radiation detected for each pixel in an image. This allows for fine differentiation between targets based on detailed reflectance and absorption responses which are not detectable using the broad wavelength ranges of conventional multispectral scanners. However, with this increased sensitivity comes significant increases in the volume of data collected. This makes both storage and manipulation of the data, even in a computer environment, much more difficult. Analyzing multiple images at one time or combining them, becomes cumbersome, and trying to identify and explain what each unique response represents in the "real world" is often difficult.

Answer 2: The total wavelength range available will be $0.90 - 0.40 \mu\text{m} = 0.50 \text{ mm}$. If there are 288 channels of 1.8 nm each, let's calculate the total wavelength range they would span if they did not overlap.

$$1.8 \text{ nm} = 1.8 \times 10^{-9} \text{ m}$$

$$1.8 \times 10^{-9} \text{ m} \times 288 = 0.0000005184 \text{ m}$$

$$0.0000005184 \text{ m} = 0.5184 \mu\text{m}$$

Since 0.5184 is greater than 0.50 , the answer is YES, there will have to be some overlap between some or all of the 288 bands to fit into this $0.50 \mu\text{m}$ range.

2.5 Whiz Quiz



Suppose you have a digital image which has a radiometric resolution of 6 bits. What is the maximum value of the digital number which could be represented in that image?

2.5 Whiz Quiz - Answers



The number of digital values possible in an image is equal to the number two (2 - for binary codings in a computer) raised to the exponent of the number of bits in the image (i.e. $2^{\# \text{ of bits}}$). The number of values in a 6-bit image would be equal to $2^6 = 2 \times 2 \times 2 \times 2 \times 2 \times 2 = 64$. Since the range of values displayed in a digital image normally starts at zero (0), in order to have 64 values, the maximum value possible would be 63.

2.9 Whiz Quiz



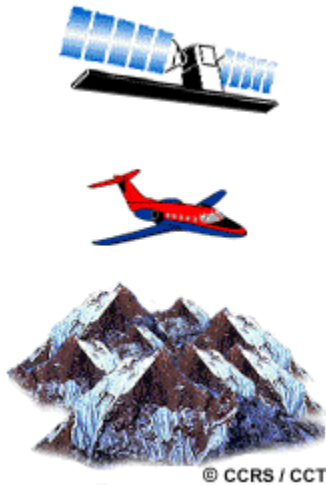
How would thermal imagery be useful in an urban environment?

2.9 Whiz Quiz - Answers



Detecting and monitoring heat loss from buildings in urban areas is an excellent application of thermal remote sensing. Heating costs, particularly in northern countries such as Canada, can be very expensive. Thermal imaging in both residential and commercial areas allows us to identify specific buildings, or parts of buildings, where heat is escaping. If the amount of heat is significant, these areas can be targeted for repair and re-insulation to reduce costs and conserve energy.

2.10 Whiz Quiz



If you wanted to map a mountainous region, limiting geometric distortions as much as possible, would you choose a satellite-based or aircraft-based scanning system? Explain why in terms of imaging geometry.

2.10 Whiz Quiz Answers

Although an aircraft scanning system may provide adequate geometric accuracy in most instances, a satellite scanner would probably be preferable in a mountainous region. Because of the large variations in relief, geometric distortions as a result of relief displacement would be amplified at aircraft altitudes much more than from satellite altitudes. Also, given the same lighting conditions, shadowing would be a greater problem using aircraft imagery because of the shallower viewing angles and would eliminate the possibility for practical mapping in these areas.

2.12 Whiz Quiz



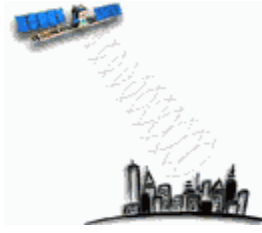
Explain why data from the Landsat TM sensor might be considered more useful than data from the original MSS sensor. Hint: Think about their spatial, spectral, and radiometric resolutions.

2.12 Whiz Quiz - Answers

There are several reasons why TM data may be considered more useful than MSS data. Although the areal coverage of a TM scene is virtually the same as a MSS scene, TM offers higher spatial, spectral, and radiometric resolution. The spatial resolution is 30 m compared to 80 m (except for the TM thermal channels, which are 120 m to 240 m). Thus, the level of spatial detail detectable in TM data is better. TM has more spectral channels which are narrower and better placed in the spectrum for certain applications, particularly vegetation discrimination. In addition, the increase from 6 bits to 8 bits for data recording represents a four-fold increase in the radiometric resolution of the data.

(Remember, 6 bits = $2^6 = 64$, and 8 bits = $2^8 = 256$ - therefore, $256/64 = 4$). However, this does not mean that TM data are "better" than MSS data. Indeed, MSS data are still used to this day and provide an excellent data source for many applications. If the desired information cannot be extracted from MSS data, then perhaps the higher spatial, spectral, and radiometric resolution of TM data may be more useful.

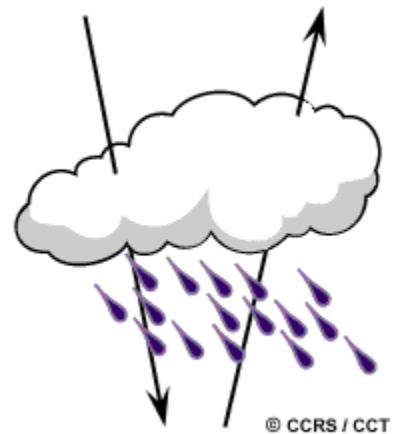




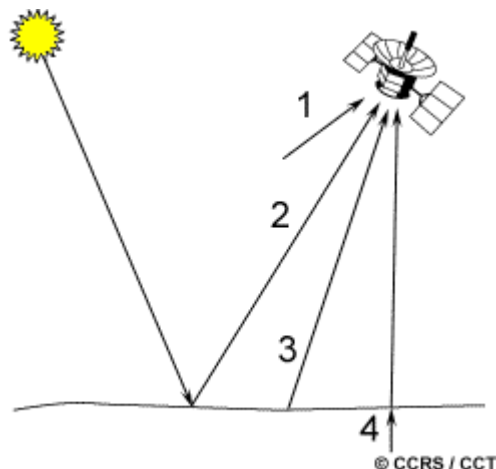
3. Microwave Remote Sensing

3.1 Introduction

Microwave sensing encompasses both active and passive forms of remote sensing. As described in Chapter 2, the microwave portion of the spectrum covers the range from approximately 1cm to 1m in wavelength. Because of their long wavelengths, compared to the visible and infrared, microwaves have special properties that are important for remote sensing. **Longer wavelength microwave radiation can penetrate through cloud cover, haze, dust, and all but the heaviest rainfall** as the longer wavelengths are not susceptible to atmospheric scattering which affects shorter optical wavelengths. This property allows detection of microwave energy under almost all weather and environmental conditions so that data can be collected at any time.



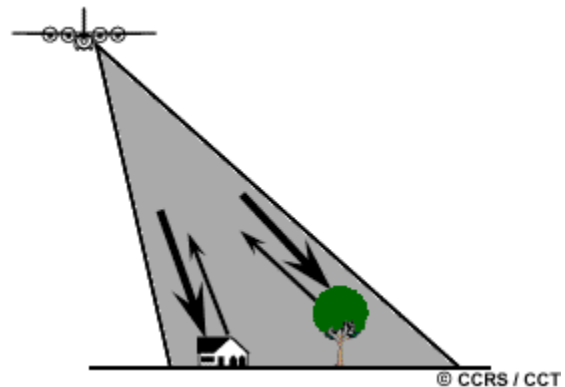
Passive microwave sensing is similar in concept to thermal remote sensing. All objects emit microwave energy of some magnitude, but the amounts are generally very small. A passive microwave sensor detects the naturally emitted microwave energy within its field of view. This emitted energy is related to the temperature and moisture properties of the emitting object or surface. Passive microwave sensors are typically radiometers or scanners and operate in much the same manner as systems discussed previously except that an antenna is used to detect and record the microwave energy.



The microwave energy recorded by a passive sensor can be emitted by the atmosphere (1), reflected from the surface (2), emitted from the surface (3), or transmitted from the subsurface (4). Because the wavelengths are so long, the energy available is quite small compared to optical wavelengths. Thus, the fields of view must be large to detect enough energy to record a signal. Most passive microwave sensors are therefore characterized by low spatial resolution.

Applications of passive microwave remote sensing include meteorology, hydrology, and oceanography. By looking "at", or "through" the atmosphere, depending on the wavelength, meteorologists can use passive microwaves to measure atmospheric profiles and to determine water and ozone content in the atmosphere. Hydrologists use passive microwaves to measure soil moisture since microwave emission is influenced by moisture content. Oceanographic applications include mapping sea ice, currents, and surface winds as well as detection of pollutants, such as oil slicks.

Active microwave sensors provide their own source of microwave radiation to illuminate the target. Active microwave sensors are generally divided into two distinct categories: **imaging and non-imaging**. The most common form of imaging active microwave sensors is RADAR. **RADAR** is an acronym for **R**ADIO **D**ETECTION **A**ND **R**ANGING, which essentially characterizes the function and operation of a radar sensor. The sensor transmits a microwave (radio) signal towards the target and detects the backscattered portion of the signal.



The strength of the backscattered signal is measured to discriminate between different targets and the time delay between the transmitted and reflected signals determines the distance (or **range**) to the target.

Non-imaging microwave sensors include **altimeters** and **scatterometers**. In most cases these are profiling devices which take measurements in one linear dimension, as opposed to the two-dimensional representation of imaging sensors. Radar altimeters transmit short microwave pulses and measure the round trip time delay to targets to determine their distance from the sensor. Generally altimeters look straight down at nadir below the platform and thus measure height or elevation (if the altitude of the platform is accurately known). Radar altimetry is used on aircraft for altitude determination and on aircraft and satellites for topographic mapping and sea surface height estimation. Scatterometers are also generally non-imaging sensors and are used to make precise quantitative measurements of the amount of energy backscattered from targets. The amount of energy backscattered is dependent on the surface properties (roughness) and the angle at which the microwave energy strikes the target. Scatterometry measurements over ocean surfaces can be used to estimate wind speeds based on the sea surface roughness. Ground-based scatterometers are used extensively to accurately measure the backscatter from various targets in order to

characterize different materials and surface types. This is analogous to the concept of spectral reflectance curves in the optical spectrum.

For the remainder of this chapter we focus solely on **imaging radars**. As with passive microwave sensing, a major advantage of radar is the capability of the radiation to penetrate through cloud cover and most weather conditions. Because radar is an active sensor, it can also be used to image the surface at any time, day or night. These are the two primary advantages of radar: **all-weather and day or night** imaging. It is also important to understand that, because of the fundamentally different way in which an active radar operates compared to the passive sensors we described in Chapter 2, a radar image is quite different from and has special properties unlike images acquired in the visible and infrared portions of the spectrum. Because of these differences, radar and optical data can be complementary to one another as they offer different perspectives of the Earth's surface providing different information content. We will examine some of these fundamental properties and differences in more detail in the following sections.

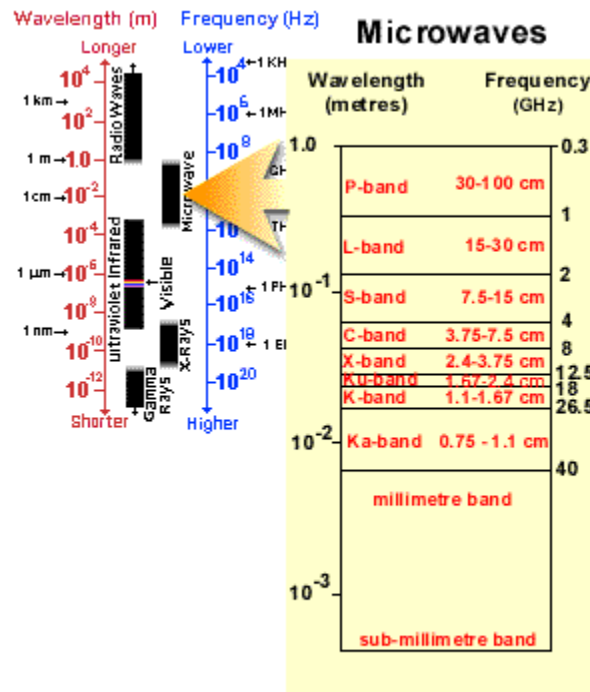
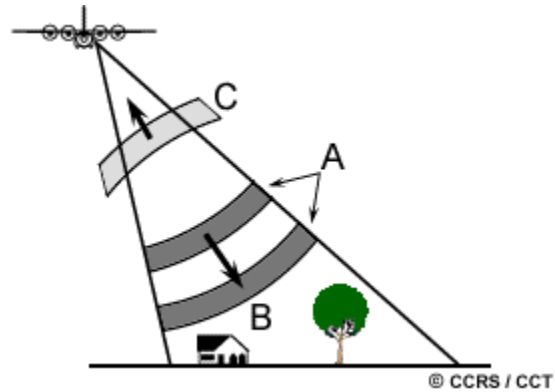
Before we delve into the peculiarities of radar, let's first look briefly at the origins and history of imaging radar, with particular emphasis on the Canadian experience in radar remote sensing. The first demonstration of the transmission of radio microwaves and reflection from various objects was achieved by Hertz in 1886. Shortly after the turn of the century, the first rudimentary radar was developed for ship detection. In the 1920s and 1930s, experimental ground-based pulsed radars were developed for detecting objects at a distance. The first imaging radars used during World War II had rotating sweep displays which were used for detection and positioning of aircrafts and ships. After World War II, side-looking airborne radar (SLAR) was developed for military terrain reconnaissance and surveillance where a strip of the ground parallel to and offset to the side of the aircraft was imaged during flight. In the 1950s, advances in SLAR and the development of higher resolution synthetic aperture radar (SAR) were developed for military purposes. In the 1960s these radars were declassified and began to be used for civilian mapping applications. Since this time the development of several airborne and spaceborne radar systems for mapping and monitoring applications use has flourished.

Canada initially became involved in radar remote sensing in the mid-1970s. It was recognized that radar may be particularly well-suited for surveillance of our vast northern expanse, which is often cloud-covered and shrouded in darkness during the Arctic winter, as well as for monitoring and mapping our natural resources. Canada's SURSAT (Surveillance Satellite) project from 1977 to 1979 led to our participation in the (U.S.) SEASAT radar satellite, the first operational civilian radar satellite. The Convair-580 airborne radar program, carried out by the Canada Centre for Remote Sensing following the SURSAT program, in conjunction with radar research programs of other agencies such as NASA and the European Space Agency (ESA), led to the conclusion that spaceborne remote sensing was feasible. In 1987, the Radar Data Development Program (RDDP), was initiated by the Canadian government with the objective of "operationalizing the use of radar data by Canadians". Over the 1980s and early 1990s, several research and commercial airborne radar systems have collected vast amounts of

imagery throughout the world demonstrating the utility of radar data for a variety of applications. With the launch of ESA's ERS-1 in 1991, spaceborne radar research intensified, and was followed by the major launches of Japan's J-ERS satellite in 1992, ERS-2 in 1995, and Canada's advanced RADARSAT satellite, also in 1995.

3.2 Radar Basics

As noted in the previous section, a **radar** is essentially a ranging or distance measuring device. It consists fundamentally of a transmitter, a receiver, an antenna, and an electronics system to process and record the data. The transmitter generates successive short bursts (or **pulses** of microwave (A) at regular intervals which are focused by the antenna into a beam (B). The radar beam illuminates the surface obliquely at a right angle to the motion of the platform. The antenna receives a portion of the transmitted energy reflected (or **backscattered**) from various objects within the illuminated beam (C). By measuring the time delay between the transmission of a pulse and the reception of the backscattered "echo" from different targets, their distance from the radar and thus their location can be determined. As the sensor platform moves forward, recording and processing of the backscattered signals builds up a two-dimensional image of the surface.

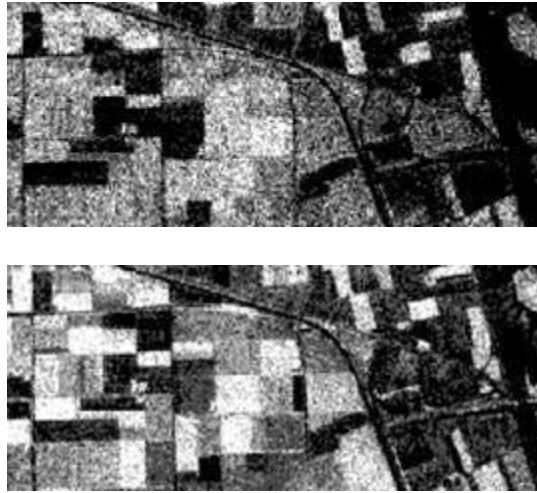


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While we have characterized electromagnetic radiation in the visible and infrared portions of the spectrum primarily by wavelength, microwave portions of the spectrum are often referenced according to both wavelength and frequency. The **microwave region of the spectrum** is quite large, relative to the visible and infrared, and there are several wavelength ranges or bands commonly used which given code letters during World War II, and remain to this day.

- Ka, K, and Ku bands: very short wavelengths used in early airborne radar systems but uncommon today.
- X-band: used extensively on airborne systems for military reconnaissance and terrain mapping.
- C-band: common on many airborne research systems (CCRS Convair-580 and NASA AirSAR) and spaceborne systems (including
- ERS-1 and 2 and RADARSAT).

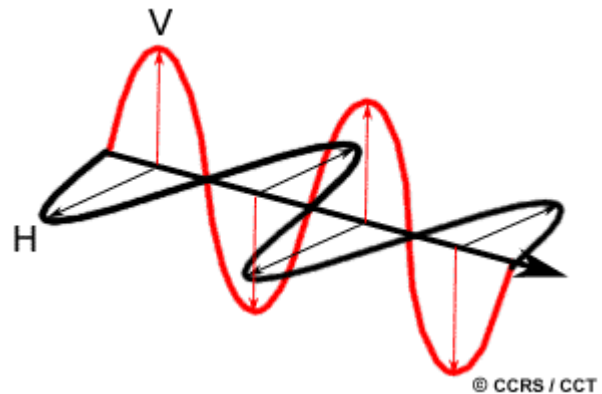
- S-band: used on board the Russian ALMAZ satellite.
- L-band: used onboard American SEASAT and Japanese JERS-1 satellites and NASA airborne system.
- P-band: longest radar wavelengths, used on NASA experimental airborne research system.



Two radar images of the same agricultural fields

Here are two radar images of the same agricultural fields, each image having been collected using a different radar band. The one on the top was acquired by a C-band radar and the one below was acquired by an L-band radar. You can clearly see that there are significant differences between the way the various fields and crops appear in each of the two images. This is due to the different ways in which the radar energy interacts with the fields and crops depending on the radar wavelength. We will learn more about this in later sections.

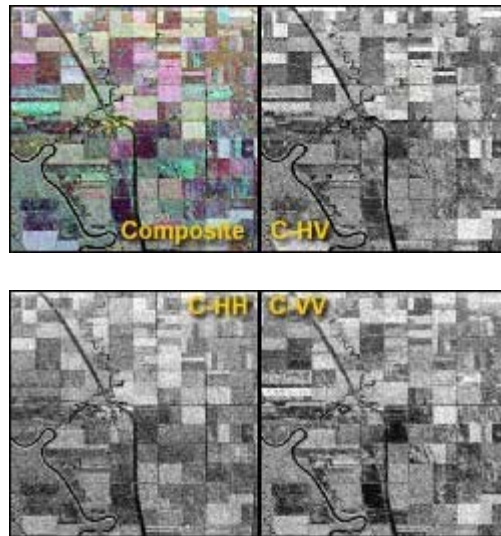
When discussing microwave energy, the **polarization** of the radiation is also important. Polarization refers to the orientation of the electric field (recall the definition of electromagnetic radiation from Chapter 1). Most radars are designed to transmit microwave radiation either horizontally polarized (H) or vertically polarized (V). Similarly, the antenna receives either the horizontally or vertically polarized backscattered energy, and some radars can receive both. These two polarization states are designated by the letters H for horizontal, and V, for vertical. Thus, there can be four combinations of both transmit and receive polarizations as follows:



- HH - for horizontal transmit and horizontal receive,
- VV - for vertical transmit and vertical receive,
- HV - for horizontal transmit and vertical receive, and
- VH - for vertical transmit and horizontal receive.

The first two polarization combinations are referred to as like-polarized because the transmit and receive polarizations are the same. The last two combinations are referred to as cross-polarized because the transmit and receive polarizations are opposite of one another. These **C-band images** of agricultural fields demonstrate the variations in radar response due to changes in polarization. The bottom two images are like-polarized (HH and VV, respectively), and the upper right image is cross-polarized (HV). The upper left image is the result of displaying each of the three different polarizations together, one through each of the primary colours (red, green, and blue). Similar to variations in wavelength, depending on the transmit and receive polarizations, the radiation will interact with and be

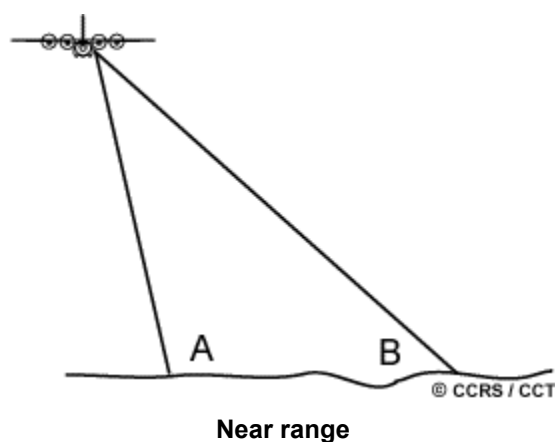
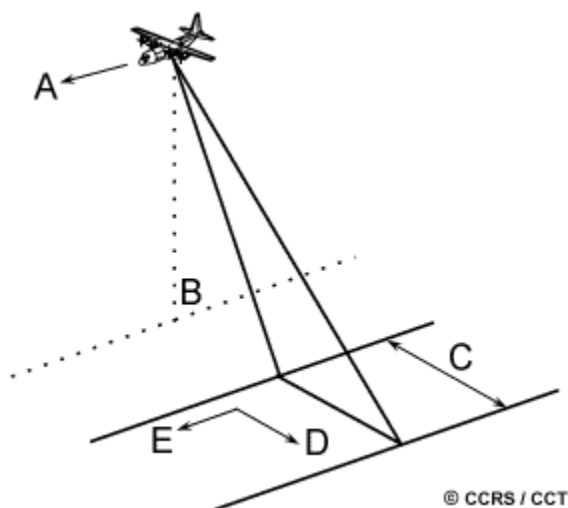
backscattered differently from the surface. Both wavelength and polarization affect how a radar "sees" the surface. Therefore, radar imagery collected using different polarization and wavelength combinations may provide different and complementary information about the targets on the surface.



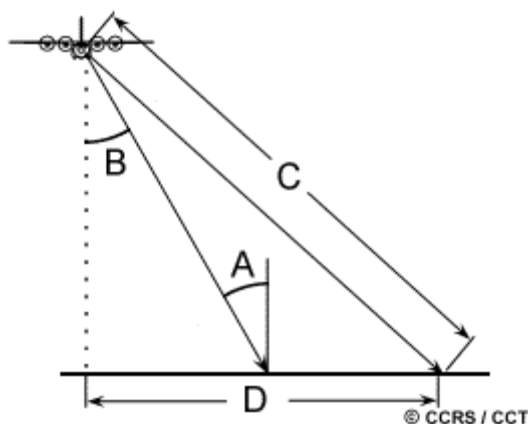
C-band images

3.3 Viewing Geometry and Spatial Resolution

The imaging geometry of a radar system is different from the framing and scanning systems commonly employed for optical remote sensing described in Chapter 2. Similar to optical systems, the platform travels forward in the **flight direction (A)** with the **nadir (B)** directly beneath the platform. The microwave beam is transmitted obliquely at right angles to the direction of flight illuminating a **swath (C)** which is offset from nadir. **Range (D)** refers to the across-track dimension perpendicular to the flight direction, while **azimuth (E)** refers to the along-track dimension parallel to the flight direction. This side-looking viewing geometry is typical of imaging radar systems (airborne or spaceborne).



The portion of the image swath closest to the nadir track of the radar platform is called the **near range (A)** while the portion of the swath farthest from the nadir is called the **far range (B)**.



Incidence angle

The incidence angle is the angle between the **radar beam and ground surface (A)** which increases, moving across the swath from near to far range. The **look angle (B)** is the angle at which the radar "looks" at the surface. In the near range, the viewing geometry may be referred to as being steep, relative to the far range, where the viewing geometry is shallow. At all ranges the radar antenna measures the radial line of sight distance between the radar and each target on the surface. This is the **slant range distance (C)**. The **ground range distance (D)** is the true horizontal distance along the ground corresponding to each point measured in slant range.

Unlike optical systems, a radar's spatial resolution is a function of the specific properties of the microwave radiation and geometrical effects. If a Real Aperture Radar (RAR) is used for image formation (as in Side-Looking Airborne Radar) a single transmit pulse and the backscattered signal are used to form the image. In this case, the resolution is dependent on the effective length of the pulse in the slant range direction and on the width of the illumination in the azimuth direction.

The **range or across-track resolution** is dependent on the length of the pulse (P). Two distinct targets on the surface will be resolved in the range dimension if their separation is greater than half the pulse length. For example, targets 1 and 2 will not be separable while targets 3 and 4 will. Slant range resolution remains constant, independent of range. However, when projected into ground range coordinates, the resolution in ground range will be dependent of the incidence angle. Thus, for fixed slant range resolution, the ground range resolution will decrease with increasing range.

