The azimuth or along-track resolution is determined by the angular width of the radiated microwave beam and the slant range distance. This beamwidth (A) is a measure of the width of the illumination pattern. As the radar illumination propagates to increasing distance from the sensor, the azimuth resolution increases (becomes coarser). In this illustration, targets 1 and 2 in the near range would be separable, but targets 3 and 4 at further range would not. The radar beamwidth is inversely proportional to the antenna length (also referred to as the aperture) which means that a longer antenna (or aperture) will produce a narrower beam and finer resolution.

Finer range resolution can be achieved by using a shorter pulse length, which can be done within certain engineering design restrictions. Finer azimuth resolution can be achieved by increasing the antenna length. However, the actual length of the antenna is limited by what can be carried on an airborne or spaceborne platform. For airborne radars, antennas are usually limited to one to two metres; for satellites they can be 10 to 15 metres in length. To overcome this size limitation, the forward motion of the platform and special recording and processing of the backscattered echoes are used to simulate a very long antenna and thus increase azimuth resolution.

This figure illustrates how this is achieved. As a target (A) first enters the radar beam (1), the backscattered echoes from each transmitted pulse begin to be recorded. As the platform continues to move forward, all echoes from the target for each pulse are recorded during the entire time that the target is within the beam. The point at which the target leaves the view of the radar beam (2) some time later, determines the length of the simulated or synthesized antenna (B). Targets at far range, where the beam is widest will be illuminated for a longer period of time than objects at near range. The expanding beamwidth, combined with the increased time a target is within the beam as ground range increases, balance each other, such that the resolution remains constant across the entire swath. This method of achieving uniform, fine azimuth resolution across the entire imaging swath is called synthetic aperture radar, or SAR. Most airborne and spaceborne radars employ this type of radar.
### 3.4 Radar Image Distortions

As with all remote sensing systems, the viewing geometry of a radar results in certain geometric distortions on the resultant imagery. However, there are key differences for radar imagery which are due to the side-looking viewing geometry, and the fact that the radar is fundamentally a distance measuring device (i.e. measuring range). **Slant-range scale distortion** occurs because the radar is measuring the distance to features in slant-range rather than the true horizontal distance along the ground. This results in a varying image scale, moving from near to far range. Although targets A1 and B1 are the same size on the ground, their apparent dimensions in slant range (A2 and B2) are different. This causes targets in the near range to appear compressed relative to the far range. Using trigonometry, ground-range distance can be calculated from the slant-range distance and platform altitude to convert to the proper ground-range format.

![Slant-range and ground-range image comparison](image)

This conversion comparison shows a radar image in slant-range display (top) where the fields and the road in the near range on the left side of the image are compressed, and the same image converted to ground-range display (bottom) with the features in their proper geometric shape.

Similar to the distortions encountered when using cameras and scanners, radar images are also subject to geometric distortions due to **relief displacement**. As with scanner imagery, this displacement is one-dimensional and occurs perpendicular to the flight path. However, the displacement is reversed with targets being displaced towards, instead of away from the sensor. Radar **foreshortening** and **layover** are two consequences which result from relief displacement.
When the radar beam reaches the base of a tall feature tilted towards the radar (e.g. a mountain) before it reaches the top foreshortening will occur. Again, because the radar measures distance in slant-range, the slope (A to B) will appear compressed and the length of the slope will be represented incorrectly (A' to B'). Depending on the angle of the hillside or mountain slope in relation to the incidence angle of the radar beam, the severity of foreshortening will vary. Maximum foreshortening occurs when the radar beam is perpendicular to the slope such that the slope, the base, and the top are imaged simultaneously (C to D). The length of the slope will be reduced to an effective length of zero in slant range (C'D'). The figure below shows a radar image of steep mountainous terrain with severe foreshortening effects. The foreshortened slopes appear as bright features on the image.
Layover occurs when the radar beam reaches the top of a tall feature (B) before it reaches the base (A). The return signal from the top of the feature will be received before the signal from the bottom. As a result, the top of the feature is displaced towards the radar from its true position on the ground, and "lays over" the base of the feature (B' to A'). Layover effects on a radar image look very similar to effects due to foreshortening. As with foreshortening, layover is most severe for small incidence angles, at the near range of a swath, and in mountainous terrain.

Both foreshortening and layover result in radar shadow. Radar shadow occurs when the radar beam is not able to illuminate the ground surface. Shadows occur in the down range dimension (i.e. towards the far range), behind vertical features or slopes with steep sides. Since the radar beam does not illuminate the surface, shadowed regions will appear dark on an image as no energy is available to be backscattered. As incidence angle increases from near to far range, so will shadow effects as the radar beam looks more and more obliquely at the surface. This image illustrates radar shadow effects on the right side of the hillsides which are being illuminated from the left.
Red surfaces are completely in shadow. Black areas in image are shadowed and contain no information.

Radar shadow effects
3.5 Target Interaction and Image Appearance

The brightness of features in a radar image is dependent on the portion of the transmitted energy that is returned back to the radar from targets on the surface. The magnitude or intensity of this backscattered energy is dependent on how the radar energy interacts with the surface, which is a function of several variables or parameters. These parameters include the particular characteristics of the radar system (frequency, polarization, viewing geometry, etc.) as well as the characteristics of the surface (landcover type, topography, relief, etc.). Because many of these characteristics are interrelated, it is impossible to separate out each of their individual contributions to the appearance of features in a radar image. Changes in the various parameters may have an impact on and affect the response of other parameters, which together will affect the amount of backscatter. Thus, the brightness of features in an image is usually a combination of several of these variables. However, for the purposes of our discussion, we can group these characteristics into three areas which fundamentally control radar energy/target interactions. They are:

- Surface roughness of the target
- Radar viewing and surface geometry relationship
- Moisture content and electrical properties of the target

The surface roughness of a feature controls how the microwave energy interacts with that surface or target and is generally the dominant factor in determining the tones seen on a radar image. **Surface roughness** refers to the average height variations in the surface cover from a plane surface, and is measured on the order of centimetres. Whether a surface appears rough or smooth to a radar depends on the wavelength and incidence angle.

Simply put, a surface is considered "smooth" if the height variations are much smaller than the radar wavelength. When the surface height variations begin to approach the size of the wavelength, then the surface will appear "rough". Thus, a given surface will appear rougher as the wavelength becomes shorter and smoother as the wavelength becomes longer. A **smooth surface (A)** causes **specular** reflection of the incident energy (generally away from the sensor) and thus only a small amount of energy is returned to the radar. This results in smooth surfaces appearing as
darker toned areas on an image. A rough surface (B) will scatter the energy approximately equally in all directions (i.e. diffusely) and a significant portion of the energy will be backscattered to the radar. Thus, rough surfaces will appear lighter in tone on an image. Incidence angle, in combination with wavelength, also plays a role in the apparent roughness of a surface. For a given surface and wavelength, the surface will appear smoother as the incidence angle increases. Thus, as we move farther across the swath, from near to far range, less energy would be returned to the sensor and the image would become increasingly darker in tone.

We have already discussed incidence or look angle in relation to viewing geometry and how changes in this angle affect the signal returned to the radar. However, in relation to surface geometry, and its effect on target interaction and image appearance, the local incidence angle is a more appropriate and relevant concept. The local incidence angle is the angle between the radar beam and a line perpendicular to the slope at the point of incidence (A). Thus, local incidence angle takes into account the local slope of the terrain in relation to the radar beam. With flat terrain, the local incidence angle is the same as the look angle (B) of the radar. For terrain with any type of relief, this is not the case. Generally, slopes facing towards the radar will have small local incidence angles, causing relatively strong backscattering to the sensor, which results in a bright-toned appearance in an image.

As the concept of local incidence angle demonstrates, the relationship between viewing geometry and the geometry of the surface features plays an important role in how the radar energy interacts with targets and their corresponding brightness on an image. Variations in viewing geometry will accentuate and enhance topography and relief in different ways, such that varying degrees of foreshortening, layover, and shadow (section 3.4) may occur depending on surface slope, orientation, and shape.

The look direction or aspect angle of the radar describes the orientation of the transmitted radar beam relative to the direction or alignment of linear features on the surface. The look direction can significantly influence the appearance of features on a radar image, particularly when ground features are organized in a linear structure (such as agricultural crops or
mountain ranges). If the look direction is close to perpendicular to the orientation of the feature (A), then a large portion of the incident energy will be reflected back to the sensor and the feature will appear as a brighter tone. If the look direction is more oblique in relation to the feature orientation (B), then less energy will be returned to the radar and the feature will appear darker in tone. Look direction is important for enhancing the contrast between features in an image. It is particularly important to have the proper look direction in mountainous regions in order to minimize effects such as layover and shadowing. By acquiring imagery from different look directions, it may be possible to enhance identification of features with different orientations relative to the radar.

Features which have two (or more) surfaces (usually smooth) at right angles to one another, may cause corner reflection to occur if the 'corner' faces the general direction of the radar antenna. The orientation of the surfaces at right angles causes most of the radar energy to be reflected directly back to the antenna due to the double bounce (or more) reflection. Corner reflectors with complex angular shapes are common in urban environments (e.g. buildings and streets, bridges, other man-made structures). Naturally occurring corner reflectors may include severely folded rock and cliff faces or upright vegetation standing in water. In all cases, corner reflectors show up as very bright targets in an image, such as the buildings and other man-made structures in this radar image of a city.

The presence (or absence) of moisture affects the electrical properties of an object or medium. Changes in the electrical properties influence the absorption, transmission, and reflection of microwave energy. Thus, the moisture content will influence how targets and surfaces reflect energy from a radar and how they will appear on an image. Generally, reflectivity (and image brightness) increases with increased moisture content. For example, surfaces such as soil and vegetation cover will appear brighter when they are wet than when they are dry.
When a target is moist or wet, scattering from the topmost portion (surface scattering) is the dominant process taking place. The type of reflection (ranging from specular to diffuse) and the magnitude will depend on how rough the material appears to the radar. If the target is very dry and the surface appears smooth to the radar, the radar energy may be able to penetrate below the surface, whether that surface is discontinuous (e.g. forest canopy with leaves and branches), or a homogeneous surface (e.g. soil, sand, or ice). For a given surface, longer wavelengths are able to penetrate further than shorter wavelengths.

If the radar energy does manage to penetrate through the topmost surface, then volume scattering may occur. **Volume scattering** is the scattering of radar energy within a volume or medium, and usually consists of multiple bounces and reflections from different components within the volume. For example, in a forest, scattering may come from the leaf canopy at the tops of the trees, the leaves and branches further below, and the tree trunks and soil at the ground level. Volume scattering may serve to decrease or increase image brightness, depending on how much of the energy is scattered out of the volume and back to the radar.
3.6 Radar Image Properties

All radar images appear with some degree of what we call radar speckle. Speckle appears as a grainy "salt and pepper" texture in an image. This is caused by random constructive and destructive interference from the multiple scattering returns that will occur within each resolution cell. As an example, an homogeneous target, such as a large grass-covered field, without the effects of speckle would generally result in light-toned pixel values on an image (A). However, reflections from the individual blades of grass within each resolution cell results in some image pixels being brighter and some being darker than the average tone (B), such that the field appears speckled.

Speckle is essentially a form of noise which degrades the quality of an image and may make interpretation (visual or digital) more difficult. Thus, it is generally desirable to reduce speckle prior to interpretation and analysis. Speckle reduction can be achieved in two ways:

- multi-look processing, or
- spatial filtering.
Multi-look processing refers to the division of the radar beam (A) into several (in this example, five) narrower sub-beams (1 to 5). Each sub-beam provides an independent "look" at the illuminated scene, as the name suggests. Each of these "looks" will also be subject to speckle, but by summing and averaging them together to form the final output image, the amount of speckle will be reduced.

While multi-looking is usually done during data acquisition, speckle reduction by spatial filtering is performed on the output image in a digital (i.e. computer) image analysis environment. Speckle reduction filtering consists of moving a small window of a few pixels in dimension (e.g. 3x3 or 5x5) over each pixel in the image, applying a mathematical calculation using the pixel values under that window (e.g. calculating the average), and replacing the central pixel with the new value. The window is moved along in both the row and column dimensions one pixel at a time, until the entire image has been covered. By calculating the average of a small window around each pixel, a smoothing effect is achieved and the visual appearance of the speckle is reduced.

This graphic shows a radar image before (top) and after (bottom) speckle reduction using an averaging filter. The median (or middle) value of all the pixels underneath the moving window is also often used to reduce speckle. Other more complex filtering calculations can be performed to reduce speckle while minimizing the amount of smoothing taking place.
Both multi-look processing and spatial filtering reduce speckle at the expense of resolution, since they both essentially smooth the image. Therefore, the amount of speckle reduction desired must be balanced with the particular application the image is being used for, and the amount of detail required. If fine detail and high resolution is required then little or no multi-looking/spatial filtering should be done. If broad-scale interpretation and mapping is the application, then speckle reduction techniques may be more appropriate and acceptable.

Another property peculiar to radar images is slant-range distortion, which was discussed in some detail in section 3.4. Features in the near-range are compressed relative to features in the far range due to the slant-range scale variability. For most applications, it is desirable to have the radar image presented in a format which corrects for this distortion, to enable true distance measurements between features. This requires the slant-range image to be converted to 'ground range' display. This can be done by the radar processor prior to creating an image or after data acquisition by applying a transformation to the slant range image. In most cases, this conversion will only be an estimate of the geometry of the ground features due to the complications introduced by variations in terrain relief and topography.

A radar antenna transmits more power in the mid-range portion of the illuminated swath than at the near and far ranges. This effect is known as antenna pattern and results in stronger returns from the center portion of the swath than at the edges. Combined with this antenna pattern effect is the fact that the energy returned to the radar decreases dramatically as the range distance increases. Thus, for a given surface, the strength of the returned signal becomes smaller and smaller moving farther across the swath. These effects combine to produce an image which varies in intensity (tone) in the range direction across the image. A process known as antenna pattern correction may be applied to produce a uniform average brightness across the imaged swath, to better facilitate visual interpretation.

The range of brightness levels a remote sensing system can differentiate is related to radiometric resolution (section 2.5) and is referred to as the dynamic range. While optical sensors, such as those carried by satellites such as Landsat and SPOT, typically produce 256 intensity levels, radar systems can differentiate intensity levels up to around 100,000 levels! Since the human eye can only discriminate about 40 intensity levels at one time, this is too much information for visual interpretation. Even a typical computer would have difficulty dealing with this range of information. Therefore, most radars record and process the original
data as 16 bits (65,536 levels of intensity), which are then further scaled down to 8 bits (256 levels) for visual interpretation and/or digital computer analysis.

**Calibration** is a process which ensures that the radar system and the signals that it measures are as consistent and as accurate as possible. Prior to analysis, most radar images will require **relative calibration**. Relative calibration corrects for known variations in radar antenna and systems response and ensures that uniform, repeatable measurements can be made over time. This allows relative comparisons between the response of features within a single image, and between separate images to be made with confidence. However, if we wish to make accurate **quantitative** measurements representing the actual energy or power returned from various features or targets for comparative purposes, then **absolute calibration** is necessary.

Absolute calibration, a much more involved process than relative calibration, attempts to relate the magnitude of the recorded signal strength to the actual amount of energy backscattered from each resolution cell. To achieve this, detailed measurements of the radar system properties are required as well as quantitative measurements of the scattering properties of specific targets. The latter are often obtained using ground-based scatterometers, as described in section 3.1. Also, devices called **transponders** may be placed on the ground prior to data acquisition to calibrate an image. These devices receive the incoming radar signal, amplify it, and transmit a return signal of known strength back to the radar. By knowing the actual strength of this return signal in the image, the responses from other features can be referenced to it.
3.7 Advanced Radar Applications

In addition to standard acquisition and use of radar data, there are three specific applications worth mentioning.

The first is **stereo radar** which is similar in concept to stereo mapping using aerial photography (described in section 2.7). Stereo radar image pairs are acquired covering the same area, but with different look/incidence angles (A), or opposite look directions (B). Unlike aerial photos where the displacement is radially outward from the nadir point directly below the camera, radar images show displacement only in the range direction. Stereo pairs taken from opposite look directions (i.e. one looking north and the other south) may show significant contrast and may be difficult to interpret visually or digitally. In mountainous terrain, this will be even more pronounced as shadowing on opposite sides of features will eliminate the stereo effect. Same side stereo imaging (A) has been used operationally for years to assist in interpretation for forestry and geology and also to generate topographic maps. The estimation of distance measurements and terrain height for topographic mapping from stereo radar data is called **radargrammetry**, and is analogous to photogrammetry carried out for similar purposes with aerial photographs.

Radargrammetry is one method of estimating terrain height using radar. Another, more advanced method is called **interferometry**. Interferometry relies on being able to measure a property of electromagnetic waves called **phase**. Suppose we have two waves with the exact
same wavelength and frequency traveling along in space, but the starting point of one is offset slightly from the other. The offset between matching points on these two waves (A) is called the phase difference. Interferometric systems use two antennas, separated in the range dimension by a small distance, both recording the returns from each resolution cell. The two antennas can be on the same platform (as with some airborne SARs), or the data can be acquired from two different passes with the same sensor, such as has been done with both airborne and satellite radars. By measuring the exact phase difference between the two returns (A), the path length difference can be calculated to an accuracy that is on the order of the wavelength (i.e. centimetres). Knowing the position of the antennas with respect to the Earth’s surface, the position of the resolution cell, including its elevation, can be determined. The phase difference between adjacent resolution cells, is illustrated in this interferogram, where colours represents the variations in height. The information contained in an interferogram can be used to derive topographic information and produce three-dimensional imagery of terrain height.

The concept of radar polarimetry was already alluded to in our discussion of radar fundamentals in section 3.2. As its name implies, polarimetry involves discriminating between the polarizations that a radar system is able to transmit and receive. Most radars transmit microwave radiation in either horizontal (H) or vertical (V) polarization, and similarly, receive the backscattered signal at only one of these polarizations. Multi-polarization radars are able to transmit either H or V polarization and receive both the like- and cross-polarized returns (e.g. HH and HV or VV and VH, where the first letter stands for the polarization transmitted and the second letter the polarization received). Polarimetric radars are able to transmit and receive both horizontal and vertical polarizations. Thus, they are able to receive and process all four combinations of these polarizations: HH, HV, VH, and VV. Each of these "polarization channels" have varying sensitivities to different surface characteristics and properties. Thus,
the availability of multi-polarization data helps to improve the identification of, and the
discrimination between features. In addition to recording the magnitude (i.e. the strength) of
the returned signal for each polarization, most polarimetric radars are also able to record the
**phase** information of the returned signals. This can be used to further characterize the
polarimetric "signature" of different surface features.
3.8 Radar Polarimetry

Introduction to Polarization

When discussing microwave energy propagation and scattering, the polarization of the radiation is an important property. For a plane electromagnetic (EM) wave, polarization refers to the locus of the electric field vector in the plane perpendicular to the direction of propagation. While the length of the vector represents the amplitude of the wave, and the rotation rate of the vector represents the frequency of the wave, polarization refers to the orientation and shape of the pattern traced by the tip of the vector.

The waveform of the electric field strength (voltage) of an EM wave can be predictable (the wave is polarized) or random (the wave is unpolarized), or a combination of both. In the latter case, the degree of polarization describes the ratio of polarized power to total power of the wave. An example of a fully polarized wave would be a monochromatic sine wave, with a single, constant frequency and stable amplitude.

Examples of horizontal (black) and vertical (red) polarizations of a plane electromagnetic wave

Many radars are designed to transmit microwave radiation that is either horizontally polarized (H) or vertically polarized (V). A transmitted wave of either polarization can generate a backscattered wave with a variety of polarizations. It is the analysis of these transmit and receive polarization combinations that constitutes the science of radar polarimetry.

Any polarization on either transmission or reception can be synthesized by using H and V components with a well-defined relationship between them. For this reason, systems that transmit and receive both of these linear polarizations are commonly used. With these radars, there can be four combinations of transmit and receive polarizations:

- **HH** - for horizontal transmit and horizontal receive
- **VV** - for vertical transmit and vertical receive

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- 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 orthogonal to one another.

Radar systems can have one, two or all four of these transmit/receive polarization combinations. Examples include the following types of radar systems:

- **single polarized** - HH or VV (or possibly HV or VH)
- **dual polarized** - HH and HV, VV and VH, or HH and VV
- **alternating polarization** - HH and HV, alternating with VV and VH
- **polarimetric** - HH, VV, HV, and VH

Note that "quadrature polarization" and "fully polarimetric" can be used as synonyms for "polarimetric". The relative phase between channels is measured in a polarimetric radar, and is a very important component of the measurement. In the other radar types, relative phase may or may not be measured. The alternating polarization mode has been introduced on ENVISAT - relative phase is measured but the important HH-VV phase is not meaningful because of the time lapse between the measurements.

These C-band images of agricultural fields demonstrate the dependence of the radar response on polarization. The top two images are like-polarized (HH on left, VV on right), and the lower left image is cross-polarized (HV). The lower right image is the result of displaying these three images as a colour composite (in this case, HH - red, VV - green, and HV - blue).

Both wavelength and polarization affect how a radar system "sees" the elements in the scene. Therefore, radar imagery collected using different polarization and wavelength combinations may provide different and complementary information. Furthermore, when three polarizations are combined in a colour composite, the information is presented in a way that an image interpreter can infer more information of the surface characteristics.
Illustration of how different polarizations (HH, VV, HV & colour composite) bring out different features in an agricultural scene

Polarimetric Information

The primary description of how a radar target or surface feature scatters EM energy is given by the scattering matrix. From the scattering matrix, other forms of polarimetric information can be derived, such as synthesized images and polarization signatures.

Polarization Synthesis

A polarimetric radar can be used to determine the target response or scattering matrix using two orthogonal polarizations, typically linear H and linear V on each of transmit and receive. If a scattering matrix is known, the response of the target to any combination of incident and received polarizations can be computed. This is referred to as polarization synthesis, and illustrates the power and flexibility of a fully polarimetric radar.

Through polarization synthesis, an image can be created to improve the detectability of
selected features. An example is the detection of ships in ocean images. To find the best transmit-receive polarization combination to use, the polarization signature of a typical ship and that of the ocean is calculated for a number of polarizations. Then the ratio of the ship to ocean backscatter is computed for each polarization. The transmit-receive polarization combination that maximises the ratio of backscatter strength is then used to improve the detectability of ships. This procedure is called "polarimetric contrast enhancement" or the use of a "polarimetric matched filter".

**Polarization Signatures**

Because the incident and scattered waves can take on so many different polarizations, and the scattering matrix consists of four complex numbers, it is helpful to simplify the interpretation of the scattering behaviour using three-dimensional plots. The "polarization signature" of the target provides a convenient way of visualising a target's scattering properties. The signatures are also called "polarization response plots".

An incident electromagnetic wave can be selected to have an electric field with ellipticity between -45° and +45°, and an orientation between 0 and 180°. These variables are used as the x- and y-axes of a 3-D plot portraying the polarization signature. For each of these possible incident polarizations, the strength of the backscatter can be computed for the same polarization on transmit and receive (the co-polarized signature) and for orthogonal polarizations on transmit and receive (the cross-polarized signature). The strength is displayed on the z-axis of the signatures.

**Co-polarized signature**

**Cross-polarized signature**

This figure shows the polarization signatures of the most simple of all targets - a large conducting sphere or a trihedral corner reflector. The wave is backscattered with the same polarization, except for a change of sign of the ellipticity (or in the case of linear polarization, a
change of the phase angle between $E_h$ and $E_v$ of $180\degree$). The sign changes once for every reflection - the sphere represents a single reflection, and the trihedral gives three reflections, so each behaves as an "odd-bounce" reflector.

For more complicated targets, the polarization signature takes on different shapes. Two interesting signatures come from a dihedral corner reflector and Bragg scattering from the sea surface. In the case of the dihedral reflector, the co-pol signature has a double peak, characteristic of "even-bounce" reflectors. In the case of Bragg scattering, the response is similar to the single-bounce sphere, except that the backscatter of the vertical polarization is higher than that of the horizontal polarization.

**Data Calibration**

One critical requirement of polarimetric radar systems is the need for calibration. This is because much of the information lies in the ratios of amplitudes and the differences in phase angle between the four transmit-receive polarization combinations. If the calibration is not sufficiently accurate, the scattering mechanisms will be misinterpreted and the advantages of using polarization will not be realised.

Calibration is achieved by a combination of radar system design and data analysis. Imagine the response to a trihedral corner reflector. Its ideal response is only obtained if the four channels of the radar system all have the same gain, system-dependent phase differences between channels are absent, and there is no energy leakage from one channel to another.

In terms of the radar system design, the channel gains and phases should be as carefully matched as possible. In the case of the phase balance, this means that the signal path lengths should be effectively the same in all channels. Calibration signals are often built into the design to help verify these channel balances.

In terms of data analysis, channel balances, cross-talk and noise effects can be measured and corrected by analysing the received data. In addition to analysing the response of internal calibration signals, the signals from known targets such as corner reflectors, active transponders, and uniform clutter can be used to calibrate some of the parameters.

**Polarimetric Applications**

Synthetic Aperture Radar polarimetry has been limited to a number of experimental airborne SAR systems and the SIR-C (shuttle) mission. With these data, researchers have studied a number of applications, and have shown that the interpretation of a number of features in a scene is facilitated when the radar is operated in polarimetric mode. The launch of RADARSAT-2 will make polarimetric data available on an operational basis, and uses of such data will become more routine and more sophisticated.

Some applications in which polarimetric SAR has already proved useful include:
- Agriculture: for crop type identification, crop condition monitoring, soil moisture measurement, and soil tillage and crop residue identification;
- Forestry: for clearcuts and linear features mapping, biomass estimation, species identification and fire scar mapping;
- Geology: for geological mapping;
- Hydrology: for monitoring wetlands and snow cover;
- Oceanography: for sea ice identification, coastal windfield measurement, and wave slope measurement;
- Shipping: for ship detection and classification;
- Coastal Zone: for shoreline detection, substrate mapping, slick detection and general vegetation mapping.
3.9 Airborne versus Spaceborne Radars

Like other remote sensing systems, an imaging radar sensor may be carried on either an airborne or spaceborne platform. Depending on the use of the prospective imagery, there are trade-offs between the two types of platforms. Regardless of the platform used, a significant advantage of using a Synthetic Aperture Radar (SAR) is that the spatial resolution is independent of platform altitude. Thus, fine resolution can be achieved from both airborne and spaceborne platforms.

Although spatial resolution is independent of altitude, viewing geometry and swath coverage can be greatly affected by altitude variations. At aircraft operating altitudes, an airborne radar must image over a wide range of incidence angles, perhaps as much as 60 or 70 degrees, in order to achieve relatively wide swaths (let's say 50 to 70 km). As we have learned in the preceding sections, incidence angle (or look angle) has a significant effect on the backscatter from surface features and on their appearance on an image. Image characteristics such as foreshortening, layover, and shadowing will be subject to wide variations, across a large incidence angle range. Spaceborne radars are able to avoid some of these imaging geometry problems since they operate at altitudes up to one hundred times higher than airborne radars. At altitudes of several hundred kilometres, spaceborne radars can image comparable swath widths, but over a much narrower range of incidence angles, typically ranging from five to 15 degrees. This provides for more uniform illumination and reduces undesirable imaging variations across the swath due to viewing geometry.
Although airborne radar systems may be more susceptible to imaging geometry problems, they are flexible in their capability to collect data from different look angles and look directions. By optimizing the geometry for the particular terrain being imaged, or by acquiring imagery from more than one look direction, some of these effects may be reduced. Additionally, an airborne radar is able to collect data anywhere and at any time (as long as weather and flying conditions are acceptable!). A spaceborne radar does not have this degree of flexibility, as its viewing geometry and data acquisition schedule is controlled by the pattern of its orbit. However, satellite radars do have the advantage of being able to collect imagery more quickly over a larger area than an airborne radar, and provide consistent viewing geometry. The frequency of coverage may not be as often as that possible with an airborne platform, but depending on the orbit parameters, the viewing geometry flexibility, and the geographic area of interest, a spaceborne radar may have a revisit period as short as one day.

As with any aircraft, an airborne radar will be susceptible to variations in velocity and other motions of the aircraft as well as to environmental (weather) conditions. In order to avoid image artifacts or geometric positioning errors due to random variations in the motion of the aircraft, the radar system must use sophisticated navigation/positioning equipment and advanced image processing to compensate for these variations. Generally, this will be able to correct for all but the most severe variations in motion, such as significant air turbulence. Spaceborne radars are not affected by motion of this type. Indeed, the geometry of their orbits is usually very stable and their positions can be accurately calculated. However, geometric correction of imagery from spaceborne platforms must take into account other factors, such as the rotation and curvature of the Earth, to achieve proper geometric positioning of features on the surface.
3.10 Airborne and Spaceborne Radar Systems

In order to more clearly illustrate the differences between airborne and spaceborne radars, we will briefly outline a few of the representative systems of each type, starting with airborne systems.

The Convair-580 C/X SAR system developed and operated by the Canada Centre for Remote Sensing was a workhorse for experimental research into advanced SAR applications in Canada and around the world, particularly in preparation for satellite-borne SARs. The system was transferred to Environment Canada in 1996 for use in oil spill research and other environmental applications. This system operates at two radar bands, C- (5.66 cm) and X- (3.24 cm). Cross-polarization data can be recorded simultaneously for both the C- and X-band channels, and the C-band system can be operated as a fully polarimetric radar. Imagery can be acquired at three different imaging geometries (nadir, narrow and wide swath modes) over a wide range of incidence angles (five degrees to almost 90 degrees). In addition to being a fully calibratable system for quantitative measurements, the system has a second antenna mounted on the aircraft fuselage to allow the C-band system to be operated as an interferometric radar.

The Sea Ice and Terrain Assessment (STAR) systems operated by Intera Technologies Limited of Calgary, Alberta, Canada, (later Intermap Technologies ) were among the first SAR systems used commercially around the world. Both STAR-1 and STAR-2 operate at X-band (3.2 cm) with HH polarization in two different resolution modes. The swath coverage varies from 19 to 50 km, and the resolution from 5 to 18 m. They were primarily designed for monitoring sea ice (one of the key applications for radar, in Canada) and for terrain analysis. Radar's all-weather, day or night imaging capabilities are well-suited to monitoring ice in Canada's northern and coastal waters. STAR-1 was also the first SAR system to use on-board data processing and to offer real-time downlinking of data to surface stations.
The United States National Aeronautics and Space Administration (NASA) has been at the forefront of multi-frequency, multi-polarization synthetic aperture radar research for many years. The Jet Propulsion Laboratory (JPL) in California has operated various advanced systems on contract for NASA. The AirSAR system is a C-, L-, and P-band advanced polarimetric SAR which can collect data for each of these bands at all possible combinations of horizontal and vertical transmit and receive polarizations (i.e. HH, HV, VH, and VV). Data from the AirSAR system can be fully calibrated to allow extraction of quantitative measurements of radar backscatter. Spatial resolution of the AirSAR system is on the order of 12 metres in both range and azimuth. Incidence angle ranges from zero degrees at nadir to about 70 degrees at the far range. This capability to collect multi-frequency, multi-polarization data over such a diverse range of incidence angles allows a wide variety of specialized research experiments to be carried out.

With the advances and success of airborne imaging radar, satellite radars were the next logical step to complement the optical satellite sensors in operation. SEASAT, launched in 1978, was the first civilian remote sensing satellite to carry a spaceborne SAR sensor. The SAR operated at L-band (23.5 cm) with HH polarization. The viewing geometry was fixed between nine and 15 degrees with a swath width of 100 km and a spatial resolution of 25 metres. This steep viewing geometry was designed primarily for observations of ocean and sea ice, but a great deal of imagery was also collected over land areas. However, the small incidence angles amplified foreshortening and layover effects over terrain with high relief, limiting its utility in these areas. Although the satellite was only operational for three months, it demonstrated the wealth of information (and the large volumes of data!) possible from a spaceborne radar.

With the success of the short-lived SEASAT mission, and impetus provided from positive results with several airborne SARs, the European Space Agency (ESA) launched ERS-1 in July of 1991. ERS-1 carried on-board a radar altimeter, an infrared radiometer and microwave sounder, and a C-band (5.66 cm), active microwave instrument. This is a flexible instrument which can be operated as a scatterometer to measure reflectivity of the ocean surface, as well as ocean surface wind speed and direction. It can also operate as a synthetic aperture radar, collecting imagery over a 100 km swath over an incidence angle range of 20 to 26 degrees, at a resolution of approximately 30 metres. Polarization is
vertical transmit and vertical receive (VV) which, combined with the fairly steep viewing angles, make ERS-1 particularly sensitive to surface roughness. The revisit period (or repeat cycle) of ERS-1 can be varied by adjusting the orbit, and has ranged from three to 168 days, depending on the mode of operation. Generally, the repeat cycle is about 35 days. A second satellite, ERS-2, was launched in April of 1995 and carries the same active microwave sensor as ERS-1. Designed primarily for ocean monitoring applications and research, ERS-1 provided the worldwide remote sensing community with the first wide-spread access to spaceborne SAR data. Imagery from both satellites has been used in a wide range of applications, over both ocean and land environments. Like SEASAT, the steep viewing angles limit their utility for some land applications due to geometry effects.

The National Space Development Agency of Japan (NASDA), launched the JERS-1 satellite in February of 1992. In addition to carrying two optical sensors, JERS-1 has an L-band (23.5 cm) SAR operating at HH polarization. The swath width is approximately 75 km and spatial resolution is approximately 18 metres in both range and azimuth. The imaging geometry of JERS-1 is slightly shallower than either SEASAT or the ERS satellites, with the incidence angle at the middle of the swath being 35 degrees. Thus, JERS-1 images are slightly less susceptible to geometry and terrain effects. The longer L-band wavelength of JERS-1 allows some penetration of the radar energy through vegetation and other surface types.

Spaceborne SAR remote sensing took a giant leap forward with the launch of Canada's RADARSAT satellite on Nov. 4, 1995. The RADARSAT project, led by the Canadian Space Agency (CSA), was built on the development of remote sensing technologies and applications work carried out by the Canada Centre for Remote Sensing (CCRS) since the 1970s. RADARSAT carries an advanced C-band (5.6 cm), HH-polarized SAR with a steerable radar beam allowing various imaging options over a 500 km range. Imaging swaths can be varied from 35 to 500 km in width, with resolutions from 10 to 100 metres. Viewing geometry is also flexible, with incidence angles ranging from less than 20 degrees to more than 50 degrees. Although the satellite's orbit repeat cycle is 24 days, the flexibility of the steerable radar beam gives RADARSAT the ability to image regions much more frequently and to address specific geographic requests for data acquisition. RADARSAT's orbit is optimized for frequent coverage of mid-latitude to polar regions, and is able to provide daily images of the entire Arctic region as well as view any part of Canada within three days. Even at equatorial latitudes, complete coverage can be obtained within six days using the widest swath of 500 km.
Imaging options over a 500 km range
3.11 Endnotes

You have just completed Chapter 3 - Microwave Sensing. You can continue to Chapter 4 - Image Interpretation and Analysis or first browse the CCRS Web site for other articles related to microwave remote sensing.

You can get more information about remote sensing radars by checking out an the overview\(^1\) or the more detailed technical specifications\(^2\) of Canada's own microwave satellite: RADARSAT. You can even see photos\(^3\) of the satellite being built, watch a video of the launch and see the very first image!\(^4\) As well, learn how microwave remote sensing is used for various applications such as agriculture\(^5\), forestry\(^6\), and geology\(^7\), and see international applications\(^8\) of RADARSAT imagery.

Learn about a new way of reducing speckle\(^9\) in a radar image that was developed by scientists at CCRS in co-operation with scientists in France. As well, learn how a digital elevation model can be used to correct topographic distortions\(^10\) in radar images or how a radar image is calibrated using precision transponders\(^11\) and see the mysterious movement of the transponder\(^12\) when shown in an image!

A training manual\(^13\) has been prepared on how radar data can be used to obtain stereo images. Interferometry\(^14\) is another fascinating technique studied extensively at CCRS. It has been tried with both airborne and satellite data and applied to detecting changes in the land\(^15\), glacier movement\(^16\) and ocean studies\(^17\).

Our Remote Sensing Glossary has extensive terminology and explanations of microwave-related concepts which can be accessed through individual term searches\(^18\) or by selecting the radar\(^a\) category.

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\(^1\)http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/specs/rsatoview_e.html
\(^2\)http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/specs/radspec_e.html
\(^3\)http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/photos/radpix_e.html
\(^4\)http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/photos/radpix_e.html
\(^5\)http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/airborne/sarbro/sbagri_e.html
\(^6\)http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/airborne/sarbro/sbfort_e.html
7 http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/airborne/sarbro/sbgeol_e.html
8 http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/airborne/sarbro/sbgbsar_e.html
9 http://www.ccrs.nrcan.gc.ca/ccrs/com/rsnews1tr/2303/2303ap1_e.html
10 http://www.ccrs.nrcan.gc.ca/ccrs/com/rsnews1tr/2401/2401ap3_e.html
11 http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/trans/transpo_e.html
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14 http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/airborne/sarbro/sbinter_e.html
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16 http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/images/ant/rant01_e.html
17 http://www.ccrs.nrcan.gc.ca/ccrs/rd/ana/split/insar_e.html
18 http://www.ccrs.nrcan.gc.ca/ccrs/learn/terms/glossary/glossary_e.html
'S' band magnetrons are typically used for microwave oven power sources. They operate in the range of 2-4 GHz. The corresponding wavelengths are 15 cm to 7.5 cm. The screening mesh used on microwave oven doors is sufficiently fine (much smaller than 7.5 cm) that it behaves as a continuous, thin, metal sheet, preventing the escape of the radar energy, yet allowing good visibility of the interior (using visible wavelengths, which are much shorter yet).
3.2 Did You Know?

"....Just what do those numbers mean?!!"

Typical output products (e.g. RADARSAT imagery) have used 8-bit or 16-bit data formats (digital numbers) for data storage. In order to obtain the original physically meaningful backscatter values ($\sigma^0$, sigma nought, $\beta^0$, beta nought) of calibrated radar products, it is necessary to reverse the final steps in the SAR processing chain. For RADARSAT imagery, this must include the squaring of the digital values and the application of a lookup table (which can have range dependent values). Thus, as you can see, the relationships among the digital numbers in the imagery are not that simple!

3.4 Did You Know?

"...look to the left, look to the right, stand up, sit down..."

...although a radar's side-looking geometry can result in several image effects such as foreshortening, layover, and shadow, this geometry is exactly what makes radar so useful for terrain analysis. These effects, if not too severe, actually enhance the visual appearance of relief and terrain structure, making radar imagery excellent for applications such as topographic mapping and identifying geologic structure.
3.5 Did You Know?

"...rivers in the Sahara desert?...you're crazy!..."

... that an L-band radar (23.5 cm wavelength) imaging from the orbiting space shuttle was able to discover ancient river channels beneath the Sahara Desert in Northern Africa. Because of the long wavelength and the extreme dryness of the sand, the radar was able to penetrate several metres below the desert surface to reveal the old river beds during ancient times when this area was not so dry.

3.7 Did You Know?

"...we've picked up an unidentified moving object on the radar, sir..."

... besides being able to determine terrain height using interferometry, it is also possible to measure the velocity of targets moving towards or away from the radar sensor, using only one pass over the target. This is done by recording the returns from two antennas mounted on the platform, separated by a short distance in the along-track or flight direction. The phase differences between the returns at each antenna are used to derive the speed of motion of targets in the illuminated scene. Potential applications include determination of sea-ice drift, ocean currents, and ocean wave parameters.
3.8 Did You Know?

That many other polarizations can be transmitted (or received) if a radar system can transmit or receive the H and V channels simultaneously. For example, if a radar system transmits an H and a V signal simultaneously, and the V signal is 90° out of phase with respect to the H signal, the resulting transmitted wave will have circular polarization.
3.2 Whiz Quiz

How could we use radar images of different wavelengths and/or polarizations to extract more information about a particular scene? Think back to Chapter 1, the general characteristics of remote sensing images, and Chapter 2, interpretation of data from optical sensors.

Explain how data from a non-imaging scatterometer could be used to extract more accurate information from an imaging radar.

3.2 Answers

1. Much the same as with optical sensors that have different bands or channels of data, multi-wavelength and multi-frequency radar images can provide complementary information. Radar data collected at different wavelengths is analogous to the different bands of data in optical remote sensing. Similarly, the various polarizations may also be considered as different bands of information. Depending on the wavelength and polarization of the radar energy, it will interact differently with features on the surface. As with multi-band optical data, we can combine these different "channels" of data together to produce colour images which may highlight subtle variations in features as a function of wavelength or polarization.

2. A scatterometer is used to precisely measure the intensity of backscatter reflected from an object or surface. By accurately characterizing (i.e. measuring) the intensity of energy reflected from a variety of objects or surface types, these measurements can be used to generate typical backscatter signatures, similar to the concept of spectral signatures with optical data. These measurements can be used as references for calibrating imagery from an imaging radar sensor so that more accurate comparisons can be made of the response between different features.
3.3 Whiz Quiz

Explain why the use of a synthetic aperture radar (SAR) is the only practical option for radar remote sensing from space.

3.3 Answer

The high altitudes of spaceborne platforms (i.e. hundreds of kilometres) preclude the use of real aperture radar (RAR) because the azimuth resolution, which is a function of the range distance, would be too coarse to be useful. In a spaceborne RAR, the only way to achieve fine resolution would be to have a very, very narrow beam which would require an extremely long physical antenna. However, an antenna of several kilometres in length is physically impossible to build, let alone fly on a spacecraft. Therefore, we need to use synthetic aperture radar to synthesize a long antenna to achieve fine azimuth resolution.
3.5 Whiz Quiz

If an agricultural area, with crops such as wheat and corn, became flooded, what do you think these areas might look like on a radar image? Explain the reasons for your answers based on your knowledge of how radar energy interacts with a target.

3.5 Answer

Generally, image brightness increases with increased moisture content. However, in the case of flooding, the surface is completely saturated and results in standing water. Areas where the water has risen above the height of the crops will likely appear dark in tone, as the water acts as a specular reflector bouncing the energy away from the radar sensor. Flooded areas would generally be distinguishable by a darker tone from the surrounding agricultural crops which are not flooded and would scatter more diffusely. However, if the wheat and corn stalks are not completely submersed, then these areas may actually appear brighter on the image. In this situation, specular reflections off the water which then bounce and hit the wheat and corn stalks may act like corner reflectors and return most of the incoming energy back to the radar. This would result in these areas appearing quite bright on the image. Thus, the degree of flooding and how much the crops are submersed will impact the appearance of the image.
3.6 Whiz Quiz

Outline the basic steps you might want to perform on a radar image before carrying out any visual interpretation.

3.6 Answer

Before visually interpreting and analyzing a radar image, there are several procedures which would be useful to perform, including:

- Converting the slant-range image to the ground-range plane display. This will remove the effects of slant-range scale distortion so that features appear in their proper relative size across the entire swath and distances on the ground are represented correctly.
- Correcting for antenna pattern. This will provide a uniform average brightness of image tone making visual interpretation and comparison of feature responses at different ranges easier.
- Reducing the effects of speckle to some degree. Unless there is a need for detailed analysis of very small features (i.e. less than a few pixels in size), speckle reduction will reduce the "grainy" appearance of the image and make general image interpretation simpler.
- Scaling of the dynamic range in the image to a maximum of 8-bits (256 grey levels). Because of the limitations of most desktop computer systems, as well as of the human eye in discriminating brightness levels, any more grey levels would not be useful.
3.8 Whiz Quiz

Can sound waves be polarized?

3.8 Answer

Polarization is a phenomenon which is characteristic of those waves that vibrate in a direction perpendicular to their direction of propagation. While electromagnetic waves vibrate up/down, side to side and in intermediate directions, sound waves vibrate in the same direction as their direction of travel, so cannot be polarized.
3.10 Whiz Quiz

A particular object or feature may not have the same appearance (i.e. backscatter response) on all radar images, particularly airborne versus spaceborne radars. List some of the factors which might account for this.

3.10 Answer

The backscatter response, and thus the appearance of an object or feature on a radar image, is dependent on several things.

- Different radar wavelengths or frequencies will result in variations due to their differing sensitivities to surface roughness, which controls the amount of energy backscattered.
- Using different polarizations will also affect how the energy interacts with a target and the subsequent energy that is reflected back to the radar.
- Variations in viewing geometry, including look/incidence angle, the look direction and orientation of features to the radar, and the local incidence angle at which the radar energy strikes the surface, play a major role in the amount of energy reflected. Generally, these differences can be quite significant between airborne and spaceborne platforms.
- Changes in the moisture content of an object or feature will also change the amount of backscatter.
4. Image Analysis

4.1 Introduction

In order to take advantage of and make good use of remote sensing data, we must be able to extract meaningful information from the imagery. This brings us to the topic of discussion in this chapter - **interpretation and analysis** - the sixth element of the remote sensing process which we defined in Chapter 1. Interpretation and analysis of remote sensing imagery involves the identification and/or measurement of various targets in an image in order to extract useful information about them. Targets in remote sensing images may be any feature or object which can be observed in an image, and have the following characteristics:

- Targets may be a point, line, or area feature. This means that they can have any form, from a bus in a parking lot or plane on a runway, to a bridge or roadway, to a large expanse of water or a field.
- The target must be distinguishable; it must contrast with other features around it in the image.
Much interpretation and identification of targets in remote sensing imagery is performed manually or visually, i.e. by a human interpreter. In many cases this is done using imagery displayed in a pictorial or photograph-type format, independent of what type of sensor was used to collect the data and how the data were collected. In this case we refer to the data as being in **analog** format. As we discussed in Chapter 1, remote sensing images can also be represented in a computer as arrays of pixels, with each pixel corresponding to a digital number, representing the brightness level of that pixel in the image. In this case, the data are in a **digital** format. Visual interpretation may also be performed by examining digital imagery displayed on a computer screen. Both analogue and digital imagery can be displayed as black and white (also called monochrome) images, or as colour images (refer back to Chapter 1, Section 1.7) by combining different channels or bands representing different wavelengths.

When remote sensing data are available in digital format, **digital processing and analysis** may be performed using a computer. Digital processing may be used to enhance data as a prelude to visual interpretation. Digital processing and analysis may also be carried out to automatically identify targets and extract information completely without manual intervention by a human interpreter. However, rarely is digital processing and analysis carried out as a complete replacement for manual interpretation. Often, it is done to supplement and assist the human analyst.

Manual interpretation and analysis dates back to the early beginnings of remote sensing for
air photo interpretation. Digital processing and analysis is more recent with the advent of digital recording of remote sensing data and the development of computers. Both manual and digital techniques for interpretation of remote sensing data have their respective advantages and disadvantages. Generally, manual interpretation requires little, if any, specialized equipment, while digital analysis requires specialized, and often expensive, equipment. Manual interpretation is often limited to analyzing only a single channel of data or a single image at a time due to the difficulty in performing visual interpretation with multiple images. The computer environment is more amenable to handling complex images of several or many channels or from several dates. In this sense, digital analysis is useful for simultaneous analysis of many spectral bands and can process large data sets much faster than a human interpreter. Manual interpretation is a subjective process, meaning that the results will vary with different interpreters. Digital analysis is based on the manipulation of digital numbers in a computer and is thus more objective, generally resulting in more consistent results. However, determining the validity and accuracy of the results from digital processing can be difficult.

It is important to reiterate that visual and digital analyses of remote sensing imagery are not mutually exclusive. Both methods have their merits. In most cases, a mix of both methods is usually employed when analyzing imagery. In fact, the ultimate decision of the utility and relevance of the information extracted at the end of the analysis process, still must be made by humans.
4.2 Elements of Visual Interpretation

As we noted in the previous section, analysis of remote sensing imagery involves the identification of various targets in an image, and those targets may be environmental or artificial features which consist of points, lines, or areas. Targets may be defined in terms of the way they reflect or emit radiation. This radiation is measured and recorded by a sensor, and ultimately is depicted as an image product such as an air photo or a satellite image.

What makes interpretation of imagery more difficult than the everyday visual interpretation of our surroundings? For one, we lose our sense of depth when viewing a two-dimensional image, unless we can view it stereoscopically so as to simulate the third dimension of height. Indeed, interpretation benefits greatly in many applications when images are viewed in stereo, as visualization (and therefore, recognition) of targets is enhanced dramatically. Viewing objects from directly above also provides a very different perspective than what we are familiar with. Combining an unfamiliar perspective with a very different scale and lack of recognizable detail can make even the most familiar object unrecognizable in an image. Finally, we are used to seeing only the visible wavelengths, and the imaging of wavelengths outside of this window is more difficult for us to comprehend.

Recognizing targets is the key to interpretation and information extraction. Observing the differences between targets and their backgrounds involves comparing different targets based on any, or all, of the visual elements of tone, shape, size, pattern, texture, shadow, and association. Visual interpretation using these elements is often a part of our daily lives, whether we are conscious of it or not. Examining satellite images on the weather report, or following high speed chases by views from a helicopter are all familiar examples of visual image interpretation. Identifying targets in remotely sensed images based on these visual elements allows us to further interpret and analyze. The nature of each of these interpretation elements is described below, along with an image example of each.

**Tone** refers to the relative brightness or colour of objects in an image. Generally, tone is the fundamental element for distinguishing between different targets or features. Variations in
tone also allows the elements of shape, texture, and pattern of objects to be distinguished.

**Shape** refers to the general form, structure, or outline of individual objects. Shape can be a very distinctive clue for interpretation. Straight edge shapes typically represent urban or agricultural (field) targets, while natural features, such as forest edges, are generally more irregular in shape, except where man has created a road or clear cuts. Farm or crop land irrigated by rotating sprinkler systems would appear as circular shapes.

**Size** of objects in an image is a function of scale. It is important to assess the size of a target relative to other objects in a scene, as well as the absolute size, to aid in the interpretation of that target. A quick approximation of target size can direct interpretation to an appropriate result more quickly. For example, if an interpreter had to distinguish zones of land use, and had identified an area with a number of buildings in it, large buildings such as factories or warehouses would suggest commercial property, whereas small buildings would indicate residential use.
**Pattern** refers to the spatial arrangement of visibly discernible objects. Typically an orderly repetition of similar tones and textures will produce a distinctive and ultimately recognizable pattern. Orchards with evenly spaced trees, and urban streets with regularly spaced houses are good examples of pattern.

**Texture** refers to the arrangement and frequency of tonal variation in particular areas of an image. Rough textures would consist of a mottled tone where the grey levels change abruptly in a small area, whereas smooth textures would have very little tonal variation. Smooth textures are most often the result of uniform, even surfaces, such as fields, asphalt, or grasslands. A target with a rough surface and irregular structure, such as a forest canopy, results in a rough textured appearance. Texture is one of the most important elements for distinguishing features in radar imagery.

**Shadow** is also helpful in interpretation as it may provide an idea of the profile and relative height of a target or targets which may make identification easier. However, shadows can also reduce or eliminate interpretation in their area of influence, since targets within shadows are much less (or not at all) discernible from their surroundings. Shadow is also useful for enhancing or identifying topography and landforms, particularly in radar imagery.

**Association** takes into account the relationship between other recognizable objects or features in proximity to the target of interest. The identification of features that one would expect to associate with other features may provide information to facilitate identification. In the example given above, commercial properties may be associated with proximity to major transportation routes, whereas residential areas would be associated with schools, playgrounds, and sports fields. In our example, a lake is associated with boats, a marina, and adjacent recreational land.
4.3 Digital Image Processing

In today's world of advanced technology where most remote sensing data are recorded in digital format, virtually all image interpretation and analysis involves some element of digital processing. Digital image processing may involve numerous procedures including formatting and correcting of the data, digital enhancement to facilitate better visual interpretation, or even automated classification of targets and features entirely by computer. In order to process remote sensing imagery digitally, the data must be recorded and available in a digital form suitable for storage on a computer tape or disk. Obviously, the other requirement for digital image processing is a computer system, sometimes referred to as an image analysis system, with the appropriate hardware and software to process the data. Several commercially available software systems have been developed specifically for remote sensing image processing and analysis.

For discussion purposes, most of the common image processing functions available in image analysis systems can be categorized into the following four categories:

- Preprocessing
- Image Enhancement
- Image Transformation
- Image Classification and Analysis

Preprocessing functions involve those operations that are normally required prior to the main data analysis and extraction of information, and are generally grouped as radiometric or geometric corrections. Radiometric corrections include correcting the data for sensor irregularities and unwanted sensor or atmospheric noise, and converting the data so they accurately represent the reflected or emitted radiation measured by the sensor. Geometric corrections include correcting for geometric distortions due to sensor-Earth geometry variations, and conversion of the data to real world coordinates (e.g. latitude and longitude) on the Earth's surface.
The objective of the second group of image processing functions grouped under the term of *image enhancement*, is solely to **improve the appearance of the imagery** to assist in visual interpretation and analysis. Examples of enhancement functions include contrast stretching to increase the tonal distinction between various features in a scene, and **spatial filtering** to enhance (or suppress) specific spatial patterns in an image.

**Image transformations** are operations similar in concept to those for image enhancement. However, unlike image enhancement operations which are normally applied only to a single channel of data at a time, image transformations usually involve combined processing of data from multiple spectral bands. Arithmetic operations (i.e. subtraction, addition, multiplication, division) are performed to combine and transform the original bands into "new" images which better display or highlight certain features in the scene. We will look at some of these operations including various methods of **spectral or band** ratioing, and a procedure called **principal components analysis** which is used to more efficiently represent the information in multichannel imagery.

**Image classification and analysis** operations are used to digitally identify and classify pixels in the data. **Classification** is usually performed on multi-channel data sets (A) and this process assigns each pixel in an image to a particular class or theme (B) based on statistical characteristics of the pixel brightness values. There are a variety of approaches taken to perform digital classification. We will briefly describe the two generic approaches which are used most often, namely **supervised** and **unsupervised** classification.

In the following sections we will describe each of these four categories of digital image processing functions in more detail.
4.4 Pre-processing

Pre-processing operations, sometimes referred to as image restoration and rectification, are intended to correct for sensor- and platform-specific radiometric and geometric distortions of data. Radiometric corrections may be necessary due to variations in scene illumination and viewing geometry, atmospheric conditions, and sensor noise and response. Each of these will vary depending on the specific sensor and platform used to acquire the data and the conditions during data acquisition. Also, it may be desirable to convert and/or calibrate the data to known (absolute) radiation or reflectance units to facilitate comparison between data.

Variations in illumination and viewing geometry between images (for optical sensors) can be corrected by modeling the geometric relationship and distance between the area of the Earth's surface imaged, the sun, and the sensor. This is often required so as to be able to more readily compare images collected by different sensors at different dates or times, or to mosaic multiple images from a single sensor while maintaining uniform illumination conditions from scene to scene.

As we learned in Chapter 1, scattering of radiation occurs as it passes through and interacts with the atmosphere. This scattering may reduce, or attenuate, some of the energy illuminating the surface. In addition, the atmosphere will further attenuate the signal propagating from the target to the sensor. Various methods of atmospheric correction can be
applied ranging from detailed modeling of the atmospheric conditions during data acquisition, to simple calculations based solely on the image data. An example of the latter method is to examine the observed brightness values (digital numbers), in an area of shadow or for a very dark object (such as a large clear lake - A) and determine the minimum value (B). The correction is applied by subtracting the minimum observed value, determined for each specific band, from all pixel values in each respective band. Since scattering is wavelength dependent (Chapter 1), the minimum values will vary from band to band. This method is based on the assumption that the reflectance from these features, if the atmosphere is clear, should be very small, if not zero. If we observe values much greater than zero, then they are considered to have resulted from atmospheric scattering.

Noise in an image may be due to irregularities or errors that occur in the sensor response and/or data recording and transmission. Common forms of noise include systematic striping or banding and dropped lines. Both of these effects should be corrected before further enhancement or classification is performed. Striping was common in early Landsat MSS data due to variations and drift in the response over time of the six MSS detectors. The "drift" was different for each of the six detectors, causing the same brightness to be represented differently by each detector. The overall appearance was thus a "striped" effect. The corrective process made a relative correction among the six sensors to bring their apparent values in line with each other. Dropped lines occur when there are systems errors which result in missing or defective data along a scan line. Dropped lines are normally "corrected" by replacing the line with the pixel values in the line above or below, or with the average of the two.

For many quantitative applications of remote sensing data, it is necessary to convert the digital numbers to measurements in units which represent the actual reflectance or emittance from the surface. This is done based on detailed knowledge of the sensor response and the way in which the analog signal (i.e. the reflected or emitted radiation) is converted to a digital number, called analog-to-digital (A-to-D) conversion. By solving this relationship in the reverse direction, the absolute radiance can be calculated for each pixel, so that comparisons can be accurately made over time and between different sensors.

In section 2.10 in Chapter 2, we learned that all remote sensing imagery are inherently subject
to geometric distortions. These distortions may be due to several factors, including: the perspective of the sensor optics; the motion of the scanning system; the motion of the platform; the platform altitude, attitude, and velocity; the terrain relief; and, the curvature and rotation of the Earth. Geometric corrections are intended to compensate for these distortions so that the geometric representation of the imagery will be as close as possible to the real world. Many of these variations are **systematic**, or **predictable** in nature and can be accounted for by accurate modeling of the sensor and platform motion and the geometric relationship of the platform with the Earth. Other **unsystematic**, or **random**, errors cannot be modeled and corrected in this way. Therefore, **geometric registration** of the imagery to a known ground coordinate system must be performed.

The **geometric registration process** involves identifying the image coordinates (i.e. row, column) of several clearly discernible points, called **ground control points** (or **GCPs**), in the distorted image (A - A1 to A4), and matching them to their true positions in ground coordinates (e.g. latitude, longitude). The true ground coordinates are typically measured from a map (B - B1 to B4), either in paper or digital format. This is **image-to-map registration**. Once several well-distributed GCP pairs have been identified, the coordinate information is processed by the computer to determine the proper transformation equations to apply to the original (row and column) image coordinates to map them into their new ground coordinates. Geometric registration may also be performed by registering one (or more) images to another image, instead of to geographic coordinates. This is called **image-to-image registration** and is often done prior to performing various image transformation procedures, which will be discussed in section 4.6, or for multitemporal image comparison.
In order to actually geometrically correct the original distorted image, a procedure called **resampling** is used to determine the digital values to place in the new pixel locations of the corrected output image. The resampling process calculates the new pixel values from the original digital pixel values in the uncorrected image. There are three common methods for resampling: **nearest neighbour**, **bilinear interpolation**, and **cubic convolution**. **Nearest neighbour** resampling uses the digital value from the pixel in the original image which is nearest to the new pixel location in the corrected image. This is the simplest method and does not alter the original values, but may result in some pixel values being duplicated while others are lost. This method also tends to result in a disjointed or blocky image appearance.

**Bilinear interpolation** resampling takes a weighted average of four pixels in the original image nearest to the new pixel location. The averaging process alters the original pixel values and creates entirely new digital values in the output image. This may be undesirable if further processing and analysis, such as classification based on spectral response, is to be done. If this is the case, resampling may best be done after the classification process. **Cubic convolution** resampling goes even further to calculate a distance weighted average of a block of sixteen pixels from the original image which surround the new output pixel location. As with bilinear interpolation, this method results in completely new pixel values. However, these two methods both produce images which have a much sharper appearance and avoid the blocky appearance of the nearest neighbour method.
4.5 Image Enhancement

Enhancements are used to make it easier for visual interpretation and understanding of imagery. The advantage of digital imagery is that it allows us to manipulate the digital pixel values in an image. Although radiometric corrections for illumination, atmospheric influences, and sensor characteristics may be done prior to distribution of data to the user, the image may still not be optimized for visual interpretation. Remote sensing devices, particularly those operated from satellite platforms, must be designed to cope with levels of target/background energy which are typical of all conditions likely to be encountered in routine use. With large variations in spectral response from a diverse range of targets (e.g. forest, deserts, snowfields, water, etc.) no generic radiometric correction could optimally account for and display the optimum brightness range and contrast for all targets. Thus, for each application and each image, a custom adjustment of the range and distribution of brightness values is usually necessary.

In raw imagery, the useful data often populates only a small portion of the available range of digital values (commonly 8 bits or 256 levels). Contrast enhancement involves changing the original values so that more of the available range is used, thereby increasing the contrast between targets and their backgrounds. The key to understanding contrast enhancements is to understand the concept of an image histogram. A histogram is a graphical representation of the brightness values that comprise an image. The brightness values (i.e. 0-255) are displayed along the x-axis of the graph. The frequency of occurrence of each of these values in the image is shown on the y-axis.

By manipulating the range of digital values in an image, graphically represented by its histogram, we can apply various enhancements to the data. There are many different techniques and methods of enhancing contrast and detail in an image; we will cover only a
few common ones here. The simplest type of enhancement is a **linear contrast stretch**. This involves identifying lower and upper bounds from the histogram (usually the minimum and maximum brightness values in the image) and applying a transformation to stretch this range to fill the full range. In our example, the minimum value (occupied by actual data) in the histogram is 84 and the maximum value is 153. These 70 levels occupy less than one-third of the full 256 levels available. A linear stretch uniformly expands this small range to cover the full range of values from 0 to 255. This enhances the contrast in the image with light toned areas appearing lighter and dark areas appearing darker, making visual interpretation much easier. This graphic illustrates the increase in contrast in an image before (left) and after (right) a linear contrast stretch.

A uniform distribution of the input range of values across the full range may not always be an appropriate enhancement, particularly if the input range is not uniformly distributed. In this case, a **histogram-equalized stretch** may be better. This stretch assigns more display values (range) to the frequently occurring portions of the histogram. In this way, the detail in these areas will be better enhanced relative to those areas of the original histogram where values occur less frequently. In other cases, it may be desirable to enhance the contrast in only a specific portion of the histogram.

For example, suppose we have an image of the mouth of a river, and the water portions of the image occupy the digital values from 40 to 76 out of the entire image histogram. If we wished to enhance the detail in the water, perhaps to see variations in sediment load, we could stretch only that small portion of the histogram represented by the water (40 to 76) to the full grey level range (0 to 255). All pixels below or above these values would be assigned to 0 and 255, respectively, and the detail in these areas would be lost. However, the detail in the water would be greatly enhanced.
Spatial filtering encompasses another set of digital processing functions which are used to enhance the appearance of an image. Spatial filters are designed to highlight or suppress specific features in an image based on their spatial frequency. Spatial frequency is related to the concept of image texture, which we discussed in section 4.2. It refers to the frequency of the variations in tone that appear in an image. "Rough" textured areas of an image, where the changes in tone are abrupt over a small area, have high spatial frequencies, while "smooth" areas with little variation in tone over several pixels, have low spatial frequencies. A common filtering procedure involves moving a 'window' of a few pixels in dimension (e.g. 3x3, 5x5, etc.) over each pixel in the image, applying a mathematical calculation using the pixel values under that window, and replacing the central pixel with the new value. The window is moved along in both the row and column dimensions one pixel at a time and the calculation is repeated until the entire image has been filtered and a "new" image has been generated. By varying the calculation performed and the weightings of the individual pixels in the filter window, filters can be designed to enhance or suppress different types of features.

A low-pass filter is designed to emphasize larger, homogeneous areas of similar tone and reduce the smaller detail in an image. Thus, low-pass filters generally serve to smooth the appearance of an image. Average and median filters, often used for radar imagery (and described in Chapter 3), are examples of low-pass filters. High-pass filters do the opposite and serve to sharpen the appearance of fine detail in an image. One implementation of a high-pass filter first applies a low-pass filter to an image and then subtracts the result from the original, leaving behind only the high spatial frequency information. Directional, or edge detection filters are designed to highlight linear features, such as roads or field boundaries. These filters can also be designed to enhance features which are oriented in specific directions. These filters are useful in applications such as geology, for the detection of linear geologic structures.
4.6 Image Transformations

Image transformations typically involve the manipulation of multiple bands of data, whether from a single multispectral image or from two or more images of the same area acquired at different times (i.e. multitemporal image data). Either way, image transformations generate "new" images from two or more sources which highlight particular features or properties of interest, better than the original input images.

Basic image transformations apply simple arithmetic operations to the image data. **Image subtraction** is often used to identify changes that have occurred between images collected on different dates. Typically, two images which have been geometrically registered (see section 4.4), are used with the pixel (brightness) values in one image (1) being subtracted from the pixel values in the other (2). Scaling the resultant image (3) by adding a constant (127 in this case) to the output values will result in a suitable 'difference' image. In such an image, areas where there has been little or no change (A) between the original images, will have resultant brightness values around 127 (mid-grey tones), while those areas where significant change has occurred (B) will have values higher or lower than 127 - brighter or darker depending on the 'direction' of change in reflectance between the two images. This type of image transform can be useful for mapping changes in urban development around cities and for identifying areas where deforestation is occurring, as in this example.

Image division or **spectral ratioing** is one of the most common transforms applied to image data. Image ratioing serves to highlight subtle variations in the spectral responses of various surface covers. By ratioing the data from two different spectral bands, the resultant image enhances variations in the slopes of the spectral reflectance curves between the two different spectral ranges that may otherwise be masked by the pixel brightness variations in each of the bands. The following example illustrates the concept of spectral ratioing. Healthy vegetation reflects strongly in the near-infrared portion of the spectrum while absorbing strongly in the visible red. Other surface types, such as soil and water, show near equal reflectances in both the near-infrared and red portions. Thus, a ratio image of Landsat MSS Band 7 (Near-Infrared - 0.8 to 1.1 mm) divided by Band 5 (Red - 0.6 to 0.7 mm) would result in ratios much greater than 1.0 for vegetation, and ratios around 1.0 for soil and water. Thus the discrimination of vegetation from other surface cover types is significantly enhanced. Also, we may be better able to identify areas of unhealthy or stressed vegetation, which show low near-infrared reflectance, as the ratios would be lower than for healthy green vegetation.
Another benefit of spectral ratioing is that, because we are looking at relative values (i.e. ratios) instead of absolute brightness values, variations in scene illumination as a result of topographic effects are reduced. Thus, although the absolute reflectances for forest covered slopes may vary depending on their orientation relative to the sun’s illumination, the ratio of their reflectances between the two bands should always be very similar. More complex ratios involving the sums of and differences between spectral bands for various sensors, have been developed for monitoring vegetation conditions. One widely used image transform is the **Normalized Difference Vegetation Index (NDVI)** which has been used to monitor vegetation conditions on continental and global scales using the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard the NOAA series of satellites (see Chapter 2, section 2.11).

Different bands of multispectral data are often highly correlated and thus contain similar information. For example, Landsat MSS Bands 4 and 5 (green and red, respectively) typically have similar visual appearances since reflectances for the same surface cover types are almost equal. Image transformation techniques based on complex processing of the statistical characteristics of multi-band data sets can be used to reduce this data redundancy and correlation between bands.

One such transform is called **principal components analysis**. The objective of this transformation is to reduce the dimensionality (i.e. the number of bands) in the data, and compress as much of the information in the original bands into fewer bands. The "new" bands that result from this statistical procedure are called components. This process attempts to maximize (statistically) the amount of information (or variance) from the original data into the least number of new components. As an example of the use of principal components analysis, a seven band Thematic Mapper (TM) data set may be transformed such that the first three principal components contain over 90 percent of the information in the original seven bands. Interpretation and analysis of these three bands of data, combining them either visually or
digitally, is simpler and more efficient than trying to use all of the original seven bands. Principal components analysis, and other complex transforms, can be used either as an enhancement technique to improve visual interpretation or to reduce the number of bands to be used as input to digital classification procedures, discussed in the next section.
A human analyst attempting to classify features in an image uses the elements of visual interpretation (discussed in section 4.2) to identify homogeneous groups of pixels which represent various features or land cover classes of interest. **Digital image classification** uses the spectral information represented by the digital numbers in one or more spectral bands, and attempts to classify each individual pixel based on this spectral information. This type of classification is termed **spectral pattern recognition**. In either case, the objective is to assign all pixels in the image to particular classes or themes (e.g. water, coniferous forest, deciduous forest, corn, wheat, etc.). The resulting classified image is comprised of a mosaic of pixels, each of which belong to a particular theme, and is essentially a thematic "map" of the original image.

When talking about classes, we need to distinguish between **information classes and spectral classes**. Information classes are those categories of interest that the analyst is actually trying to identify in the imagery, such as different kinds of crops, different forest types or tree species, different geologic units or rock types, etc. Spectral classes are groups of pixels that are uniform (or near-similar) with respect to their brightness values in the different spectral channels of the data. The objective is to match the spectral classes in the data to the information classes of interest. Rarely is there a simple one-to-one match between these two types of classes. Rather, unique spectral classes may appear which do not necessarily correspond to any information class of particular use or interest to the analyst. Alternatively, a broad information class (e.g. forest) may contain a number of spectral **sub-classes** with unique spectral variations. Using the forest example, spectral sub-classes may be due to variations in age, species, and density, or perhaps as a result of shadowing or variations in scene illumination. It is the analyst's job to decide on the utility of the different spectral classes and their correspondence to useful information classes.
Common classification procedures can be broken down into two broad subdivisions based on the method used: **supervised classification and unsupervised classification**. In a **supervised classification**, the analyst identifies in the imagery homogeneous representative samples of the different surface cover types (information classes) of interest. These samples are referred to as **training areas**. The selection of appropriate training areas is based on the analyst's familiarity with the geographical area and their knowledge of the actual surface cover types present in the image. Thus, the analyst is "supervising" the categorization of a set of specific classes. The numerical information in all spectral bands for the pixels comprising these areas are used to "train" the computer to recognize spectrally similar areas for each class. The computer uses a special program or algorithm (of which there are several variations), to determine the numerical "signatures" for each training class. Once the computer has determined the signatures for each class, each pixel in the image is compared to these signatures and labeled as the class it most closely "resembles" digitally. Thus, in a supervised classification we are first identifying the information classes which are then used to determine the spectral classes which represent them.

**Unsupervised classification** in essence reverses the supervised classification process. Spectral classes are grouped first, based solely on the numerical information in the data, and are then matched by the analyst to information classes (if possible). Programs, called **clustering algorithms**, are used to determine the natural (statistical) groupings or structures in the data. Usually, the analyst specifies how many groups or clusters are to be looked for in the data. In addition to specifying the desired number of classes, the analyst may also specify parameters related to the separation distance among the clusters and the variation within each cluster. The final result of this iterative clustering process may result in some clusters
that the analyst will want to subsequently combine, or clusters that should be broken down further - each of these requiring a further application of the clustering algorithm. Thus, unsupervised classification is not completely without human intervention. However, it does not start with a pre-determined set of classes as in a supervised classification.
In the early days of analog remote sensing when the only remote sensing data source was aerial photography, the capability for integration of data from different sources was limited. Today, with most data available in digital format from a wide array of sensors, data integration is a common method used for interpretation and analysis. Data integration fundamentally involves the combining or merging of data from multiple sources in an effort to extract better and/or more information. This may include data that are multitemporal, multiresolution, multisensor, or multi-data type in nature.

Multitemporal data integration has already been alluded to in section 4.6 when we discussed image subtraction. Imagery collected at different times is integrated to identify areas of change. Multitemporal change detection can be achieved through simple methods such as these, or by other more complex approaches such as multiple classification comparisons or classifications using integrated multitemporal data sets. Multiresolution data merging is useful for a variety of applications. The merging of data of a higher spatial resolution with data of lower resolution can significantly sharpen the spatial detail in an image and enhance the discrimination of features. SPOT data are well suited to this approach as the 10 metre panchromatic data can be easily merged with the 20 metre multispectral data. Additionally, the multispectral data serve to retain good spectral resolution while the panchromatic data provide the improved spatial resolution.
Data from different sensors may also be merged, bringing in the concept of multisensor data fusion. An excellent example of this technique is the combination of **multispectral optical data with radar imagery**. These two diverse spectral representations of the surface can provide complementary information. The optical data provide detailed spectral information useful for discriminating between surface cover types, while the radar imagery highlights the structural detail in the image.

Applications of multisensor data integration generally require that the data be geometrically registered, either to each other or to a common geographic coordinate system or map base. This also allows other **ancillary** (supplementary) data sources to be integrated with the remote sensing data. For example, elevation data in digital form, called **Digital Elevation or Digital Terrain Models (DEM/DTM)**, may be combined with remote sensing data for a variety of purposes. DEMs/DTMs may be useful in image classification, as effects due to terrain and slope variability can be corrected, potentially increasing the accuracy of the resultant classification. DEMs/DTMs are also useful for generating **three-dimensional perspective views** by draping remote sensing imagery over the elevation data, enhancing visualization of the area imaged.

Combining data of different types and from different sources, such as we have described above, is the pinnacle of data integration and analysis. In a digital environment where all the data sources are geometrically registered to a common geographic base, the potential for information extraction is extremely wide. This is the concept for analysis within a digital **Geographical Information System (GIS)** database. Any data source which can be referenced spatially can be used in this type of environment. A DEM/DTM is just one example of this kind of data. Other examples could include digital maps of soil type, land cover classes, forest species, road networks, and many others, depending on the application. The results from a classification of a remote sensing data set in map format, could also be used in a GIS as another data source to update existing map data. In essence, by analyzing diverse data sets together, it is possible to extract better and more accurate information in a synergistic manner than by using a single data source alone. There are a myriad of potential applications and analyses possible for many applications. In the next and final chapter, we will look at examples of various applications of remote sensing data, many involving the integration of data from different sources.
4.9 Endnotes

You have just completed Chapter 4 - Image Interpretation and Analysis. You can continue to Chapter 5 - Applications or first browse the CCRS Web site for other articles related to Image Interpretation and Analysis.

By browsing the "Images of Canada"\(^1\), you can learn in detail about the visual elements of interpretation and test yourself with a variety of remote sensing questions and answers.

We have a downloadable tutorial\(^2\) and exercise on the topic of digital images and digital analysis techniques that makes a good start into this field.

See how the Intensity, Hue and Saturation (IHS) transformation, as applied to 3-D images are used to help visualize terrain relief\(^3\). As well, an IHS transformation can also be used to exploit the synergy of two different image data sets; in the case shown here, to study the hydrogeology\(^4\) of an area. Image fusion\(^5\) of data from different sensors is well demonstrated in an image of Canada's Capital - Ottawa.

Image compression is important for storage and transmission of large images. One compression technique developed at CCRS uses multiscale methods\(^6\) to compress images and reduce file size.

There are many other image manipulation / interpretation techniques demonstrated on the CCRS Web site. You may also want to check our Remote Sensing Glossary for terms in the "techniques"\(^7\) category.

\(^1\)http://www.ccrs.nrcan.gc.ca/ccrs/learn/tour/tour_e.html
\(^2\)http://www.ccrs.nrcan.gc.ca/ccrs/learn/tutorials/digitech/digitech_e.html
\(^3\)http://www.ccrs.nrcan.gc.ca/ccrs/rd/ana/chromo/chromo_e.html
\(^4\)http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/images/jor/rjor04_e.html
\(^5\)http://www.ccrs.nrcan.gc.ca/ccrs/learn/tour/06/06ont_e.html
\(^6\)http://www.ccrs.nrcan.gc.ca/ccrs/com/rsnewsltr/2302/2302ap1_e.html
\(^7\)http://dweb.ccrs.nrcan.gc.ca/ccrs/db/glossary/glossary_e.cfm
4. Did You Know?

4.2 Did You Know?

"...What will they think of next ?!..."

Remote sensing (image interpretation) has been used for archeological investigations. Sometimes the 'impression' that a buried artifact, such as an ancient fort foundation, leaves on the surface, can be detected and identified. That surface impression is typically very subtle, so it helps to know the general area to be searched and the nature of the feature being sought. It is also useful if the surface has not been disturbed much by human activities.
4.3 Did You Know?
"...our standard operating procedure is...

... the remote sensing industry and those associated with it have attempted to standardize the way digital remote sensing data are formatted in order to make the exchange of data easier and to standardize the way data can be read into different image analysis systems. The Committee on Earth Observing Satellites (CEOS) have specified this format which is widely used around the world for recording and exchanging data.

4.5 Did You Know?

An image 'enhancement' is basically anything that makes it easier or better to visually interpret an image. In some cases, like 'low-pass filtering', the enhanced image can actually look worse than the original, but such an enhancement was likely performed to help the interpreter see low spatial frequency features among the usual high frequency clutter found in an image. Also, an enhancement is performed for a specific application. This enhancement may be inappropriate for another purpose, which would demand a different type of enhancement.
4.7 Did You Know?

"...this image has such lovely texture, don't you think?..."

...texture was identified as one of the key elements of visual interpretation (section 4.2), particularly for radar image interpretation. Digital texture classifiers are also available and can be an alternative (or assistance) to spectral classifiers. They typically perform a "moving window" type of calculation, similar to those for spatial filtering, to estimate the "texture" based on the variability of the pixel values under the window. Various textural measures can be calculated to attempt to discriminate between and characterize the textural properties of different features.
4. Whiz Quiz and Answers

4.2 Whiz Quiz

Take a look at the aerial photograph above. Identify the following features in the image and explain how you were able to do so based on the elements of visual interpretation described in this section.

- race track
- river
- roads
- bridges
- residential area
- dam

4.2 Answers

- The race track in the lower left of the image is quite easy to identify because of its characteristic shape.
- The river is also easy to identify due to its contrasting tone with the surrounding land and also due to its shape.
- The roads in the image are visible due to their shape (straight in many cases) and their generally bright tone contrasting against the other darker features.
- Bridges are identifiable based on their shape, tone, and association with the river - they cross it!
- Residential areas on the left hand side of the image and the upper right can be identified by the pattern that they make in conjunction with the roads. Individual houses and other buildings can also be identified as dark and light tones.
- The dam in the river at the top center of the image can be identified based on its contrasting tone with the dark river, its shape, and its association with the river - where else would a dam be!

Canada Centre for Remote Sensing
4.3 Whiz Quiz

One 8-bit pixel takes up one single byte of computer disk space. One kilobyte (Kb) is 1024 bytes. One megabyte (Mb) is 1024 kilobytes. How many megabytes of computer disk space would be required to store an 8-bit Landsat Thematic Mapper (TM) image (7 bands), which is 6000 pixels by 6000 lines in dimension?

The answer is ...

4.3 Answers

If we have seven bands of TM data, each 6000 pixels by 6000 lines, and each pixel takes up one byte of disk space, we have:

\[7 \times 6000 \times 6000 = 252,000,000 \text{ bytes of data}\]

To convert this to kilobytes we need to divide by 1024, and to convert that answer to megabytes we need to divide by 1024 again!

\[252,000,000 \div (1024 \times 1024) = 240.33 \text{ megabytes}\]

So, we would need over 240 megabytes of disk space just to hold one full TM image, let alone analyze the imagery and create any new image variations! Needless to say, it takes a lot of storage space and powerful computers to analyze the data from today's remote sensing systems.
4.4 Whiz Quiz

What would be the advantage of geometrically correcting an image to geographic coordinates prior to further analysis and interpretation?

4.4 Answers

The advantage of geometrically correcting an image prior to further analysis and interpretation is that it would then allow proper measurements of distances and areas to be made from features in the image. This may be particularly useful in different applications where true measurements are necessary, such as in urban mapping applications. Also, the geographic locations of features could be determined. Once an image is geometrically registered to a known geographic base, it can be combined with other mapped data in a digital environment for further analysis. This is the concept of data integration which is discussed in section 4.8.
4.7 Whiz Quiz

You want to perform a classification on a satellite image, but when examining its histogram, you notice that the range of useful data is very narrow. Prior to attempting classification, would you enhance the image with a linear contrast stretch?

4.7 Answer

An 'enhancement' of an image is done exclusively for visually appreciating and analyzing its contents. An enhancement would not add anything useful, as far as the classification algorithm is concerned. Another way of looking at this is: if two pixels have brightness values just one digital unit different, then it would be very difficult to notice this subtle difference by eye. But for the computer, the difference is just as 'obvious' as if it was 100 times greater.

An enhanced version of the image may help in selecting 'training' sites (by eye), but you would still perform the classification on the unenhanced version.
5. Applications

5.1 Introduction

As we learned in the section on sensors, each one was designed with a specific purpose. With optical sensors, the design focuses on the spectral bands to be collected. With radar imaging, the incidence angle and microwave band used plays an important role in defining which applications the sensor is best suited for.

Each application itself has specific demands, for spectral resolution, spatial resolution, and temporal resolution.

To review, spectral resolution refers to the width or range of each spectral band being recorded. As an example, panchromatic imagery (sensing a broad range of all visible wavelengths) will not be as sensitive to vegetation stress as a narrow band in the red wavelengths, where chlorophyll strongly absorbs electromagnetic energy.

Spatial resolution refers to the discernible detail in the image. Detailed mapping of wetlands requires far finer spatial resolution than does the regional mapping of physiographic areas.

Temporal resolution refers to the time interval between images. There are applications requiring data repeatedly and often, such as oil spill, forest fire, and sea ice motion monitoring. Some applications only require seasonal imaging (crop identification, forest insect infestation, and wetland monitoring), and some need imaging only once (geology structural mapping). Obviously, the most time-critical applications also demand fast turnaround for image processing and delivery - getting useful imagery quickly into the user's hands.
In a case where repeated imaging is required, the revisit frequency of a sensor is important (how long before it can image the same spot on the Earth again) and the reliability of successful data acquisition. Optical sensors have limitations in cloudy environments, where the targets may be obscured from view. In some areas of the world, particularly the tropics, this is virtually a permanent condition. Polar areas also suffer from inadequate solar illumination, for months at a time. Radar provides reliable data, because the sensor provides its own illumination, and has long wavelengths to penetrate cloud, smoke, and fog, ensuring that the target won't be obscured by weather conditions, or poorly illuminated.

Often it takes more than a single sensor to adequately address all of the requirements for a given application. The combined use of multiple sources of information is called integration. Additional data that can aid in the analysis or interpretation of the data is termed "ancillary" data.

The applications of remote sensing described in this chapter are representative, but not exhaustive. We do not touch, for instance, on the wide area of research and practical application in weather and climate analysis, but focus on applications tied to the surface of the Earth. The reader should also note that there are a number of other applications that are practiced but are very specialized in nature, and not covered here (e.g. terrain trafficability analysis, archeological investigations, route and utility corridor planning, etc.).

**Multiple sources of information**

Each band of information collected from a sensor contains important and unique data. We know that different wavelengths of incident energy are affected differently by each target - they are absorbed, reflected or transmitted in different proportions. The appearance of targets can easily change over time, sometimes within seconds. In many applications, using information from several different sources ensures that target identification or information extraction is as accurate as possible. The following describe ways of obtaining far more information about a target or area, than with one band from a sensor.

**Multispectral**

The use of multiple bands of spectral information attempts to exploit different and independent "views" of the targets so as to make their identification as confident as possible. Studies have been conducted to determine the optimum spectral bands for analyzing specific targets, such as insect damaged trees.

**Multisensor**

Different sensors often provide complementary information, and when integrated together, can facilitate interpretation and classification of imagery. Examples include combining high resolution panchromatic imagery with coarse resolution multispectral imagery, or merging actively and passively sensed data. A specific example is the integration of SAR imagery with multispectral imagery. SAR data adds the expression of surficial topography and relief to an otherwise flat image. The multispectral image contributes meaningful colour information about the composition or cover of the land surface. This type of image is often used in geology,
where lithology or mineral composition is represented by the spectral component, and the structure is represented by the radar component.

**Multitemporal**

Information from multiple images taken over a period of time is referred to as multitemporal information. Multitemporal may refer to images taken days, weeks, or even years apart. Monitoring land cover change or growth in urban areas requires images from different time periods. Calibrated data, with careful controls on the quantitative aspect of the spectral or backscatter response, is required for proper monitoring activities. With uncalibrated data, a classification of the older image is compared to a classification from the recent image, and changes in the class boundaries are delineated. Another valuable multitemporal tool is the observation of vegetation phenology (how the vegetation changes throughout the growing season), which requires data at frequent intervals throughout the growing season.

"Multitemporal information" is acquired from the interpretation of images taken over the same area, but at different times. The time difference between the images is chosen so as to be able to monitor some dynamic event. Some catastrophic events (landslides, floods, fires, etc.) would need a time difference counted in days, while much slower-paced events (glacier melt, forest regrowth, etc.) would require years. This type of application also requires consistency in illumination conditions (solar angle or radar imaging geometry) to provide consistent and comparable classification results.

The ultimate in critical (and quantitative) multitemporal analysis depends on calibrated data. Only by relating the brightnesses seen in the image to physical units, can the images be precisely compared, and thus the nature and magnitude of the observed changes be determined.
5.2 Agriculture

Agriculture plays a dominant role in economies of both developed and undeveloped countries. Whether agriculture represents a substantial trading industry for an economically strong country or simply sustenance for a hungry, overpopulated one, it plays a significant role in almost every nation. The production of food is important to everyone and producing food in a cost-effective manner is the goal of every farmer, large-scale farm manager and regional agricultural agency. A farmer needs to be informed to be efficient, and that includes having the knowledge and information products to forge a viable strategy for farming operations. These tools will help him understand the health of his crop, extent of infestation or stress damage, or potential yield and soil conditions. Commodity brokers are also very interested in how well farms are producing, as yield (both quantity and quality) estimates for all products control price and worldwide trading.

Satellite and airborne images are used as mapping tools to classify crops, examine their health and viability, and monitor farming practices. Agricultural applications of remote sensing include the following:

- crop type classification
- crop condition assessment
- crop yield estimation
- mapping of soil characteristics
- mapping of soil management practices
- compliance monitoring (farming practices)
5.2.1 Crop Type Mapping

Background
Identifying and mapping crops is important for a number of reasons. Maps of crop type are created by national and multinational agricultural agencies, insurance agencies, and regional agricultural boards to prepare an inventory of what was grown in certain areas and when. This serves the purpose of forecasting grain supplies (yield prediction), collecting crop production statistics, facilitating crop rotation records, mapping soil productivity, identification of factors influencing crop stress, assessment of crop damage due to storms and drought, and monitoring farming activity.

Key activities include identifying the crop types and delineating their extent (often measured in acres). Traditional methods of obtaining this information are census and ground surveying. In order to standardize measurements however, particularly for multinational agencies and consortiums, remote sensing can provide common data collection and information extraction strategies.

Why remote sensing?
Remote sensing offers an efficient and reliable means of collecting the information required, in order to map crop type and acreage. Besides providing a synoptic view, remote sensing can provide structure information about the health of the vegetation. The spectral reflection of a field will vary with respect to changes in the phenology (growth), stage type, and crop health, and thus can be measured and monitored by multispectral sensors. Radar is sensitive to the structure, alignment, and moisture content of the crop, and thus can provide complementary information to the optical data. Combining the information from these two types of sensors increases the information available for distinguishing each target class and its respective signature, and thus there is a better chance of performing a more accurate classification.

Interpretations from remotely sensed data can be input to a geographic information system (GIS) and crop rotation systems, and combined with ancillary data, to provide information of ownership, management practices etc.

Data requirements
Crop identification and mapping benefit from the use of multitemporal imagery to facilitate classification by taking into account changes in reflectance as a function of plant phenology (stage of growth). This in turn requires calibrated sensors, and frequent repeat imaging throughout the growing season. For example, crops like canola may be easier to identify when they are flowering, because of both the spectral reflectance change, and the timing of the
flowering.

Multisensor data are also valuable for increasing classification accuracies by contributing more information than a sole sensor could provide. VIR sensing contributes information relating to the chlorophyll content of the plants and the canopy structure, while radar provides information relating to plant structure and moisture. In areas of persistent cloud cover or haze, radar is an excellent tool for observing and distinguishing crop type due to its active sensing capabilities and long wavelengths, capable of penetrating through atmospheric water vapour.

**Canada vs. International**

Although the principles of identifying crop type are the same, the scale of observation in Europe and Southeast Asia is considerably smaller than in North America, primarily due to smaller field parcel sizes. Cloud cover in Europe and tropical countries also usually limits the feasibility of using high-resolution optical sensors. In these cases high-resolution radar would have a strong contribution.

The sizable leaves of tropical agricultural crops (cocoa, banana, and oil palm) have distinct radar signatures. Banana leaves in particular are characterized by bright backscatter (represented by "B" in image). Monitoring stages of rice growth is a key application in tropical areas, particularly Asian countries. Radar is very sensitive to surface roughness, and the development of rice paddies provides a dramatic change in brightness from the low returns from smooth water surfaces in flooded paddies, to the high return of the emergent rice crop.

**Case study (example)**

The countries involved in the European Communities (EC) are using remote sensing to help fulfil the requirements and mandate of the EC Agricultural Policy, which is common to all
members. The requirements are to delineate, identify, and measure the extent of important crops throughout Europe, and to provide an early forecast of production early in the season. Standardized procedures for collecting this data are based on remote sensing technology, developed and defined through the MARS project (Monitoring Agriculture by Remote Sensing).

The project uses many types of remotely sensed data, from low resolution NOAA-AVHRR, to high-resolution radar, and numerous sources of ancillary data. These data are used to classify crop type over a regional scale to conduct regional inventories, assess vegetation condition, estimate potential yield, and finally to predict similar statistics for other areas and compare results. Multisource data such as VIR and radar were introduced into the project for increasing classification accuracies. Radar provides very different information than the VIR sensors, particularly vegetation structure, which proves valuable when attempting to differentiate between crop type.

One the key applications within this project is the operational use of high resolution optical and radar data to confirm conditions claimed by a farmer when he requests aid or compensation. The use of remote sensing identifies potential areas of non-compliance or suspicious circumstances, which can then be investigated by other, more direct methods.

As part of the Integrated Administration and Control System (IACS), remote sensing data supports the development and management of databases, which include cadastral information, declared land use, and parcel measurement. This information is considered when applications are received for area subsidies.

This is an example of a truly successfully operational crop identification and monitoring application of remote sensing.
5.2.2 Crop Monitoring & Damage Assessment

Background
Assessment of the health of a crop, as well as early detection of crop infestations, is critical in ensuring good agricultural productivity. Stress associated with, for example, moisture deficiencies, insects, fungal and weed infestations, must be detected early enough to provide an opportunity for the farmer to mitigate. This process requires that remote sensing imagery be provided on a frequent basis (at a minimum, weekly) and be delivered to the farmer quickly, usually within 2 days.

Also, crops do not generally grow evenly across the field and consequently crop yield can vary greatly from one spot in the field to another. These growth differences may be a result of soil nutrient deficiencies or other forms of stress. Remote sensing allows the farmer to identify areas within a field which are experiencing difficulties, so that he can apply, for instance, the correct type and amount of fertilizer, pesticide or herbicide. Using this approach, the farmer not only improves the productivity from his land, but also reduces his farm input costs and minimizes environmental impacts.

There are many people involved in the trading, pricing, and selling of crops that never actually set foot in a field. They need information regarding crop health worldwide to set prices and to negotiate trade agreements. Many of these people rely on products such as a crop assessment index to compare growth rates and productivity between years and to see how well each country's agricultural industry is producing. This type of information can also help target locations of future problems, for instance the famine in Ethiopia in the late 1980's, caused by a significant drought which destroyed many crops. Identifying such areas facilitates in planning and directing humanitarian aid and relief efforts.

Why remote sensing?

Remote sensing has a number of attributes that lend themselves to monitoring the health of crops. One advantage of optical (VIR) sensing is that it can see beyond the visible wavelengths into the infrared, where wavelengths are highly sensitive to crop vigour as well as crop stress and crop damage. Remote sensing imagery also gives the required spatial overview of the land. Recent advances in communication and technology allow a farmer to observe images of his fields and make timely decisions about managing the crops. Remote sensing can aid in identifying crops affected by conditions that are too dry or wet, affected by insect, weed or fungal infestations or weather related damage. Images can be obtained throughout the growing season to not only detect problems, but also to monitor the success of the treatment. In the example image given here, a tornado has destroyed/damaged crops southwest of Winnipeg, Manitoba.
Healthy vegetation contains large quantities of chlorophyll, the substance that gives most vegetation its distinctive green colour. In referring to healthy crops, reflectance in the blue and red parts of the spectrum is low since chlorophyll absorbs this energy. In contrast, reflectance in the green and near-infrared spectral regions is high. Stressed or damaged crops experience a decrease in chlorophyll content and changes to the internal leaf structure. The reduction in chlorophyll content results in a decrease in reflectance in the green region and internal leaf damage results in a decrease in near-infrared reflectance. These reductions in green and infrared reflectance provide early detection of crop stress. Examining the ratio of reflected infrared to red wavelengths is an excellent measure of vegetation health. This is the premise behind some vegetation indices, such as the normalized differential vegetation index (NDVI) (Chapter 4). Healthy plants have a high NDVI value because of their high reflectance of infrared light, and relatively low reflectance of red light. Phenology and vigour are the main factors in affecting NDVI. An excellent example is the difference between irrigated crops and non-irrigated land. The irrigated crops appear bright green in a real-colour simulated image. The darker areas are dry rangeland with minimal vegetation. In a CIR (colour infrared simulated) image, where infrared reflectance is displayed in red, the healthy vegetation appears bright red, while the rangeland remains quite low in reflectance.

Examining variations in crop growth within one field is possible. Areas of consistently healthy and vigorous crop would appear uniformly bright. Stressed vegetation would appear dark amongst the brighter, healthier crop areas. If the data is georeferenced, and if the farmer has a GPS (global position satellite) unit, he can find the exact area of the problem very quickly, by matching the coordinates of his location to that on the image.

Data requirements
Detecting damage and monitoring crop health requires high-resolution imagery and multispectral imaging capabilities. One of the most critical factors in making imagery useful to farmers is a quick turnaround time from data acquisition to distribution of crop information. Receiving an image that reflects crop conditions of two weeks earlier does not help real time management nor damage mitigation. Images are also required at specific times during the growing season, and on a frequent basis.

Remote sensing doesn't replace the field work performed by farmers to monitor their fields, but it does direct them to the areas in need of immediate attention.

Canada vs. International
Efficient agricultural practices are a global concern, and other countries share many of the same requirements as Canada in terms of monitoring crop health by means of remote sensing. In many cases however, the scale of interest is smaller - smaller fields in Europe and Asia dictate higher resolution systems and smaller areal coverage. Canada, the USA, and
Russia, amongst others, have more expansive areas devoted to agriculture, and have developed, or are in the process of developing crop information systems (see below). In this situation, regional coverage and lower resolution data (say: 1km) can be used. The lower resolution facilitates computer efficiency by minimizing storage space, processing efforts and memory requirements.

As an example of an international crop monitoring application, date palms are the prospective subject of an investigation to determine if remote sensing methods can detect damage from the red palm weevil in the Middle East. In the Arabian Peninsula, dates are extremely popular and date crops are one of the region's most important agricultural products. Infestation by the weevil could quickly devastate the palm crops and swallow a commodity worth hundreds of millions of dollars. Remote sensing techniques will be used to examine the health of the date crops through spectral analysis of the vegetation. Infested areas appear yellow to the naked eye, and will show a smaller near infrared reflectance and a higher red reflectance on the remotely sensed image data than the healthy crop areas. Authorities are hoping to identify areas of infestation and provide measures to eradicate the weevil and save the remaining healthy crops.

**Case study (example)**

Canadian Crop Information System: A composite crop index map is created each week, derived from composited NOAA-AVHRR data. Based on the NDVI, the index shows the health of crops in the prairie regions of Manitoba through to Alberta. These indices are produced weekly, and can be compared with indices of past years to compare crop growth and health.

In 1988, severe drought conditions were prevalent across the prairies. Using NDVI values from NOAA AVHRR data, a **drought area analysis** determined the status of drought effects on crops across the affected area. Red and yellow areas indicate those crops in a weakened and stressed state, while green indicates healthy crop conditions. Note that most of the healthy crops are those in the cooler locations, such as in the northern Alberta (Peace River) and the higher elevations (western Alberta). Non-cropland areas (dry rangeland and forested land) are indicated in black, within the analysis region.
5.3 Forestry

Forests are a valuable resource providing food, shelter, wildlife habitat, fuel, and daily supplies such as medicinal ingredients and paper. Forests play an important role in balancing the Earth's CO₂ supply and exchange, acting as a key link between the atmosphere, geosphere, and hydrosphere. Tropical rainforests, in particular, house an immense **diversity of species**, more capable of adapting to, and therefore surviving, changing environmental conditions than monoculture forests. This diversity also provides habitat for numerous animal species and is an important source of medicinal ingredients. The main issues concerning forest management are depletion due to natural causes (fires and infestations) or human activity (clear-cutting, burning, land conversion), and monitoring of health and growth for effective commercial exploitation and conservation.

Humans generally consider the products of forests useful, rather than the forests themselves, and so extracting **wood** is a widespread and historical practice, virtually global in scale. Depletion of forest resources has long term effects on climate, soil conservation, biodiversity, and hydrological regimes, and thus is a vital concern of environmental monitoring activities. Commercial forestry is an important industry throughout the world. Forests are cropped and re-harvested, and the new areas continually sought for providing a new source of lumber. With increasing pressure to conserve native and virgin forest areas, and unsustainable forestry practices limiting the remaining areas of potential cutting, the companies involved in extracting wood supplies need to be more efficient, economical, and aware of sustainable forestry practices. Ensuring that there is a healthy regeneration of trees where forests are extracted will ensure a future for the commercial forestry firms, as well as adequate wood supplies to meet the demands of a growing population.

Non-commercial sources of forest depletion include removal for agriculture (pasture and crops), urban development, droughts, desert encroachment, loss of ground water, insect damage, fire and other natural phenomena (disease, typhoons). In some areas of the world, particularly in the tropics, (rain) forests are covering what might be considered the most valuable commodity - viable agricultural land. Forests are burned or **clear-cut** to facilitate access to, and use of, the land. This practice often occurs when the perceived need for long term sustainability is overwhelmed by short-term sustenance goals. Not only are the depletion of species-rich forests a problem, affecting the local and regional hydrological regime, the smoke caused by the burning trees pollutes the

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atmosphere, adding more CO$_2$, and furthering the greenhouse effect.

Of course, monitoring the health of forests is crucial for sustainability and conservation issues. Depletion of key species such as mangrove in environmentally sensitive coastline areas, removal of key support or shade trees from a potential crop tree, or disappearance of a large biota acting as a CO$_2$ reservoir all affect humans and society in a negative way, and more effort is being made to monitor and enforce regulations and plans to protect these areas.

International and domestic forestry applications where remote sensing can be utilized include sustainable development, biodiversity, land title and tenure (cadastre), monitoring deforestation, reforestation monitoring and managing, commercial logging operations, shoreline and watershed protection, biophysical monitoring (wildlife habitat assessment), and other environmental concerns.

General forest cover information is valuable to developing countries with limited previous knowledge of their forestry resources. General cover type mapping, shoreline and watershed mapping and monitoring for protection, monitoring of cutting practices and regeneration, and forest fire/burn mapping are global needs which are currently being addressed by Canadian and foreign agencies and companies employing remote sensing technology as part of their information solutions in foreign markets.

Forestry applications of remote sensing include the following:

1) **reconnaissance mapping:**
   - Objectives to be met by national forest/environment agencies include forest cover updating, depletion monitoring, and measuring biophysical properties of forest stands.
     - forest cover type discrimination
     - agroforestry mapping

2) **Commercial forestry:**
   - Of importance to commercial forestry companies and to resource management agencies are inventory and mapping applications: collecting harvest information, updating of inventory information for timber supply, broad forest type, vegetation density, and biomass measurements.
     - clear cut mapping / regeneration assessment
     - burn delineation
     - infrastructure mapping / operations support
     - forest inventory
     - biomass estimation
     - species inventory

3) **Environmental monitoring**
   - Conservation authorities are concerned with monitoring the quantity, health, and diversity of the Earth's forests.
     - deforestation (rainforest, mangrove colonies)
     - species inventory
     - watershed protection (riparian strips)
     - coastal protection (mangrove forests)
Canadian requirements for forestry application information differ considerably from international needs, due in part to contrasts in tree size, species diversity (monoculture vs. species rich forest), and agroforestry practices. The level of accuracy and resolution of data required to address respective forestry issues differs accordingly. Canadian agencies have extensive a priori knowledge of their forestry resources and present inventory and mapping needs are often capably addressed by available data sources.

For Canadian applications requirements, high accuracy (for accurate information content), multispectral information, fine resolution, and data continuity are the most important. There are requirements for large volumes of data, and reliable observations for seasonal coverage. There is a need to balance spatial resolution with the required accuracy and costs of the data. Resolution capabilities of 10 m to 30 m are deemed adequate for forest cover mapping, identifying and monitoring clearcuts, burn and fire mapping, collecting forest harvest information, and identifying general forest damage. Spatial coverage of 100 - 10000 km² is appropriate for district to provincial scale forest cover and clear cut mapping, whereas 1-100 km² coverage is the most appropriate for site specific vegetation density and volume studies.

Tropical forest managers will be most concerned with having a reliable data source, capable of imaging during critical time periods, and therefore unhindered by atmospheric conditions.
5.3.1 Clear Cut Mapping & Deforestation

Background
Deforestation is a global problem, with many implications. In industrialized Europe, pollution (acid rain, soot and chemicals from factory smoke plumes) has damaged a large percentage of forested land. In the former Czechoslovakia, one half of the forests are destroyed or damaged from pollutants. Similar effects are felt in Germany, Poland, and even the Scandinavian countries. In tropical countries, valuable rainforest is being destroyed in an effort to clear potentially valuable agricultural and pasture land. This has resulted in huge losses of tropical rainforest throughout Latin America (Central America, southern Mexico, Haiti), South America (Brazil), Africa and Asia. In both Haiti and Madagascar in particular, the results have been devastating. The loss of forests increases soil erosion, river siltation, and deposition, affecting navigation, fisheries, wildlife habitat, and drinking water supplies, as well as farming productivity and self-sufficiency.

Sensitive estuarine environments are protected by mangrove forest, which is cut or lost to urban growth, aquaculture, or damaged by pollutants or siltation. Monitoring the health of this forest is a step towards protecting the coastlines from erosion and degradation, and nearby inland areas from flooding.

The loss of forests also affects the genetic diversity of species on Earth, which controls our intrinsic ability to adapt to changing conditions and environment. Rainforests account for approximately one half of the plant and animal species on Earth, and destroying large sections will only serve to reduce the gene and species pool.

The rate and extent of deforestation, as well as monitoring regeneration, are the key parameters measured by remote sensing methods.

Why remote sensing?
Remote sensing brings together a multitude of tools to better analyze the scope and scale of the deforestation problem. Multitemporal data provides for change detection analyses. Images of earlier years are compared to recent scenes, to tangibly measure the differences in the sizes and extents of the clearcuts or loss of forest. Data from a variety of sources are used to provide complementary information. Radar, merged with optical data, can be used to efficiently monitor the status of existing clearcuts or emergence of new ones, and even assess regeneration condition. In countries where cutting is controlled and regulated, remote sensing serves as a monitoring tool to ensure companies are following cut guidelines and specifications.
High resolution data provide a detailed view of forest depletion, while radar can provide a view that may otherwise be obscured by clouds. All remote sensing devices, however, provide a view of often remote and inaccessible areas, where illegal cutting or damage could continue unnoticed for long periods of time if aerial surveillance wasn't possible.

Data requirements
Global monitoring initiatives, such as rain forest depletion studies, depend on large area coverage and data continuity, so it is important to use a sensor that will have successive generations launched and operational. Clear cut mapping and monitoring also require regional scale images and moderate or high resolution data depending on whether cuts are to be simply detected or delineated. As for many multi-temporal applications, a higher resolution image can be used to define the baseline, and coarser resolution images can be used to monitor changes to that baseline.

Canada vs. International
Optical sensors are still preferred for clear cut mapping and monitoring in Canada because forest vegetation, cuts, and regenerating vegetation have distinguishable spectral signatures, and optical sensors can collect sufficient cloud-free data.

Radar is more useful for applications in the humid tropics because its all weather imaging capability is valuable for monitoring all types of depletion, including clear cuts, in areas prone to cloudy conditions. Cuts can be defined on radar images because clear cuts produce less backscatter than the forest canopy, and forest edges are enhanced by shadow and bright backscatter. However, regenerating cuts are typically difficult to detect, as advanced regeneration and mature forest canopy are not separable. Mangrove forests generally occur in tropical coastal areas, which are prone to cloudy conditions, therefore a reliable monitoring tool is required to successively measure the rate of forest depletion. Radar has been proven to differentiate mangrove from other land covers, and some bands have long wavelengths capable of penetrating cloud and rain. The only limitation is in differentiating different mangrove species.
Case study (example)

In Alberta, much of the province's forestland has been sold to offshore investors who are interested in selling pulp and paper products. Around the area of Whitecourt, clear cutting of conifer forest has been occurring for decades. In recent years however, the increasing demand for wood products has accelerated the cutting of the forests, resulting in a dissected and checkered landscape. Besides cutting for wood supply, forest depletion is also occurring due to cuts for seismic lines for oil and gas exploration and extraction. Both optical and radar sensors have been used to monitor the clear cuts and regeneration.

Optical and Radar scenes of forest clear cutting.
5.3.2 Species Identification & Typing

Background
Forest cover typing and species identification are critical to both forest conservation managers and forestry companies interested in their supply inventory. Forest cover typing can consist of reconnaissance mapping over a large area, while species inventories are highly detailed measurements of stand contents and characteristics (tree type, height, density).

Why remote sensing?
Remote sensing provides a means of quickly identifying and delineating various forest types, a task that would be difficult and time consuming using traditional ground surveys. Data is available at various scales and resolutions to satisfy local or regional demands. Large scale species identification can be performed with multispectral, hyperspectral, or airphoto data, while small scale cover type delineation can be performed by radar or multispectral data interpretation. Both imagery and the extracted information can be incorporated into a GIS to further analyze or present with ancillary data, such as slopes, ownership boundaries, or roads.

Hyperspectral imagery can provide a very high spatial resolution while capturing extremely fine radiometric resolution data. This type of detailed spectral information can be used to generate signatures of vegetation species and certain stresses (e.g. infestations) on trees. Hyperspectral data offers a unique view of the forest cover, available only through remote sensing technology.

Data requirements
Requirements depend on the scale of study to be conducted. For regional reconnaissance mapping, moderate area coverage, with a sensor sensitive to differences in forest cover (canopy texture, leaf density, spectral reflection) is needed. Multitemporal datasets also contribute phenology information that may aid in interpretation by incorporating the seasonal changes of different species.

For detailed species identification associated with forest stand analysis, very high resolution, multispectral data is required. Being able to view the images in stereo helps in the delineation and assessment of density, tree height, and species. In general, monitoring biophysical properties of forests requires multispectral information and finely calibrated data.

Canada vs. International
Current sources of data used operationally for forest cover typing and species identification applications within Canada are aerial photography, orthophotography, Landsat TM, and SPOT data. Landsat data are the most appropriate for executing reconnaissance level forest surveys, while aerial photography and digital orthophoto are the preferred data source for extracting stand and local inventory information. Airphotos are the most appropriate operational data source for stand level measurements including species typing. SAR sensors such as RADARSAT are useful where persistent cloud cover limits the usefulness of optical sensors.
In humid tropical areas, forest resource assessments and measurements are difficult to obtain because of cloudy conditions hindering conventional remote sensing efforts, and difficult terrain impeding ground surveys. In this situation, reliability of data acquisition is more crucial than resolution or frequency of imaging. An active sensor may be the only feasible source of data, and its reliability will facilitate regular monitoring. Radar will serve this purpose, and an airborne sensor is sufficient for high resolution requirements such as cover typing. This type of data can be used for a baseline map, while coarser resolution data can provide updates to any changes in the baseline.

**Case study (example)**

Inventory Branch, Ministry of Forests, Province of British Columbia, Canada

This is an example of the operational requirements and procedure for a provincial department involved in a number of forestry applications using remote sensing technology.

The Inventory Branch is responsible for maintaining a database of Crown Land information concerning historical, stand, and sustainable forest management information which is used for determining timber volumes and annual allowable cuts. The inventory itself is performed every ten years with 1:15,000 scale aerial photography, and updated with satellite imagery every two years.

The Inventory branch requires geocoded, terrain corrected data. For most studies, the branch currently buys precision geocoded data, and for large scale mapping projects, they will cut costs by obtaining systematic versus precision geocoded data. Further processing is done in-house on workstations. Some location data are now being provided by the private sector, conducting field traverses with GPS (global positioning system) data.

Present planimetric accuracy requirements are 20 m, but will be more demanding in the near future. Airphotos and orthophotos meet requirements and are good for interpretation but are limited by expense. Data continuity is important, as monitoring will be an ongoing operation. TM data for updating maps is reasonable in cost and information content for interim monitoring.

Much of the updating in the Ministry of Forests is done with TM data, either brought digitally into a MicroStation workstation to perform heads-up digitizing, or in transparency form with the image overlain onto existing maps using a projection device. The Ministry of Forests is presently investigating the potential of a number of data sources with various levels of processing applied, and integration possibilities to assess accuracy versus cost relationships.

The Ministry of Forests in B.C. employs an expert system SHERI (System of Hierarchical Expert Systems for Resource Inventories) to provide a link between remotely sensed data, GIS and growth and yield modelling. The end to end information flow is complete with the generation of final products including forest cover maps incorporating planimetric and administrative boundary information.
Case study (example)

Hyperspectral image and recent stem count from hyperspectral imagery

Forest companies use hyperspectral imagery to obtain stem counts, stand attributes, and for mapping of land cover in the forest region of interest. These images depict a false colour hyperspectral image of a Douglas fir forest on Vancouver Island at a resolution of 60 cm. The imagery was acquired in the fall of 1995 by the CASI (Compact Airborne Imaging Spectrometer). Attributes obtained from the imagery (a subset is shown) include:
Stand Area (hectares) 9.0
Total number of trees 520
Tree density (stems/ha) 58
Crown closure (%) 12.46
Average tree crown area (sq m) 21.47

The corresponding land cover map contains the following classes:

- **Dark green**: conifers
- **Green**: lower branches
- **Light purple**: gravel
- **Yellow**: deciduous
- **Orange**: dry ground cover
- **Red**: wet ground cover
- **Blue (light)**: water
- **Blue (dark)**: deep or clear water

All imagery courtesy of MacMillan Bloedel and ITRES Research Limited.
5.3.3 Burn Mapping

Background
Fire is part of the natural reproductive cycle of many forests revitalizing growth by opening seeds and releasing nutrients from the soil. However, fires can also spread quickly and threaten settlements and wildlife, eliminate timber supplies, and temporarily damage conservation areas. Information is needed to help control the extent of fire, and to assess how well the forest is recovering following a burn.

Why remote sensing?
Remote sensing can be used to detect and monitor forest fires and the regrowth following a fire. As a surveillance tool, routine sensing facilitates observing remote and inaccessible areas, alerting monitoring agencies to the presence and extent of a fire. NOAA AVHRR thermal data and GOES meteorological data can be used to delineate active fires and remaining "hot-spots" when optical sensors are hindered by smoke, haze, and/or darkness. Comparing burned areas to active fire areas provides information as to the rate and direction of movement of the fire. Remote sensing data can also facilitate route planning for both access to, and escape from, a fire, and supports logistics planning for fire fighting and identifying areas not successfully recovering following a burn.

Years following a fire, updates on the health and regenerative status of an area can be obtained by a single image, and multitemporal scenes can illustrate the progression of vegetation from pioneer species back to a full forest cover.

Data requirements
While thermal data is best for detecting and mapping ongoing fires, multispectral (optical and near-infrared) data are preferred for observing stages of growth and phenology in a previous burn area. The relative ages and area extent of burned areas can be defined and delineated, and health of the successive vegetation assessed and monitored. Moderate spatial coverage, high to moderate resolution, and a low turnaround time are required for burn mapping. On the other hand, fire detection and monitoring requires a large spatial coverage, moderate resolution and a very quick turnaround to facilitate response.

Canadian vs. International
Requirements for burn mapping are the same, except where cloud cover precludes the used of optical images. In this case, radar can be used to monitor previous burn areas, and is effective from the second year following a burn, onwards.
Case study (example) Northwest Territory Burn

In the western Northwest Territories along the Mackenzie River, boreal forest covers much of the landscape. Natives rely on the forests for hunting and trapping grounds, and the sensitive northern soil and permafrost are protected from erosion by the forest cover. In the early 1990's a huge fire devastated the region immediately east of the Mackenzie and threatened the town of Fort Norman, a native town south of Norman Wells.

The extent of the burned area, and the areas still burning, can be identified on this NOAA scene, as dark regions (A). The lake in the upper right is Great Bear Lake, and the lake to the lower right is Great Slave Lake. The distance represented by the yellow line is approximately 580 km. The course of the Mackenzie River can be seen to the left of these lakes. Fort Norman (B) is located at the junction of the Mackenzie River and Great Bear River, leading out of Great Bear Lake. At that location, the fire is on both sides of the river. Norman Wells (C) is known as an oil producing area, and storage silos, oil rigs, homes, and the only commercial airport in that part of the country were threatened. Fires in this region are difficult to access because of the lack of roads into the region. Winter roads provide only seasonal access to vehicles in this part of Canada. The small population base also makes it difficult to control, let alone fight, a fire of this magnitude.

Haze and smoke reflect a large amount of energy at shorter wavelengths and appear as blue on this image.
5.4 Geology

Geology involves the study of landforms, structures, and the subsurface, to understand physical processes creating and modifying the earth's crust. It is most commonly understood as the exploration and exploitation of mineral and hydrocarbon resources, generally to improve the conditions and standard of living in society. Petroleum provides gas and oil for vehicle transportation, aggregate and limestone quarrying (sand and gravel) provides ingredients for concrete for paving and construction, potash mines contribute to fertilizer, coal to energy production, precious metals and gems for jewelry, diamonds for drill bits, and copper, zinc and assorted minerals for a variety of uses. Geology also includes the study of potential hazards such as volcanoes, landslides, and earth quakes, and is thus a critical factor for geotechnical studies relating to construction and engineering. Geological studies are not limited to Earth - remote sensing has been used to examine the composition and structure of other planets and moons.

Remote sensing is used as a tool to extract information about the land surface structure, composition or subsurface, but is often combined with other data sources providing complementary measurements. Multispectral data can provide information on lithology or rock composition based on spectral reflectance. Radar provides an expression of surface topography and roughness, and thus is extremely valuable, especially when integrated with another data source to provide detailed relief.

Remote sensing is not limited to direct geology applications - it is also used to support logistics, such as route planning for access into a mining area, reclamation monitoring, and generating basemaps upon which geological data can be referenced or superimposed.

Geological applications of remote sensing include the following:

- surficial deposit / bedrock mapping
- lithological mapping
- structural mapping
- sand and gravel (aggregate) exploration/ exploitation
- mineral exploration
- hydrocarbon exploration
- environmental geology
- geobotany
- baseline infrastructure

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- sedimentation mapping and monitoring
- event mapping and monitoring
- geo-hazard mapping
- planetary mapping
5.4.1 Structural Mapping & Terrain Analysis

Syncline structures (in Pennsylvania) on SAR imagery

Background
Structural geology plays an important role in mineral and hydrocarbon exploration, and potential hazard identification and monitoring.

Structural mapping is the identification and characterization of structural expression. Structures include faults, folds, synclines and anticlines and lineaments. Understanding structures is the key to interpreting crustal movements that have shaped the present terrain. Structures can indicate potential locations of oil and gas reserves by characterizing both the underlying subsurface geometry of rock units and the amount of crustal deformation and stress experienced in a certain locale. Detailed examination of structure can be obtained by geophysical techniques such as seismic surveying.

Structures are also examined for clues to crustal movement and potential hazards, such as earthquakes, landslides, and volcanic activity. Identification of fault lines can facilitate land use planning by limiting construction over potentially dangerous zones of seismic activity.

Why remote sensing?
A synoptic view of regional scale is a much different perspective than point ground observations when trying to map structural elements. Remote sensing offers this perspective and allows a geologist to examine other reference ancillary data simultaneously and synergistically, such as geo-magnetic information.

Certain remote sensing devices offer unique information regarding structures, such as in the relief expression offered by radar sensors. Comparing surface expression to other geological information may also allow patterns of association to be recognized. For instance, a rock unit may be characterized by a particular radar texture which may also correlate with a high magnetic intensity or geochemical anomaly. Remote sensing is most useful in combination, or in synergy, with complementary datasets.

A benefit of side looking radar is that the illumination conditions can be controlled, and the most
appropriate geometry used for type of terrain being examined. Uniform illumination conditions provided by the sun, especially at equatorial latitudes, are usually not conducive to highlighting relief features. An extra benefit of airborne SAR sensors is that acquisition missions can be customized to orient the flightline parallel to the target orientation, to maximize the illumination and shadow effect.

**Data requirements**

In areas where vegetation cover is dense, it is very difficult to detect structural features. A heavy canopy will visually blanket the underlying formation, limiting the use of optical sensors for this application. Radar however, is sensitive enough to topographic variation that it is able to discern the structural expression reflected or mirrored in the tree top canopy, and therefore the structure may be clearly defined on the radar imagery.

Structural analyses are conducted on regional scales, to provide a comprehensive look at the extent of faults, lineaments and other structural features. Geologic features are typically large (kilometre scale) and applications therefore require small-scale imagery to cover the extent of the element of interest. Aerial photos can be used in temperate areas where large-scale imagery is required, particularly to map potential geohazards (e.g. landslides).

Structural mapping applications generally are not time sensitive (other than for project deadlines!) and so a fast turnaround is not required. Unless a time series analysis of crustal deformation is being conducted, frequency of imaging is not a critical issue either. The key factor for remotely sensed data are that they provide some information on the spatial distribution and surficial relief of the structural elements. Radar is well suited to these requirements with its side-looking configuration. Imaging with shallow incidence angles enhances surficial relief and structure. **Shadows** can be used to help define the structure height and shape, and thus increasing the shadow effect, while shallow incidence angles may benefit structural analysis.

**Canadian vs. International requirements**

Requirements for remote sensing parameters of structural features are fairly constant throughout the world. Those areas of persistent cloud cover will benefit from radar imaging, while areas at very high or low latitudes can benefit from low sun angles to highlight subtle relief for optical imaging.
Case study (example): Port Coldwell, Ontario: A case for SAR integration

The structural information provided by radar complements other spatial datasets. When integrated together, SAR and spatial geological datasets provide a valuable source of geological information. In this example, radioactivity information of the area of Port Coldwell, Ontario, was provided by an airborne gamma-ray spectrometry survey, which collected potassium, thorium, and uranium readings. This data is informative, but it is difficult to put the information into perspective without the layout and recognizable characteristics of the landscape. Airborne SAR image data was also acquired of the same region. The SAR image is quite interesting in terms of micro-topography and structure, but does not provide any other geo-technical information about the terrain. These two datasets were integrated, using an IHS approach (intensity-hue-saturation to replace the conventional red-green-blue colour display). The airborne gamma-ray spectrometry data are coded as the hue and saturation information, while the SAR terrain information is coded as the intensity information. The resulting integrated image is an excellent display of structural, relief, and natural radioactivity information, allowing a geologist to have a comprehensive view of the data with only one image.
5.4.2 Geologic Unit Mapping

Background
Mapping geologic units consists primarily of identifying physiographic units and determining the rock lithology or coarse stratigraphy of exposed units. These units or formations are generally described by their age, lithology and thickness. Remote sensing can be used to describe lithology by the colour, weathering and erosion characteristics (whether the rock is resistant or recessive), drainage patterns, and thickness of bedding.

Unit mapping is useful in oil and mineral exploration, since these resources are often associated with specific lithologies. Structures below the ground, which may be conducive to trapping oil or hosting specific minerals, often manifest themselves on the Earth's surface. By delineating the structures and identifying the associated lithologies, geologists can identify locations that would most feasibly contain these resources, and target them for exploration. Bedrock mapping is critical to engineering, construction, and mining operations, and can play a role in land use and urban planning. Understanding the distribution and spatial relationships of the units also facilitates interpretation of the geologic history of the Earth's surface.

In terms of remote sensing, these "lithostratigraphic" units can be delineated by their spectral reflectance signatures, by the structure of the bedding planes, and by surface morphology.

Why remote sensing?
Remote sensing gives the overview required to 1) construct regional unit maps, useful for small scale analyses, and planning field traverses to sample and verify various units for detailed mapping; and 2) understand the spatial distribution and surface relationships between the units. VIR remote sensing provides the multispectral information relating to the composition of the unit, while radar can contribute textural information. Multiple data sources can also be integrated to provide a comprehensive view of the lithostratigraphy.

Stereo imagery can also facilitate delineation and identification of units by providing a three dimensional view of the local relief. Some rocks are resistant to erosion, whereas others erode easily. Identification elements such as weathering manifestations may be apparent on high or medium resolution imagery and airphotos.

Images or airphotos can be taken into the field and used as basemaps for field analysis.

Data requirements
Two different scales of mapping require slightly different imaging sources and parameters.

1. For site specific analysis, airphotos provide a high resolution product that can provide information on differential weathering, tone, and microdrainage. Photos may be easily viewed in stereo to assess relief characteristics.

2. Regional overviews require large coverage area and moderate resolution. An excellent data source for regional applications is a synergistic combination of radar and optical images to highlight terrain and textural information.

In either case, frequency of imaging is not an issue since in many cases the geological features of interest remain relatively static. Immediate turnaround is also not critical.

Canada vs. International
Requirements for this application do not differ significantly around the world. One of the
biggest problems faced by both temperate and tropical countries is that dense forest covers much of the landscape. In these areas, geologists can use remote sensing to infer underlying lithology by the condition of vegetation growing above it. This concept is called "geobotany". The underlying principle is that the mineral and sedimentary constituents of the bedrock may control or influence the condition of vegetation growing above.

In reality, the topography, structure, surficial materials, and vegetation combine to facilitate geologic unit interpretation and mapping. Optimal use of remote sensing data therefore, is one that integrates different sources of image data, such as optical and radar, at a scale appropriate to the study.

Image example
Even once geological unit maps are created, they can still be presented more informatively by encompassing the textural information provided by SAR data. A basic geological unit map can be made more informative by adding textural and structural information. In this example of the Sudbury, Ontario region, an integration transform was used to merge the map data (bedrock and structural geology information, 1992) with the SAR image data. The resulting image can be used on a local or regional scale to detect structural trends within and between units. The areas common to each image are outlined in black.
5.5 Hydrology

Hydrology is the study of water on the Earth's surface, whether flowing above ground, frozen in ice or snow, or retained by soil. Hydrology is inherently related to many other applications of remote sensing, particularly forestry, agriculture and land cover, since water is a vital component in each of these disciplines. Most hydrological processes are dynamic, not only between years, but also within and between seasons, and therefore require frequent observations. Remote sensing offers a synoptic view of the spatial distribution and dynamics of hydrological phenomena, often unattainable by traditional ground surveys. Radar has brought a new dimension to hydrological studies with its active sensing capabilities, allowing the time window of image acquisition to include inclement weather conditions or seasonal or diurnal darkness.

Examples of hydrological applications include:

- wetlands mapping and monitoring,
- soil moisture estimation,
- snow pack monitoring / delineation of extent,
- measuring snow thickness,
- determining snow-water equivalent,
- river and lake ice monitoring,
- flood mapping and monitoring,
- glacier dynamics monitoring (surges, ablation)
- river/delta change detection
- drainage basin mapping and watershed modelling
- irrigation canal leakage detection
- irrigation scheduling
5.5.1 Flood Delineation & Mapping

Background
A natural phenomenon in the hydrological cycle is flooding. Flooding is necessary to replenish soil fertility by periodically adding nutrients and fine grained sediment; however, it can also cause loss of life, temporary destruction of animal habitat and permanent damage to urban and rural infrastructure. Inland floods can result from disruption to natural or man-made dams, catastrophic melting of ice and snow (jökulhlaups in Iceland), rain, river ice jams and/or excessive runoff in the spring.

Why remote sensing?
Remote sensing techniques are used to measure and monitor the areal extent of the flooded areas, to efficiently target rescue efforts and to provide quantifiable estimates of the amount of land and infrastructure affected. Incorporating remotely sensed data into a GIS allows for quick calculations and assessments of water levels, damage, and areas facing potential flood danger. Users of this type of data include flood forecast agencies, hydropower companies, conservation authorities, city planning and emergency response departments, and insurance companies (for flood compensation). The identification and mapping of floodplains, abandoned river channels, and meanders are important for planning and transportation routing.

Data requirements
Many of these users of remotely sensed data need the information during a crisis and therefore require "near-real time turnaround". Turnaround time is less demanding for those involved in hydrologic modelling, calibration/validation studies, damage assessment and the planning of flood mitigation. Flooding conditions are relatively short term and generally occur during inclement weather, so optical sensors, although typically having high information content for this purpose, can not penetrate through the cloud cover to view the flooded region below. For these reasons, active SAR sensors are particularly valuable for flood monitoring. RADARSAT in particular offers a high turnaround interval, from when the data is acquired by the sensor, to when the image is delivered to the user on the ground. The land/water
interface is quite easily discriminated with SAR data, allowing the flood extent to be delineated and mapped. The SAR data is most useful when integrated with a pre-flood image, to highlight the flood-affected areas, and then presented in a GIS with cadastral and road network information.

**Canada vs. International**

Requirements for this application are similar the world over. Flooding can affect many areas of the world, whether coastal or inland, and many of the conditions for imaging are the same. Radar provides excellent water/land discrimination and is reliable for imaging despite most atmospheric limitations.

**Case study (example):**

**RADARSAT MAPS THE MANITOBA SEA:**

**THE FLOODS OF 1997**

In 1997, the worst Canadian flood of the 20th century inundated prairie fields and towns in the states of Minnesota, North Dakota, and the Canadian province of Manitoba. By May 5th, 25,000 residents of Manitoba had been evacuated from their homes, with 10,000 more on alert. The watershed of the Red River, flowing north from the United States into Canada, received unusually high winter snowfalls and heavy precipitation in April. These factors, combined with the northward flow into colder ground areas and very flat terrain beyond the immediate floodplain, caused record flooding conditions, with tremendous damage to homes and property, in addition to wildlife and livestock casualties. For weeks emergency response teams, area residents, and the media monitored the extent of the flood, with some input from remote sensing techniques. It is impossible to imagine the scale of flooding from a ground perspective, and even video and photographs from aircraft are unable to show the full extent. Spectacular satellite images however, have shown the river expand from a 200 m wide ribbon, to a body of water measuring more than 40 km across. Towns protected by sand-bag dikes, were dry islands in the midst of what was described as the "Red Sea". Many other towns weren't as fortunate, and home and business owners were financially devastated by their losses.

Insurance agents faced their own flood of claims for property, businesses, and crops ruined or damaged by the Red River flood. To quickly assess who is eligible for compensation, the insurance companies can rely on remotely sensed data to delineate the flood extent, and GIS databases to immediately identify whose land was directly affected. City and town planners could also use the images to study potential locations for future dike reinforcement and construction, as well as residential planning.
Both NOAA-AVHRR and RADARSAT images captured the scale and extent of the flood. The AVHRR sensors onboard the NOAA satellites provided **small-scale views** of the entire flood area from Lakes Manitoba and Winnipeg south to the North Dakota - South Dakota border. Some of the best images are those taken at night in the thermal infrared wavelengths, where the cooler land appears dark and the warmer water (A) appears white. Manmade dikes, such as the Brunkild Dike (B), were quickly built to prevent the flow of water into southern Winnipeg. Dikes are apparent on the image as very regular straight boundaries between the land and floodwater. Although the city of Winnipeg (C) is not clearly defined, the Winnipeg floodway (D) immediately to the east, paralleling the Red River at the northeast end of the flood waters, is visible since it is full of water. The floodway was designed to divert excess water flow from the Red River outside of the city limits. In this case, the volume of water was simply too great for the floodway to carry it all, and much of the flow backed up and spread across the prairie.

**RADARSAT** provided some excellent views of the flood, because of its ability to image in darkness or cloudy weather conditions, and its sensitivity to the land/water differences. In this image, the flood water (A) completely surrounds the town of Morris (B), visible as a bright patch within the dark flood water. The flooded areas appear dark on radar imagery because very little of the incident microwave energy directed toward the smooth water surface returns back to the sensor. The town however, has many angular (corner) reflectors primarily in the form of buildings, which cause the incident energy to "bounce" back to the sensor.

Transportation routes can still be observed. A railroad, on its raised bed, can be seen amidst the water just above (C), trending southwest - northeast. Farmland relatively unaffected by the flood (D) is quite variable in its backscatter response. This is due to differences in each field's soil moisture and surface roughness.
5.5.2 Soil Moisture

Background
Soil moisture is an important measure in determining crop yield potential in Canada and in drought-affected parts of the world (Africa) and for watershed modelling. The moisture content generally refers to the water contained in the upper 1-2m of soil, which can potentially evaporate into the atmosphere. Early detection of dry conditions which could lead to crop damage, or are indicative of potential drought, is important for amelioration efforts and forecasting potential crop yields, which in turn can serve to warn farmers, prepare humanitarian aid to affected areas, or give international commodities traders a competitive advantage. Soil moisture conditions may also serve as a warning for subsequent flooding if the soil has become too saturated to hold any further runoff or precipitation. Soil moisture content is an important parameter in watershed modelling that ultimately provides information on hydroelectric and irrigation capacity. In areas of active deforestation, soil moisture estimates help predict amounts of run-off, evaporation rates, and soil erosion.

Why remote sensing? Remote sensing offers a means of measuring soil moisture across a wide area instead of at discrete point locations that are inherent with ground measurements. RADAR is effective for obtaining qualitative imagery and quantitative measurements, because radar backscatter response is affected by soil moisture, in addition to topography, surface roughness and amount and type of vegetative cover. Keeping the latter elements static, multitemporal radar images can show the change in soil moisture over time. The radar is actually sensitive to the soil's dielectric constant, a property that changes in response to the amount of water in the soil.

Users of soil moisture information from remotely sensed data include agricultural marketing and administrative boards, commodity brokers, large scale farming managers, conservation authorities, and hydroelectric power producers.

Data requirements
Obviously, a sensor must be sensitive to moisture conditions, and radar satisfies this requirement better than optical sensors. Frequent and regular (repeated) imaging is required during the growing season to follow the change in moisture conditions, and a quick turnaround is required for a farmer to respond to unsuitable conditions (excessive moisture or dryness) in a timely manner. Using high resolution images, a farmer can target irrigation efforts more accurately. Regional coverage allows an overview of soil and growing conditions of interest to agricultural agencies and authorities.

Canada vs. International
Data requirements to address this application are similar around the world, except that higher resolution data may be necessary in areas such as Europe and Southeast Asia, where field and land parcel sizes are substantially smaller than in North America.

Case Study (example)
Rainfall distribution, Melfort, Saskatchewan, Canada

As with most Canadian prairie provinces, the topography of Saskatchewan is quite flat. The region is dominated by black and brown chernozemic soil characterized by a thick dark organic horizon, ideal for growing cereal crops such as wheat. More recently, canola has been introduced as an alternative to cereal crops.
Shown here is a radar image acquired July 7, 1992 by the European Space Agency (ESA) ERS-1 satellite. This synoptic image of an area near Melfort, Saskatchewan details the effects of a localized precipitation event on the microwave backscatter recorded by the sensor. Areas where precipitation has recently occurred can be seen as a bright tone (bottom half) and those areas unaffected by the event generally appear darker (upper half). This is a result of the complex dielectric constant which is a measure of the electrical properties of surface materials. The dielectric property of a material influences its ability to absorb microwave energy, and therefore critically affects the scattering of microwave energy.

The magnitude of the radar backscatter is proportional to the dielectric constant of the surface. For dry, naturally occurring materials, this is in the range of 3 - 8, and may reach values as high as 80 for wet surfaces. Therefore the amount of moisture in the surface material directly affects the amount of backscattering. For example, the lower the dielectric constant, the more incident energy is absorbed, the darker the object will be on the image.
5.6 Sea Ice

For people living in northern environments, ice is a common phenomenon that affects our local activities. Most of us however, don't consider its larger regional or global implications. Ice covers a substantial part of the Earth's surface and is a major factor in commercial shipping and fishing industries, Coast Guard and construction operations, and global climate change studies. Polar sea ice seasonally covers an even larger area, roughly equal in size to the North American continent, 25 million km².

Its extensive distribution means that sea ice plays a large role in the albedo of the earth. Albedo is a term referring to the measure of reflectivity of the Earth's surface. Ice and snow are highly reflective and changes in their distribution would affect how much solar energy is absorbed by the earth. Under warming conditions, the ice would melt, and less incoming energy would be reflected, thereby potentially increasing the warming trend. The opposite may also be true - an increase of ice due to cooler conditions would reflect even more of the incoming solar energy, potentially propagating even colder conditions. Of course these potential changes in sea ice distribution are of concern to scientists studying global climate change, as are sea ice interactions with the ocean and atmosphere.

During winter in the northern hemisphere, ice creates a substantial barrier to both lake and ocean going vessels trying to reach ports or navigating along coastlines. Ice floes, pack ice and icebergs create potential hazards to navigation, while landfast ice hinders access to the shore. Ice breakers are often used to create routes for ships to follow from the open water to their ports. In Canada, two important locations for this type of operation are the Gulf of St. Lawrence /Great Lakes and the Canadian Arctic. The Gulf is the main route for international cargo vessels headed for Montreal and Québec, and is affected by ice through the winter and spring. Canada's Arctic is home to mineral and hydrocarbon reserves that require shipping for construction equipment, supplies, and transport of resources to refineries and populated markets. In addition, the main method of re-supply for northern communities is by sea. In both areas, information regarding ice conditions, type, concentration and movement are required.

To address these demands, ice analysis charts, daily ice hazard bulletins, seasonal forecasts, and tactical support for observation are provided. In Canada, the Canadian Ice Service is responsible for acquiring and distributing this information and appropriate products. They also maintain an ice information archive which contains useful data for environmental impact assessments, risk assessment, short-term and seasonal route planning for ships, efficient resource transportation and infrastructure development.
Remote sensing data can be used to identify and map different ice types, locate leads (large navigable cracks in the ice), and monitor ice movement. With current technology, this information can be passed to the client in a very short timeframe from acquisition. Users of this type of information include the Coast Guard, port authorities, commercial shipping and fishing industries, ship builders, resource managers (oil and gas / mining), infrastructure construction companies and environmental consultants, marine insurance agents, scientists, and commercial tour operators.

Examples of sea ice information and applications include:

- ice concentration
- ice type / age / motion
- iceberg detection and tracking
- surface topography
- tactical identification of leads: navigation: safe shipping routes/rescue
- ice condition (state of decay)
- historical ice and iceberg conditions and dynamics for planning purposes
- wildlife habitat
- pollution monitoring
- meteorological / global change research
5.6.1 Ice type and concentration

Background
Ships navigating through high latitude seas (both northern and southern) are often faced with obstacles of pack ice and moving ice floes. Ice breakers are designed to facilitate travel in these areas, but they require knowledge about the most efficient and effective route through the ice. It is important to know the extent of the ice, what type of ice it is, and the concentration and distribution of each type. This information is also valuable for offshore exploration and construction activities, as well as coastal development planning.

Ice isn’t simply ice!
Sea ice isn't a uniform, homogeneous unit. What appears to be a single cover of ice can vary in roughness, strength, salinity, and thickness. Pack ice and ice floes consist of assemblages of different ice types patchworked together, intersected by dynamic leads or cracks. Ice is usually defined by its age - either as new, first-year or multi-year ice. New ice is smooth and relatively thin (5-30 cm) and provides the least resistance to ice breakers. First year ice is older and thicker than new ice (30-200cm) and can pose a significant hazard to all vessels, including icebreakers. When deformed into rubble fields and ridges, first year ice types can become impassable. Ice that survives into a second and later years, generally becomes thicker (>2m) and declines in salinity, increasing the internal strength. This ice is a dangerous hazard to ships and off-shore structures. Ice charts are maps of different ice types and concentration of ice, which are distributed to those working in marine environments where ice affects their operations.

Why remote sensing?
Observing ice conditions is best from a ground perspective, but this doesn't allow for determining the extent or distribution of the ice. Remote sensing from airborne or spaceborne sensors provides this very valuable view. The areas of ice can be easily mapped from an image, and when georeferenced, provide a useful information source. Remote sensing technology is capable of providing enough information for an analyst to identify ice type (and thus infer ice thickness), and from this data, ice charts can be created and distributed to those who require the information.

Active radar is an excellent sensor to observe ice conditions because the microwave energy and imaging geometry combines to provide measures of both surface and internal characteristics. Backscatter is influenced by dielectric properties of the ice (in turn dependent
on salinity and temperature), surface factors (roughness, snow cover) and internal geometry / microstructure. Surface texture is the main contributor to the radar backscatter and it is this characteristic which is used to infer ice age and thickness. New ice tends to have a low return and therefore dark appearance on the imagery due to the specular reflection of incident energy off the smooth surface. First year ice can have a wide variety of brightness depending on the degree of roughness caused by ridging and rubbing. Multi-year ice has a bright return due to diffuse scattering from its low salinity, and porous structure.

Coarse resolution optical sensors such as NOAA's AVHRR provide an excellent overview of pack ice extent if atmospheric conditions are optimal (resolution = 1km).

Passive microwave sensing also has a role in sea ice applications. Objects (including people!) emit small amounts of microwave radiation, which can be detected by sensors. Sea ice and water emit substantially different amounts of radiation, so it is relatively easy to delineate the interface between the two. The SSM/I onboard the shuttle collected data in this manner. The main drawback of passive microwave sensors is their poor spatial resolution (approx. 25km) which is too coarse for tactical ice navigation.

**Data requirements**

Ocean ice occurs in extreme latitudes - the high Arctic and Antarctica. But ice also covers prime sea and lake shipping routes in northern countries, particularly Canada, Russia, Japan and northern European and Scandinavian countries. High latitude areas experience low solar illumination conditions in the winter when the ice is at a maximum. This has traditionally hindered remote sensing effectiveness, until the operationalization of radar sensors. The all weather / day - night, capabilities of SAR systems, makes radar remote sensing the most useful for ice type and concentration mapping.

To provide sufficient information for navigation purposes, the data must be captured frequently and must be processed and ready for use within a very short time frame. High resolution data covering 1-50 km is useful for immediate ship navigation, whereas coarse resolution (1-50km), large area coverage (100 - 2000km²) images are more useful for regional strategic route planning. For navigation purposes, the value of this information has a limited time window. However, for playing a role in increasing our knowledge about climate dynamics and ice as an indicator of global climate change, the data has long term value.

RADARSAT has orbital parameters and a radar sensor designed to address the demands of the ice applications community. The Arctic area is covered once a day by RADARSAT and systems are in place to efficiently download the data direct from the ground processing station right to the vessel requiring the information, in a time frame of four hours. Airborne radar sensors are also useful for targeting specific areas and providing high resolution imagery unavailable from commercial spaceborne systems. Airborne radar is more expensive but has the benefit of directly targeting the area of interest, which may be important for time critical information, such as tactical navigation in dynamic ice. Winter is the preferred season for acquiring radar scenes for ice typing. Melting and wet conditions reduce the contrast between ice types which makes information extraction more difficult.

Future remote sensing devices are planned to provide comprehensive measurements of sea ice extent.
5.6.2 Ice motion

Background
Ice moves quickly and sometimes unpredictably in response to ocean currents and wind. Ice floes can move like tectonic plates, sometimes breaking apart like a rift valley or colliding in a style similar to the Indian and Asian plates, creating a smaller version of the Himalayan Mountains - a series of ridges and blocky ice rubble. Vessels can be trapped or damaged by the pressure resulting from these moving ice floes. Even offshore structures can be damaged by the strength and momentum of moving ice. For these reasons it is important to understand the ice dynamics in areas of construction or in the vicinity of a shipping/fishing route.

Why remote sensing?
Remote sensing gives a tangible measure of direction and rate of ice movement through mapping and change detection techniques. Ice floes actually have individual morphological characteristics (shape, structures) that allow them to be distinguished from one another. The floes can be mapped and their movement monitored to facilitate in planning optimum shipping routes, to predict the effect of ice movement on standing structures (bridges, platforms). Users of this type of information include the shipping, fishing, and tourism industries, as well as engineers involved in offshore platform and bridge design and maintenance.

Data requirements
Monitoring of ice movement requires frequent and reliable imaging. The revisit interval must be frequent enough to follow identifiable features before tracking becomes difficult due to excessive movement or change in appearance. Active microwave sensing (radar) provides a reliable source of imaging under all weather and illumination conditions. RADARSAT provides this type of sensor and is a spaceborne platform, which is advantageous for routine imaging operations. The orbital path ensures that Arctic areas are covered daily which meets the requirement for frequent imaging.

The resolution and imaging frequency requirements for ice motion tracking vary with the size of floes and the ice dynamics in a region. In areas of large slow moving floes (e.g. Beaufort Sea), 1km resolution data over 10 day intervals is adequate. In dynamic marginal ice zones (e.g. Gulf of St. Lawrence), 100m resolution data over 12-24 hr intervals is required.

Case study (example)
The significance of the force and potential effect of ice movement was brought to light recently with the design and construction of the Confederation Bridge, a 13km link from Prince Edward Island, in Canada's Maritimes, across Northumberland Strait to New Brunswick on Canada's mainland. Crossing a strait that endures ice floes moving in response to winds, currents and tides through a narrow arm of the Gulf of St. Lawrence, the bridge will have to withstand tremendous forces from moving ice impacting its supports.

"More effort was spent related to the ice engineering aspect of this bridge than probably on any other [similar] structure that has ever been built" Dr. Gus Cammaert

Ice floes in Northumberland Strait are dynamic due to oceanic and atmospheric forces, yet constricted in their movement. The result is compression collisions creating large rubbley ice masses that extend vertically above and below the water level up to 20 m1 (each direction). These ice masses have the potential of critically damaging any structure impeding its movement back and forth in the strait. The design and engineering of the bridge had to take
into account both the thickness and actual constant movement of the ice. Ice information archived at the Canadian Ice Service contributed to the understanding of the ice dynamics in the strait, and its tensile properties, critical for setting engineering parameters.

During construction, a radar image of the bridge site was obtained to observe the impact of the bridge supports on the flow of ice around the site. Due to the design of the supports, which are cone-shaped at the waterline to help bend and break the ice, the ice cracked and flowed around the supports. This is one image where ice movement can be inferred from a single image and does not require multi-temporal scenes. In the image, the ice can be seen flowing from bottom to the top with the wakes of rubble created by the bridge supports clearly visible.

Remote sensing will be used to monitor the effect of the bridge on the ice movement and ensure that ice build up isn't occurring beyond expectations. As exemplified in the image, the bridge will have an impact on the ice dynamics, by breaking up large floes into smaller pieces which may accumulate on the shore in piles. This effect will be monitored, as will any subsequent effects on microclimate, which might affect the agriculture or fishing industries of PEI.

**Bridge web site:**

For more information on ice applications:
Canadian Ice Service, Environment Canada:
http://ice-glaces.ec.gc.ca/App/WsvPageDsp.cfm?ID=1&Lang=eng
Although the terms land cover and land use are often used interchangeably, their actual meanings are quite distinct. Land cover refers to the surface cover on the ground, whether vegetation, urban infrastructure, water, bare soil or other. Identifying, delineating and mapping land cover is important for global monitoring studies, resource management, and planning activities. Identification of land cover establishes the baseline from which monitoring activities (change detection) can be performed, and provides the ground cover information for baseline thematic maps.

Land use refers to the purpose the land serves, for example, recreation, wildlife habitat, or agriculture. Land use applications involve both baseline mapping and subsequent monitoring, since timely information is required to know what current quantity of land is in what type of use and to identify the land use changes from year to year. This knowledge will help develop strategies to balance conservation, conflicting uses, and developmental pressures. Issues driving land use studies include the removal or disturbance of productive land, urban encroachment, and depletion of forests.

It is important to distinguish this difference between land cover and land use, and the information that can be ascertained from each. The properties measured with remote sensing techniques relate to land cover, from which land use can be inferred, particularly with ancillary data or a priori knowledge.

Land cover / use studies are multidisciplinary in nature, and thus the participants involved in such work are numerous and varied, ranging from international wildlife and conservation foundations, to government researchers, and forestry companies. Regional (in Canada, provincial) government agencies have an operational need for land cover inventory and land use monitoring, as it is within their mandate to manage the natural resources of their respective regions. In addition to facilitating sustainable management of the land, land cover and use information may be used for planning, monitoring, and evaluation of development, industrial activity, or reclamation. Detection of long term changes in land cover may reveal a response to a shift in local or regional climatic conditions, the basis of terrestrial global monitoring.

Ongoing negotiations of aboriginal land claims have generated a need for more stringent
knowledge of land information in those areas, ranging from cartographic to thematic information.

Resource managers involved in parks, oil, timber, and mining companies, are concerned with both land use and land cover, as are local resource inventory or natural resource agencies. Changes in land cover will be examined by environmental monitoring researchers, conservation authorities, and departments of municipal affairs, with interests varying from tax assessment to reconnaissance vegetation mapping. Governments are also concerned with the general protection of national resources, and become involved in publicly sensitive activities involving land use conflicts.

Land use applications of remote sensing include the following:

- natural resource management
- wildlife habitat protection
- baseline mapping for GIS input
- urban expansion / encroachment
- routing and logistics planning for seismic / exploration / resource extraction activities
- damage delineation (tornadoes, flooding, volcanic, seismic, fire)
- legal boundaries for tax and property evaluation
- target detection - identification of landing strips, roads, clearings, bridges, land/water interface
5.7.1 Land Use Change (Rural / Urban)

Background
As the Earth’s population increases and national economies continue to move away from agriculture based systems, cities will grow and spread. The urban sprawl often infringes upon viable agricultural or productive forest land, neither of which can resist or deflect the overwhelming momentum of urbanization. City growth is an indicator of industrialization (development) and generally has a negative impact on the environmental health of a region.

The change in land use from rural to urban is monitored to estimate populations, predict and plan direction of urban sprawl for developers, and monitor adjacent environmentally sensitive areas or hazards. Temporary refugee settlements and tent cities can be monitored and population amounts and densities estimated.

Analyzing agricultural vs. urban land use is important for ensuring that development does not encroach on valuable agricultural land, and to likewise ensure that agriculture is occurring on the most appropriate land and will not degrade due to improper adjacent development or infrastructure.

Why remote sensing?
With multi-temporal analyses, remote sensing gives a unique perspective of how cities evolve. The key element for mapping rural to urban landuse change is the ability to discriminate between rural uses (farming, pasture forests) and urban use (residential, commercial, recreational). Remote sensing methods can be employed to classify types of land use in a practical, economical and repetitive fashion, over large areas.

Data requirements
Requirements for rural / urban change detection and mapping applications are 1) high resolution to obtain detailed information, and 2) multispectral optical data to make fine distinction among various land use classes.

Sensors operating in the visible and infrared portion of the spectrum are the most useful data sources for land use analysis. While many urban features can be detected on radar and other imagery (usually because of high reflectivity), VIR data at high resolution permits fine distinction among more subtle land cover/use classes. This would permit a confident identification of the urban fringe and the transition to rural land usage. Optical imagery acquired during winter months is also useful for roughly delineating urban areas vs. non-urban. Cities appear in dramatic contrast to smooth textured snow covered fields.
Radar sensors also have some use for all urban/rural delineation applications, due to the ability of the imaging geometry to enhance anthropogenic features, such as buildings, in the manner of corner reflectors. The optimum geometric arrangement between the sensor and urban area is an orientation of linear features parallel to the sensor movement, perpendicular to the incoming incident EM energy.

Generally, this type of application does not require a high turnaround rate, or a frequent acquisition schedule.

**Canada vs. International**

Throughout the world, requirements for rural/urban delineation will differ according to the prevalent atmospheric conditions. Areas with frequently cloudy skies may require the penetrating ability of radar, while areas with clear conditions can use airphoto, optical satellite or radar data. While the land use practices for both rural and urban areas will be significantly different in various parts of the world, the requirement for remote sensing techniques to be applied (other than the cloud-cover issue) will be primarily the need for fine spatial detail.

**Case study (example)**

This image of land cover change provides multitemporal information in the form of urban growth mapping. The colours represent urban land cover for two different years. The green delineates those areas of urban cover in 1973, and the pink, urban areas for 1985. This image dramatically shows the change in expansion of existing urban areas, and the clearing of new land for settlements over a 12 year period. This type of information would be used for upgrading government services, planning for increased transportation routes, etc.
5.7.2 Land Cover / Biomass Mapping

Background
Land cover mapping serves as a basic inventory of land resources for all levels of government, environmental agencies, and private industry throughout the world. Whether regional or local in scope, remote sensing offers a means of acquiring and presenting land cover data in a timely manner. Land cover includes everything from crop type, ice and snow, to major biomes including tundra, boreal or rainforest, and barren land.

Regional land cover mapping is performed by almost anyone who is interested in obtaining an inventory of land resources, to be used as a baseline map for future monitoring and land management. Programs are conducted around the world to observe regional crop conditions as well as investigating climatic change on a regional level through biome monitoring. Biomass mapping provides quantifiable estimates of vegetation cover, and biophysical information such as leaf area index (LAI), net primary productivity (NPP) and total biomass accumulations (TBA) measurements - important parameters for measuring the health of our forests, for example.

Why remote sensing?

There is nothing as practical and cost efficient for obtaining a timely regional overview of land cover than remote sensing techniques. Remote sensing data are capable of capturing changes in plant phenology (growth) throughout the growing season, whether relating to changes in chlorophyll content (detectable with VIR) or structural changes (via radar). For regional mapping, continuous spatial coverage over large areas is required. It would be difficult to detect regional trends with point source data. Remote sensing fulfills this requirement, as well as providing multispectral, multisource, and multitemporal information for an accurate classification of land cover. The multisource example image shows the benefit of increased information content when two data sources are integrated. On the left is TM data, and on the right it has been merged with airborne SAR.
Data requirements
For continental and global scale vegetation studies, moderate resolution data (1km) is appropriate, since it requires less storage space and processing effort, a significant consideration when dealing with very large area projects. Of course the requirements depend entirely on the scope of the application. Wetland mapping for instance, demands a critical acquisition period and a high resolution requirement.

Coverage demand will be very large for regional types of surveying. One way to adequately cover a large area and retain high resolution, is to create mosaics of the area from a number of scenes.

Land cover information may be time sensitive. The identification of crops, for instance canola, may require imaging on specific days of flowering, and therefore, reliable imaging is appropriate. Multi-temporal data are preferred for capturing changes in phenology throughout the growing season. This information may be used in the classification process to more accurately discriminate vegetation types based on their growing characteristics.

While optical data are best for land cover mapping, radar imagery is a good replacement in very cloudy areas.

Case study (example)
NBIOME: Classification of Canada's Land Cover

A major initiative of the Canada Centre for Remote Sensing is the development of an objective, reproducible classification of Canada's landcover. This classification methodology is used to produce a baseline map of the major biomes and land cover in Canada, which can then be compared against subsequent classifications to observe changes in cover. These changes may relate to regional climatic or anthropogenic changes affecting the landscape.

The classification is based on NOAA-AVHRR LAC (Local Area Coverage) (1km) data. The coarse resolution is required to ensure efficient processing and storage of the data, when dealing with such a large coverage area. Before the classification procedure, cloud-cover reduced composites of the Canadian landmass, each spanning 10 day periods are created. In the composite, the value for each pixel used is the...
one most cloud free of the ten days. This is determined by the highest normalized difference
vegetation index (NDVI) value, since low NDVI is indicative of cloud cover (low infrared
reflectance, high visible reflectance). The data also underwent a procedure to minimize
atmospheric, bidirectional, and contamination effects.

The composites consist of four channels, mean reflectance of AVHRR channels 1 and 2,
NDVI and area under the (temporal NDVI) curve. 16 composites (in 1993) were included in a
customized land cover classification procedure (named: classification by progressive
generalization), which is neither a supervised nor unsupervised methodology, but incorporates
aspects of both. The classification approach is based on finding dominant spectral clusters
and conducting progressive merging methodology. Eventually the clusters are labelled with
the appropriate land cover classes. The benefit is that the classification is more objective than
a supervised approach, while not controlling the parameters of clustering, which could alter
the results.

The result of this work is an objective, reproducible classification of Canada's land cover.
5.8 Mapping

Mapping constitutes an integral component of the process of managing land resources, and mapped information is the common product of analysis of remotely sensed data. Natural features and manufactured infrastructures, such as transportation networks, urban areas, and administrative boundaries can be presented spatially with respect to referenced co-ordinate systems, which may then be combined with thematic information. Baseline, thematic, and topographic maps are essential for planning, evaluating, and monitoring, for military or civilian reconnaissance, or land use management, particularly if digitally integrated into a geographic information system as an information base. Integrating elevation information is crucial to many applications and is often the key to the potential success of present day mapping programs.

Canada has been, and continues to be a world leader in mapping technology. Canada's immense land area with a rich resource potential, coupled with a small population base has necessitated the development of thorough and efficient mechanisms of investigating and recording land information. Traditionally, this information was obtained through surveying and photogrammetric techniques, which have been costly and time consuming, particularly for periodic revision of outdated information. Recent advances in computer technology (speed, data handling and storage capability) and a growing demand for digital databases and computer based mapping production capabilities have encouraged the use of remotely sensed information as a data source for cartographic applications.

There is a growing demand for the utilization of remote sensing data in map production, since the following benefits may be provided: stereo coverage, frequent revisits, timely delivery, wide area coverage, low labour intensity, virtually global coverage, and storage in digital format to facilitate subsequent updating and compatibility with current GIS technology.

End users of base maps and mapping products include resource companies (forestry, mining, oil), support and service industries (engineering), utility and infrastructure development agencies (pipelines, telecommunications, transportation, power), government mapping agencies, and the military. This diversification from traditionally military users to commercial applications has resulted in a greater demand for a wider range of mapping products, with emphasis placed upon the benefits of improved information content and scale, and accuracy versus data costs.

Canadian companies offering mapping services are likely to be looking abroad, as the greatest commercial potential exists within the international community. Developing countries
are currently initiating mapping programs to cover large unsurveyed areas to increase their
topographic and planimetric knowledge base. The derived information will be used to support
territorial sovereignty issues, assess and monitor resource potential and exploitation, and
encourage economic opportunity. Radar data will be relied on in tropical areas for remote
sensing mapping solutions.

Mapping applications of remote sensing include the following:

1. planimetry
2. digital elevation models (DEM's)
3. baseline thematic mapping / topographic mapping
5.8.1 Planimetry

Background
Planimetry consists of the identification and geolocation of basic land cover (e.g. forest, marsh), drainage, and anthropogenic features (e.g. urban infrastructure, transportation networks) in the x, y plane. Planimetric information is generally required for large-scale applications - urban mapping, facilities management, military reconnaissance, and general landscape information.

Why remote sensing?
Land surveying techniques accompanied by the use of a GPS can be used to meet high accuracy requirements, but limitations include cost effectiveness, and difficulties in attempting to map large, or remote areas. Remote sensing provides a means of identifying and presenting planimetric data in convenient media and efficient manner. Imagery is available in varying scales to meet the requirements of many different users. Defence applications typify the scope of planimetry applications - extracting transportation route information, building and facilities locations, urban infrastructure, and general land cover.

Data requirements
Very high resolution is usually a requirement for accurate planimetric mapping. Concerns of the mapping community with regard to use of satellite data are spatial accuracy and the level of detail of extractable information content. The concern for information content focusses not only on interpretability of features, but on the ability to determine the correct spatial location of a feature. An example of the latter would be the difficulty associated with defining the centre of a river or precise location of a powerline or pipeline right-of-way in vector format, when interpreting from a relatively coarse raster base. Spatial resolution is a critical element in this case.

The turnaround time of one or two weeks will generally meet the requirements for this type of mapping, although defence requirements may be more stringent.

Canada vs. International
For general Canadian applications, the ability to provide planimetric information is best addressed by current VIR sensors, and for large scale mapping- aerial photography. The importance of adequate resolution and information content outweigh the need for near real time products. Presently, TM and SPOT data provide optimal information for extracting planimetric information for regional applications. Air photos, and particularly orthophotos when available, are preferred for smaller, well defined areas.

Tawausar radar image
For cloud covered areas, **radar** is the obvious choice for providing **planimetric data**. The detectability of linear features improves when they are oriented perpendicular to the radar look direction. This can be controlled with airborne sensors, by planning the flightlines appropriately. Another issue is that a balance between resolution and speckle has to be reached. Although single look data provides the finest resolution, speckle can be a hindrance to interpretation, and invites multilook processing.
5.8.2 Digital Elevation Models

**Background**

The availability of digital elevation models (DEMs) is critical for performing geometric and radiometric corrections for terrain on remotely sensed imagery, and allows the generation of contour lines and terrain models, thus providing another source of information for analysis.

Present mapping programs are rarely implemented with only planimetric considerations. The demand for digital elevation models is growing with increasing use of GIS and with increasing evidence of improvement in information extracted using elevation data (for example, in discriminating wetlands, flood mapping, and forest management). The incorporation of elevation and terrain data is crucial to many applications, particularly if radar data is being used, to compensate for foreshortening and layover effects, and slope induced radiometric effects. Elevation data is used in the production of popular topographic maps.

Elevation data, integrated with imagery is also used for generating perspective views, useful for tourism, route planning, to optimize views for developments, to lessen visibility of forest clearcuts from major transportation routes, and even golf course planning and development. Elevation models are integrated into the programming of cruise missiles, to guide them over the terrain.

Resource management, telecommunications planning, and military mapping are some of the applications associated with DEMs.

**Why remote sensing?**

There are a number of ways to generate elevation models. One is to create point data sets by collecting elevation data from altimeter or Global Positioning System (GPS) data, and then interpolating between the points. This is extremely time and effort consuming. Traditional surveying is also very time consuming and limits the timeliness of regional scale mapping.

Generating DEMs from remotely sensed data can be cost effective and efficient. A variety of sensors and methodologies to generate such models are available and proven for mapping applications. Two primary methods if generating elevation data are 1. Stereogrammetry techniques using airphotos (photogrammetry), VIR imagery, or radar data (radargrammetry), and 2. Radar interferometry.
Stereogrammetry involves the extraction of elevation information from stereo overlapping images, typically airphotos, SPOT imagery, or radar. To give an example, stereo pairs of airborne SAR data are used to find point elevations, using the concept of parallax. Contours (lines of equal elevation) can be traced along the images by operators constantly viewing the images in stereo.

The potential of radar interferometric techniques to measure terrain height, and to detect and measure minute changes in elevation and horizontal base, is becoming quickly recognized.

Interferometry involves the gathering of precise elevation data using successive passes (or dual antenna reception) of spaceborne or airborne SAR. Subsequent images from nearly the same track are acquired and instead of examining the amplitude images, the phase information of the returned signals is compared. The phase images are coregistered, and the differences in phase value for each pixel is measured, and displayed as an interferogram. A computation of phase "unwrapping" or phase integration, and geometric rectification are performed to determine altitude values. High accuracies have been achieved in demonstrations using both airborne (in the order of a few centimetres) and spaceborne data (in the order of 10m).

Primary applications of interferometry include high quality DEM generation, monitoring of surface deformations (measurement of land subsidence due to natural processes, gas removal, or groundwater extraction; volcanic inflation prior to eruption; relative earth movements caused by earthquakes), and hazard assessment and monitoring of natural landscape features and fabricated structures, such as dams. This type of data would be useful for insurance companies who could better measure damage due to natural disasters, and for hydrology-specialty companies and researchers interested in routine monitoring of ice jams.
for bridge safety, and changes in mass balance of glaciers or volcano growth prior to an eruption.

From elevation models, contour lines can be generated for topographic maps, slope and aspect models can be created for integration into (land cover) thematic classification datasets or used as a sole data source, or the model itself can be used to orthorectify remote sensing imagery and generate perspective views.

Data requirements
The basic data requirement for both stereogrammetric and interferometric techniques is that the target site has been imaged two times, with the sensor imaging positions separated to give two different viewing angles.

In virtually all DEM and topographic map generation applications, cartographic accuracy is the important limiting factor. Turnaround time is not critical and repeat frequency is dependent on whether the application involves change detection, and what the temporal scope of the study is.
Canada vs. International

Aerial photography is the primary data source for DEM generation in Canada for national topographic mapping. For other applications of DEMs, there are additional satellite sources such as SPOT, with its pointable sensors and 10m panchromatic spatial resolution, producing adequate height information at scales smaller than 1:50,000.

The height accuracy requirement for 1:50,000 mapping in Canada is between 5 and 20 m. In developing countries it is typically 20 m. The original elevation information used in the Canadian National Topographic Series Maps was provided from photogrammetric techniques.

In foreign markets, airborne radar mapping is most suited for approximately 1:50,000 scale topographic mapping. Spaceborne radar systems will be able to provide data for the generation of coarser DEMs through radargrammetry, in areas of cloud cover and with less stringent accuracy requirements. Stereo data in most modes of operation will be available because of the flexible incidence angles, allowing most areas to be captured during subsequent passes. Interferometry from airborne and spaceborne systems should meet many mapping requirements.
5.8.3 Topographic & Baseline Thematic Mapping

Background
There is a growing demand for digital databases of topographic and thematic information to facilitate data integration and efficient updating of other spatially oriented data. Topographic maps consist of elevation contours and planimetric detail of varied scale, and serve as general base information for civilian and military use.

Baseline thematic mapping (BTM) is a digital integration of satellite imagery, land use, land cover, and topographic data to produce an "image map" with contour lines and vector planimetry information. This new concept of thematic mapping was developed to take advantage of improvements in digital processing and integration of spatial information, increased compatibility of multisource data sets, the wide use of geographic information systems to synthesize information and execute analyses customized for the user, and increased ability to present the data in cartographic form.

The data for baseline thematic maps are compiled from topographic, land cover, and infrastructure databases. Appropriate thematic information is superimposed on a base map, providing specific information for specific end users, such as resource managers. Various combinations of thematic information may be displayed to optimize the map information for application specific purposes, whether for land use allocation, utility site selection and route planning, watershed management, or natural resource management and operations.

Why remote sensing?
As a base map, imagery provides ancillary information to the extracted planimetric or thematic detail. Sensitivity to surface expression makes radar a useful tool for creating base maps and providing reconnaissance abilities for hydrocarbon and mineralogical companies involved in exploration activities. This is particularly true in remote northern regions, where vegetation cover does not mask the microtopography and generally, information may be sparse. Multispectral imagery is excellent for providing ancillary land cover information, such as forest cover. Supplementing the optical data with the topographic relief and textural nuance inherent in radar imagery can create an extremely useful image composite product for interpretation.

Data requirements
The prime data requirement is for high information content and a balance between resolution and data handling ability. There is a moderate turnaround requirement for this application; processed data should be available less than a year after imagery acquisition.
Canada vs. International
VIR imagery is excellent as a base map for planimetry detail on a varied landscape, providing information on forest, agriculture cover and gross geomorphology of the land. SAR is also good for providing surficial topographic expression.

Case study (example) BTM's in BC
(Baseline Thematic Mapping in British Columbia)
Baseline thematic mapping involves the compilation of varied data sources, ranging from satellite imagery to detailed forest stand information to planimetric data from the 1:250,000 National Topographic database. Base map sheets overlain by various combinations of thematic data are produced with an aim toward resource management applications. British Columbia's Ministry of Environment, Lands, and Parks routinely produces BTMs. The most recent Landsat TM data available is used as a source for classifications of ground cover and interpretation of land use. DEMs are also integrated into the satellite data to provide 3 dimensional perspective views. Although B.C. is quite advanced in this application, other Canadian provinces have contemplated or are doing similar work, as are private consultants in conjunction with forestry companies.

Baseline thematic mapping incorporates not only interpretations of ground cover data and land use, but topographic information such as elevation contours and planimetry to provide an optimal tool for resource management. This information may be portrayed in traditional map format, or as an image-map, which is an excellent means of presenting spatial data to resource managers and many other users.
5.9 Oceans & Coastal Monitoring

The oceans not only provide valuable food and biophysical resources, they also serve as transportation routes, are crucially important in weather system formation and CO² storage, and are an important link in the earth's hydrological balance. Understanding ocean dynamics is important for fish stock assessment, ship routing, predicting global circulation consequences of phenomena such as El Nino, forecasting and monitoring storms so as to reduce the impact of disaster on marine navigation, off-shore exploration, and coastal settlements. Studies of ocean dynamics include wind and wave retrieval (direction, speed, height), mesoscale feature identification, bathymetry, water temperature, and ocean productivity.

Coastlines are environmentally sensitive interfaces between the ocean and land and respond to changes brought about by economic development and changing land-use patterns. Often coastlines are also biologically diverse inter-tidal zones, and can also be highly urbanized. With over 60% of the world's population living close to the ocean, the coastal zone is a region subject to increasing stress from human activity. Government agencies concerned with the impact of human activities in this region need new data sources with which to monitor such diverse changes as coastal erosion, loss of natural habitat, urbanization, effluents and offshore pollution. Many of the dynamics of the open ocean and changes in the coastal region can be mapped and monitored using remote sensing techniques.

Ocean applications of remote sensing include the following:

- **Ocean pattern identification:**
  - currents, regional circulation patterns, shears
  - frontal zones, internal waves, gravity waves, eddies, upwelling zones, shallow water bathymetry,
- **Storm forecasting**
  - wind and wave retrieval
- **Fish stock and marine mammal assessment**
  - water temperature monitoring
  - water quality
  - ocean productivity, phytoplankton concentration and drift
- aquaculture inventory and monitoring
- **Oil spill**
  - mapping and predicting oilspill extent and drift
  - strategic support for oil spill emergency response decisions
  - identification of natural oil seepage areas for exploration
- **Shipping**
  - navigation routing
  - traffic density studies
  - operational fisheries surveillance
  - near-shore bathymetry mapping
- **Intertidal zone**
  - tidal and storm effects
  - delineation of the land /water interface
  - mapping shoreline features / beach dynamics
  - coastal vegetation mapping
  - human activity / impact
5.9.1 Ocean Features

Background
Ocean feature analysis includes determining current strength and direction, amplitude and direction of surface winds, measuring sea surface temperatures, and exploring the dynamic relationship and influences between ocean and atmosphere. Knowledge of currents, wind speed, tides, storm surges and surface wave height can facilitate ship routing. Sea floor modelling supports waste disposal and resource extraction planning activities.

Ocean circulation patterns can be determined by the examination of mesoscale features such as eddies, and surface gravity waves. This knowledge is used in global climate modelling, pollution monitoring, navigation and forecasting for offshore operations.

Why remote sensing?
Remote sensing offers a number of different methods for acquiring information on the open ocean and coastal region. Scatterometers collect wind speed and direction information, altimeters measure wave height, and identify wind speed. Synthetic aperture radar (SAR) is sensitive to spatially varying surface roughness patterns caused by the interaction of the upper ocean with the atmosphere at the marine boundary layer, and scanning radiometers and microwave sounders collect sea surface temperature data. Buoy-collected information can be combined with remote sensing data to produce image maps displaying such things as hurricane structure with annotated wind direction and strength, and wave height. This information can be useful for offshore engineering activities, operational fisheries surveillance and storm forecast operations.

Data requirements
For general sea-state information (waves, currents, winds), the data are usually time sensitive, meaning that the information is only valuable if it is received while the conditions exist. For forecasting and ship routing, real time data handling / turnaround facilities are necessary, requiring two way data links for efficient dissemination between the forecast centre and data user.

Certain wind speed conditions are necessary in order for the SAR to receive signal information from the ocean surface. At very low wind speeds (2-3m/s) the SAR is not sensitive enough to detect the ocean 'clutter' and at very high winds speeds (greater than 14 m/s) the ocean clutter masks whatever surface features may be present. The principal scattering mechanism for ocean surface imaging is Bragg scattering, whereby the short waves on the ocean surface create spatially varying surface patterns. The backscatter intensity is a function of the incidence angle and radar wavelength, as well as the sea state conditions at the time of imaging. The surface waves that lead to Bragg scattering are roughly equivalent to the wavelength used by RADARSAT. (5.3 cm) These short waves are generally formed in response to the wind stress at the upper ocean layer. Modulation in the short (surface) waves may be caused by long gravity waves, variable wind speed, and surface currents associated with upper ocean processes such as eddies, fronts and internal waves. These variations
result in spatially variable surface roughness patterns which are detectable on SAR imagery.

**Case study (example)**

Internal waves form at the interfaces between layers of different water density, which are associated with velocity shears (i.e., where the water above and below the interface is either moving in opposite directions or in the same direction at different speeds). Oscillations can occur if the water is displaced vertically resulting in internal waves. Internal waves in general occur on a variety of scales and are widespread phenomena in the oceans. The most important are those associated with tidal oscillations along continental margins. The internal waves are large enough to be detected by satellite imagery. In this image, the internal waves, are manifested on the ocean surface as a repeating curvilinear patterns of dark and light banding, a few kilometres east of the Strait of Gibraltar, where the Atlantic Ocean and Mediterranean Sea meet. Significant amounts of water move into the Mediterranean from the Atlantic during high tide and/or storm surges.
5.9.2 Ocean Colour & Phytoplankton Concentration

Background

Ocean colour analysis refers to a method of indicating the "health" of the ocean, by measuring oceanic biological activity by optical means. Phytoplankton, are significant building blocks in the world's food chain and grow with the assistance of sunlight and the pigment chlorophyll. Chlorophyll, which absorbs red light (resulting in the ocean's blue-green colour) is considered a good indicator of the health of the ocean and its level of productivity. The ability to map the spatial and temporal patterns of ocean colour over regional and global scales has provided important insights into the fundamental properties and processes in the marine biosphere.

Mapping and understanding changes in ocean colour can assist in the management of fish stocks and other aquatic life, help define harvest quotas, monitor the water quality and allow for the identification of human and natural water pollution such as oil or algal blooms, which are dangerous to fish farms and other shellfish industries.

In general, ocean productivity appears highest in coastal areas due to their proximity to nutrient upwelling and circulation conditions that favour nutrient accumulation.

Why remote sensing?

Remotely sensed data can provide the necessary spatial perspective to collect information about the ocean surface on a regional scale. Optical data can detect such targets as suspended sediments, dissolved organic matter, and discern between algal blooms and oilslicks. SAR data can provide additional information on current, wave and mesoscale features so as to observe trends over time when optical data are not available due to periods of cloud cover. Many commercial fishing and aquaculture operators use this information to predict catch sizes and locate potential feeding areas.

Remote sensing provides a near-surface view of the ocean, but is limited in the amount of information it can derive from the water column. However, many applications of ocean colour are in their infancy and with the recent and upcoming missions of advanced sensors, the development and scope of applications will improve substantially.

Data requirements

Multispectral data are required for ocean colour measurements, and wide spatial coverage provides the best synoptic view of distribution and spatial variability of phytoplankton, water temperature and suspended matter concentration. Hyperspectral data, (collected in many and narrow ranges of the visible and infrared wavelengths), allows for greater precision in characterizing target spectral signatures. Monthly and seasonal imaging provides necessary
data for modelling. For fish harvesting activities and for fish farm operators, information is required on a daily or weekly basis.

We are entering a new era of ocean colour data. The Coastal Zone Colour Scanner (CZCS) on-board the US Nimbus 7 satellite collected colour data from 1978 until 1986. In 1996 after a decade of limited data availability, the Germans launched the Modular Opto-electronic Sensor (MOS) and the Japanese followed with the Ocean Colour Thermal Sensor (OCTS). New sensors include SeaWiFs, launched in 1997 (NASA), MERIS (ESA) scheduled for launch in 1999, MODIS (NASA) in 2000, GLI (Japan) in 1999, and OCI (Taiwan) in 1998. These advanced sensors will collect data on primary productivity, chlorophyll variability and sea surface temperature using advanced algorithms. Their spectral channels are designed to optimize target reflectance and support quantitative measurements of specific biophysical properties. Most offer regional perspectives with relatively coarse (500-1200m) resolution and wide fields of view.

Case study (example)
El Nino and the Plankton Disappearance
Understanding the dynamics of ocean circulation can play a key role in predicting global weather patterns, which can directly impact agriculture and fishing industries around the world. Detecting the arrival of the El Nino Current off the coast of Peru is an example of how remote sensing can be used to improve our understanding of, and build prediction models for global climate patterns.

El Nino is a warm water current that appears off the coast of South America approximately every seven years. Nutrients in the ocean are associated with cold water upwelling, so the arrival of a warm water current such as El Nino, which displaces the cold current further offshore, causes changes in the migration of the fish population. In 1988, El Nino caused a loss in anchovy stocks near Peru, then moved north, altering the regional climatic patterns and creating an unstable weather system. The resulting storms forced the jet stream further north, which in turn blocked the southward flow of continental precipitation from Canada over the central United States. Central and eastern American States suffered drought, reducing crop production, increasing crop prices, and raising commodity prices on the international markets.
5.9.3 Oil Spill Detection

Background
Oil spills can destroy marine life as well as damage habitat for land animals and humans. The majority of marine oil spills result from ships emptying their bilge tanks before or after entering port. Large area oil spills result from tanker ruptures or collisions with reefs, rocky shoals, or other ships. These spills are usually spectacular in the extent of their environmental damage and generate widespread media coverage. Routine surveillance of shipping routes and coastal areas is necessary to enforce maritime pollution laws and identify offenders.

Following a spill, the shipping operator or oil company involved is responsible for setting up emergency evaluation and response teams, and employing remediating measures to minimize the extent of a spill. If they do not have the resources, the government regulatory agencies responsible for disaster mitigation become involved and oversee the activity. In all spills, the government agencies play a key role in ensuring the environmental protection laws are being met. To limit the areas affected by the spill and facilitate containment and cleanup efforts, a number of factors have to be identified.

1. Spill location
2. Size and extent of the spill
3. Direction and magnitude of oil movement
4. Wind, current and wave information for predicting future oil movement

Why remote sensing?
Remote sensing offers the advantage of being able to observe events in remote and often inaccessible areas. For example, oil spills from ruptured pipelines, may go unchecked for a period of time because of uncertainty of the exact location of the spill, and limited knowledge of the extent of the spill. Remote sensing can be used to both detect and monitor spills.

For ocean spills, remote sensing data can provide information on the rate and direction of oil movement through multi-temporal imaging, and input to drift prediction modelling and may facilitate in targeting clean-up and control efforts. Remote sensing devices used include the use of infrared video and photography from airborne platforms, thermal infrared imaging, airborne laser fluorosensors, airborne and space-borne optical sensors, as well as airborne and spaceborne SAR. SAR sensors have an advantage over optical sensors in that they can provide data under poor weather conditions and during darkness. Users of remotely sensed data for oil spill applications include the Coast Guard, national environmental protection agencies and departments, oil companies, shipping industry, insurance industry, fishing industry, national departments of fisheries and oceans, and departments of defence.

Data requirements
The key operational data requirements are fast turnaround time and frequent imaging of the site to monitor the dynamics of the spill. For spill identification, high resolution sensors are generally required, although wide area coverage is very important for initial monitoring and detection. Airborne sensors have the advantage of frequent site specific coverage on
demand, however, they can be costly. Spills often occur in inclement weather, which can hinder airborne surveillance.

Laser fluorosensors are the best sensors for oil spill detection, and have the capability of identifying oil on shores, ice and snow, and determining what type of oil has been spilled. However, they require relatively cloud free conditions to detect the oilspill. SAR sensors can image oilspills through the localized suppression of Bragg scale waves. Oilspills are visible on a radar image as circular or curvilinear features with a darker tone than the surrounding ocean. The detection of an oilspill is strongly dependent upon the wind speed. At wind speeds greater than 10 m/s, the slick will be broken up and dispersed, making it difficult to detect. Another factor that can play a role in the successful detection of an oilspill is the difficulty in distinguishing between a natural surfactant and an oilspill. Multi-temporal data and ancillary information can help to discriminate between these two phenomena.

Case study (example)
A supertanker, the Sea Empress, was grounded near the town of Milford Haven, Wales on February 15, 1996. After hitting rocks, the outer hull was breached and approximately 70,000 tonnes of light grade crude oil was dispersed southward under storm conditions.

In this RADARSAT image taken a week after the spill, the extent of the oil is visible. The dark areas off the coast represent the areas where oil is present and areas of lighter tone directly south are areas where dispersant was sprayed on the oil to encourage emulsification. Oil, which floats on the top of water, suppresses the ocean's capillary waves, creating a surface smoother than the surrounding water. This smoother surface appears dark in the radar image. As the oil starts to emulsify and clean-up efforts begin to take effect, the capillary waves are not as effectively damped and the oil appears lighter. Size, location and dispersal of the oil spill can be determined using this type of imagery.
5. Endnotes

5.10 Endnotes

You have just completed Chapter 5 - Applications. As a follow-on, you may want to browse the CCRS Web site where you will find articles dealing with applications of remote sensing in the fields of agriculture, geology, environmental monitoring, hydrology, ice, oceans, forestry. As a starting point, try our 'Images of Canada'¹, the RADARSAT 'Applications In Action'², and the articles in our Technology and R&D Section³.

Additionally, you may want to browse the terminology in our glossary⁴, or review some of the technical papers⁵ written by CCRS staff.

¹http://www.ccrs.nrcan.gc.ca/ccrs/learn/tour/tour_e.html
²http://www.ccrs.nrcan.gc.ca/ccrs/data/satsens/radarsat/images/imgact_e.html
³http://www.ccrs.nrcan.gc.ca/ccrs/rd/rd_e.html
⁴http://www.ccrs.nrcan.gc.ca/ccrs/learn/terms/glossary/glossary_e.html
⁵http://www.ccrs.nrcan.gc.ca/ccrs/rd/sci_pub/biblio_e.html
5. Did You Know?

5.2 Did You Know?

Did you know that remote sensing of agricultural areas could give us clues about our heritage? In Québec, farmer's field shapes are very different than in Saskatchewan. In Québec, long thin strips of land extend from riverbanks, following French settlers' tradition. These types of fields are also visible in Nova Scotia, where the Acadians farmed, in New Brunswick, and in parts of Ontario. In the prairies, the fields are square and strictly follow the township and range plan.

Fields in Quebec

Fields in Saskatchewan
5.3 Did You Know?

The forest around Mt. St. Helens after the eruption

Natural disasters can also wipe out huge areas of forest. Burns can destroy several thousand of hectares, landslides can displace trees down a slope, and excessive flooding can damage trees. Volcanoes however, have the greatest potential for destroying forests in the shortest amount of time. In 1980, Mt. St. Helens in northwestern United States violently erupted. The volcanic blast, reaching 320 km/hour, levelled over 600km² of forest.

5.3.2 Did You Know?

Forest interpretation from SAR data

Interpreting forest cover type with radar data is very similar to interpreting multispectral images. The same interpretation elements are used (tone, texture, shape, pattern, size, association), but texture plays a dominant role in the discrimination of different forest types. Viewing the images in stereo helps to differentiate relative tree heights, as well as define rivers that have specific vegetation along their banks.
5.5 Did You Know?

Catastrophic flooding can happen almost anywhere. In Iceland, huge floods that carry boulders the size of houses occur relatively frequently. These floods are called jökulhlaups, roughly meaning "glacial flood". Iceland is situated upon the mid-Atlantic rift, an area of frequent volcanic activity. The island itself is a product of this activity, and continues to grow in size with each volcanic event. Covering much of the island, and some of the volcanic craters, is an 8300 km² ice cap. During sub-glacial eruptions, glacial ice is melted, and temporarily dammed by either the crater or the ice itself. Eventually the pressure of the water is released in a catastrophic flood. A flood in 1996 discharged a 3km³ volume of water, lasting 2 ½ days. The glaciers and landscape are abruptly and extensively modified by this strong force, which erodes channels, moves and deposits huge blocks of ice and rock, and deposits kilometre scale alluvial fans.

Scientists can use radar imagery to create topographic models of the glaciers and extensive outwash plains to use as baseline maps for multitemporal change detection and mapping studies. Radar is preferred because persistently cloudy conditions limit the use of optical data. With new monitoring methods, including the analysis of glacial dynamics related to volcanic activity, scientists are better able to predict the timing of these extreme jökulhlaups.
5.5.1 Did You Know?

![Polarization Diagram]

© CCRS / CCT

It is worth your while to pay attention to the polarization characteristics of the radar imagery that you are collecting. If your target is to map flooded versus dry land, then HH (horizontal transmit, horizontal receive) is a much better choice than (say) VV (vertical transmit, vertical receive) polarization. The HH imagery will produce a noticeably stronger contrast between these two types of surfaces, allowing greater accuracy in the mapped result.

5.5.2 Did You Know?

\[10^{-12} m = 0.000000000001 m\]

Another part of the electromagnetic spectrum that has been used for soil moisture measurement is the gamma ray wavelength range. Recording the natural emission of gamma rays from the earth, aircraft carrying gamma ray spectrometers are used to detect the attenuation or alteration by soil moisture, of the intensity of the emanation. The gamma ray wavelength is extremely short - about 10-12 metres in length (!) and the intensity of this natural radiation at the earth's surface is very weak. As a result satellite altitudes are not practical for this form of remote sensing. Even the aircraft used for this purpose must fly as close to the ground as possible.

Canada Centre for Remote Sensing
5.6 Did You Know?

"...GPS = Good Protection Sidekick..."

Accidents like the sinking of the Titanic are virtually eliminated now, with iceberg reconnaissance (provided by the International Ice Patrol) and GPS navigation onboard ships. And even if a ship did collide with an iceberg, search and rescue operations using remote sensing and GPS navigation could save many lives in such an incident.
5.6.1 Did You Know?

"...I like my eggs on ice..."

Creating an Ice Chart
The Canadian Ice Service of Environment Canada (CISEC) creates charts for ice type that are distributed to their clients on a near-real time basis. These charts are essentially ice maps with Egg Codes superimposed, which explain the development stage (thickness), size, and concentration of ice at both regional and site specific scales. The codes used to represent the ice information are displayed in an oval symbol, resembling an egg, hence the term Egg Code. Egg codes are used not only for sea ice, but also lake ice. Also they conform to the WMO (World Meteorological Organization) standards.

Once you understand the meaning of the various codes, the interpretation of the ice charts is relatively easy.

For more detailed information about the coding procedure and terminology, go to the Canadian Ice Service homepage.
Case study (example)
RADARSAT Expedites Expedition to the Magnetic North Pole!

In March of 1996, teams of Arctic adventurers set out on an expedition to reach the magnetic North Pole, located on the west coast of Ellef Ringnes Island, in Canada's high Arctic. Travelling across sea ice by ski, the teams required a route on smooth first year ice in order to haul their gear and conserve energy. Ice blocks, rubble and irregular relief made deformed and multi-year ice virtually impassable. One team relied on remote sensing - image maps created from RADARSAT data - to plan their route.

The ScanSAR image covered the entire extent of the route, from Resolute Bay on Cornwallis Island to the pole (78°6’N, 104°3’W). The resolution of 100m provided information about the ice cover and type, and mapped coastlines were added following geometric processing, to provide a geographic reference. The team was also equipped with GPS and communication technologies.

On the image map, passable ice appears uniformly dark, due to the specular reflection of incident radiation from the radar on the smooth surface. Rubbly, rough ice that often contained enough relief to make skiing impossible appears bright, due to the reflection of the radar energy back to the sensor.

The team using RADARSAT image maps was the only one to complete their journey to the magnetic North Pole. The other teams were hindered by rough ice and could not efficiently plan their route without the synoptic view provided by remote sensing. RADARSAT, with its sensitivity to ice type, far northern coverage, and reliable imaging was the most suitable sensor for this type of application. Its success bodes well for future exploration endeavors!


Expedition Web Site: http://www.jeaneudes.qc.ca/2

1http://www.msc-smc.ec.gc.ca
2http://www.jeaneudes.qc.ca/
5.7 Did You Know?

"...let me make this perfectly clear...

[Image of Calgary (Landsat-TM)]

This is a TM scene of Calgary, Canada, where the 1988 Winter Olympics were held. Calgary appears quite blue; the agricultural fields to the east are red, while grazing land to the west is green. Abutting the southwest corner of the city, is a long rectangular section of land stretching towards the west that is darker and more monotone than the other areas around it. This is the area of the Sarcee Reserve (T’suu T’ina) which has been held by native people, and protected from urbanization and residential construction. Of all the land on the image, this land is the closest to the original state of the Calgary region before agriculture and settlements reworked the landscape. It looks like an oasis amidst suburbia and farmland.

5.8.2 Did You Know?

[Image of a stereo pair of images]

When you look at a stereo pair of images you perceive a virtual 3D model of the terrain or object that was imaged. Through this 3D virtual terrain model (VTM?), it is possible to extract cartographic information without using a DEM!

Canada Centre for Remote Sensing
5.8.3 Did You Know?

A ‘close’ relative of 3D terrain mapping is ‘close range photogrammetry’. Using very similar techniques but at very close range, this method is used for ‘mapping’ an object like a building, sculpture or a human face in three dimensions in order to have a precise record of its shape.

5.9.3 Did You Know?

A typical laser fluorosensor operates by emitting radiation at a particular wavelength that will be easily absorbed by the intended target, for instance: oil. The energy thus absorbed by the target is given off by emitting another wavelength of radiation, which is then detected by a sensor (spectrometer) linked to the laser. With aromatic hydrocarbons, this form of fluorescence allows a ‘fingerprinting’ of the oil, measuring both the spectra of the radiation given off, as well as the decay rate of the fluorescence. Thus oils can be differentiated from other fluorescing targets and even identified into basic oil types (light, heavy, etc.).
Every spring seems to bring a resurgence of the mysterious crop circles seen in farmers' fields around the world, often attributed to the work of aliens. Finally, these crop circles have been observed by a remote sensing device! Landsat TM captured this view while over southern Alberta. Look at the green circles on the image - how could they have been caused, other than by alien activity?

5.2 Whiz Quiz Answer

The "crop circles" are in fact, healthy crops irrigated using a pivot irrigation system - not the result of alien tricks. In the dry southern prairies, farmers rely on pivot irrigation systems to keep the crops watered and healthy. You can see that in the corners of the fields where the water fails to reach, the vegetation is missing or has suffered. The brownish grey areas in this image are primarily rangeland, while the crops appear green. Crops can be successfully grown if a regular irrigation routine is followed, but this puts a heavy demand on water resources in a typically dry area.
5.3 Whiz Quiz

Why are lines being cut out of this forested area in northern Alberta?

5.3 Whiz Quiz Answer

In northern Alberta, forests are being cut for pulp and paper mills, but they are also being cut for another reason. Exploration and infrastructure for gas wells requires that forests be cut for seismic lines, pipeline routing, access to sites, and pumping stations.
5.7 Whiz Quiz

More alien circles?
These are even stranger circles than the ones we first encountered. The outer circles are tens of kilometers across. What could have created this shape, and other than being a landing target for UFOs, what possible land use could it serve?

5.7 Answer

You had a good guess if you thought these circles were created by an ancient civilization, like the Aztecs, or it represents a giant teepee ring. But it's not correct. Try again.

The circles are part of a military base in southern Alberta. The land is used for practice maneuvers and is "protected" from the ranging and farming on nearby dry grassland. The circles identify radial distances from 'ground zero', where various real and simulated explosions were conducted by the military.
5.9.1 Whiz Quiz

What on earth is this 'feature' and how is it that RADARSAT can 'see' it?

5.9.1 Answer

Imaged over the Labrador Sea, this RADARSAT image shows a number of 'imprints' made on the ocean surface by unusual atmospheric conditions. Though the radar beams themselves are not affected by the atmosphere, they have recorded the ocean topographic effects from atmospheric phenomena such as a large low pressure cell (A), atmospheric gravity waves (B) and a region of multiple rising/falling air currents (C). In each case, where the falling air mass dampens ocean waves, the radar backscatter is lessened, while the rising air mass induces surface wind, which in turn increases ocean waves and therefore, radar backscatter. Higher backscatter is shown in the imagery as brighter areas.
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References

The following publications were used in the preparation of this tutorial:

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The tutorial is structured as a course, with each section building on the concepts introduced in the previous sections and chapters. The numerous images and graphics, as well as interesting facts, help explain and illustrate difficult concepts. Each chapter also includes several questions and quizzes to test the reader's understanding of the subject matter. These quizzes may serve as excellent reviews of each chapter. Informative and sometimes humorous facts in the "Did You Know?" pages are designed to complement the associated section with anecdotes and examples of how remote sensing is used throughout the world.

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