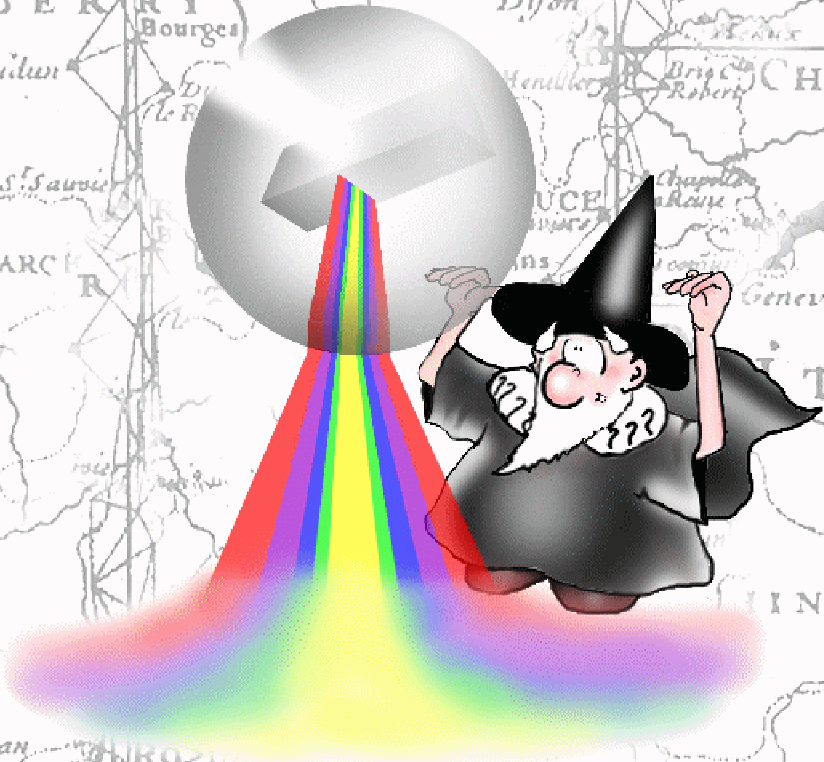
INTRO TO RSE

Introduction to

Remote Sensing of Environment (RSE)



with

TNTmips®

TNTview®

Before Getting Started

Imagery acquired by airborne or satellite sensors provides an important source of information for mapping and monitoring the natural and manmade features on the land surface. Interpretation and analysis of remotely sensed imagery requires an understanding of the processes that determine the relationships between the property the sensor actually measures and the surface properties we are interested in identifying and studying. Knowledge of these relationships is a prerequisite for appropriate processing and interpretation. This booklet presents a brief overview of the major fundamental concepts related to remote sensing of environmental features on the land surface.

Sample Data The illustrations in this booklet show many examples of remote sensing imagery. You can find many additional examples of imagery in the sample data that is distributed with the TNT products. If you do not have access to a TNT products CD, you can download the data from MicroImages' Web site. In particular, the CB_DATA, SF_DATA, BEREA, and COMBRAST data collections include sample files with remote sensing imagery that you can view and study.

More Documentation This booklet is intended only as an introduction to basic concepts governing the acquisition, processing, and interpretation of remote sensing imagery. You can view all types of imagery in TNTmips using the standard Display process, which is introduced in the tutorial booklet entitled *Displaying Geospatial Data*. Many other processes in TNTmips can be used to process, enhance, or analyze imagery. Some of the most important ones are mentioned on the appropriate pages in this booklet, along with a reference to an accompanying tutorial booklet.

TNTmips® Pro and TNTmips Free TNTmips (the Map and Image Processing System) comes in three versions: the professional version of TNTmips (TNTmips Pro), the low-cost TNTmips Basic version, and the TNTmips Free version. All versions run exactly the same code from the TNT products DVD and have nearly the same features. If you did not purchase the professional version (which requires a software license key) or TNTmips Basic, then TNTmips operates in TNTmips Free mode.

Randall B. Smith, Ph.D., 4 January 2012

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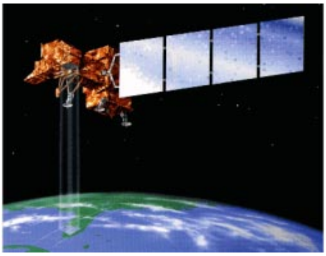
Introduction to Remote Sensing



Artist's depiction of the Landsat 7 satellite in orbit, courtesy of NASA. Launched in late 1999, this satellite acquires multispectral images using reflected visible and infrared radiation.

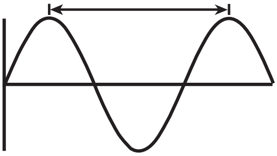
Remote sensing is the science of obtaining and interpreting information from a distance, using sensors that are not in physical contact with the object being observed. Though you may not realize it, you are familiar with many examples. Biological evolution has exploited many natural phenomena and forms of energy to enable animals (including people) to sense their environment. Your eyes detect electromagnetic energy in the form of visible light. Your ears detect acoustic (sound) energy, while your nose contains sensitive chemical receptors that respond to minute amounts of airborne chemicals given off by the materials in our surroundings. Some research suggests that migrating birds can sense variations in Earth's magnetic field, which helps explain their remarkable navigational ability.

The science of remote sensing in its broadest sense includes aerial, satellite, and spacecraft observations of the surfaces and atmospheres of the planets in our solar system, though the Earth is obviously the most frequent target of study. The term is customarily restricted to methods that detect and measure electromagnetic energy, including visible light, that has interacted with surface materials and the atmosphere. Remote sensing of the Earth has many purposes, including making and updating planimetric maps, weather forecasting, and gathering military intelligence. Our focus in this booklet will be on remote sensing of the environment and resources of Earth's surface. We will explore the physical concepts that underlie the acquisition and interpretation of remotely sensed images, the important characteristics of images from different types of sensors, and some common methods of processing images to enhance their information content.

Fundamental concepts of electromagnetic radiation and its interactions with surface materials and the atmosphere are introduced on pages 4-9. Image acquisition and various concepts of image resolution are discussed on pages 10-16. Pages 17-23 focus on images acquired in the spectral range from visible to middle infrared radiation, including visual image interpretation and common processes used to correct or enhance the information content of multispectral images. Pages 23-24 discuss images acquired on multiple dates and their spatial registration and normalization. You can learn some basic concepts of thermal infrared imagery on pages 26-27, and radar imagery on pages 28-29. Page 30 presents an example of combine images from different sensors. Sources of additional information on remote sensing are listed on page 31.

The Electromagnetic Spectrum

Electromagnetic radiation behaves in part as wavelike energy fluctuations traveling at the speed of light. The wave is actually composite, involving electric and magnetic fields fluctuating at right angles to each other and to the direction of travel.

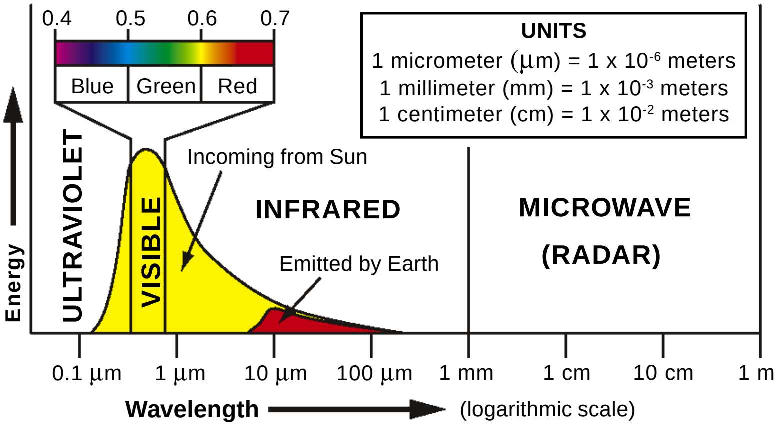


Wavelength

A fundamental descriptive feature of a waveform is its **wavelength**, or distance between succeeding peaks or troughs. In remote sensing, wavelength is most often measured in **micrometers**, each of which equals one millionth of a meter. The variation in wavelength of electromagnetic radiation is so vast that it is usually shown on a logarithmic scale.

The field of remote sensing began with aerial photography, using visible light from the sun as the energy source. But visible light makes up only a small part of the *electromagnetic spectrum*, a continuum that ranges from high energy, short wavelength gamma rays, to lower energy, long wavelength radio waves. Illustrated below is the portion of the electromagnetic spectrum that is useful in remote sensing of the Earth's surface.

The Earth is naturally illuminated by electromagnetic radiation from the Sun. The peak solar energy is in the wavelength range of visible light (between 0.4 and 0.7 µm). It's no wonder that the visual systems of most animals are sensitive to these wavelengths! Although visible light includes the entire range of colors seen in a rainbow, a cruder subdivision into blue, green, and red wavelength regions is sufficient in many remote sensing studies. Other substantial fractions of incoming solar energy are in the form of invisible ultraviolet and infrared radiation. Only tiny amounts of solar radiation extend into the microwave region of the spectrum. Imaging radar systems used in remote sensing generate and broadcast microwaves, then measure the portion of the signal that has returned to the sensor from the Earth's surface.



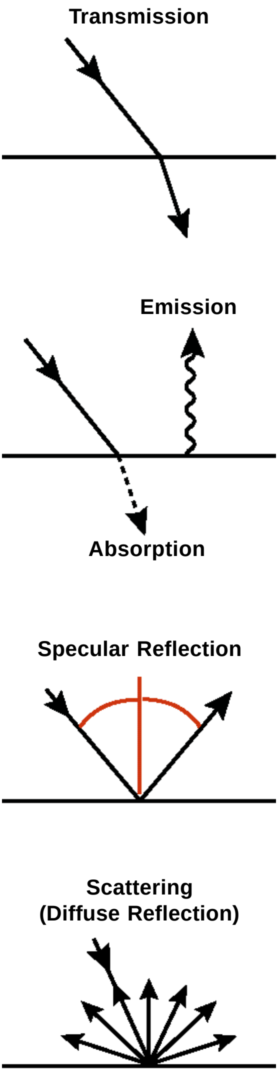
Interaction Processes

Remote sensors measure electromagnetic (EM) radiation that has interacted with the Earth's surface. Interactions with matter can change the direction, intensity, wavelength content, and polarization of EM radiation. The nature of these changes is dependent on the chemical make-up and physical structure of the material exposed to the EM radiation. Changes in EM radiation resulting from its interactions with the Earth's surface therefore provide major clues to the characteristics of the surface materials.

The fundamental interactions between EM radiation and matter are diagrammed to the right. Electromagnetic radiation that is *transmitted* passes through a material (or through the boundary between two materials) with little change in intensity. Materials can also *absorb* EM radiation. Usually absorption is wavelength-specific: that is, more energy is absorbed at some wavelengths than at others. EM radiation that is absorbed is transformed into heat energy, which raises the material's temperature. Some of that heat energy may then be emitted as EM radiation at a wavelength dependent on the material's temperature. The lower the temperature, the longer the wavelength of the emitted radiation. As a result of solar heating, the Earth's surface emits energy in the form of longer-wavelength infrared radiation (see illustration on the preceding page). For this reason the portion of the infrared spectrum with wavelengths greater than 3 µm is commonly called the *thermal infrared* region.

Electromagnetic radiation encountering a boundary such as the Earth's surface can also be reflected. If the surface is smooth at a scale comparable to the wavelength of the incident energy, *specular reflection* occurs: most of the energy is reflected in a single direction, at an angle equal to the angle of incidence. Rougher surfaces cause *scattering*, or *diffuse reflection* in all directions.

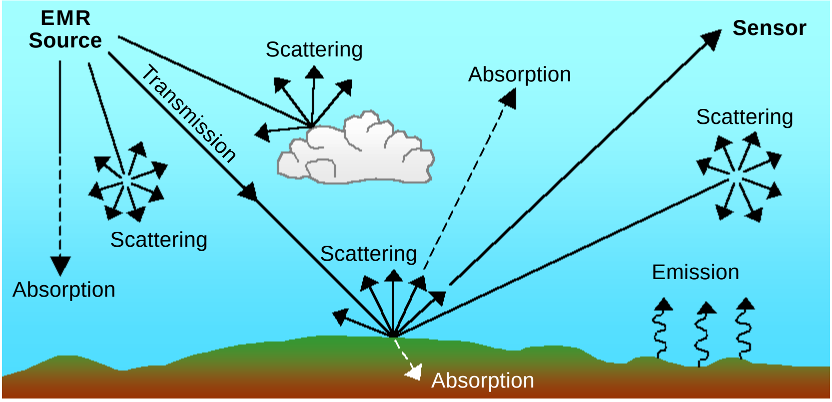
Matter - EM Energy Interaction Processes
The horizontal line represents a boundary between two materials.



Interaction Processes in Remote Sensing

To understand how different interaction processes impact the acquisition of aerial and satellite images, let's analyze the reflected solar radiation that is measured at a satellite sensor. As sunlight initially enters the atmosphere, it encounters gas molecules, suspended dust particles, and aerosols. These materials tend to scatter a portion of the incoming radiation in all directions, with shorter wavelengths experiencing the strongest effect. (The preferential scattering of blue light in comparison to green and red light accounts for the blue color of the daytime sky. Clouds appear opaque because of intense scattering of visible light by tiny water droplets.) Although most of the remaining light is transmitted to the surface, some atmospheric gases are very effective at absorbing particular wavelengths. (The absorption of dangerous ultraviolet radiation by ozone is a well-known example). As a result of these effects, the illumination reaching the surface is a combination of highly filtered solar radiation transmitted directly to the ground and more diffuse light scattered from all parts of the sky, which helps illuminate shadowed areas.

As this modified solar radiation reaches the ground, it may encounter soil, rock surfaces, vegetation, or other materials that absorb a portion of the radiation. The amount of energy absorbed varies in wavelength for each material in a characteristic way, creating a sort of spectral signature. (The selective absorption of different wavelengths of visible light determines what we perceive as a material's *color)*. Most of the radiation not absorbed is diffusely reflected (scattered) back up into the atmosphere, some of it in the direction of the satellite. This upwelling radiation undergoes a further round of scattering and absorption as it passes through the atmosphere before finally being detected and measured by the sensor. If the sensor is capable of detecting thermal infrared radiation, it will also pick up radiation emitted by surface objects as a result of solar heating.

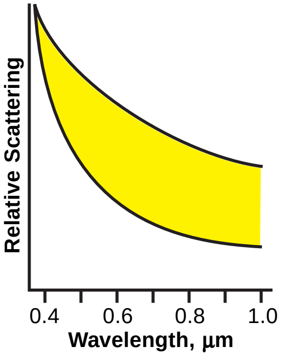


Typical EMR interactions in the atmosphere and at the Earth's surface.

Atmospheric Effects

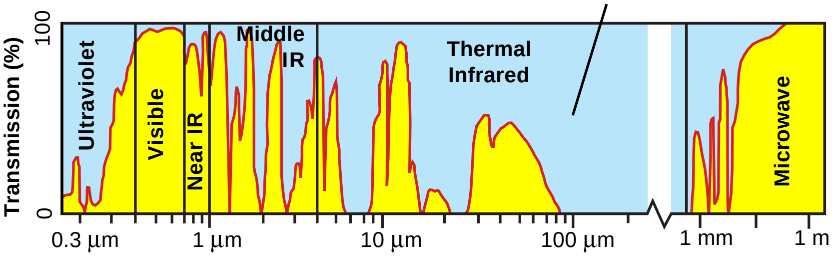
Scattering and absorption of EM radiation by the atmosphere have significant effects that impact sensor design as well as the processing and interpretation of images. When the concentration of scattering agents is high, scattering produces the visual effect we call haze. Haze increases the overall brightness of a scene and reduces the contrast between different ground materials. A hazy atmosphere scatters some light upward, so a portion of the radiation recorded by a remote sensor, called *path radiance*, is the result of this scattering process. Since the amount of scattering varies with wavelength, so does the contribution of path radiance to remotely sensed images. As shown by the figure to the right, the path radiance effect is greatest for the shortest wavelengths, falling off rapidly with increasing wavelength. When images are captured over several wavelength ranges, the differential path radiance effect complicates comparison of brightness values at the different wavelengths. Simple methods for correcting for path radiance are discussed later in this booklet.

The atmospheric components that are effective absorbers of solar radiation are water vapor, carbon dioxide, and ozone. Each of these gases tends to absorb energy in specific wavelength ranges. Some wavelengths are almost completely absorbed. Consequently, most broad-band remote sensors have been designed to detect radiation in the "atmospheric windows", those wavelength ranges for which absorption is minimal, and, conversely, transmission is high.



Range of scattering for typical atmospheric conditions (colored area) versus wavelength. Scattering increases with increasing humidity and particulate load but decreases with increasing wavelength. In most cases the path radiance produced by scattering is negligible at wavelengths longer than the near infrared.

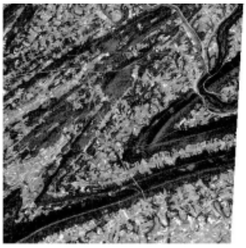
Variation in atmospheric transmission with wavelength of EM radiation, due to wavelength-selective absorption by atmospheric gases. Only wavelength ranges with moderate to high transmission values are suitable for use in remote sensing.



EMR Sources, Interactions, and Sensors

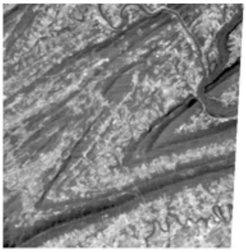
All remote sensing systems designed to monitor the Earth's surface rely on energy that is either diffusely reflected by or emitted from surface features. Current remote sensing systems fall into three categories on the basis of the source of the electromagnetic radiation and the relevant interactions of that energy with the surface.

Reflected solar radiation sensors These sensor systems detect solar radiation that has been diffusely reflected (scattered) upward from surface features. The wavelength ranges that provide useful information include the ultraviolet, visible, near infrared and middle infrared ranges. Reflected solar sensing systems discriminate materials that have differing patterns of wavelength-specific absorption, which relate to the chemical make-up and physical structure of the material. Because they depend on sunlight as a source, these systems can only provide useful images during daylight hours, and changing atmospheric conditions and changes in illumination with time of day and season can pose interpretive problems. Reflected solar remote sensing systems are the most common type used to monitor Earth resources, and are the primary focus of this booklet.



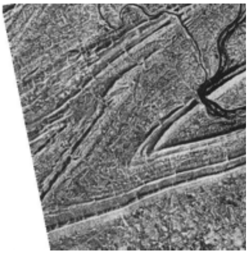
Reflected red image

Thermal infrared sensors Sensors that can detect the thermal infrared radiation emitted by surface features can reveal information about the thermal properties of these materials. Like reflected solar sensors, these are *passive* systems that rely on solar radiation as the ultimate energy source. Because the temperature of surface features changes during the day, thermal infrared sensing systems are sensitive to time of day at which the images are acquired.



Thermal Infrared image

Imaging radar sensors Rather than relying on a natural source, these "active" systems "illuminate" the surface with broadcast microwave radiation, then measure the energy that is diffusely reflected back to the sensor. The returning energy provides information about the surface roughness and water content of surface materials and the shape of the land surface. Long-wavelength microwaves suffer little scattering in the atmosphere, even penetrating thick cloud cover. Imaging radar is therefore particularly useful in cloud-prone tropical regions.



Radar image

Spectral Signatures

The spectral signatures produced by wavelength-dependent absorption provide the key to discriminating different materials in images of reflected solar energy. The property used to quantify these spectral signatures is called *spectral reflectance*: the ratio of reflected energy to incident energy as a function of wavelength. The spectral reflectance of different materials can be measured in the laboratory or in the field, providing reference data that can be used to interpret images. As an example, the illustration below shows contrasting spectral reflectance curves for three very common natural materials: dry soil, green vegetation, and water.

The reflectance of dry soil rises uniformly through the visible and near infrared wavelength ranges, peaking in the middle infrared range. It shows only minor dips in the middle infrared range due to absorption by clay minerals. Green vegetation has a very different spectrum. Reflectance is relatively low in the visible range, but is higher for green light than for red or blue, producing the green color we see. The reflectance pattern of green vegetation in the visible wavelengths is due to selective absorption by chlorophyll, the primary photosynthetic pigment in green plants. The most noticeable feature of the vegetation spectrum is the dramatic rise in reflectance across the visible-near infrared boundary, and the high near infrared reflectance. Infrared radiation penetrates plant leaves, and is intensely scattered by the leaves' complex internal structure, resulting in high reflectance. The dips in the middle infrared portion of the plant spectrum are due to absorption by water. Deep clear water bodies effectively absorb all wavelengths longer than the visible range, which results in very low reflectivity for infrared radiation.

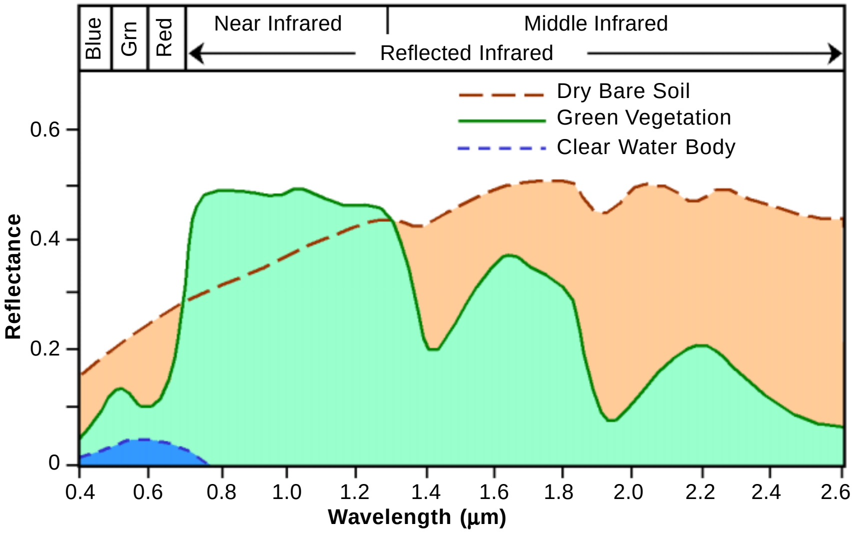
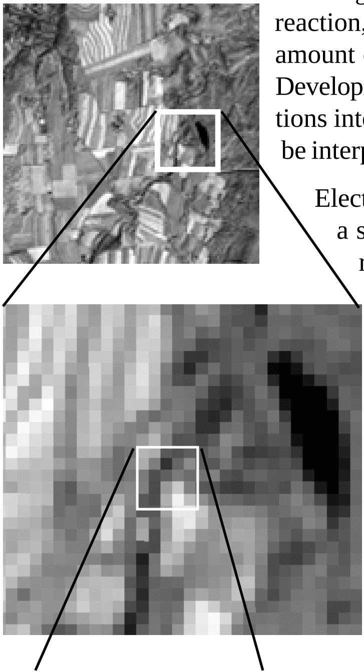


Image Acquisition

We have seen that the radiant energy that is measured by an aerial or satellite sensor is influenced by the radiation source, interaction of the energy with surface materials, and the passage of the energy through the atmosphere. In addition, the illumination geometry (source position, surface slope, slope direction, and shadowing) can also affect the brightness of the upwelling energy. Together these effects produce a composite "signal" that varies spatially and with the time of day or season. In order to produce an image which we can interpret, the remote sensing system must first detect and measure this energy.

The electromagnetic energy returned from the Earth's surface can be detected by a light-sensitive film, as in aerial photography, or by an array of electronic sensors. Light striking photographic film causes a chemical reaction, with the rate of the reaction varying with the amount of energy received by each point on the film. Developing the film converts the pattern of energy variations into a pattern of lighter and darker areas that can be interpreted visually.



115	111	71	67	74
111	89	52	77	95
87	66	74	87	80
89	64	102	125	90
70	65	113	144	119

Electronic sensors generate an electrical signal with a strength proportional to the amount of energy received. The signal from each detector in an array can be recorded and transmitted electronically in digital form (as a series of numbers). Today's digital still and video cameras are examples of imaging systems that use electronic sensors. All modern satellite imaging systems also use some form of electronic detectors.

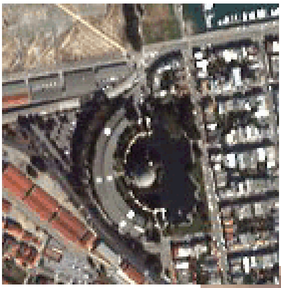
An image from an electronic sensor array (or a digitally scanned photograph) consists of a two-dimensional rectangular grid of numerical values that represent differing brightness levels. Each value represents the average brightness for a portion of the surface, represented by the square unit areas in the image. In computer terms the grid is commonly known as a *raster*, and the square units are *cells* or *pixels*. When displayed on your computer, the brightness values in the image raster are translated into display brightness on the screen.

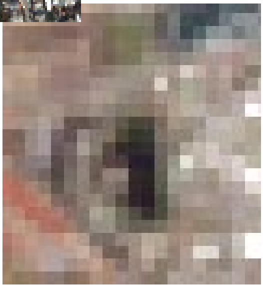
Spatial Resolution

The spatial, spectral, and temporal components of an image or set of images all provide information that we can use to form interpretations about surface materals and conditions. For each of these properties we can define the *resolution* of the images produced by the sensor system. These image resolution factors place limits on what information we can derive from remotely sensed images.

Spatial resolution is a measure of the spatial detail in an image, which is a function of the design of the sensor and its operating altitude above the surface. Each of the detectors in a remote sensor measures energy received from a finite patch of the ground surface. The smaller these individual patches are, the more detailed will be the spatial information that we can interpret from the image. For digital images, spatial resolution is most commonly expressed as the ground dimensions of an image cell.

Shape is one visual factor that we can use to recognize and identify objects in an image. Shape is usually discernible only if the object dimensions are several times larger than the cell dimensions. On the other hand, objects smaller than the image cell size may be *detectable* in an image. If such an object is sufficiently brighter or darker than its surroundings, it will dominate the averaged brightness of the image cell it falls within, and that cell will contrast in brightness with the adjacent cells. We may not be able to identify what the object is, but we can see that something is present that is different from its surroundings, especially if the "background" area is relatively uniform. Spatial context may also allow us to recognize linear features that are narrower than the cell dimensions, such as roads or bridges over water. Evidently there is no clear dimensional boundary between detectability and recognizability in digital images.



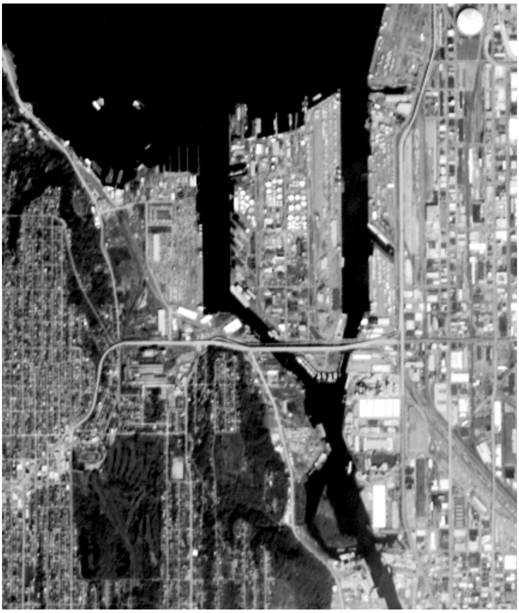


The image above is a portion of a Landsat Thematic Mapper scene showing part of San Francisco, California. The image has a cell size of 28.5 meters. Only larger buildings and roads are clearly recognizable. The boxed area is shown below left in an IKONOS image with a cell size of 4 meters. Trees, smaller buildings, and narrower streets are recognizable in the Ikonos image. The bottom image shows the boxed area of the Thematic Mapper scene enlarged to the same scale as the IKONOS image, revealing the larger cells in the Landsat image.

Spectral Resolution

The *spectral resolution* of a remote sensing system can be described as its ability to distinguish different parts of the range of measured wavelengths. In essence, this amounts to the number of wavelength intervals (“bands”) that are measured, and how narrow each interval is. An “image” produced by a sensor system can consist of one very broad wavelength band, a few broad bands, or many narrow wavelength bands. The names usually used for these three image categories are *panchromatic*, *multispectral*, and *hyperspectral*, respectively.

Aerial photographs taken using black and white film record an average response over the entire visible wavelength range (blue, green, and red). Because this film is sensitive to all visible colors, it is called *panchromatic* film. A panchromatic image reveals spatial variations in the gross visual properties of surface materials, but does not allow spectral discrimination. Some satellite remote sensing systems record a single very broad band to provide a synoptic overview of the scene, commonly at a higher spatial resolution than other sensors on board. Despite varying wavelength ranges, such bands are also commonly referred to as panchromatic bands. For example, the sensors on the first three SPOT satellites included a panchromatic band with a spectral range of 0.51 to 0.73 micrometers (green and red wavelength ranges). This band has a spatial resolution of 10 meters, in contrast to the 20-meter resolution of the multispectral sensor bands. The panchromatic band of the Enhanced Thematic Mapper Plus sensor aboard NASA’s Landsat 7 satellite covers a wider spectral range of 0.52 to 0.90 micrometers (green, red, and near infrared), with a spatial resolution of 15 meters (versus 30-meters for the sensor’s multispectral bands).

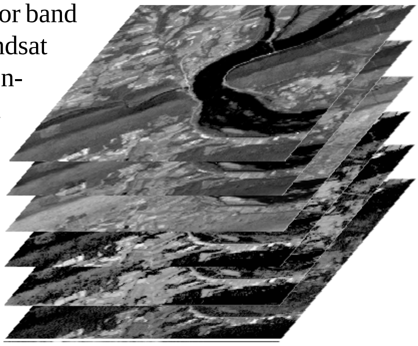


SPOT panchromatic image of part of Seattle, Washington. This image band spans the green and red wavelength ranges. Water and vegetation appear dark, while the brightest objects are building roofs and a large circular tank.

Multispectral Images

In order to provide increased spectral discrimination, remote sensing systems designed to monitor the surface environment employ a *multispectral* design: parallel sensor arrays detecting radiation in a small number of broad wavelength bands. Most satellite systems use from three to six spectral bands in the visible to middle infrared wavelength region. Some systems also employ one or more thermal infrared bands. Bands in the infrared range are limited in width to avoid atmospheric water vapor absorption effects that significantly degrade the signal in certain wavelength intervals (see the previous page *Atmospheric Effects*). These broad-band multispectral systems allow discrimination of different types of vegetation, rocks and soils, clear and turbid water, and some man-made materials.

A three-band sensor with green, red, and near infrared bands is effective at discriminating vegetated and nonvegetated areas. The HRV sensor aboard the French SPOT (Système Probatoire d'Observation de la Terre) 1, 2, and 3 satellites (20 meter spatial resolution) has this design. Color-infrared film used in some aerial photography provides similar spectral coverage, with the red emulsion recording near infrared, the green emulsion recording red light, and the blue emulsion recording green light. The IKONOS satellite from Space Imaging (4-meter resolution) and the LISS II sensor on the Indian Research Satellites IRS-1A and 1B (36-meter resolution) add a blue band to provide complete coverage of the visible light range, and allow natural-color band composite images to be created. The Landsat Thematic Mapper (Landsat 4 and 5) and Enhanced Thematic Mapper Plus (Landsat 7) sensors add two bands in the middle infrared (MIR). Landsat TM band 5 (1.55 to 1.75 µm) and band 7 (2.08 to 2.35 µm) are sensitive to variations in the moisture content of vegetation and soils. Band 7 also covers a range that includes spectral absorption features found in several important types of minerals. An additional TM band (band 6) records part of the thermal infrared wavelength range (10.4 to 12.5 µm). (Bands 6 and 7 are not in wavelength order because band 7 was added late in the sensor design process.) Current multispectral satellite sensor systems with spatial resolution better than 200 meters are compared on the following pages.



To provide even greater spectral resolution, so-called *hyperspectral* sensors make measurements in dozens to hundreds of adjacent, narrow wavelength bands (as little as 0.1 µm in width). For more information on these systems, see the booklet *Introduction to Hyperspectral Imaging*.

Multispectral Satellite Sensors

Platform / Sensor / Launch Yr.	Image Cell Size	Image Size (Cross x Along-Track)	Spec. Bands	Visible Bands (µm)	Near IR Bands (µm)
ResourceSAT-2 2011	5.8 m (LISS-4)	70 km	3	G 0.52-0.59 R 0.62-0.68	0.77-0.86
	23.5 m (LISS-3)		3	G 0.52-0.59 R 0.62-0.68	0.77-0.86
WorldView-2 2009	1.8 m	16.4 km	8	0.40-0.45 B 0.45-0.51 G 0.51-0.58 Y 0.585-0.625 R 0.655-0.69	0.705-0.745 0.860-1.04
GeoEye-1 2008	1.65 m	15 x 15 km	4	B 0.45-0.51 G 0.51-0.58 R 0.655-0.69	0.78-0.92
RapidEye 2008	6.5 m	77 km	5	B 0.44-0.51 G 0.52-0.59 R 0.63-0.685	0.69-0.73 0.76-0.85
SPOT 5 **HRG** 2002	10 m (Vis, NIR) 20 m (MIR)	60 x 60 km	4	G 0.50-0.59 R 0.61-0.68	0.79-0.89
QuickBird 2001	2.4 or 2.8 m	16.5 x 16.5 km	4	B 0.45-0.52 G 0.52-0.60 R 0.63-0.69	0.76-0.90
Ikonos-2 **VNIR** 1999	4 m	11 x 11 km	4	B 0.45-0.52 G 0.52-0.60 R 0.63-0.69	0.76-0.90
Terra **(EOS-AM-1)** **ASTER** 1999	15 m (Vis, NIR) 30 m (MIR) 90 m (TIR)	60 x 60 km	14	G 0.52-0.60 R 0.63-0.69	0.76-0.86
SPOT 4 **HRVIR (XS)** 1999	20 m	60 x 60 km	4	G 0.50-0.59 R 0.61-0.68	0.79-0.89
Landsat 7 **ETM+** 1999	30 m	185 x 170 km	7	B 0.45-0.515 G 0.525-0.605 R 0.63-0.69	0.75-0.90
Landsat 4, 5 **TM** 1982	30 m	185 x 170 km	7	B 0.45-0.52 G 0.52-0.60 R 0.63-0.69	0.76-0.90

Ikonos-2: Space Imaging, Inc., USA **ResourceSAT-2:** Indian Space Research Org.
Terra, Landsat: NASA, USA **QuickBird, WorldView**: DigitalGlobe, Inc., USA
SPOT: Centre National d’Etudes Spatiales (CNES), France

Satellite Sensors Table (Continued)

Platform / Sensor / Launch Yr.	Mid. IR Bands (µm)	Thermal IR Bands (µm)	Panchrom. Band Range (µm)	Pan Cell Size	Nominal Revisit Interval*
ResourceSAT-2 2011	None	None	None	X	24 days (5 days†)
	1.55-1.70	None	None	X	
WorldView-2 2009	None	None	0.45-0.80 B, G, R, NIR	0.41 m	3.7 days (1.1 day†)
GeoEye-1 2008	None	None	0.45-0.80 B, G, R, NIR	0.41 m	5.5 days (1 day†)
RapidEye 2008	None	None	None	X	5.5 days (1 day†)
SPOT 5 **HRG** 2002	1.58-1.75	None	0.51-0.73 G, R	5 m	26 days (3 days†)
QuickBird 2001	None	None	0.45-0.90 B, G, R, NIR	0.6 or 0.7 m	(3.5 days†)
Ikonos-2 **VNIR** 1999	None	None	0.45-0.90 B, G, R, NIR	1 m	11 days (2.9 days†)
Terra **(EOS-AM-1)** **ASTER** 1999	1.60-1.70 2.145-2.185 2.185-2.225 2.235-2.285 2.295-2.365 2.36-2.43	8.125-8.475 8.475-8.825 8.925-9.275 10.25-10.95 10.95-11.65	None	X	16 days
SPOT 4 **HRVIR (XS)** 1999	1.58-1.75	None	0.61-0.68 R	10 m	26 days (5 days†)
Landsat 7 **ETM+** 1999	1.55-1.75 2.09-2.35	10.40-12.50	0.52-0.90 G, R, NIR	15 m	16 days
Landsat 4, 5 **TM** 1982	1.55-1.75 2.08-2.35	10.40-12.50	None	X	16 days

You can import imagery from any of these sensors into the TNTmips Project File format using the Import / Export process. Each image band is stored as a raster object.

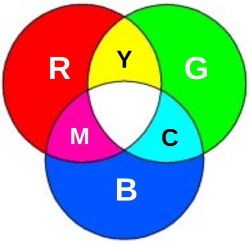
* Single satellite, nadir view at equator

† With off-nadir pointing

Radiometric Resolution

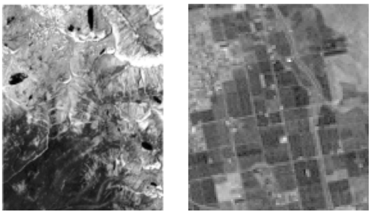
In order to digitally record the energy received by an individual detector in a sensor, the continuous range of incoming energy must be *quantized*, or subdivided into a number of discrete levels that are recorded as integer values. Many current satellite systems quantize data into 256 levels (8 bits of data in a binary encoding system). The thermal infrared bands of the ASTER sensor are quantized into 4096 levels (12 bits). The more levels that can be recorded, the greater is the *radiometric resolution* of the sensor system.

High radiometric resolution is advantageous when you use a computer to process and analyze the numerical values in the bands of a multispectral image. (Several of the most common analysis procedures, band ratio analysis and spectral classification, will be described subsequently.) Visual analysis of multispectral images also benefits from high radiometric resolution because a selection of wavelength bands can be combined to form a color display or print. One band is assigned to each of the three color channels used by the computer monitor: red, green, and blue. Using the additive color model, differing levels of these three primary colors combine to form millions of subtly different colors. For each cell in the multispectral image, the brightness values in the selected bands determine the red, green, and blue values used to create the displayed color. Using 256 levels for each color channel, a computer display can create over 16 million colors. Experiments indicate that the human visual system can distinguish close to seven million colors, and it is also highly attuned to spatial relationships. So despite the power of computer analysis, visual analysis of color displays of multispectral imagery can still be an effective tool in their interpretation.

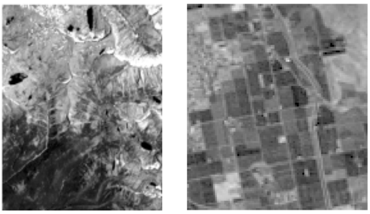


Individual band images in the visible to middle infrared range from the Landsat Thematic Mapper are illustrated for two sample areas on the next page. The left image is a mountainous terrane with forest (lower left), bare granitic rock, small clear lakes, and snow patches. The right image is an agricultural area with both bare and vegetated fields, with a town in the upper left and yellowed grass in the upper right. The captions for each image pair discuss some of the diagnostic uses of each band. Many color combinations are also possible with these six image bands. Three of the most widely-used color combinations are illustrated on a later page.

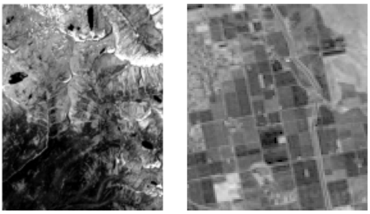
Visible to Middle Infrared Image Bands



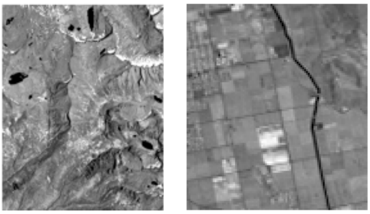
Blue (TM 1): Provides maximum penetration of shallow water bodies, though the mountain lakes in the left image are deep and thus appear dark, as does the forested area. In the right image, the town and yellowed grassy areas are brighter than the bare and cultivated agricultural fields. The brightness of the bare fields varies widely with moisture content.



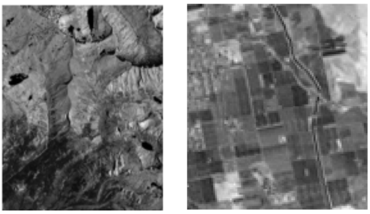
Green (TM 2): Includes the peak visible light reflectance of green vegetation, thus helps assess plant vigor and differentiate green and yellowed vegetation. But note that forest is still darker than bare rocks and soil. Snow is very bright, as it is throughout the visible and near-infrared range.



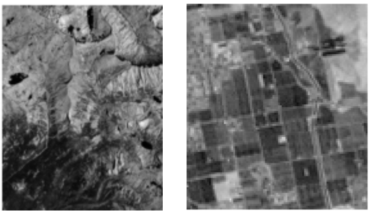
Red (TM 3): Due to strong absorption by chlorophyll, green vegetation appears darker than in the other visible light bands. The strength of this absorption can be used to differentiate different plant types. The red band is also important in determining soil color, and for identifying reddish, iron-stained rocks that are often associated with ore deposits.



Near Infrared (TM 4): Green vegetation is much brighter than in any of the visible bands. In the agricultural image, the few very bright fields indicate the maximum crop canopy cover. An irrigation canal is also very evident due to strong absorption by water and contrast with the brighter vegetated fields.



Middle Infrared, 1.55 to 1.75 µm (TM 5): Strongly absorbed by water, ice, and snow, so the lakes and snow patches in the mountain image appear dark. Reflected by clouds, so is useful for differentiating clouds and snow. Sensitive to the moisture content of soils: recently irrigated fields in the agricultural image appear in darker tones.

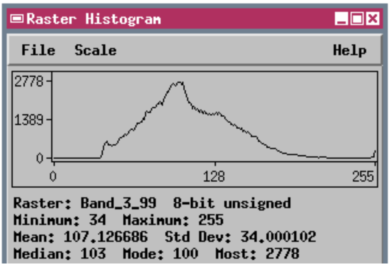


Middle Infrared, 2.08 to 2.35 µm (TM 7): Similar to TM band 5, but includes an absorption feature found in clay minerals; materials with abundant clay appear darker than in TM band 5. Useful for identifying clayey soils and alteration zones rich in clay that are commonly associated with economic mineral deposits.

Interpreting Single Image Bands

Much useful information can be obtained by visual examination of individual image bands. Here our visual abilities to rapidly assess the shape and size of ground features and their spatial patterns (texture) play important roles in interpretation. We also have the ability to quickly assess patterns of topographic shading and shadows and interpret from them the shape of the land surface and the direction of illumination.

One of the most important characteristics of an image band is its distribution of brightness levels, which is most commonly represented as a *histogram*. (You can view an image histogram using the Histogram tool in the TNTmips Spatial Data Display process.) A sample image and its histogram are shown below. The horizontal axis of the histogram shows the range of possible brightness levels (usually 0 to 255), and the vertical axis represents the number of image cells that have a particular brightness. The sample image has some very dark areas, and some very bright areas, but the majority of cells are only moderately bright. The shape of the histogram reflects this, forming a broad peak that is highest near the middle of the brightness range. The breadth of this histogram peak indicates the significant brightness variability in the scene. An image with more uniform surface cover, with less brightness variation, would show a much narrower histogram peak. If the scene includes extensive areas of different surface materials with distinctly different brightness, the histogram will show multiple peaks.



```
Raster: Band_3_99  8-bit unsigned
Minimum: 34  Maximum: 255
Mean: 107.126686  Std Dev: 34.000102
Median: 103  Mode: 100  Most: 2778
```

In contrast to our phenomenal color vision, we are only able to distinguish 20 to 30 distinct brightness levels in a grayscale image, so *contrast* (the relative brightness difference between features) is an important image attribute. Because of its wide range in brightness, the sample image above has relatively good contrast. But it is common for the majority of cells in an image band to be clustered in a relatively narrow brightness range, producing poor contrast. You can increase the interpretability of grayscale (and color) images by using the Contrast Enhancement procedure in the TNTmips Spatial Data Display process to spread the brightness values over more of the display brightness range. (See the tutorial booklet entitled *Getting Good Color* for more information.)

Color Combinations of Visible-MIR Bands

Four image areas are shown below to illustrate useful color combinations of bands in the visible to middle infrared range. The two left image sets are shown as separate bands and described on a preceding page. The third image set shows a desert valley with a central riparian zone and a few irrigated fields, and a dark basaltic cinder cone in the lower left. The fourth image set shows another desert area with varied rock types and an area of irrigated fields in the upper right.

Red (TM 3) = R, Green (TM 2) = G, Blue (TM 1) = B: Simulates "natural" color. Note the small lake in the upper left corner of the third image, which appears blue-green due to suspended sediment or algae.

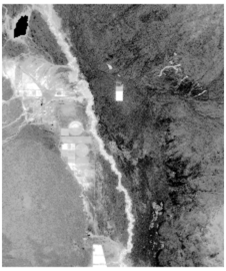
Near infrared (TM 4) = R, Red (TM 3) = G, Green (TM 2) = B: Simulates the colors of a color-infrared photo. Healthy green vegetation appears red, yellowed grass appears blue-green, and typical agricultural soils appear blue-green to brown. Snow is white, and deeper water is black. Rock materials typically appear in shades of gray to brown.

Middle infrared (TM 7) = R, Near infrared (TM 4) = G, Green (TM 2) = B: Healthy green vegetation appears bright green. Yellowed grass and typical agricultural soils appear pink to magenta. Snow is pale cyan, and deeper water is black. Rock materials typically appear in shades of brown, gray, pink, and red.

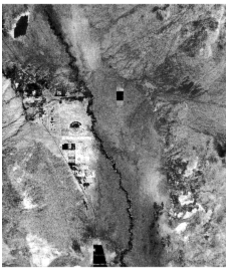
Band Ratios

Aerial images commonly exhibit illumination differences produced by shadows and by differing surface slope angles and slope directions. Because of these effects, the brightness of each surface material can vary from place to place in the image. Although these variations help us to visualize the three-dimensional shape of the landscape, they hamper our ability to recognize materials with similar spectral properties. We can remove these effects, and accentuate the spectral differences between materials, by computing a *ratio image* using two spectral bands. For each cell in the scene, the ratio value is computed by dividing the brightness value in one band by the value in the second band. Because the contribution of shading and shadowing is approximately constant for all image bands, dividing the two band values effectively cancels them out. Band ratios can be computed in TNTmips using the Predefined Raster Combination process, which is discussed in the tutorial booklet entitled *Combining Rasters*.

Band ratios have been used extensively in mineral exploration and to map vegetation condition. Bands are chosen to accentuate the occurrence of a particular material. The analyst chooses one wavelength band in which the material is highly reflective (appears bright), and another in which the material is strongly absorbing (appears dark). Usually the more reflective band is used as the numerator of the ratio, so that occurrences of the target material yield higher ratio values (greater than 1.0) and appear bright in the ratio image.



Ratio NIR / RED



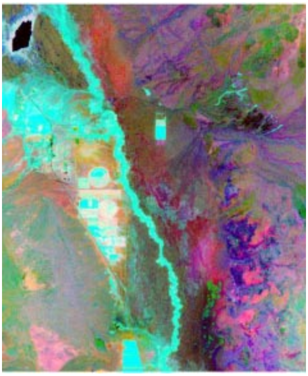
Ratio TM3 / TM1

A ratio of near infrared (NIR) and red bands (TM4 / TM3) is useful in mapping vegetation and vegetation condition. The ratio is high for healthy vegetation, but lower for stressed or yellowed vegetation (lower near infrared and higher red values) and for nonvegetated areas. Exploration geologists use several ratios of Landsat Thematic Mapper bands to help map alteration zones that commonly host ore deposits. A band ratio of red (TM3) to blue (TM1) highlights reddish-colored iron oxide minerals found in many alteration zones. Nearly all minerals are highly reflective in the shorter-wavelength middle infrared band (TM5), but the clay minerals such as kaolinite that are abundant in alteration zones have an absorption feature within the longer-wavelength middle infrared band (TM7). A ratio of TM5 to TM7 thus highlights these clay minerals, along with the carbonate minerals that make up limestone and dolomite. Compare the ratio images shown at left to the color composites of the third image set on the preceding page.

Normalized Difference Vegetation Index

Simple band ratio images, while very useful, have some disadvantages. First, any sensor noise that is localized in a particular band is amplified by the ratio calculation. (Ideally, the image bands you receive should have been processed to remove such sensor artifacts.) Another difficulty lies in the range and distribution of the calculated values, which we can illustrate using the NIR / RED ratio. Ratio values can range from decimal values less than 1.0 (for NIR less than RED) to values much greater than 1.0 (for NIR greater than RED). This range of values posed some difficulties in interpretation, scaling, and contrast enhancement for older image processing systems that operated primarily with 8-bit integer data values. (TNTmips allows you to work directly with the fractional ratio values in a floating-point raster format, with full access to different contrast enhancement methods).

A *normalized difference index* is a variant of the simple ratio calculation that avoids these problems. Corresponding cell values in the two bands are first subtracted, and this difference is then “normalized” by dividing by the sum of two brightness values. (You can compute normalized difference indices automatically in TNTmips using the Predefined Raster Combination process). The normalization tends to reduce artifacts related to sensor noise, and most illumination effects still are removed. The most widely used example is the Normalized Difference Vegetation Index (NDVI), which is (NIR - RED) / (NIR + RED). Raw index values range from -1 to +1, and the data range is symmetrical around 0 (NIR = RED), making interpretation and scaling easy. Compare the NDVI image of the mountain scene to the right with the color composite images shown on a previous page. The forested area in the lower left is very bright, and clearly differentiated from the darker nonvegetated areas.



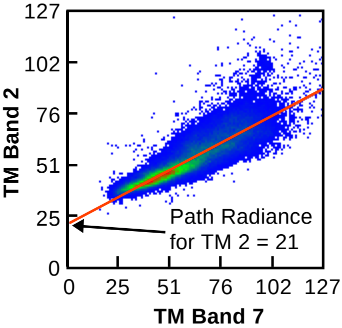
Different ratio or normalized difference images can be combined to form color composite images for visual interpretation. The color image to the left incorporates three ratio images with R = TM3 / TM1, G = TM4 / TM3, and B = TM7 / TM5. Vegetated areas appear bright blue-green, iron-stained areas appear in shades of pink to orange, and other rock and soil materials are shown in a variety of hues that portray subtle variations in their spectral characteristics.

Removing Haze (Path Radiance)

Before you compute band ratios or normalized difference images, you should adjust the brightness values in the bands to remove the effects of atmospheric path radiance. Recall that scattering by a hazy atmosphere adds a component of brightness to each cell in an image band. If atmospheric conditions were uniform across the scene (not always a safe assumption!), then we can assume that the brightness of each cell in a particular band has been increased by the same amount, shifting the entire band histogram uniformly toward higher values. This additive effect decreases with increasing wavelength, so calculating ratios with raw brightness values (especially ratios involving blue and green bands) can produce spurious results, including incomplete removal of topographic shading.

The adjustment of band values for path radiance effects is mathematically simple: subtract the appropriate value from each cell. (This operation can be performed in TNTmips in the Predefined Raster Combinations process, using the arithmetic operation Scale/Offset; use a scale factor of 1.0 and set the path radiance value as a negative offset). But how do you know what value to subtract?

Fortunately there are several simple ways to estimate path radiance values from the image itself. If the image includes areas that are completely shadowed, such as parts of the canyon walls in the image to the right, the brightness of the shadowed cells should be entirely due to path radiance. You can use DataTips or the Examine Raster tool in the TNTmips Spatial Data Display process to determine the value for the shadowed areas. In the absence of complete shadows, deep clear water bodies can provide suitably dark areas. The danger in this method is that the selected cell may actually have a component of brightness from the surface (such as a partial shadow or turbid water), in which case the subtracted value is too high. A more reliable estimate can be found for Landsat TM bands by using the Raster Correlation tool to display a scatterplot of brightness values for the selected band and the longer-wavelength middle infrared band (TM7) for which path radiance should be essentially 0. Because of path radiance, the best-fit line through the point distribution (computed automatically using the Regression Line option) does not pass through the origin of the plot. Instead its intersection with the axis for the shorter-wavelength band approximates the band's path radiance value (illustration at left).

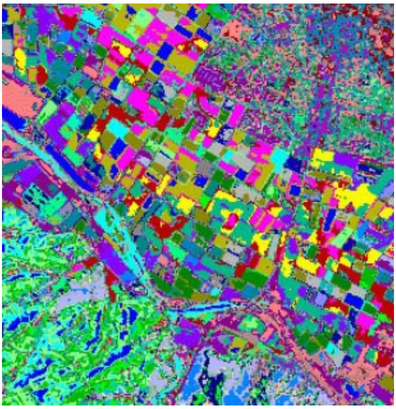


Spectral Classification

Color composite Landsat Thematic Mapper image with Red = TM7, Green = TM4, and Blue = TM2. Scene shows farmland flanked by an urban area (upper right) and grassy hills (lower left).

Spectral classification is another popular method of computer image analysis. In a multispectral image the brightness values in the different wavelength bands encode the spectral information for each image cell, and can be regarded as a *spectral pattern*. Spectral classification methods seek to categorize the image cells on the basis of these spectral patterns, without regard to spatial relationships or associations.

The spectral pattern of a cell in a multispectral image can be quantified by plotting the brightness value from each wavelength band on a separate coordinate axis to locate a point in a hypothetical "spectral space". This spectral space has one dimension for each image band that is used in the classification. Most classification methods assess the similarity of spectral patterns by using some measure of the distance between points in this spectral space. Cells whose spectral patterns are close together in spectral space have similar spectral characteristics and have a high likelihood of representing the same surface materials.

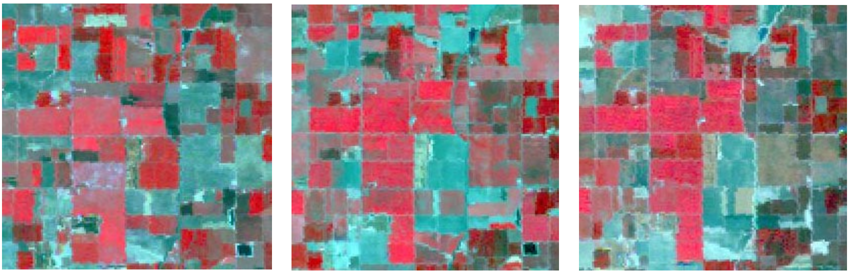


Result of unsupervised classification of six nonthermal Landsat TM bands for the above scene. Each arbitrary color indicates a separate class.

In *supervised* classification the analyst designates a set of "training areas" in the image, each of which is a known surface material that represents a desired spectral class. The classification algorithm computes the average spectral pattern for each training class, then assigns the remaining image cells to the most similar class. In *unsupervised* classification the algorithm derives its own set of spectral classes from an arbitrary sample of the image cells before making class assignments. You can perform both types of classification in TNTmips using the Automatic Classification process, which is described in the tutorial booklet entitled *Image Classification*.

Temporal Resolution

The surface environment of the Earth is dynamic, with change occurring on time scales ranging from seconds to decades or longer. The seasonal cycle of plant growth that affects both natural ecosystems and crops is an important example. Repeat imagery of the same area through the growing season adds to our ability to recognize and distinguish plant or crop types. A time-series of images can also be used to monitor changes in surface features due to other natural processes or human activity. The time-interval separating successive images in such a series can be considered to define the *temporal resolution* of the image sequence.



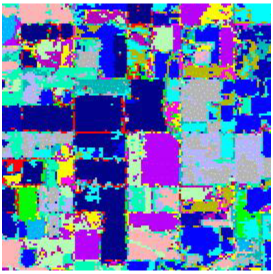
This sequence of Landsat TM images of an agricultural area in central California was acquired during a single growing season: 27 April (left), 30 June (center), and 20 October (right). In this 4-3-2 band combination vegetation appears red and bare soil in shades of blue-green. Some fields show an increase in crop canopy cover from April to June, and some were harvested prior to October.

Most surface-monitoring satellites are in low-Earth orbits (between 650 and 850 kilometers above the surface) that pass close to the Earth's poles. The satellites complete many orbits in a day as the Earth rotates beneath them, and the orbital parameters and swath width determine the time interval between repeat passes over the same point on the surface. For example, the repeat interval of the individual Landsat satellites is 16 days. Placing duplicate satellites in offset orbits (as in the SPOT series) is one strategy for reducing the repeat interval. Satellites such as SPOT and IKONOS also have sensors that can be pointed off to the side of the orbital track, so they can image the same areas within a few days, well below the orbital repeat interval. Such frequent repeat times may soon allow farmers to utilize weekly satellite imagery to provide information on the condition of their crops during the growing season.

Growth in urban area of Tracy, California recorded by Landsat TM images from 1985 (left) and 1999 (right).

Spatial Registration and Normalization

You can make qualitative interpretations from an image time-sequence (or images from different sensors) by simple visual comparison. If you wish to combine information from the different dates in a color composite display, or to perform a quantitative analysis such as spectral classification, first you need to ensure that the images are spatially registered and and spectrally normalized.



Classification result for the area shown in the images on the preceding page, using six Landsat TM bands for each date.

Spatial registration means that corresponding cells in the different images are correctly identified, matched in size, and sample the same areas on the ground. Registering a set of images requires several steps. The first step is usually *georeferencing* the images: identifying in each image a set of control points with known map coordinates. The control point coordinates can come from another georeferenced image or map, or from a set of positions collected in the field using a Global Positioning System (GPS) receiver. Control points are assigned in TNTmips in the Georeference process (Edit / Georeference). You can find step-by-step instructions on using the Georeference process in the tutorial booklet entitled *Georeferencing*. After all of the images have been georeferenced, you can use the Automatic Resampling process (Process / Raster / Resample / Automatic) to reproject each image to a common map coordinate system and cell size. For more information about this process, consult the tutorial booklet entitled *Rectifying Images*.

Images of the same area acquired on different dates may have different brightness values for the same ground location and surface material because of differences in sensor calibration, atmospheric conditions, and illumination. The path radiance correction described previously removes most of the between-date variance due to atmospheric conditions and sensor offset. To correct for remaining differences in sensor gain and illumination, the values in the image bands must be rescaled by some multiplicative factor. If spectral measurements have been made of ground materials in the scene, the images can be rescaled to represent actual reflectance values (spectral calibration). In the absence of field spectra, you can pick one image as the “standard”, and rescale the others to match its conditions (image normalization). One normalization procedure requires that the scene includes identifiable features whose spectral properties have not varied through time (called *pseudoinvariant* features). Good candidates include manmade materials such as asphalt and concrete, or natural materials such as deep water bodies or dry bare soil areas. Normalization procedures using this method are outlined in the *Combining Rasters* booklet .

Thermal Infrared Images

Thermal infrared images add another dimension to passive remote sensing techniques. They provide information about surface temperatures and the thermal properties of surface materials. Many applications of thermal infrared images are possible, including mapping rock types, soils, and soil moisture variations, and monitoring vegetation condition, sea ice, and ocean current patterns. Thermal images also can be used in more dramatic circumstances to monitor unusual heat sources such as wildfires, volcanic activity, or hot water plumes released into rivers or lakes by power plants.

The Earth's surface emits EM radiation in the thermal infrared wavelength range as determined by typical surface temperatures. Most thermal infrared images are acquired at wavelengths between 8 and 14 μm, a range that includes the peak emissions. Nearly all incoming solar radiation at these wavelengths is absorbed by the surface, so there is little interference from reflected radiation, and this range also is a good "atmospheric window" (see pages 6 and 7). The natural sources that heat the Earth's surface are solar energy and geothermal energy (heat produced by decay of radioactive elements in rocks). Geothermal heating is much smaller in magnitude and is nearly uniform over large areas, so solar heating is the dominant source of temperature variation for most images. The daily solar heating of the surface is influenced by the physical and thermal properties of the surface materials, by topography (slopes facing the sun absorb more solar energy), and by clouds and wind.

The cool river surface, its flanking wooded strips, and agricultural fields with full crop cover appear dark in this summer mid-morning thermal image of an area in Kansas (USA). Brighter fields are bare soil. From Landsat 7 ETM+, band 6, with 60-meter ground resolution.

The brightness values in a thermal image measure the amount of energy emitted by different parts of the surface, which depends not only on the material's temperature, but also on a property called *emissivity*. Emissivity describes how efficiently a material radiates energy compared to a hypothetical ideal emitter and absorber, called a *blackbody*. Emissivity is defined as the ratio of the amount of radiant energy emitted by a real material at a given temperature to the amount emitted by a blackbody at the same temperature. Emissivity is wavelength dependent, so materials can be characterized by an emissivity spectrum just as they are by a reflectance spectrum. Most natural materials are relatively strong emitters. Average emissivity values for the wavelength range from 8 to 12 μm vary from 0.815 for granite rock to 0.993 for pure water.

Thermal Processes and Properties

Some analogies can be drawn between thermal infrared images and the more familiar images created with reflected solar radiation. Both types of images reveal spatial variations in a material property that governs an instantaneous interaction process between radiation and matter: emissivity for thermal images and reflectance for reflected solar images. Topographic effects can be present in both types of images as well, as temperature variations in thermal images and as illumination differences in reflected images. But the interpretation of thermal images is more complex because surface temperature also varies spatially as a result of other material properties. These temperature variations also involve processes that extend below the visible surface and that are not instantaneous in nature.

The temperatures of all surface materials change in a daily cycle of solar heating and subsequent nighttime cooling, but different materials respond to this daily cycle in different ways. Darker materials tend to absorb more incoming radiation and so are heated more than brighter materials, which reflect much of the solar radiation. Even if two materials do absorb the same amount of radiation, one may achieve a higher maximum temperature than the other. In part this may be due to the fact that the materials have different *thermal capacities*: different amounts of heat are required to induce a given rise in their temperatures. But as the surface warms, heat is transferred by conduction to cooler levels below the surface, and the reverse process occurs during nocturnal cooling. Temperature changes during the daily solar cycle may extend as deep as 30 centimeters below the surface. Because rates of heat transfer vary between materials due to differences in density and thermal conductivity, this vertical heat exchange also gives rise to spatial variations in temperature. These effects can be expressed as a property called *thermal inertia*, the resistance to change in temperature, which is a function of density, thermal capacity, and thermal conductivity.

Surface materials constantly emit infrared radiation, so thermal images can be acquired day or night. Materials that warm slowly during the day, and thus are cooler than their surroundings, also cool slowly at night, and so become warmer than their surroundings in nighttime images. Successful interpretation of thermal images requires a knowledge of the time of acquisition of the image, the topography of the area, and the thermal properties of the materials likely to be present in the scene.

In this nighttime thermal infrared image of northern Eritrea and the Red Sea, the water is warmer than the land surface, and thus appears in brighter tones at the upper right. The brightness variations on land relate to variations in thermal properties and, to a smaller degree, topography.

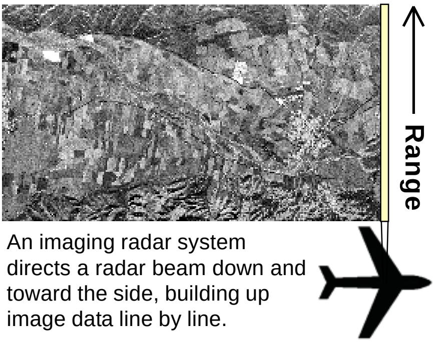
Radar Images

Imaging radar systems are versatile sources of remotely sensed images, providing day-night, all-weather imaging capability. Radar images are used to map landforms and geologic structure, soil types, vegetation and crops, and ice and oil slicks on the ocean surface. Aircraft-mounted commercial and research systems have been in use for decades, and two satellite systems are currently operational (the Canadian Radarsat and the European Space Agency's ERS-1).


Hilly terrain dominates the right half and flatter surfaces the left half of this radar image. A broad braided stream channel on the left edge is flanked by agricultural fields. Residential areas with bright vegetation and structures and dark streets are found in the lower left and upper right portions.

Radar images have a unique, unfamiliar appearance compared to other forms of images. They appear grainy and can also include significant spatial distortions of ground features. As with any remote sensing system, an understanding of the nature of the relevant EMR interactions and the acquisition geometry is important for successful interpretation of radar images.

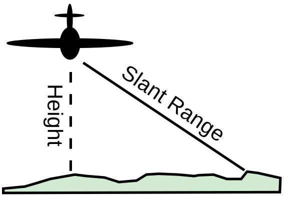
An imaging radar system uses an antenna to transmit microwave energy downward and toward the side of the flight path (see illustration below). As the radar beam strikes ground features, energy is scattered in various directions, and the radar antenna receives and measures the strength of the energy that is scattered back toward the sensor platform. A surface that is smooth and flat (such a lake or road) will reflect nearly all of the incident energy away from the sensor. So flat surfaces appear dark in a radar image. A surface that is rough, with "bumps" comparable in height to the wavelength of the microwaves, will scatter more energy back to the sensor, and so will appear bright. (The range of wavelengths commonly used in imaging radar systems is between 0.8 cm and 1 meter). Slopes that face the sensor will also appear brighter than surfaces that slope away from it, and steep backslopes may be completely shadowed. Terrane shape and surface roughness are thus the dominant controls on radar brightness variations.



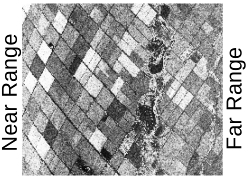
An imaging radar system directs a radar beam down and toward the side, building up image data line by line.

Radar Image Geometry

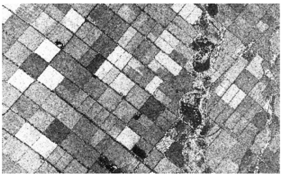
Imaging radar systems broadcast very short (10 to 50 microsecond) pulses of microwave energy and, in the pauses between them, receive the fluctuating return signal of backscattered energy. Each broadcast pulse is directed across a narrow strip perpendicular to the flight direction. This pulsing mode is necessary because the system measures not only the strength of the returning signal, but also its round-trip travel time. Because the microwaves travel at the speed of light, the travel time for each part of the return signal can be converted directly to straight-line distance to the reflecting object, known as the *slant range* (see illustration below). In the initial image produced by most radar systems, the positions of radar returns in the range (across-track) direction are based on their slant range distances. Because the angle of the radar reflections varies in the range direction, the horizontal scale of a slant range image is not constant. Features in the part of the image close to the flight line (the near range) appear compressed in the range direction compared to those in the far range. Using the sensor height and the assumption that the terrain is flat, a slant range image can be processed to produce an approximation of the true horizontal positions of the radar returns. The result is a *ground range* image. TNTmips offers the slant range to ground range transformation as one of its raster resampling options (Process / Raster / Resample / Radar Slant to Ground).



Slant Range Image



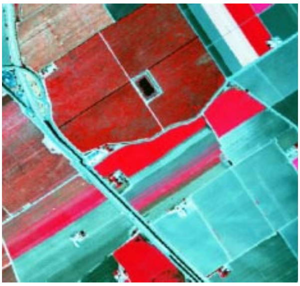
Ground Range Image



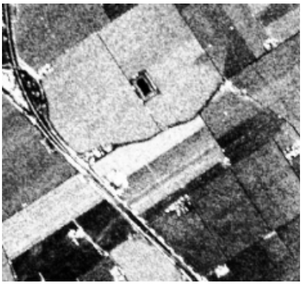
The side-looking geometry of radar systems also creates internal image distortions related to topography. Slopes that face the sensor are narrowed relative to slopes facing away from it. As a result hills and ridges appear to lean toward the flight path. This *foreshortening* is illustrated in the image to the right by the brighter slopes on the left side, which face toward the sensor (left). If the foreslope is too steep, returns from the top may arrive before any others, and the front slope disappears completely (called *layover*). An accurate elevation model of the surface is required to remove these distortions.

Fusing Data from Different Sensors

Materials commonly found at the Earth's surface, such as soil, rocks, water, vegetation, and man-made features, possess many distinct physical properties that control their interactions with electromagnetic radiation. In the preceding pages we have discussed remote sensing systems that use three separate parts of the radiation spectrum: reflected solar radiation (visible and infrared), emitted thermal infrared, and imaging radar. Because the interactions of EM radiation with surface features in these spectral regions are different, each of the corresponding sensor systems measures a different set of physical properties. Although each type of system by itself can reveal a wealth of information about the identity and condition of surface materials, we can learn even more by combining image data from different sensors. Interpretation of the merged data set can employ rigorous quantiative analysis, or more qualitative visual analysis. The illustrations below show an example of the latter approach.



These images show a small area (about 1.5 by 1.5 km) of cropland in the Salinas Valley, California. Data used in the color image to the right was acquired 8 October 1998 by NASA's AVIRIS sensor. This hyperspectral sensor acquires images in numerous narrow spectral bands in the visible to middle infrared range. The band combination to the right uses bands from the near infrared, green, and blue wavelength regions to simulate a color infrared image; red indicates vegetated areas, in this case fields with full crop canopy.



Data for the center radar image was acquired by NASA's AIRSAR imaging radar system on 24 October 1998, about two weeks after the AVIRIS image. Acquired using a 24-cm radar wavelength, the image has been transformed to ground range. The brightest radar returns come from crops with a tall, bushy structure. The brightest field in the center is a broccoli field, and a vineyard with vines trained to a vertical trellis is at bottom center. (Both the AIRSAR and AVIRIS data were georeferenced and resampled to the same cell size and geographic extents.)

The image to the right combines the AVIRIS and AIRSAR data in a single color image using the RGBI raster display procedure. This process converts the AVIRIS color band combination to the Hue-Intensity-Saturation color space, substitutes the AIRSAR image for grayscale intensity, and converts back to the RGB color space to create the final image (see the *Getting Good Color* tutorial booklet for more information). Colors in the combined image differentiate fields by degree of plant cover (red hue) and plant structure (intensity).

Other Sources of Information

This booklet has provided a brief overview of the rich and complex field of remote sensing of environmental resources. If you are interested in exploring further, you may wish to begin with one of the traditional printed texts listed below, or take advantage of a variety of on-line internet resources.

Introductory Textbooks

Campbell, James B. and Wynne, Randolph H. (2011). *Introduction to Remote Sensing* (5th ed.). The Guilford Presss. 667 p.

Drury, S. A. (1993). *Image Interpretation in Geology* (3rd ed.). London: Taylor & Francis. 290 p.

Lillesand, Thomas M., Kiefer, Ralph W., and Chipman, Jonathan (2007). *Remote Sensing and Image Interpretation* (6th ed.). New York: John Wiley and Sons. 750 p.

Sabins, Floyd F. (1997). *Remote Sensing: Principles and Interpretation* (3rd ed.). Waveland Press Inc. 512 p.

More Advanced Texts

Jensen, John R. (1996). *Introductory Digital Image Processing: a Remote Sensing Perspective* (2nd ed.). Upper Saddle River, NJ: Prentice-Hall. 316 p.

Rencz, Andrew N., ed. (1999). *Remote Sensing for the Earth Sciences*. Manual of Remote Sensing, (3rd ed.), Volume 3. New York: John Wiley and Sons. 707 p.

Schowengerdt, Robert A. (1997). *Remote Sensing: Models and Methods for Image Processing* (2nd ed.). New York: Academic Press. 522 p.

Internet Resources

Remote Sensing Tutorial created by the Goddard Space Flight Center
http://rst.gsfc.nasa.gov or **http://www.fas.org/irp/imint/docs/rst/**
An application-oriented on-line tutorial covering all aspects of remote sensing, including thermal images and radar, with many sample images.

Remote Sensing Tutorials created by the Canada Centre for Remote Sensing
http://www.nrcan.gc.ca/earth-sciences/geography-boundary/remote-sensing/1599#tutor
On-line tuturials in remote sensing fundamentals, radar and stereoscopy, and digital image analysis.

Advanced Software for Geospatial Analysis

MicroImages, Inc. publishes a complete line of professional software for advanced geospatial data visualization, analysis, and publishing. Contact us or visit our web site for detailed product information.

TNTmips Pro TNTmips Pro is a professional system for fully integrated GIS, image analysis, CAD, TIN, desktop cartography, and geospatial database management.

TNTmips Basic TNTmips Basic is a low-cost version of TNTmips for small projects.

TNTmips Free TNTmips Free is a free version of TNTmips for students and professionals with small projects. You can download TNTmips Free from MicroImages' web site.

TNTedit TNTedit provides interactive tools to create, georeference, and edit vector, image, CAD, TIN, and relational database project materials in a wide variety of formats.

TNTview TNTview has the same powerful display features as TNTmips and is perfect for those who do not need the technical processing and preparation features of TNTmips.

TNTatlas TNTatlas lets you publish and distribute your spatial project materials on CD or DVD at low cost. TNTatlas CDs/DVDs can be used on any popular computing platform.

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