Satellite and Aerial Imagery
Demonstration Project

Introduction to Landsat 7 Imagery

Bonneville
Power Administration

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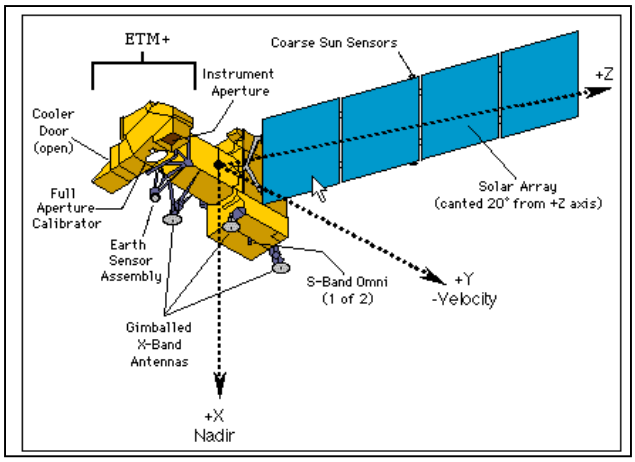
Part A. The Landsat 7 Satellite

Landsat 7 is part of NASA's Earth Science Enterprise (ESE) and is the latest in a series of land observing satellites that provide global change information to users worldwide. Scientists use Landsat satellites to gather remotely sensed images of the land surface and surrounding coastal regions for global change research, regional environmental change studies and other civil and commercial purposes. Over thirty years of Landsat images offer a mostly unexplored resource for the study and assessment of aquatic resources in the Columbia River Basin.



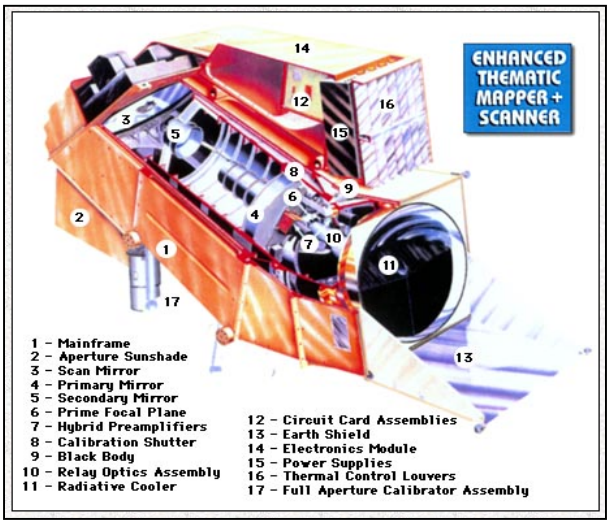
Landsat 7 acquires repetitive, synoptic coverage of continental surfaces with multispectral images in the visible, near infrared, shortwave, and thermal infrared regions of the electromagnetic spectrum. Visible, near infrared and shortwave infrared bands (bands 1,2,3,4,5,7) have a spatial resolution of 30 meters (98-feet) and the thermal band (band 6) has a 60-meter resolution. The spectral and spatial characteristics of Landsat 7 are nearly equivalent to that of Landsat 5 so images of both series may be readily compared. Landsat 7 also has a panchromatic sensor (band 8) that produces images with a 15-meter resolution that greatly enhances feature identification and interpretation.

Landsat History

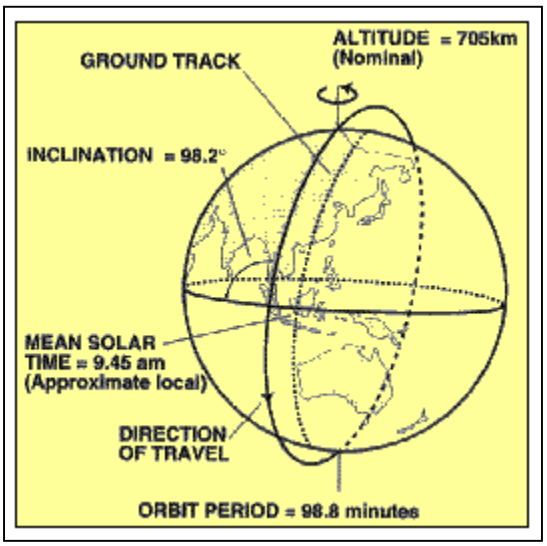
Images acquired by Landsat satellites were used to produce the first composite multi-spectral mosaic of the 48 contiguous United States. Landsat imagery serves a broad user scientific community. Landsat imagery are being used for monitoring agricultural productivity, water resources, urban growth, deforestation, and natural change due to fires and insect infestations. Landsat images are applied in commercial activities including mineral exploration, forest cover assessment, and monitoring of mining operations.

The first Landsat satellites were originally called ERTS for Earth Resources Technology Satellite and were developed and launched by NASA between July 1972 and March 1978. An improved Landsat 4 was launched in July 1982 with Landsat 5 following in March 1984. Amazingly, Landsat 5 is still transmitting images. Landsat 6 failed shortly after launch. Landsat 7 was launched on April 15, 1999.

Enhanced Thermatic Mapper Plus



The ETM+ instrument is an eight-band multispectral scanning radiometer. It detects radiation at visible, near-infrared, short wave, and thermal infrared frequency bands from the sun-lit Earth in a 183 kilometer-wide swath when orbiting at an altitude of 705 kilometers. Nominal ground sample distances (GSD) or "pixel" sizes are 15 meters in the panchromatic band; 30 meters in the six visible, near and short-wave infrared bands; and 60 meters in the thermal infrared band.

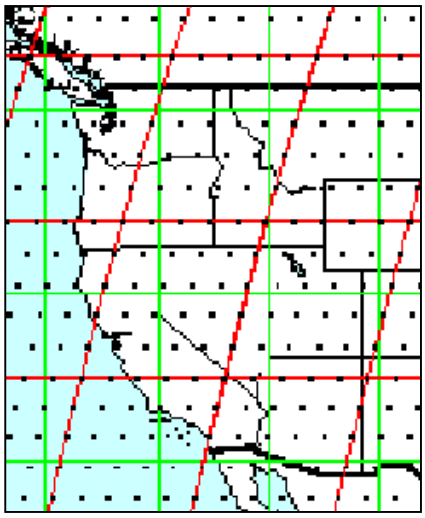


The satellite orbits the Earth with a sun-synchronous 98-degree inclination and a descending equatorial crossing time of 10 a.m. local solar time. The orbit is maintained with periodic adjustments for the life of the satellite. A three-axis attitude control subsystem stabilizes the satellite keeps the instrument pointed toward Earth to within 0.05 degrees.

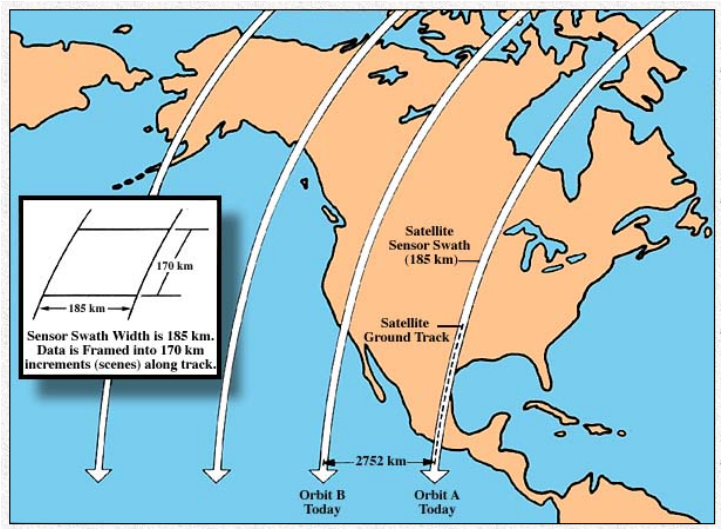
Calibration and Validation

Landsat 7 sensors are routinely calibrated to preserve radiometric accuracy. The Landsat 7 full-aperture-solar-calibrator and a partial-aperture-solar-calibrator use the sun, with its known exo-atmospheric irradiance, as an absolute radiometric calibration source. On-board solar calibration procedures in conjunction with an internal calibration lamp and ground-based validation experiments, permit calibration to an uncertainty of less than five percent.

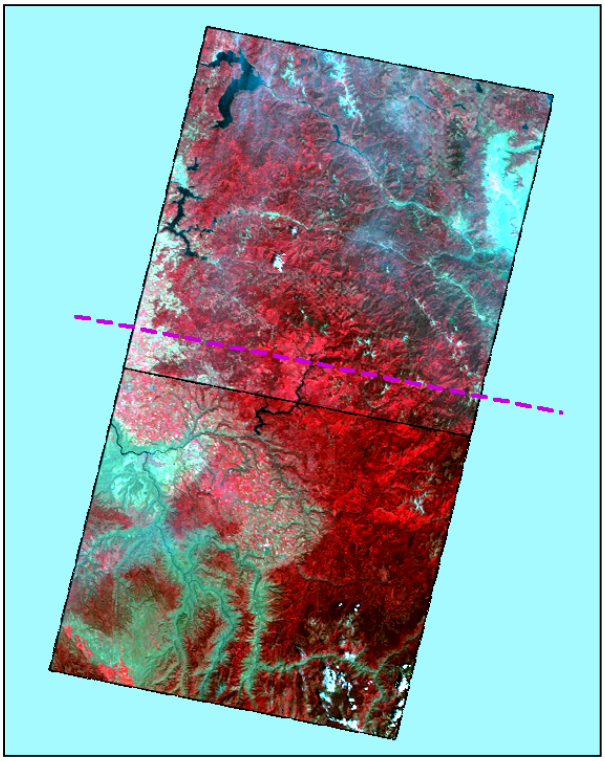
World-Wide-Reference system



Landsat images are catalogued according to the Landsat World-Wide-Reference system (WRS). The WRS divides the Earth's surface into 57,784 scenes, 233 paths by 248 rows, each 183 kilometers wide by 170 kilometers long. Orbit swaths are repeated once every 16 days. Landsat 7 overflights adhere to a fixed schedule. The swath to the west of a particular swath is collected 7 days later. Landsat 7 images are identified and ordered by WRS coordinates.



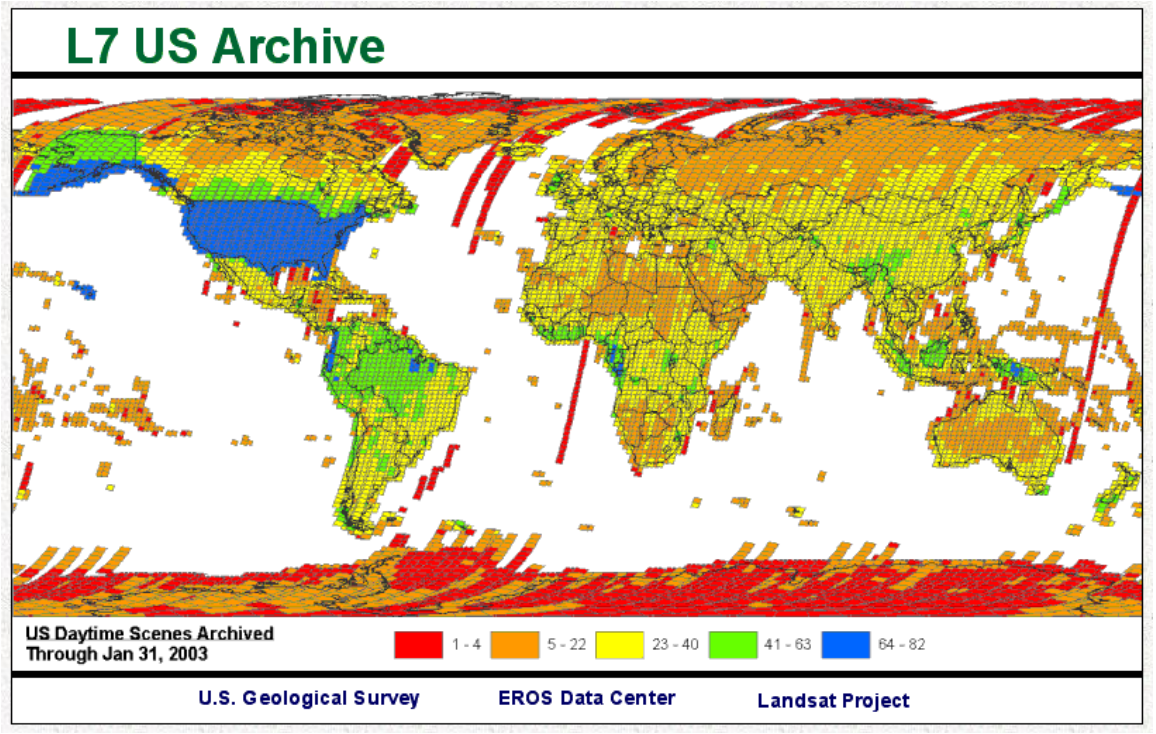
Adjacent swaths overlap at the equator by 7.3 percent. Moving from the Equator toward either pole the sidelap increases because the fixed 185 km swath width. Overlap is about 20% at 30° latitude, increasing to about 30% at 40° latitude.



Two Landsat 7 scenes cover most of the Lower Clearwater Basin. These scenes are in the same orbital path are identified by the WRS designations Path 42 Row 27 and Path 42 Row 28. Daytime Landsat 7 are collected as the satellite orbits from north to south (descending) so Scene P42R27 is acquired a few minutes before scene P42R28. Endlap between scenes is normally between 10-15%. Endlap between the images is about 13%. The dashed line shows the edge of the underlying image.

Acquisition and Coverage

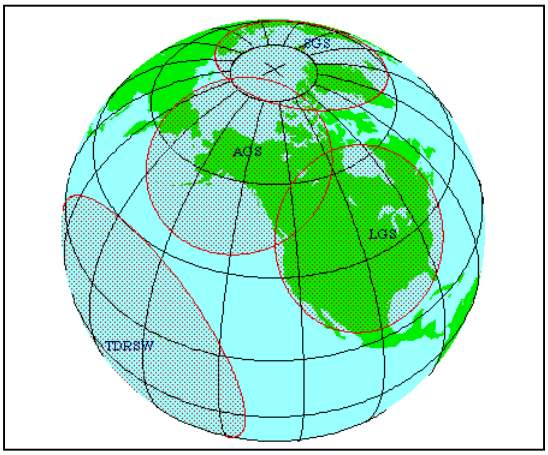
Landsat 7 has acquired approximately 300,000 daytime images through January 2003. The densest coverage is over the U.S., but repeat coverage is available worldwide. The Landsat-7 Long Term Acquisition Plan (LTAP) selects scenes to update a global archive of sunlit, substantially cloud-free land images. A foremost objective is to monitor changes in vegetation across the planet. The LTAP schedules acquisitions more frequently during periods of change, such as growth and senescence of vegetation, and less frequently during relatively stable periods, such as when full growth canopy exists or during the winter.



Approximately 70% the 250 scenes per day acquired by Landsat 7 are routine acquisitions to support vegetation analysis. The other 30% of the collection capacity is devoted to other scientific "niche" requests, including about 3% for night images or special high-priority acquisitions (natural disasters, national needs, etc). Identified annual scientific priorities include:

- 282 scenes for agricultural monitoring and research
- 35 scenes for instrument calibration
- 896 scenes of reefs (acquired 2 – 6 times each year)
- 30 scenes of wildfire
- 1392 scenes of land ice (acquire once during certain months)
- 3601 scenes of Antarctica (acquire once during Jan-Feb)
- 60 scenes of oceanic islands (acquire twice each year)
- 1175 scenes of rainforest
- 352 scenes of sea ice (acquired 1 – 3 times each year)
- 11 scenes of Siberia (annual)
- 72 scenes of volcanoes (acquired 2 – 12 times each year)

Landsat Ground and Archive System



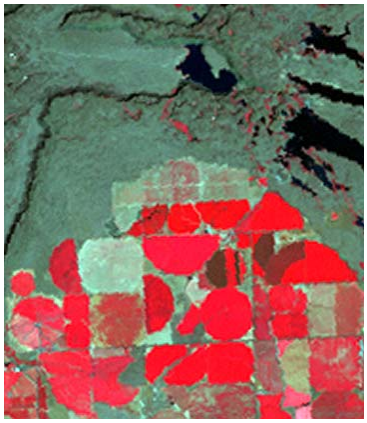
The Landsat ground system includes a spacecraft control center, ground stations for uplinking commands and receiving data, a data handling facility and a data archive developed by the Goddard Space Flight Center, Greenbelt, Md., in conjunction with the U.S. Geological Survey (USGS) EROS Data Center (EDC), Sioux Falls, SD. These facilities, augmented by existing NASA institutional facilities, communicate with the Landsat 7 satellite, control all spacecraft and instrument operations, and receive, process, archive, and distribute ETM+ data.

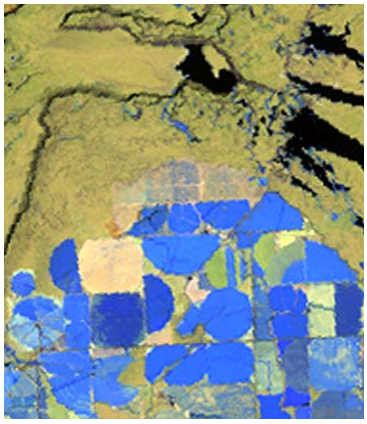
The USGS manages the primary ground station, the data handling facility and archive at the EROS Data Center. NASA managed flight operations from the control center at the Goddard Space Flight Center until October 1, 2000 then passed responsibility for flight operations to the USGS.

The ground system at the data center can capture and process 250 Landsat scenes per day and deliver at least 100 of the scenes to users each day. The ground system is capable of distributing raw ETM+ data within 24 hours of its reception at the EROS Data Center. All 100 of these scenes can be radiometrically corrected to within five percent and geometrically located on the Earth to within 250 meters of true location.

Part B. Characteristics of Landsat 7 Imagery

Spectral and spatial resolution



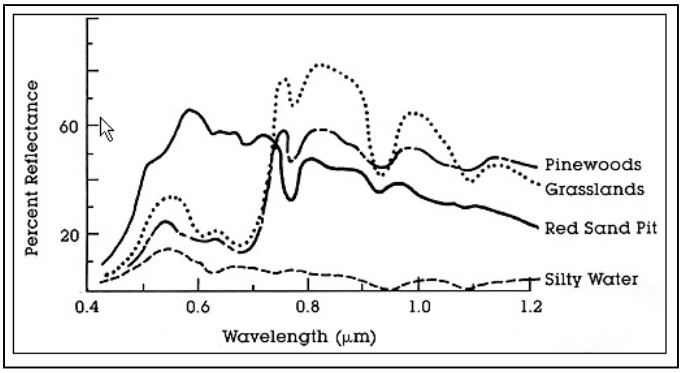


Spectral and spatial resolution of satellite and aerial imagery indicate the suitability of imagery for particular remote sensing tasks. Landsat-7 collects seven bands (channels) of reflected energy and one band of emitted (thermal) energy. The ETM+ sensor converts solar energy to radiance. Radiance is the flux of energy (primarily irradiant or incident energy) per solid angle leaving a unit surface area in a given direction. Conventional units of radiance are watts per square meter per steradian[1] per micron of wavelength ($W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$). Radiance is different from reflectance, which is the dimensionless ratio of reflected versus total power energy. Land surface reflectance may be computed from at-sensor radiance by adjusting for sun angle, satellite orientation, atmospheric effects, and normalizing by assumed values of total solar energy incident on the earth within a wavelength interval. The table below lists Landsat 7 band numbers and wavelength intervals along with spatial resolution and sensor type. Bands 1 through 5 and band 7 record reflected solar energy and are called the visible, near infrared and shortwave infrared bands. Band 8 responds to a wide spectral region in the visible and near infrared and is called the panchromatic band. Band 6 records emitted thermal energy and is called the thermal band. Together these bands cover the portion of solar spectrum found to be scientifically useful for studying the characteristics of the earth surface.

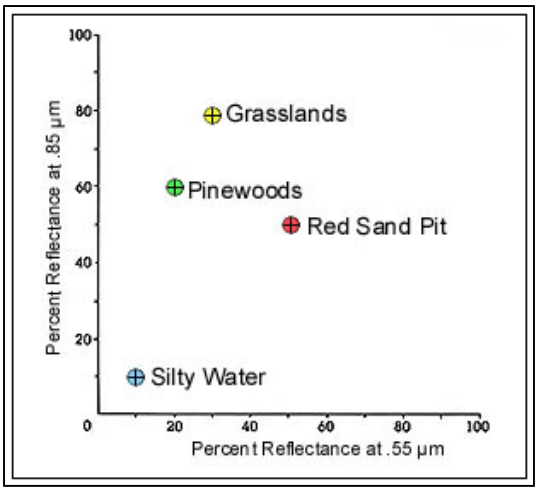
[1] A steradian is a cone shaped unit solid angle. There are 4π steradians in a full sphere.

Landsat 7 Spectral Bands			
Band No.	Interval	Resolution	Sensor Type
1	0.45 - 0.52 µm	30	SiPD
2	0.52 - 060 µm	30	SiPD
3	0.63 - 069 µm	30	SiPD
4	0.76 - 0.90 µm	30	SiPD
5	1.55 - 1.75 µm	30	InSb
6	10.4 - 12.5 µm	60	HgCdTe
7	2.08 - 2.35 µm	30	InSb
8	0.50 - 0.90 µm	15	SiPD

[1] A steradian is a cone shaped unit solid angle. There are 4π steradians in a full sphere.



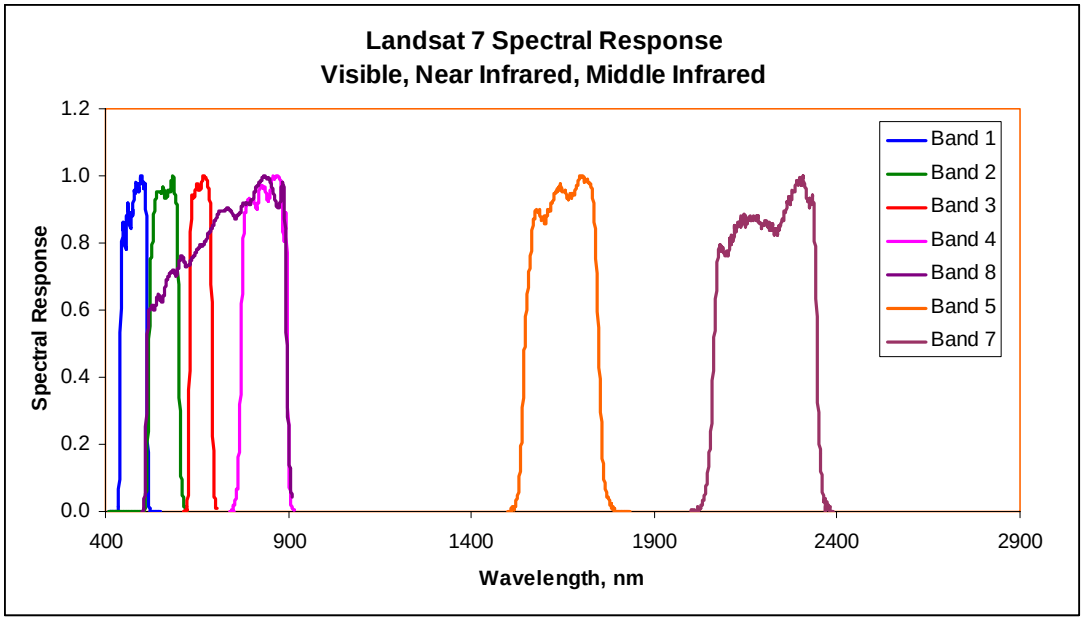
Different surface materials reflect and emit varying levels of radiation. Land cover can often be identified by reflectance characteristics. Unique spectral signatures of reflected and emitted energy are identified by laboratory spectrometer measurements or by interpretation of calibrated satellite and aerial imagery. A basic premise of the science of remote sensing is that spectral signatures of similar objects or classes of objects will have similar interactive properties with electromagnetic radiation at any given wavelength.

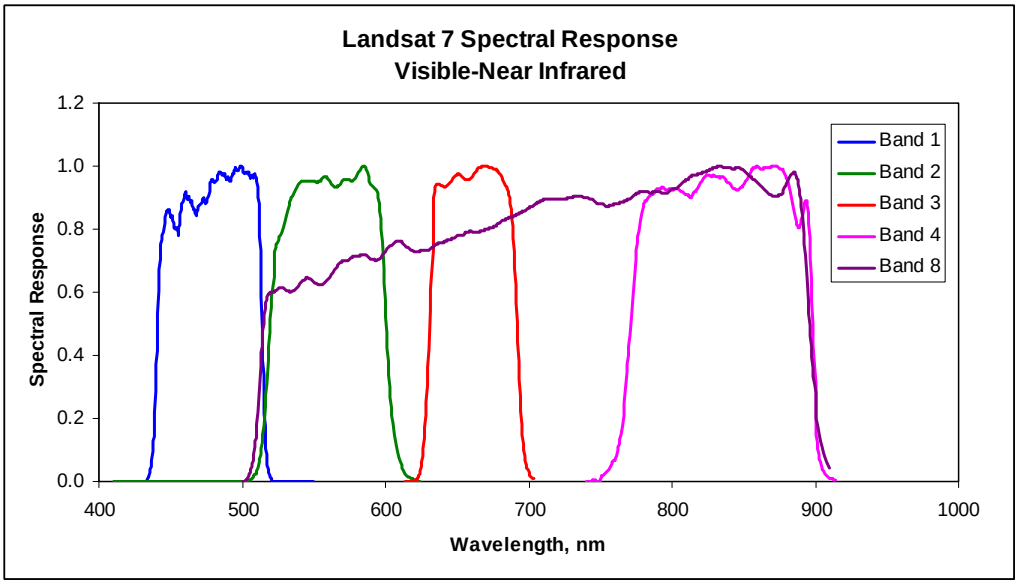


The seven bands of Landsat 7 imagery give seven points on the spectral reflectance curve. Each band is defined by its mid point and width on the electromagnetic spectrum. Landsat 7 bands are relatively broad. Other sensors, such as hyperspectral sensors may collect hundreds of individual spectral bands each just a few microns wide. Hyperspectral images yield highly detailed spectral signatures. More detailed spectral signatures improve the ability of imagery to discriminate surface materials. The spectral signatures developed Landsat 7 imagery often overlap among materials because of its a relatively low number of bands. Landsat 7 images are most often used to identify general surface type such as open water, forest, desert, agricultural land, bare soil, rock, ice and urbanized areas. It is usually much more difficult or impossible to distinguish individual species plants within a particular vegetative community with Landsat imagery, for example discriminating wheat from barley or pine from fir.

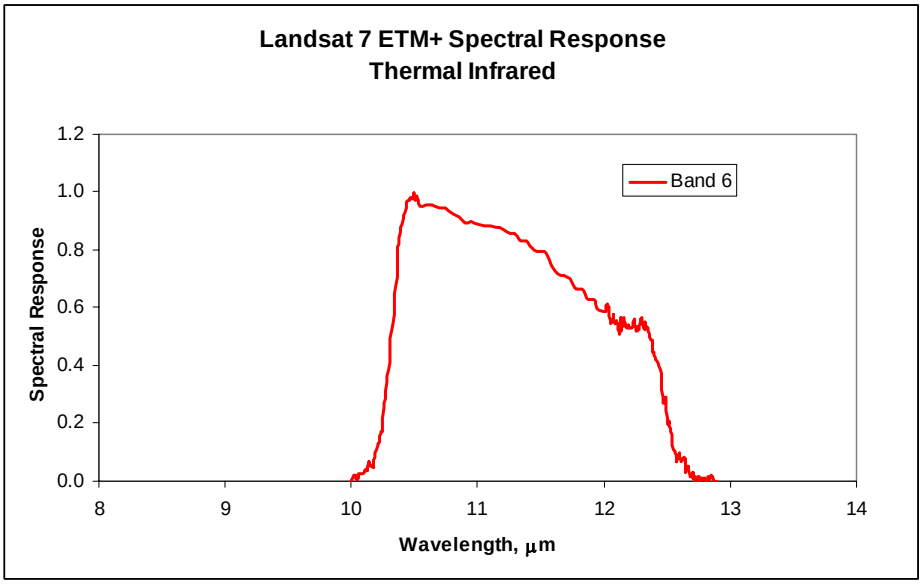
Spectral Response

Spectral Response plots for the ETM+ bands are shown in the plots below. Spectral Response indicates the relative sensitivity of a detector as a function of wavelength. Greater spectral response values indicate more energy of the corresponding wavelengths is recorded. The maximum value of any spectral response curve is 1. Wavelengths outside the spectral response region are not detected. For example, band 4 (near infrared) does not record green light, but band 8, the panchromatic band, records light through the green, red and near infrared region. The distinct separation of the band wavelengths is what gives the sensor its ability to "see" spectral reflections of features on the earth surface.



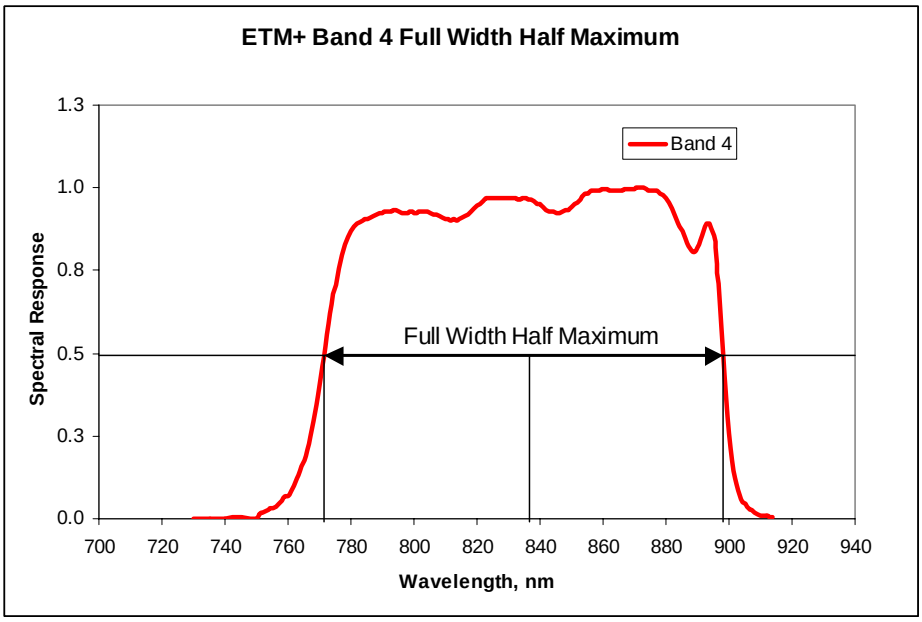


Emitted thermal energy has a wavelength about 300 times longer than visible light. The band 6 thermal spectral response is usually plotted against wavelength in microns (μm). Landsat thermal imagery is discussed in more detail in another tutorial.



Spectral response curves are sometimes described by three parameters, upper and lower values of the Full Width Half Maximum (FWHM) and the Band Center. The full width half maximum is the range of wavelengths corresponding to points on either edge of the spectral response plot that are one-half the maximum value (i.e., 0.5

since the maximum value is always 1). The band center is the mid point of the FWHM. The FWHM range for the band 4 spectral response is plotted below. The limits of the band 4 FWHM are approximately 0.77 μm and 0.90 μm, and the band center is about 0.84 μm. This spectral response plot was developed from USGS spectral response data and give slightly different values than the nominal parameters reported in the Landsat 7 Users Handbook shown in the table below. Also in the table is the extraterrestrial solar irradiance, Eo, for each band interval. Use of the solar irradiance values will be discussed in Part D.



Landsat 7 ETM+ Band Wavelength Data

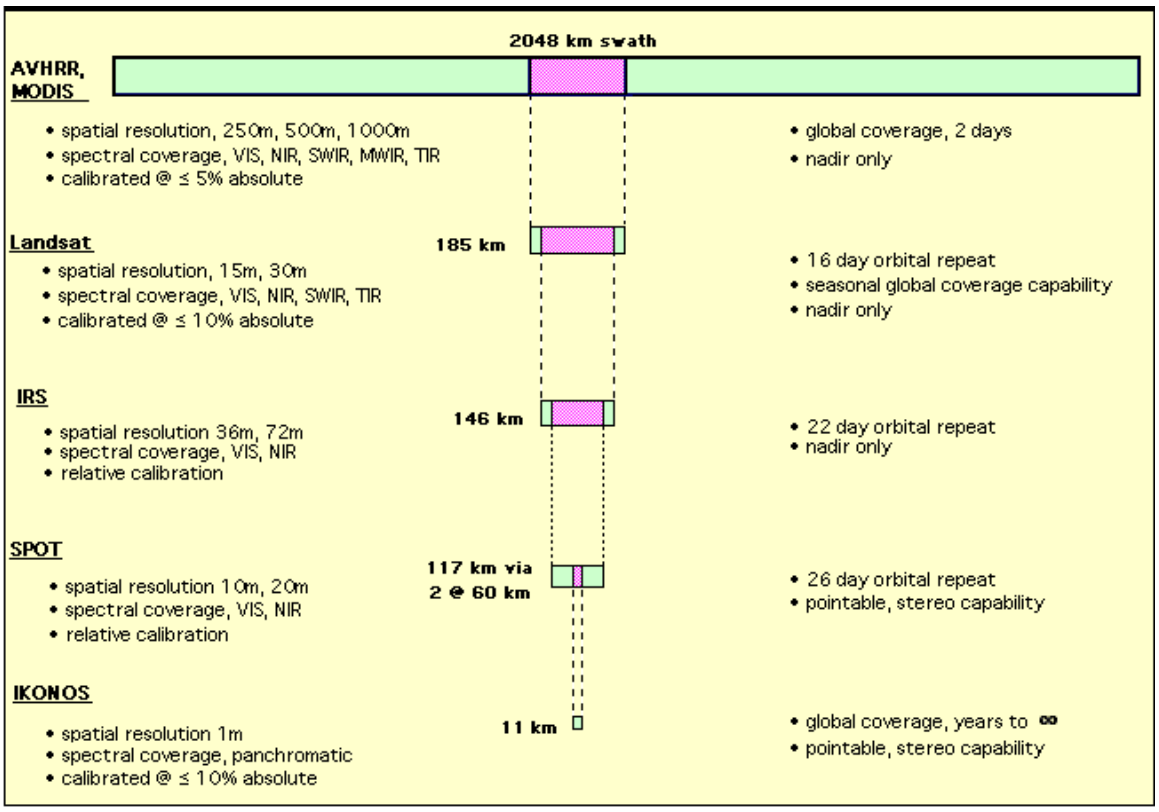
	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7	Band 8
FWHM lower, μm	0.45	0.53	0.63	0.78	1.55	2.09	0.52
FWHM upper, μm	0.52	0.61	0.69	0.90	1.75	2.35	0.90
Band center, μm	0.49	0.57	0.66	0.84	1.65	2.22	0.71
Irradiance, Eo, $mW \cdot cm^{-2} \cdot \mu m^{-1}$	196.9	184.0	155.1	104.4	22.57	8.207	136.8

Spatial Resolution

Spatial resolution can be described as the area of the earth surface represented by an individual picture element (pixel) in a digital satellite or aerial image. The scientific theory and terminology related to the definition of spatial resolution, electronic recording and interpretation by human observers is complex.

Common descriptive terms for spatial resolution encountered by imagery users are instantaneous field of view (IFOV), ground sample distance (GSD) and ground pixel resolution (GPR). The IFOV, or pixel size, is the area of surface covered by the field of view of a single electronic detector in the sensor. The IFOV can be thought of as a discrete sample of energy reflected or emitted from the Earth surface. The ETM+ on board Landsat 7 samples at three different resolutions; 30 meters for bands 1-5, and 7, 60 meters for band 6, and 15 meters for band 8. The IFOV of a sensor may be described as an angle, usually in radians, in the longitudinal and transverse directions of the sensor. It is necessary to know the distance from the earth surface to compute the spatial coverage of an individual detector from IFOV in degrees or radians. The term IFOV is more commonly used to describe sensors on board aircraft because images can be acquired at a range of flight altitudes.

Satellite orbital altitudes are relatively constant, so the terms Ground sampling distance (GSD) and ground pixel resolution (GPR) are widely adopted by satellite imagery users. The two terms have essentially the same meaning: the linear dimension of the square surface area sampled by an individual detector in the sensor. The preferred term among scientific users is GSD. Many imagery suppliers and GIS companies use the term GPR, especially if imagery is resampled to a different resolution than the original satellite product. The figure below compares the nominal spatial resolution and coverage width of several satellites.



It should be noted that none of these terms adequately or consistently describe the size of the smallest feature that may be discerned in an image. Many factors affect the appearance of spatial detail in an image including scene contrast, atmospheric effects, processing methods, and sensor settings. Techniques from spatial resolution theory, such as the development of the modulation transfer function (MTF) must be employed to gain a more precise description of true resolving power of a sensor-image combination. Fortunately, most users do not need to apply complex techniques to understand what

can likely be discerned in an image. Users quickly learn by examining images whether a particular satellite imagery product will support an intended analysis.

There is a trade-off between spatial resolution and the area covered by a single image (scene). High spatial resolution satellites cover less area with each image than medium or low-resolution satellites. High-resolution satellites available to civilian users offer fewer spectral bands than Landsat 7. Higher spatial resolution is not always better, especially when project areas are large (regional scale) and or must be evaluated quickly at least cost. High-resolution satellite imagery is justifiable both in initial cost and processing time when critical remote sensing tasks require images with high spatial resolution, especially for inaccessible locations not routinely imaged or impractical to image by airborne sensors.

Part C. Landsat 7 Image Products

Two Landsat 7 image products are routinely available from USGS: the Level 0R, Level 1R and Level 1G products. These are produced from the same scene acquisition so have equivalent image content. They differ by the level of processing USGS applies to prepare the image for use. Raw satellite imagery must be corrected for geometric and radiometric (spectral) bias of the satellite optical assembly and electronic sensor components.

Level 0R Products

The Level 0R product is a raw data form that is marginally useful prior to radiometric and geometric correction. A Level 0R product includes ancillary data required to perform geometric and radiometric corrections.

Specialized users with appropriate software may prefer Level 0R products to allow greater control of image processing. The figure to the left is an example of a Level 0R image. Pixels from one scan line to the next are offset. Most users would find it difficult or impossible to use without further processing. The Level 0R product is only available in the Hierarchical Data Format (HDF), a self-describing gridded data format only partially supported by common remote sensing and GIS software packages.

Level 1R Products

Level 1R products are radiometrically corrected with sensor calibration data. Image artifacts such as banding, striping, and scan correlated shift are removed prior to radiometric correction. Image pixels are converted to units of absolute radiance calculations during 1R product processing. The Level 1R product, like Level 0R is not geometrically corrected. Again, most users would find it difficult or impossible to use Level 1R products without further processing.

Level 1G Products

Most users will likely prefer the Level 1G product for routine remote sensing tasks. Level 1G products are radiometrically and geometrically (systematically) corrected. Correction algorithms model the spacecraft and sensor using data recorded by onboard computers during image acquisition. Geometric parameters include satellite attitude and ephemeris profiles. During processing the image data is resampled to user-specified parameters including output map projection, rotation angle, pixel size, and resampling kernal. USGS supports several map projections. The most popular for general use is the Universal Transverse Mercator. The full list of projections include:

- Universal Transverse Mercator
- Lambert Conformal Conic
- Polyconic
- Transverse Mercator
- Polar Stereographic
- Hotine Oblique Mercator A
- Hotine Oblique Mercator A
- Space Oblique Mercator

Level 1G image products are ready for use in many remote sensing tasks. The figure below is the Level 1G version of the example image. Compared to the Level 0R figure above, scan lines are correctly registered to each other and angular orientation closely approximates true surface geometry.

USGS employs the WGS84 ellipsoid for coordinate transformation and resampling. The Level 1G product is a geometrically rectified and free from distortion related to the sensor (e.g. jitter, view angle effects), satellite (e.g. attitude deviations from nominal), and Earth geometry (e.g. rotation, curvature). The systematic Level 1G correction process does not use ground control or elevation data during processing. Accuracy of the systematically corrected Level 1G product is approximately 250 meters (1 sigma) in flat areas at sea level.

Other geometric correction processes may be applied by USGS for additional cost. Precision correction employs ground control points to reduce geodetic error of the output product to approximately 30 meters. This accuracy is attained in areas where relief is moderate. Terrain correction processing employs both ground control points and digital elevation models to reduce geodetic error of the output product to less than 30 meters in areas where terrain relief is substantial. Online archives of Landsat imagery may contain images produced with any of the correction processes. Image metadata and header files usually, but not always, describe the level of processing.

Tip

The USGS EarthExplorer web interface refers to Level 1G products as **Systematically Corrected.** The image selection procedure helps prevent selection of the wrong type of imagery. Most users cannot order Level 0R or 1R imagery. However, a common mistake is to select the wrong image format. See the tutorial for ordering Landsat imagery from the USGS EarthExplorer for more details.

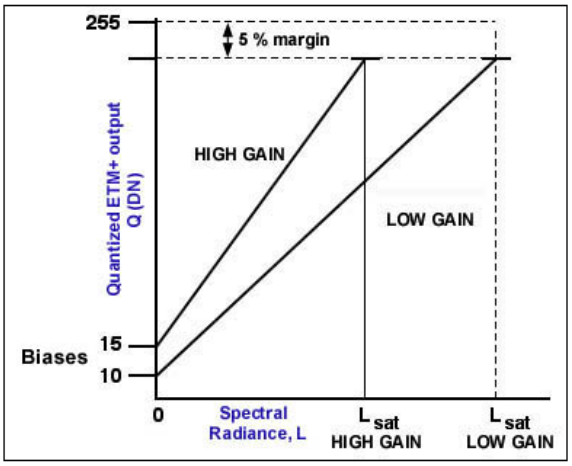
Part D. User Processing of Landsat 7 Images

Many remote sensing tasks can be accomplished with Level 1G Landsat 7 images without further geometric rectification or manipulation of pixel values (digital number, DN). Simple measurements such as determining approximate areas of distinct land surface classes such as open water or urban land can be made directly from Level 1G images without much concern for positional accuracy or spectral characteristics. Some scientific users derive spectral indices such as the Normalized Vegetation Difference Index (NDVI) from original Level 1G images knowing that atmospheric effects remain. This may provide comparable results for clear atmospheres if a consistent method is applied among images.

Other remote sensing tasks require a higher level of geometric precision and place more importance on spectral differences. Objectives such as analysis of vegetation changes between seasons or over several years require that images be comparable and that extraneous influences be removed. The scientific and academic community has developed numerous approaches of image correction and normalization. This tutorial will introduce the basics of a popular and useful technique—conversion of at-sensor radiances to surface reflectances. Another popular approach is to compute of spectral indices from various band combinations. This technique will be explored in another tutorial. Improvement of spatial accuracy is highlighted in the tutorial about georeferencing.

ETM+ Gain Settings

Pixel values in Landsat images produced by USGS are scaled at-satellite radiances and must normally be processed by the user into land surface radiances or reflectance. In USGS production of Level 1G images, pixel values (digital number) of absolute radiance are rounded off and scaled to integers values between 0 and 255 (byte values). This allows most GIS and remote sensing software to easily read the Landsat image data and reduces the image file size. Byte scaling is controlled by ETM+ sensor gain settings.



Landsat 7 managers can electronically increase or decrease the sensitivity of the ETM+ sensors to compensate for varying light conditions. Prior to image acquisition each band in the ETM+ sensor is set to low or high gain depending on the expected brightness of the land cover within the scene. The goal to maximize the sensor's 8-bit radiometric resolution without saturating the detectors. Bright scenes are imaged at low gain setting and lower light scenes at high gain. The low gain setting is preferred because it has a dynamic range approximately 1.5 times that of high gain. Remote sensing analysts apply gain setting parameters in the conversion of Landsat images to reflectance images. Gain settings are reported in the image metadata.

Gain settings vary depending on the type of terrain and time of year. For example, in desert regions USGS protocols require the following gain settings:

- Bands 1-3 set to high gain except where sun elevation is greater than 28° - to avoid bright desert target (reflectance >0.65 in band 3, [>0.66 in band 1, >0.71 in band 2]) saturation.

- Band 4 set to high gain except where sun elevation is greater than 45°(set to low gain) - to avoid bright desert (reflectance > 0.66) saturation.

- Band 5,7 set to high gain except where sun elevation is greater than 38¡ -- to avoid bright desert target (reflectance >0.70 in band 5, [>0.68 in band 7] saturation.

- Band 8 set to low gain.

Other typical gain settings are listed in the Landsat 7 Science Date Users Handbook.

Conversion of Pixel DN to Radiance

Scaled at-satellite pixel Digital Numbers (DN) are converted to units of absolute radiance with the equation:

$$L_\lambda = Gain \times Qcal + Offset$$

In terms of image metadata parameters the equation becomes,

$$L_\lambda = \frac{L\max_\lambda - L\min_\lambda}{Qcal_{\max} - Qcal_{\min}} \cdot \left(Qcal - Qcal_{\min}\right) + L\min_\lambda$$

where:

$\boldsymbol{L_\lambda}$ = spectral radiance at the sensor aperture, $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$

Gain = rescaled gain (the data product "gain" contained in the Level 1 product header or ancillary data record), $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$

Offset = rescaled bias (the data product "offset" contained in the Level 1 product header or ancillary data record), $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$

Qcal = the quantized calibrated pixel value, digital number

$\boldsymbol{Lmin_\lambda}$ = the spectral radiance that is scaled to $\boldsymbol{QCAL_{MIN}}$, $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$

$\boldsymbol{Lmax_\lambda}$ = the spectral radiance that is scaled to $\boldsymbol{QCAL_{MAX}}$, $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$

$\boldsymbol{QCAL_{MIN}}$ = the minimum quantized calibrated pixel value (corresponding to $\boldsymbol{Lmin_\lambda}$), digital number. Value is 1 for LPGS processed products and 0 for NLAPS products.

$\boldsymbol{QCAL_{MAX}}$ = 255, the maximum quantized calibrated pixel value (corresponding to $\boldsymbol{Lmax_\lambda}$), digital number.

For example, a patch of homogeneous pixels of a maturing wheat field might have a band 4 (near infrared) DN of 100. Image metadata lists the following parameters:

$\boldsymbol{Lmin_\lambda}$ = -5.1, $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$

$\boldsymbol{Lmax_\lambda}$ = 241, $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$

The image was produced by NLAPS so,

$\boldsymbol{QCAL_{MIN}}$ = 0

$\boldsymbol{QCAL_{MAX}}$ = 255

Absolute radiance is computed,

$$L_\lambda = \frac{L\max_\lambda - L\min_\lambda}{Qcal_{\max} - Qcal_{\min}} \cdot \left(Qcal - Qcal_{\min}\right) + L\min_\lambda$$

$$L_\lambda = \frac{241-(-5.1)}{255-0} \cdot \left(100-0\right) + (-5.1) = 91.4, \quad W \cdot m^{-2} \cdot sr^{-1} \cdot mm^{-1}$$

This computation is repeated by remote sensing software for every pixel in the image to produce the at-sensor radiance image. Gain settings differ for each band, so the user must be careful to select the correct parameters for each band. Conversion of Landsat 7 image pixel digital numbers to radiance is explored further in the tutorial exercises.

Effect of Atmosphere

Landsat 7 images produced by USGS have pixel values in scaled units of radiance as measured by the satellite sensor outside the earth atmosphere. The previous section described how the scaled digital numbers are converted to physically meaningful radiance in units of $W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$. The next step in producing a surface reflectance image is to transform the at-sensor (exoatmospheric)

radiance values pixel to ground surface radiance or reflectance values. The transformation must take into consideration the position of the sun and attenuation of reflected and emitted radiation by the atmosphere between the satellite and surface.

Molecules of atmospheric gas scatter shorter wavelength radiation (Rayleigh scattering). This is the reason that the sky appears blue to a surface observer. Blue light has a shorter wavelength than green, red or infrared radiation. Certain atmospheric gases including oxygen, carbon dioxide, ozone and water vapor also selectively absorb specific wavelengths of light drastically reducing the transmission of these wavelengths. Relatively constant atmospheric absorption leads to a preference for recording certain wavelengths of light by satellite sensors. Sensor engineers see little practical value to recording wavelengths that reveal little detail about the earth surface. Light is also non-selectively scattered by airborne particulates and aerosols (Mie scattering). Particulates are the primary cause of haze.

Several practical approaches for correcting satellite imagery for atmospheric effects evolved from the science of atmospheric light attenuation. Essential theoretical details are treated in the standard remote sensing references cited in this tutorial. Most remote sensing software packages have semi-automated algorithms that combine simplified atmospheric correction techniques with illumination corrections to directly compute ground surface reflectances from exoatmospheric radiances. It is only necessary for the user to supply appropriate orbital, sun position and atmospheric parameters. One popular approach, the Chavez Cos(t) model, does not even require atmospheric parameters. The Cos(t) model and a simpler approach, Dark Object Subtraction will be briefly discussed. An exercise in this tutorial will compute reflectances for a Landsat 7 image of the Jordan Valley using the Cos(t) approach.

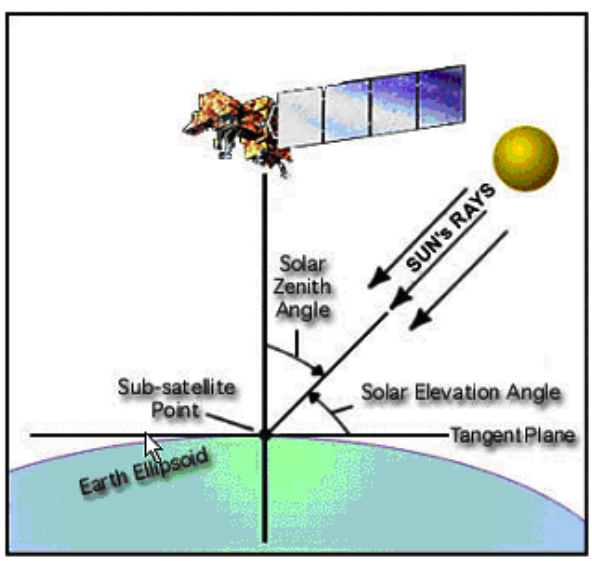
Dark Object Subtraction (DOS) Model

Particulate induced scatter (haze) slightly increases light energy received by the satellite sensor because of backscatter of solar radiation. The effect is relatively uniform across a scene in the absence of significant local emissions of particulates such as smoke

from wildfire or urban air pollution. In the Dark Object Subtraction (DOS) method a uniform haze ($Lhaze_{\lambda}$) value is subtracted from each pixel in each band in the image. The correction value is estimated from pixel values of objects in the scene that should reflect little or no light in a given wavelength band (i.e., the dark object). Good dark objects (actually areas) are bodies of deep clear water and very dark shadows. Some analysts assume more realistically that a dark object has a reflectance value of 1% in reflectance computations (Chavez 1986).

A user finds dark objects by exploring the image and observing pixel values in each band for several candidate objects. The lowest pixel value for each band is haze correction value if it is not an obvious image artifact or sensor fault. Band haze correction values are subtracted from each pixel in the image during final processing. The result of this process is an image with reduced values of radiance that may be helpful when visually comparing scenes taken at different times or locations or when computing relatively robust band indices such as the NDVI. Dark object subtraction by itself does not produce a reflectance value and does not correct for sun angle or solar intensity effects, although adaptations of the DOS approach can accommodate the other effects.

Sun Position Effects



The amount of solar energy received on a unit surface varies with the distance between the earth and sun (intensity) and the angle between the sun and the surface. When the sun is directly overhead (0° solar zenith angle) a unit area on the surface receives the full irradiance of the sun. As the sun elevation angle decreases, the direct rays of the sun are spread over a larger area,

decreasing the irradiance on a unit surface on the tangent plane by a factor equivalent to the cosine of the solar zenith angle. Reflectance computations typically account for these effects.

Cos(t) Model Transformation to Reflectance

The Cos(t) model (Chavez 1996) is a useful technique to produce a reflectance image from sensor (at-satellite) radiances when atmospheric parameters are not readily available. It works well with Landsat images acquired through a relatively clear atmosphere. Chavez developed the Cos(t) model from the more generalized equation given by Moran et al. (1992) that was based on the derivations of Chadresekhar (1950),

$$\rho_\lambda = \frac{\pi(Lsat_\lambda - Lhaze_\lambda)}{TAUv_\lambda\left(\frac{Esun_\lambda}{d^2}\cos\theta \cdot TAUz_\lambda + Edown_\lambda\right)}. \qquad (1)$$

Where

ρ_λ = Spectral reflectance of the surface, dimensionless decimal.

$Lsat_\lambda$ = At-satellite spectral radiance for a given spectral band, $W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$.

$Lhaze_\lambda$ = Upwelling atmospheric spectral radiance scattered in the direction of the sensor (path radiance), $W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$.

$TAUv_\lambda$ = Atmospheric transmittance along the path from the ground surface to the sensor, dimensionless.

$TAUz_\lambda$ = Atmospheric transmittance along the path from the sun to the ground surface, dimensionless.

$Esun_\lambda$ = Solar spectral irradiance on a surface perpendicular to the sun's rays outside the atmosphere (exoatmospheric), $W\ m^{-2}\ \mu m^{-1}$.

Edown$_\lambda$ = Downwelling spectral irradiance at the surface due to scattered solar flux in the atmosphere, W m^{-2} μm^{-1}.

Chavez (1996) found good first order approximations for the atmospheric transmittance coefficients are the cosine of the solar zenith angle for ***TAUz***$_\lambda$ and a value of 1.0 for ***TAUv***$_\lambda$ for the nadir viewing Landsat sensor. With these approximations and assuming that downwelling spectral irradiance is zero the reflectance equation becomes,

$$\rho_\lambda = \frac{\pi\, d^2 (Lsat_\lambda - Lhaze_\lambda)}{Esun_\lambda \cos^2 \theta} \qquad (2)$$

This equation is called the Cos(t) model. The subscript λ refers to spectral band λ. For each Landsat7 ETM+ image the gains, biases and sun elevation (90 - θ) are provided in the header file that accompanies the image. The Solar irradiance Eo_λ is obtained from Table 11.3 of the Landsat 7 Science Data Users Handbook (Irish 2000). The normalized Sun-Earth distance *d* in astronomical units for any day of the year may be interpolated from Table 11.4 of Landsat 7 Science Data Users Handbook or computed directly from astronomical equations.

The Idrisi software package includes a semi-automated Cos(t) model transformation that is fairly easy to apply. A Cos(t) model transformation of the March 8, 2002 Landsat 7 image of Path 174 Row 38 is demonstrated in a tutorial exercise.

At-satellite reflectance values can be computed by excluding the haze correction and atmospheric transmission coefficient in Equation 2. The at-satellite reflectance equation then becomes,

$$\rho_\lambda = \frac{\pi\, d^2 Lsat_\lambda}{Esun_\lambda \cos\theta} \qquad (3)$$

This approach was adopted for development of the 2000 Multi-resolution Land Cover Dataset of the U.S. from Landsat 7 data (Huang et al. 2002). At-satellite reflectance values are further processed with a tasseled cap transformation to produce derivative images for use in land classification.

Cos(t) Model Parameters

The tables below from the Landsat 7 Science Data Users Handbook are useful sources of data for applying the Cos(t) model and similar reflectance transformations. The Idrisi atmospheric correction module ATMOSC has similar values built in to its procedure. The values below offer a check on the values assumed by ATMOSC.

Table 11.3 ETM+ Solar Spectral Irradiances

Band	$W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$
1	1969.000
2	1840.000
3	1551.000
4	1044.000
5	225.700
7	82.07
8	1368.000

Table 11.4 Earth-Sun Distance in Astronomical Units

Julian Day	Distance	Julian Day	Distance	Julian Day	Distance	Julian Day	Distance	Julian Day	Distance
1	.9832	74	.9945	152	1.0140	227	1.0128	305	.9925
15	.9836	91	.9993	166	1.0158	242	1.0092	319	.9892
32	.9853	106	1.0033	182	1.0167	258	1.0057	335	.9860
46	.9878	121	1.0076	196	1.0165	274	1.0011	349	.9843
60	.9909	135	1.0109	213	1.0149	288	.9972	365	.9833

Part E. Landsat 7 Mission Specifications

Overall System Characteristics

- 5 year design life
- Expendables for 6 years
- Collect and transmit up to 532 scenes/day

Orbit

- Sun-synchronous, polar
- Altitude: 705 km +/- 5km (at equator)
- Inclination: 98.2 degrees, +/- 0.15 degrees
- Descending Node: 10:00 am local time, +/- 15 min
- Period: 98.9 min
- Repeat cycle: 16 days (233 orbits)

Ground System

- Capture, process and archive 250 scenes/day
- Generate 100 products/day
- Geodetic accuracy: 250 m (1 sigma)

Satellite

- Weight: 1973 kg
- Size: 404 cm long, 274 cm diameter
- Power: 1550 watts, ~1000 watt orbit average load
- Solar Array: silicon cells four panels, 17.1 m^2 total area
- Propellant: 122 kg of hydrazine
- Transmitters: 3.5 watt (X-band), 5.0 watt (S-band)
- Sensor: Enhanced Thematic Mapper+ (ETM+)
- Scene Size: 183 km cross-track, 170 km along-track 3.6 Gbits in 24 seconds 42.6 mrad/30m pixel
- Radiometric Accuracy: 5% absolute, 2% relative Band-to-Band Registration: 0.28 pixel (90%)
- Data Rate: 150 Mbps on two 75 Mbps channels (I & Q)
- Scan Frequency: 7 Hz

Landsat 7 Spectral Bands			
Band No.	Interval	Resolution	Sensor Type
1	0.45 - 0.52 µm	30	SiPD
2	0.52 - 060 µm	30	SiPD
3	0.63 - 069 µm	30	SiPD
4	0.76 - 0.90 µm	30	SiPD
5	1.55 - 1.75 µm	30	InSb
6	10.4 - 12.5 µm	60	HgCdTe
7	2.08 - 2.35 µm	30	InSb
8	0.50 - 0.90 µm	15	SiPD

Summary of Landsat Missions and Sensors			
Satellite	**Launch Date**	**Sensors**	**Status**
Landsat 1	7-23-72	MSS	Expired 1-6-78
Landsat 2	1-22-75	MSS	Expired 2-5-82
Landsat 3	3-5-78	MSS	Expired 3-31-83
Landsat 4	7-16-82	MSS, TM	Sensors no longer operational since 7-87; expired 6-15-01.
Landsat 5	3-1-84	MSS, TM	Operational
Landsat 6	10-5-93	MSS, ETM	Lost at launch
Landsat 7	4-15-99	ETM+	Operational