The formula for the circumference of a circle is:

$$\mathbf{C = 2\pi r}$$

Since one radian subtends an arc length equal to the radius, there must be 2π radians in a circle. There are also 360^o in a circle, so we can relate radians to degrees and vice versa:

How many degrees are there in one radian?

$$2\pi \text{ radians} = 360^o$$

$$\pi \text{ radians} = 180^o$$

$$1 \text{ radian} = 180^o / \pi = 57.296^o$$

Question 4. How many radians are there in one degree?

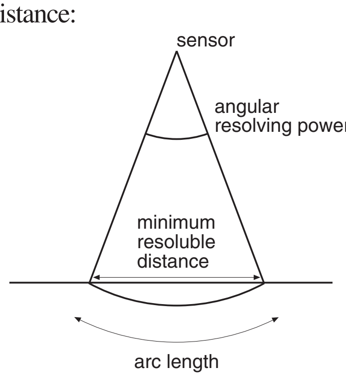
$$360^o = 2\pi \text{ radians}$$

$$1^o = 2\pi / 360^o$$

$$1^o = 0.01745 \text{ radians}$$

Note that this angular measure **has no dimensions**; it is the ratio of a length (the arc) to a length (the radius).

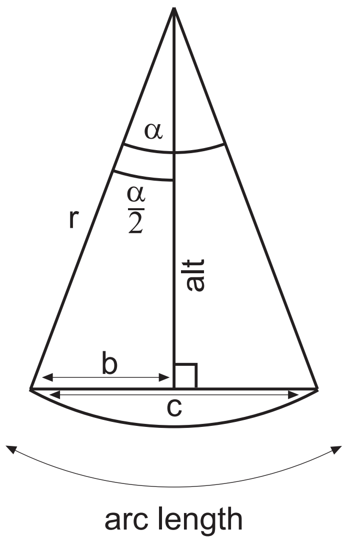
In remote sensing, we frequently express resolving power in terms of the angle (in radians) subtended between the imaging system and two targets spaced at the minimum resolvable distance:



Although we report the angular resolving power in terms of radians, in reality the minimum resolvable distance we measure is **NOT** the arc length, but rather the **chord length**.

Also, as you can see in the diagram, the reported altitude is **NOT** actually the radius. How serious are these discrepancies?

Let's find out by assuming a 10° field-of-view instrument is flown at an altitude of 1000 meters.



$\alpha = 10^\circ \qquad 10^\circ = 0.1745$ radians

alt = 1000 m

$$r = \frac{\text{alt}}{\cos\frac{\alpha}{2}} = \frac{1000\text{ m}}{\cos 5^\circ}$$

$= 1000$ m / 0.9961947

radius = 1003.82 m

$$0.1745\text{ rad} = \frac{\text{arc length}}{\text{radius}}$$

arc length = 0.1745 x 1003.82 m

arc length = 175.17 m

The **chord length** (c) can be calculated as follows:

$$\tan\frac{\alpha}{2} = \frac{\text{b (opposite side)}}{\text{alt (adjacent side)}}$$

b = tan 5° x 1000 m

since b = 1/2 c (the chord length),

c = 2 (tan 5° x 1000 m) **chord length = 174.98 m**

So, you can see that the chord length is actually 0.19 m shorter than the arc length. But, this is only a 0.1% difference which is not significant for most remote sensing applications.

Most non-photographic remote sensing systems have fields of view which are too narrow to conveniently use radians. Instead, we express angular resolving power in **milliradians** (mrad, 10^{-3} radians). A useful relationship to remember is that at an altitude of 1000 units, a 1 mrad system can resolve 1 unit of length. The formula is simple:

$$\text{angular resolution}_{\text{(in mrad)}} = \frac{\text{minimum resolvable distance}}{\text{altitude}} \times 1000$$

For example, a sensor with an angular resolution of 1 mrad could resolve high-contrast targets which were 10 m apart from an altitude of 10 km, but could also resolve targets spaced 1 m apart from an altitude of 1000 m.

$$1 \text{ mrad} = \frac{10 \text{ m}}{10{,}000 \text{ m}} = \frac{1 \text{m}}{1000 \text{ m}}$$

Using this formula for angular resolution, let's calculate the resolving power of the interpreter's eyes from the opening example **in milliradians (mrad)**.

$$\text{angular resolution}_{\text{(in mrad)}} = \frac{\text{minimum resolvable distance}}{\text{altitude}} \times 1000$$

$$= \frac{\text{width of bars resolved}}{\text{distance from target}} \times 1000 \quad = \frac{0.83 \text{ mm}}{5000 \text{ mm}} \times 1000$$

$$= 0.166 \; mrad$$

The minimum ground resolved distance for six of the bands of the ETM+ instrument on Landsat 7 is 30 meters from its nominal altitude of 705 km. What is the angular resolution of this system **in milliradians**?

$$mrad = \frac{30 \text{ m}}{705 \text{ km}} \times 1000$$

$$= \frac{30 \text{ m}}{705{,}000 \text{ m}} \times 1000$$

$$= 0.0426 \; mrad$$

What is the angular resolution of the ETM+ expressed in microradians (μrad, 10^{-6} radians)?

42.6 μrad

How many times better is the resolution of the ETM+ instrument (30 m bands only) than the eyes of the interpreter in our example?

$$\frac{0.166\ mrad}{0.0426\ mrad} = 3.9 \text{ times improvement}$$

4.4 Landsat Satellites

1. Landsat 1, 2, and 3

The launch of the first Earth Resources Technology Satellite (ERTS-1) on July 23, 1972 marked the beginning of a program of remote sensing from space. Initially conceived in the late 1960s, this program was designed to demonstrate the feasibility of remotely sensing earth resources from unstaffed satellites. Mission requirements were developed by scientists in the National Aeronautics and Space Administration and the U.S. Department of Interior. These included the acquisition of medium-resolution, multispectral data from systematic, repetitive observations taken at a constant local time. In addition, both photographic and digital data were to be produced and made available to interested users. Both the satellites and the program were renamed Landsat (for land satellite) with the launch of Landsat-2 on January 22, 1975. Although the satellites were designed for an operational lifespan of one year, they have greatly exceeded these original expectations. Landsat-1, which was retired in January, 1978, acquired more than 270,000 scenes of portions of the Earth during its five-and-a-half year operation. Landsat-2 acquired 185,105 scenes from January, 1975 to July, 1983 (nearly 8.5 years) while Landsat-3 acquired 324,655 scenes from March, 1978 to September, 1983.

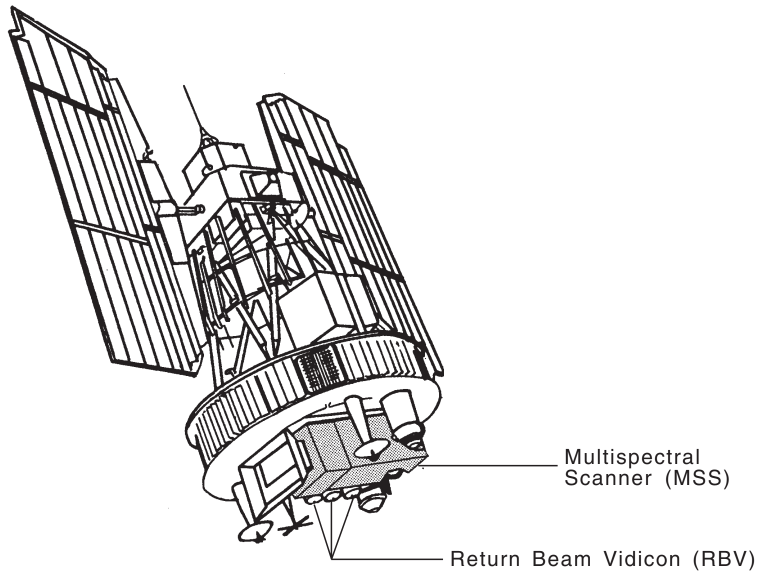
2. Spacecraft and Orbital Characteristics

The actual vehicle for Landsats 1, 2, and 3 is a reconfigured Nimbus weather satellite (Figure 4.1). These butterfly-shaped satellites weigh 959 kg (2100 lb), are 3 meters (10 feet) high by 1.5 meters (5 feet) wide with solar panels 4 meters (13 feet) wide. These satellites were launched by a Thor-Delta rocket from Vandenberg Air Force Base in California.

The satellites were placed into a near-polar, circular orbit at a nominal altitude of 917 km (570 miles) (Figure 4.2). This orbit is sun-synchronous, which means that the angle between the sun, the center of the earth, and the satellite are held constant. To maintain this constant angle (37.5 degrees), the orbital plane of the satellite is inclined 99 degrees (measured clockwise from the equator) so that it rotates at a rate equivalent to the rate of the earth about the sun (Figure 4.3). This configuration insures that the spacecraft will cross over the same area of the Earth at a constant local time, thereby creating repeatable illumination conditions. A mid-morning (about 9:30 a.m. local time) overpass time was chosen as providing neither excessively long shadows nor shadowless conditions while avoiding the tendency of afternoon cloud buildup over terrestrial areas. The Sun's rays strike the Earth at different angles during different times of

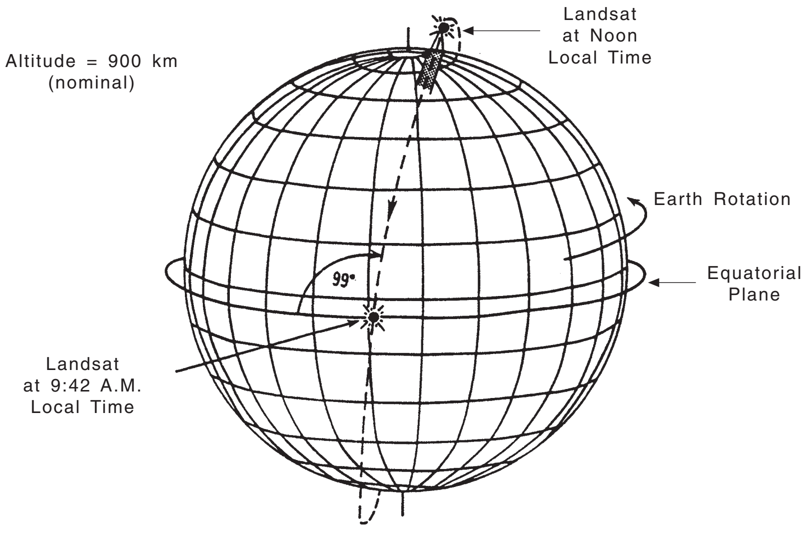
Landsat 1–3

4.1



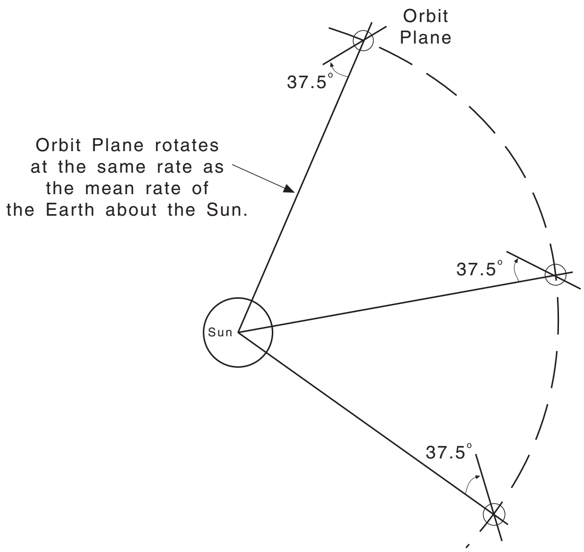
Landsat 1–3 Orbital Parameters

4.2



Sun–Synchronous Orbit

4.3



the year and also vary by latitude. At 45^0 north latitude the solar elevation angle changes from 60^0 in June to 18^0 in December (Figure 4.4), thereby creating changing illumination conditions seasonally. In addition, the azimuth of solar illumination will change seasonally providing illumination from different directions (Figure 4.5).

It requires 103 minutes for the satellite to complete one orbit about the Earth. During a single orbit the Earth will have rotated 2,760 km (at the Equator) beneath the satellite. Thus, successive orbits will be displaced westward at a rate equivalent to the westward progress of the sun's illumination (Figure 4.6). After the satellite completes a pass over Michigan the next pass would be over Montana. After 24 hours the satellite will have completed 14 orbits. The westward progression of the orbit will be such that the next pass will be one orbital pass to the west of first orbital pass (Figure 4.7). After 18 days, the satellite will have completed 251 orbits. The next orbital pass will then coincide with the first pass producing repetitive coverage on an 18-day cycle.

Data acquired by the satellite are segmented into scenes of about 185 km along track. This segmentation process is applied so that consistent scene centering is accomplished with the resulting scenes indexed by a worldwide system of paths and rows (Figures 4.8 and 4.9). Scenes acquired at about 45^0 latitude will have approximately 40% sidelap between adjacent paths with an arbitrary 10% endlap created from scenes acquired within a single pass (i.e. a small amount of redundant data will be produced for two scenes segmented from a single orbital pass).

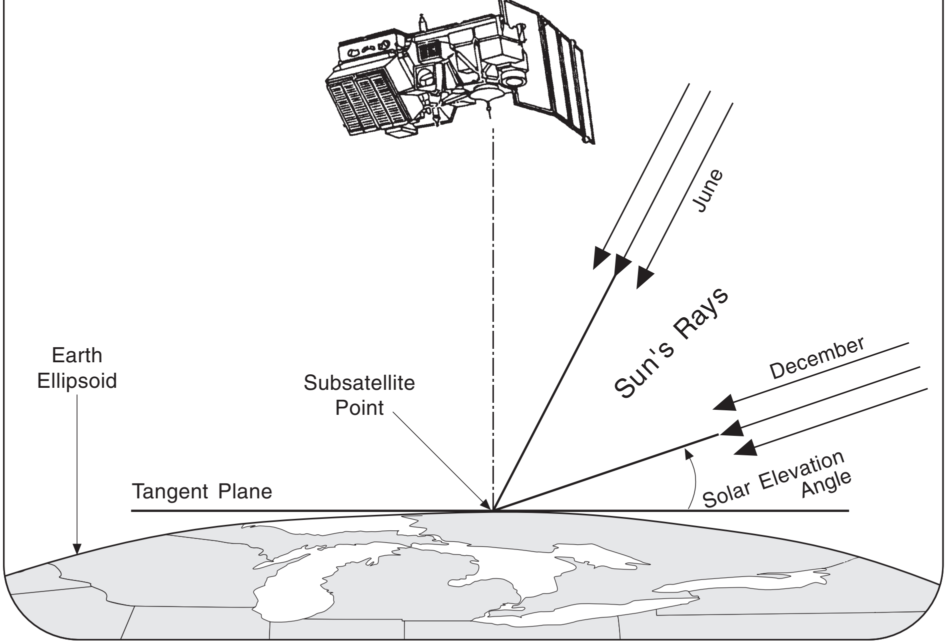
3. Landsat 1 and 2 Sensor Systems

The payloads for Landsats 1 and 2 were identical and included two imaging instruments, a return beam vidicon (RBV) camera and a multispectral scanner (MSS).

The RBV system was designed to acquire high-resolution television-like images of the Earth. The system consisted of three cameras which were aligned to view the same 185 km by 185 km ground area (which coincides with the ground area coverage of the MSS). The three cameras obtained images simultaneously in three different broad spectral bands. Camera 1 (Band 1) measured reflected solar radiation from 0.475 to 0.575 µm (visible, yellow-green), camera 2 (Band 2) 0.580 to 0.680 µm (visible, green-red) and camera 3 (Band 3) 0.690 to 0.830 µm (visible red and reflected infrared). Images were generated by the RBV system by shuttering the cameras and storing the resulting image on the photosensitive surface of the camera tube. This surface is then scanned to produce a video signal for subsequent trans-

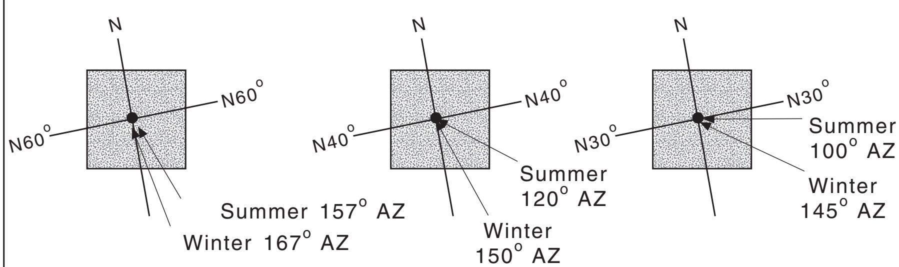
Seasonal Solar Angle Changes

4.4



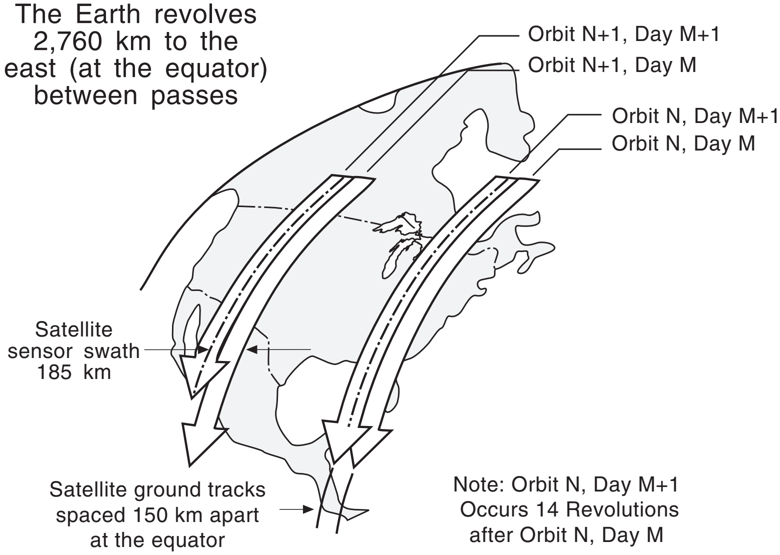
Variations of Solar Illumination

4.5



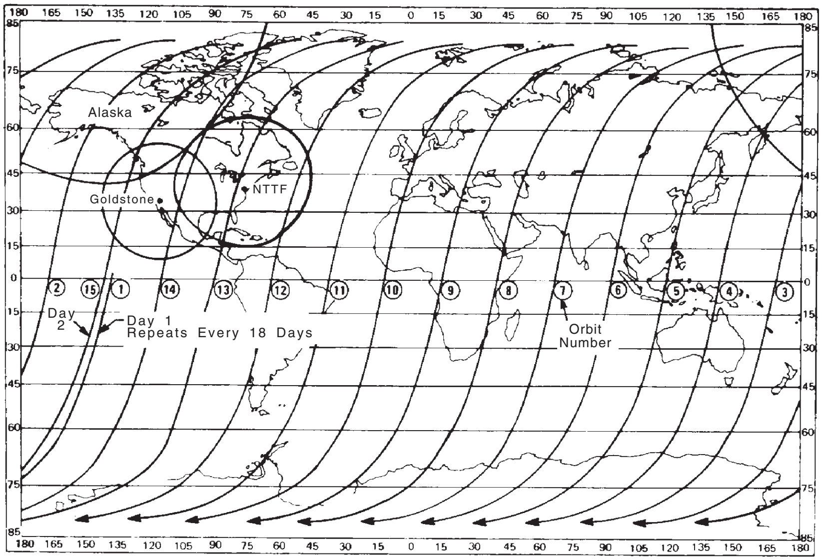
Landsat 1–3 Orbital Cycle

4.6



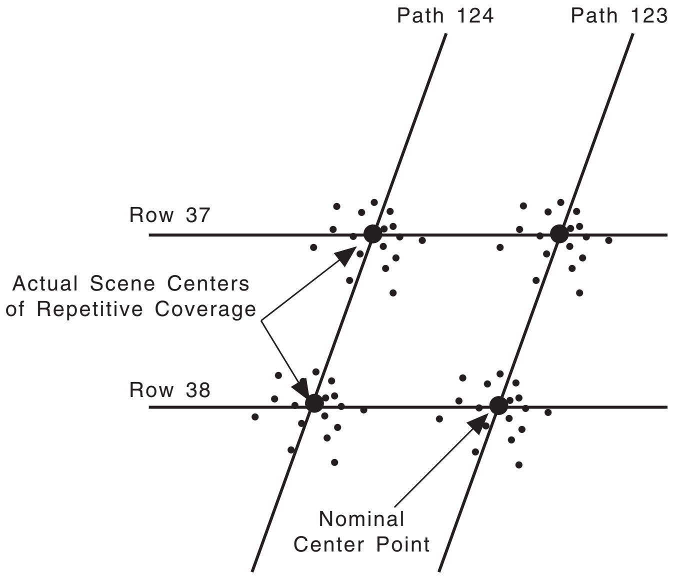
Landsat Orbital Tracks

4.7



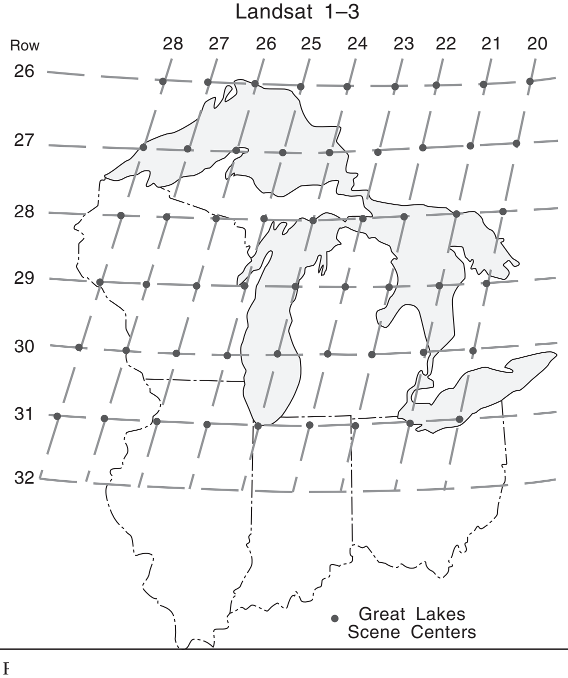
Nominal Scene Center Points

4.8



Worldwide Reference System (WRS)

4.9



mission to a ground receiving station. Because of early problems with the tape recorders on Landsats 1 and 2, only a limited quantity of RBV data were ever collected.

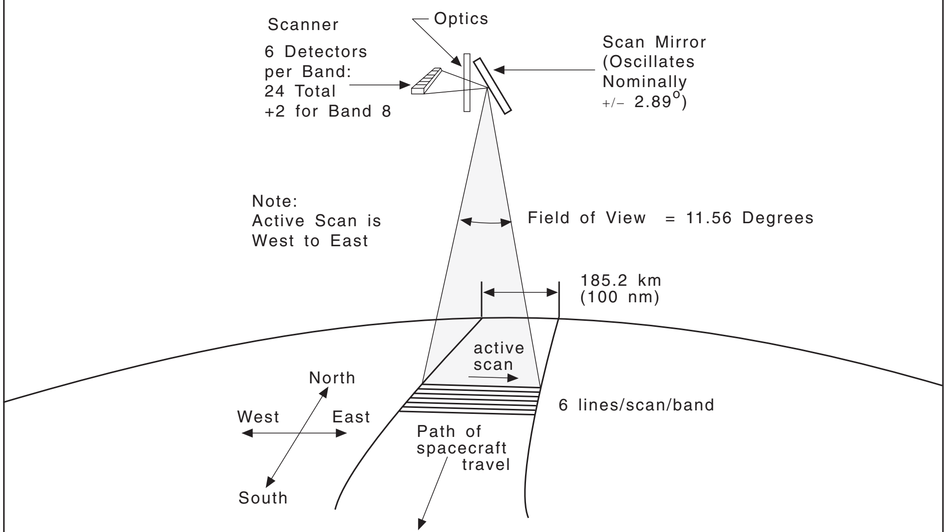
Contrary to pre-launch expectations, the MSS system become the primary data collection instrument utilized on Landsats 1 and 2. The multispectral scanner is a line-scanning device which utilized an oscillating mirror to scan a 185 km swath perpendicular to the satellite's path. Each active scan produced by the mirror sweep scans six lines simultaneously, collecting data in four wavelength bands (Figures 4.10 and 4.11). The forward motion of the satellite during the mirror retrace is such to position the next six scan lines immediately below the last six lines, thus providing a continuous scan of the Earth beneath the satellite.

The MSS on Landsats 1 and 2 acquired data in four wavelength bands, labeled 4, 5, 6,and 7 (because the RBV bands were labeled 1-3). Band 4 detects reflected solar radiation from 0.5 to 0.6 µm (visible, green), Band 5 from 0.6 to 0.7 µm (visible, red), Band 6 from 0.7 to 0.8 µm (reflected infrared), and Band 7 from 0.8 to 1.1 µm (reflected infrared).

The scan mirror of the MSS reflected radiation coming from the surface of the Earth (and its atmosphere) onto the detectors through fiber optic bundles. Filters were utilized to permit only certain wavelengths to strike the detectors. Each detector produced a voltage, from zero to four volts, which is related to the amount of radiation that strikes the detector. In order to produce individual area measurements, the output voltage from each detector was sampled during each active scan (Figure 4.14). Individual measurements are taken from a ground area of approximately 79 m by 79 m, the instantaneous field of view (IFOV). The sampling rate was such that, in order to maintain proper spatial relationships, these measurements are formatted as if they were taken from an area of 56 m by 79 m. This latter area is called a Landsat pixel (picture element) (Figure 4.15). The voltages produced by each detector for each pixel were converted from an analog signal to a digital form by means of a multiplexer. The resulting numbers, from 0 to 63, called brightness values (BV) or digital numbers (DN), are directly related to the amount of solar radiation reflected from the surface of the Earth for a specific wavelength band. These data were transmitted to a ground receiving station where they were reformatted into computer compatible tapes and converted into image products.

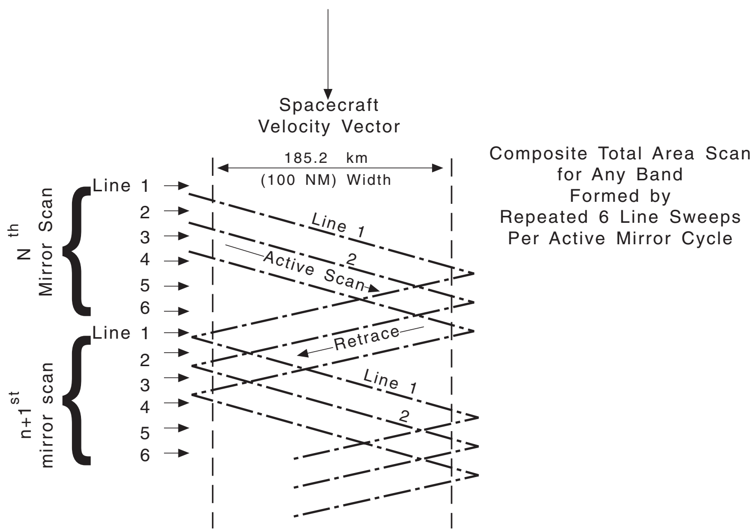
MSS Scan Pattern

4.10



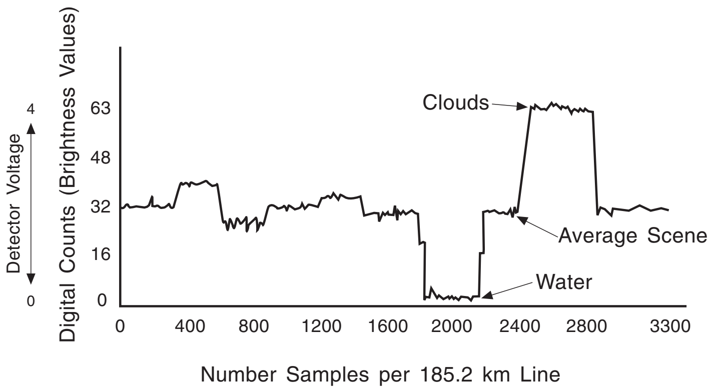
MSS Ground Scan Pattern

4.11



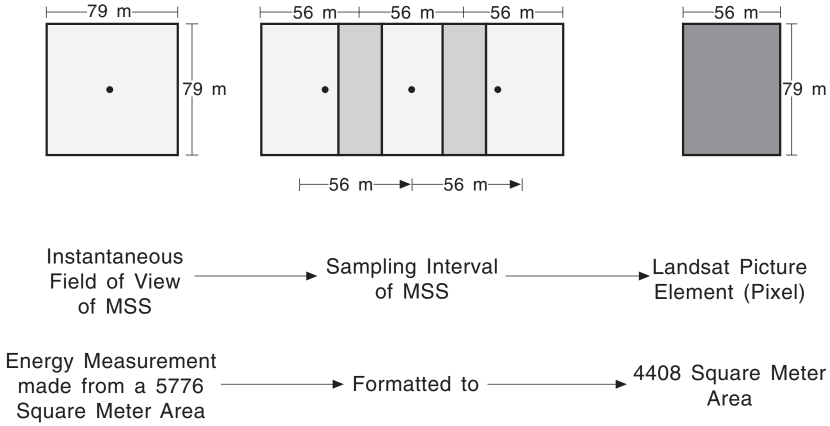
Voltage to Digital Count Conversion

4.14



MSS Pixel Formatting

4.15



4. Landsat 3 Sensor Systems

Based on the experience from sensor operation and subsequent analysis of data from Landsats 1 and 2, two system changes were made on Landsat 3. The three-camera, multispectral, RBV system was replaced by a two-camera, single spectral response system. Both cameras had the same broad-band spectral sensitivity, from 0.51 to 0.75 µm (green to near infrared) and were configured to produce side-by-side pictures approximately 99 km on a side, thus, they cover the same 185 km swath width as the MSS. Whenever two adjacent series of exposures were made, the resulting four images corresponded to a single MSS scene. To produce such an image format, the focal lengths of the cameras were doubled, thereby increasing the ground resolution to approximately 30 m.

A fifth channel (Band 8) was added to the MSS on Landsat 3. This thermal channel detected emitted radiation from 10.4 to 12.6 µm. The resulting quantizied values are therefore related to apparent temperature. The ground resolution of the thermal detectors is 237 meters square, resulting in pixels that are approximately three times as large as those in bands 4,5,6, and 7. This channel failed shortly after the launch of Landsat 3 and very few scenes were ever acquired.

4.5 Landsat MSS Imagery Characteristics

The geographical coverage of a single Landsat MSS scene is approximately 185 km on a side. A comparison of the coverage of a single Landsat scene with conventional aerial photography (assuming a 9-by-9 inch format, a 6-inch focal length lens, and 60% overlap with 30% sidelap) is given in Table 4.2.

Table 4.2 Comparison of Landsat coverage with aircraft coverage

Coverage of 1 Landsat scene

185 km by 178 km = 32,930 square kilometers

115 mi by 111 mi = 12,765 square miles

Standard aircraft coverage of 1 Landsat scene

Platform	Scale	No. Photos
Low-altitude aircraft	1:15,000	5,000
Low-altitude aircraft	1:30,000	1,500
High-altitude aircraft	1:60,000	300
Commercial jet aircraft	1:90,000	150
Military aircraft	1:250,000	30

4.6 The Second Generation -- Landsat 4 and 5

In response to the needs for improving the characteristics of the original multispectral scanner (MSS), NASA developed a second-generation of Landsat satellites. This program was a significant advance in remote sensing technology with the addition of the Thematic Mapper (TM) instrument, along with the MSS, on Landsats 4 and 5.

Landsat 4 was launched in July 1982; Landsat 3 continued operation until September 1983. Early on, Landsat 4 developed solar array and communications problems that restricted its use to MSS acquisition only. Landsat 5, a twin of Landsat 4, was launched ahead of original plans in March 1984.

Operational responsibility for the Landsat program was transferred from NASA to NOAA in January 1983 (for the MSS, and September 1984 for the TM). The Earth Observation Satellite Company (EOSAT), a private-sector joint venture, began operating the Landsat system under government contract in October 1985.

1. Spacecraft and Orbital Characteristics

The spacecraft vehicle for Landsats 4 and 5 was the newly designed Multimission Modular Spacecraft. The Landsat 4/5 configuration (Figure 4.16) was originally designed to be retrievable by the space shuttle, but this was never attempted.

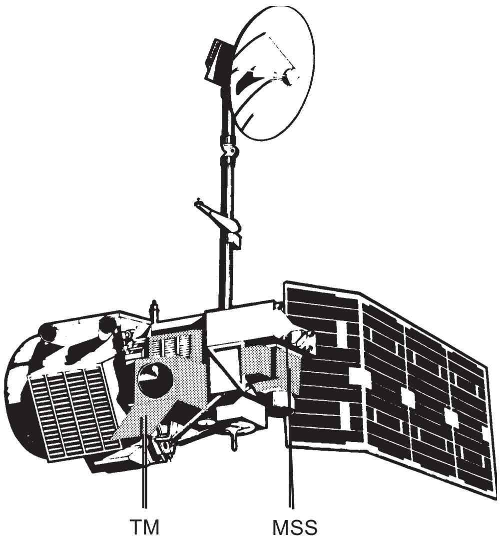
Compared to the earlier Landsat satellites, Landsat 4/5 is in a lower orbit (705 km), with a slightly later equatorial crossing time - 9:45 a.m (Figure 4.17). Landsat 4/5 have a 16-day repeat cycle. The lower orbit was necessary to produce the higher ground resolution of the TM (30 meters versus 80 meters for MSS). The 9:45 acquisition time was chosen to optimize the scanning characteristics of the TM sensor. Because of these orbital differences, a second Worldwide Reference System (WRS-2) was created for indexing Landsat 4 and 5 coverage data (Figure 4.18).

2. Thematic Mapper (TM) Characteristics

The Thematic Mapper was configured to improve the spatial, spectral and radiometric resolution compared to the MSS. A comparison of the sensor characteristics of the TM and MSS systems is presented in Table 4.3. The TM has been configured with seven spectral bands (Figure 4.19, 4.20, 4.21, 4.22, 4.23, 4.24 and

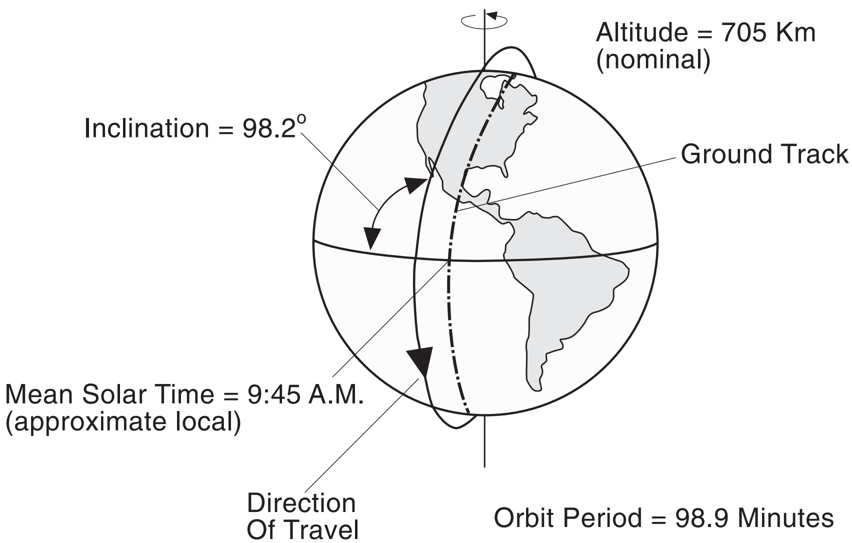
Landsat 4–5

4.16



Landsat 4–5 Orbital Parameters

4.17



Worldwide Reference System (WRS)

4.18

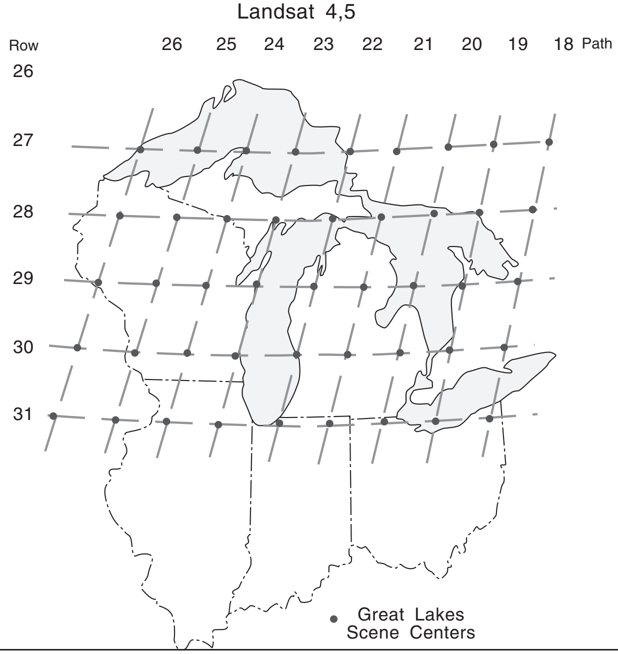


Table 4.3 Comparison of Landsat Thematic Mapper and Multispectral Scanner Sensor Characteristics

Band No.	Spectral Sensitivity (micrometers) TM	MSS
1	0.45 - 0.52	0.5 - 0.6[1]
2	0.52 - 0.60	0.6 - 0.7
3	0.63 - 0.69	0.7 - 0.8
4	0.76 - 0.90	0.8 - 1.1
5	1.55 - 1.75	--
6	10.40 - 12.50	--
7	2.08 - 2.35	--
IFOV	30 m (Bands 1 - 5, 7) 120 m (Band 6)	80 m (Bands 1 - 4)
BV Levels	256	64

[1]Band numbers 1, 2, and 3 were utilized for the Return Beam Vidicon Cameras on Landsat 1 and 2.

4.25, compared to four on the MSS. Comparative band regions are narrower on the TM and include sensitivities into the middle infrared and thermal infrared regions of the electromagnetic spectrum. The ground resolution (except for the thermal band) has been changed from approximately 80 meters to 30 meters. The number of quantization levels has been increased from 64 to 256.

The present configuration of the TM sensor was primarily designed for monitoring vegetation. Specific sensor characteristics were derived from an analysis of research efforts designed to determine optimum spectral resolution for monitoring vegetation from space, and consideration of political, technical and economic limitations.

Spectral resolution (i.e., the width and placement of spectral bands) has been shown to be highly correlated with successful vegetation monitoring. Within the reflective portion of the electromagnetic spectrum (including the visible and reflective infrared between 0.38 and 3.00 µm), five primary regions and two transition regions have been identified. These wavelength regions, useful for monitoring green vegetation, are listed in Table 4.4 in order of descending overall usefulness. The spectral channels utilized in the TM are presented in Table 4.5 for comparison with these primary spectral findings. Additional research has identified the interval

Table 4.4 Spectral Regions for Monitoring Vegetation

Ordered List of Spectral Regions in Descending Usefulness for Monitoring Green Vegetation

Number	Wavelength	Utility
1st	0.74 - 1.10	Direct biomass sensitivity
2nd	0.63 - 0.69	Direct *in vivo* chlorophyll sensitivity
3rd	1.35 - 2.50	Direct *in vivo* foliar water sensitivity
4th	0.37 - 0.50	Direct *in vivo* carotenoid and chlorophyll sensitivity
5th	0.50 - 0.62	Direct/indirect and slight sensitivity to chlorophyll
6th	0.70 - 0.74	Indirect and minimal sensitivity to vegetation; perhaps valuable non-vegetational information
7th	1.1 - 1.3	

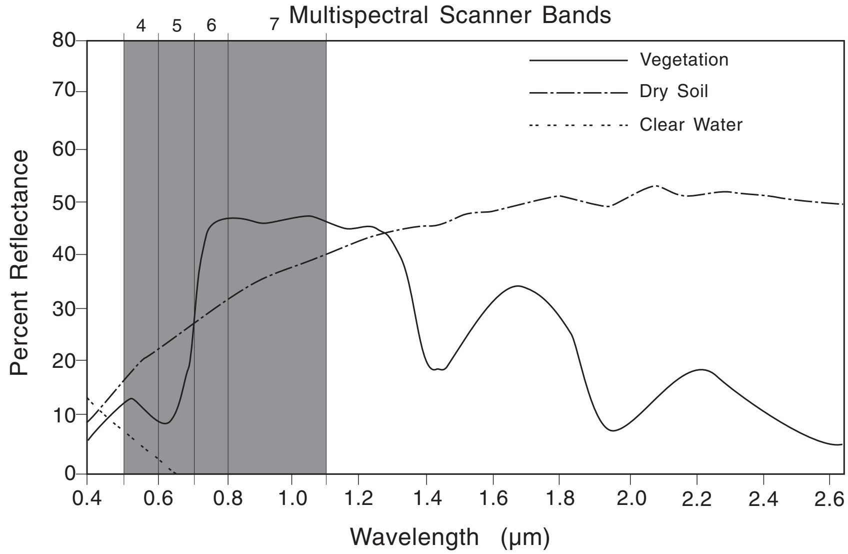
between 1.55 and 1.75 µm (corresponding to TM band 5) as the region best suited for monitoring plant canopy water status. The placement of spectral bands, in relation to reflectance of green vegetation, are shown for the MSS (Figure 4.26) and the TM (Figure 4.27).

Table 4.5 TM Bandwidths for Monitoring Vegetation

Band	Wavelength (µm)	Rationale
TM1	0.45 - 0.52	Sensitivity to chlorophyll and carotenoid concentrations
TM2	0.52 - 0.60	Slight sensitivity to chlorophyll plus the green region characteristics
TM3	0.63 - 0.69	Sensitivity to chlorophyll
TM4	0.76 - 0.90	Sensitivity to vegetational density or biomass
TM5	1.55 - 1.75	Sensitivity to water in plant leaves
TM6	10.40 - 12.50	Thermal properties
TM7	2.08 - 2.35	Sensitivity to water in plant leaves

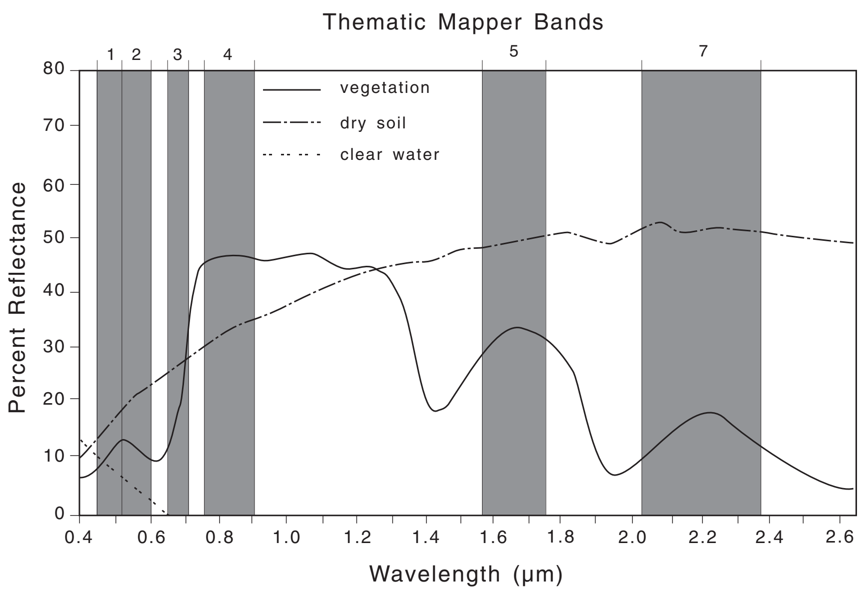
Multispectral Scanner Band Sensitivities

4.26



Thematic Mapper Band Sensitivities

4.27



4.7 The Next Generation -- Landsat 7

1. Introduction

In 1992, the US Congress authorized the procurement, launch and operation of a new Landsat satellite. At 11:36 am on April 15, 1999, the latest member of the Landsat family was launched into orbit (Figure 4.28). No other remote sensing system, public or private, fills the role of Landsat in global change research or in civil and commercial applications. Landsat 7 will fulfill its mission by providing repetitive, synoptic coverage of continental surfaces using spectral bands in the visible, near-infrared, short-wave infrared, and thermal infrared regions of the electromagnetic spectrum. Five of its eight bands are acquired at a spatial resolution of 30 meters.

The primary new features on Landsat 7 are:

- a panchromatic band with 15 m spatial resolution
- on board, full aperture, 5% absolute radiometric calibration
- a thermal IR channel with 60 m spatial resolution

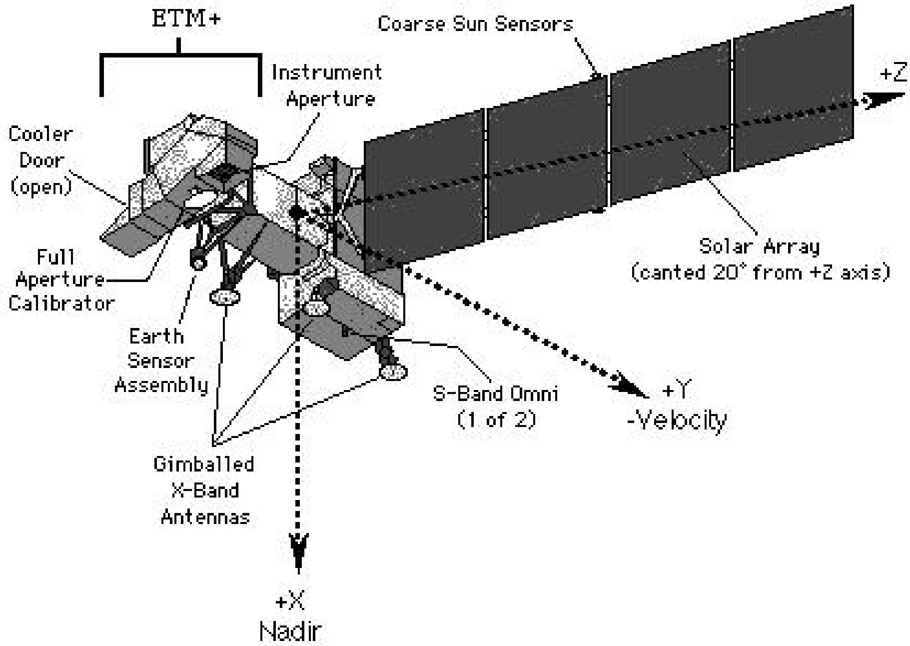
The Landsat Program is committed to provide Landsat digital data to the user community in greater quantities, more quickly and at a lower cost than at any previous time in the history of the program

The continuation of the Landsat mission is important for several reasons. Repetitive, broad-area coverage is needed for observation of seasonal changes on regional, continental and global scales. Other systems afford frequent global coverage (e.g. AVHRR), but none provide global coverage at the 30-meter spatial resolution of Landsat 7. Unlike the ocean and atmosphere, characterizing the land surface is distinguished by high-spatial-frequency processes that require a high spatial resolution. Both man-made (deforestation) and natural changes (glacial recession) are often initiated at scales requiring high resolution for early detection.

The Landsat 7 system offers the unique capability to seasonally monitor important small-scale processes on a global scale, such as the inter- and intra-annual cycles of vegetation growth; deforestation; agricultural land use; erosion and other forms of land degradation; snow accumulation and melt and the associated fresh-water reservoir replenishment; and urbanization. The other systems affording global coverage do not provide the resolution needed to observe these processes in detail and only the Landsat system provides a 26-plus year record of these processes.

Landsat 7

4.28



2. Orbit

The orbit of Landsat 7 is repetitive, circular, sun-synchronous, and near-polar at a nominal altitude of 705 km at the Equator. The spacecraft crosses the Equator from north to south on the descending orbital node at 10:00 AM +/- 15 minutes on each pass. Each orbit takes nearly 99 minutes, and the spacecraft completes just over 14 orbits per day, covering the entire Earth between 81 degrees north and south latitude every 16 days. Figure 4.29 illustrates the orbit characteristics of Landsat 7.

The TERRA spacecraft (formally known as EOS-AM) is scheduled for launch on October 4, 1999 on an Atlas-IIAS expendable launch vehicle from Vandenberg Air Force Base in Lompoc, California. TERRA will be injection into an identical 705 kilometer, sun synchronous orbit as Landsat 7. This same-day orbit configuration will space the satellites ideally 15 minutes apart (i.e. equatorial crossing times of 10:00 to 10:15 AM for Landsat 7 and 10:30 for TERRA). A multispectral data set having both high (i.e. 30 meter) and medium-to-coarse (i.e. 250 to 1000 meter) spatial resolution will thus be acquired on a global basis repetitively and under nearly identical atmospheric and plant physiological conditions.

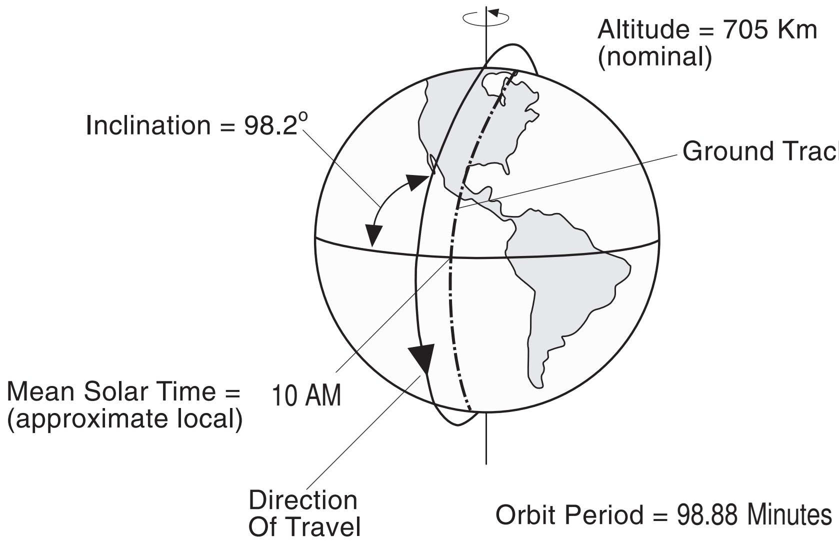
3. Swathing Pattern

Landsat 7 orbits the Earth in a preplanned ground track. The ETM+ sensor onboard the spacecraft obtains data along the ground track at a fixed width or swath as depicted in Figure 4.30. The 16-day Earth coverage cycle for Landsat 7 is shown in Figure 4.31. The adjacent swath to the west of a previous swath is traveled by Landsat 7 one week later (and the adjacent swath to the east occurred one week earlier and will recur nine days later).

Every 16 days, a Landsat satellite returns to its starting point and repeats the cycle. Working together, Landsats 5 and 7 will offer repeat coverage of any location every eight days. At the equator, the ground track separation is 172 km, with a 7.6 percent overlap. This overlap gradually increases (due to the fixed 185 km swath width) as the satellites approach the poles, reaching 54 percent at 60° latitude (Table 4.6).

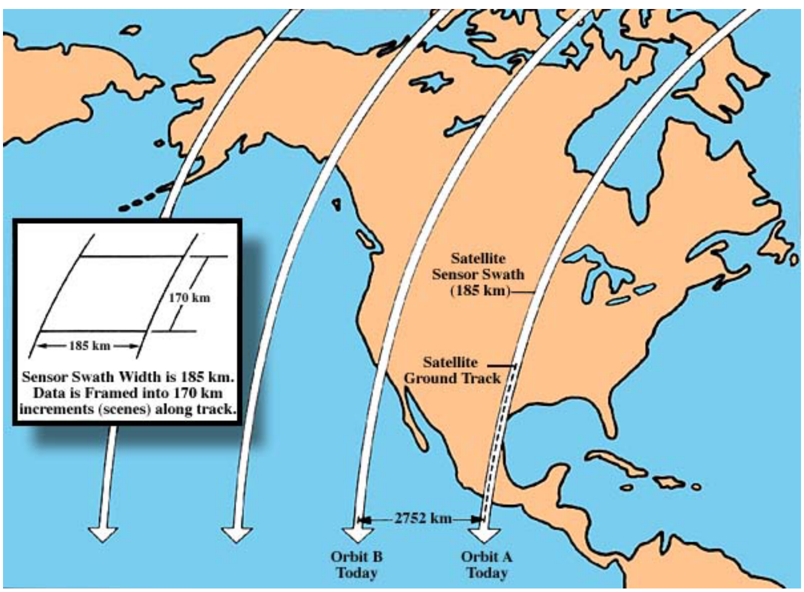
Landsat 7 Orbital Parameters

4.29



Landsat 7 ETM+ Swath Pattern

4.30



Landsat 7 ETM+ 16-Day Coverage Pattern

4.31

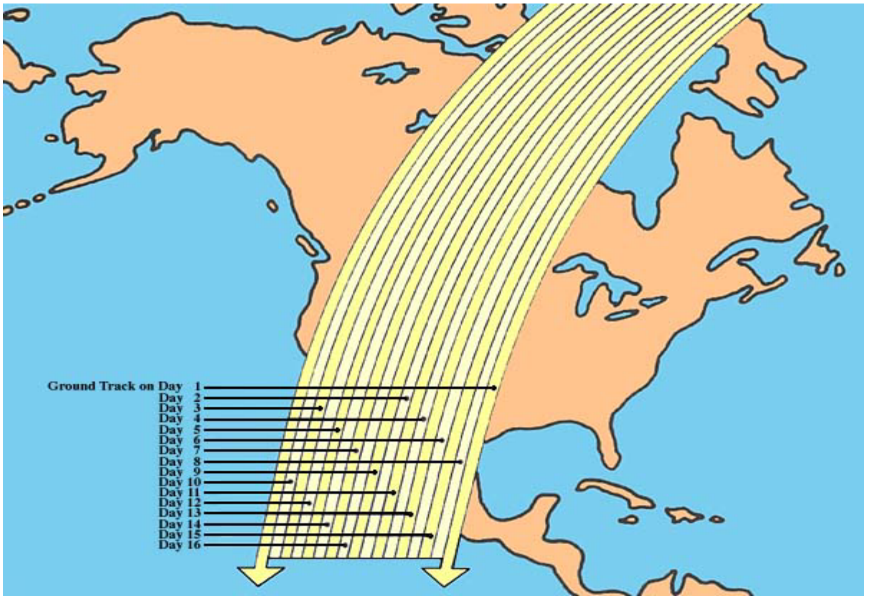


Table 4. 6. ETM+ Image Sidelap of Adjacent Swaths

Latitude (degrees)	Image Sidelap (%)
0	7.3
10	8.7
20	12.9
30	19.7
40	29.0
50	40.4
60	53.6
70	68.3
80	83.9

4. Landsat 7 Worldwide Reference System

The standard worldwide reference system as defined for Landsat 4 and 5 (WRS-2) was preserved for Landsat 7. The WRS-2 indexes orbits (paths) and scene centers (rows) onto a global grid system comprising 233 paths by 248 rows. The term row refers to the latitudinal center line across a frame of imagery along any given path.

The 16-day ground coverage cycle for Landsats 4 and 5 was accomplished in 233 orbits. Thus, for Landsats 4 and 5 (and now Landsat 7), the WRS-2 system is made up of 233 paths numbered 001 to 233, east to west, with Path 001 crossing the equator at 64.60 degrees west longitude.

Landsat 4, 5 and 7 scenes are chosen at 23.92-second increments of spacecraft time in both directions calculated from the equator in order to create 248 Row intervals per complete orbit. Note that this is the same as the Landsat 1 through 3 WRS-1 system. The Rows have been positioned in such a way that Row 60 coincides with the equator during the descending node on the day side part of the orbit and Row 184 during the ascending node. Row one of each Path starts at 80 degrees, 47 minutes north latitude and the numbering increases southward to a maximum latitude 81 degrees, 51 minutes south (Row 122) and then turns northward, crosses the equator (Row 184), and continues to a maximum latitude of 81 degrees, 51 minutes north (Row 246). Row 248 is located at latitude 81 degrees 22 minutes north whereupon another Path begins.

5. The Long Term Acquisition Plan

The Long Term Acquisition Plan (LTAP) is used to direct the acquisition by Landsat 7 of Worldwide Reference System (WRS) scenes around the world for archiving in the U.S. EROS Data Center. The WRS land data base identifies those WRS scenes containing land or shallow water which will be imaged at least once every year. Table 4. 7 shows the WRS scenes for Brazil that are included in the LTAP.

6. Enhanced Thematic Mapper Plus

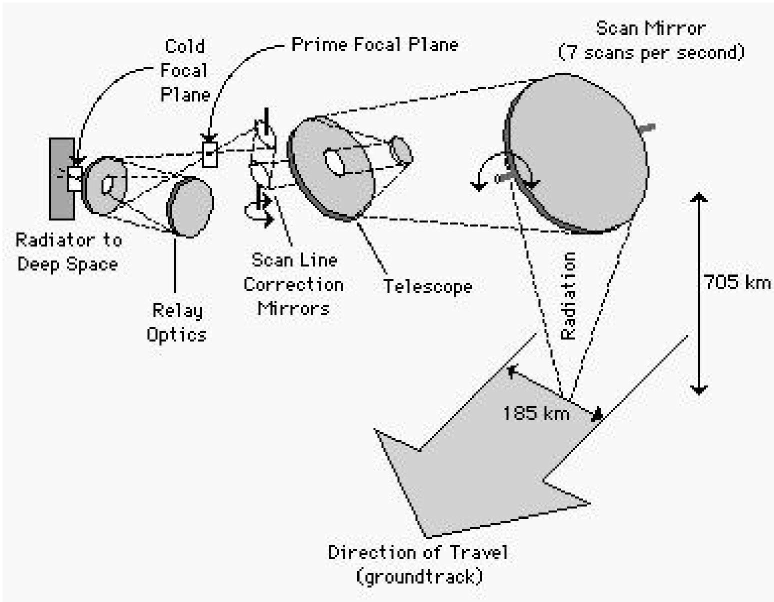
The earth observing instrument on Landsat 7, the Enhanced Thematic Mapper Plus (ETM+), replicates the capabilities of the highly successful Thematic Mapper instruments on Landsats 4 and 5. The ETM+ also includes new features that make it a more versatile and efficient instrument for global change studies, land cover monitoring and assessment, and large area mapping than its design forebears (Table 4.8)

The ETM+ instrument is a fixed "whisk-broom", eight-band, multispectral scanning radiometer capable of providing high-resolution imaging information of the Earth's surface. It detects spectrally-filtered radiation in VIS, NIR, SWIR, LWIR and panchromatic bands (Table 4.9) from the sun-lit Earth in a 183 km-wide swath when orbiting at its nominal altitude of 705 km.

The ETM+ scanner contains 2 focal planes. The primary focal plane consists of optical filters, detectors, and preamplifiers for 5 of the 8 ETM+ spectral bands (bands 1-4 and 8). The second focal plane is cooled and includes the optical filters, infrared detectors, and input stages for ETM+ spectral bands 5,6, and 7 (Figures 4.32 and 4.33).

ETM+ Optics

4.32



ETM+ Detector Array

4.33

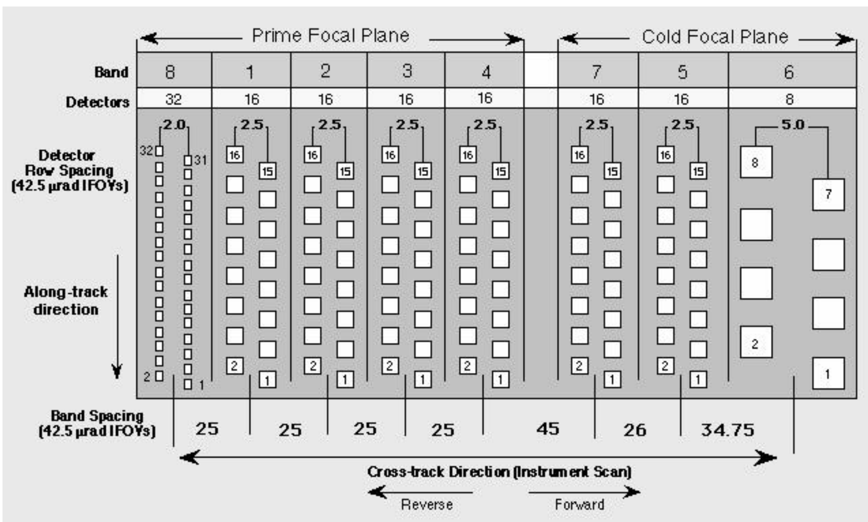


Table 4.7

LANDSAT 7
WRS GLOBAL LAND DATA BASE (for Brazil)
Rev. 2.1 8 January 1999

Path	Rows	Path	Rows
001	057-068	219	062-080
002	059-068	220	062-082
003	059-068	221	061-084
004	059-067	222	060-083
005	059-060	223	060-082
005	063-067	224	059-082
006	063-066	225	058-077
208	074-074	225	080-081
211	059-059	226	057-075
213	063-063	227	058-075
214	063-063	228	058-072
214	064-068	229	058-071
215	063-076	230	059-070
216	063-076	231	057-069
217	062-076	232	056-069
218	062-077	233	057-068

On board solar calibration and payload correction data allow the ground processing segment to radiometrically correct the data to an absolute accuracy of 5% and to geometrically register a scene to within 250 meters. Nominal ground sample distances (i.e.”pixel” sizes) are 15 meters in the panchromatic band, 30 meters in the VIS, NIR and SWIR bands and 60 meters in the LWIR band.

Landsat 7 will collect data in accordance with the Worldwide Reference System, which has catalogued the world’s land mass into 57,784 scenes, each 183 km wide by 170 km long. The ETM+ will produce approximately 3.8 gigabits of data for each

Table 4.8 ETM+ Technical Specifications

Type:	opto-mechanical scanner
Spatial resolution:	15/30/60 m
Spectral range:	0.45-12.5 µm
Number of bands:	8
Temporal resolution:	16 days
Size of image:	183 x 170 km
Swath:	183 km
Stereo:	no
Programmable:	yes
Quantization:	Best 8 of 9 bits
On-board data storage:	~375 Gb (solid state)

Table 4.9 ETM+ Bands

Band	Spectral Bandpass (Micrometers)	Resolution (Meters)
1	.45 to .515	30
2	.525 to .605	30
3	.63 to .690	30
4	.75 to .90	30
5	1.55 to 1.75	30
6	10.40 to 12.5	60
7	2.09 to 2.35	30
Pan	.52 to .90	15

Wideband data downlink

Landsat 7 carries the ETM+ instrument and a solid state recorder (SSR). The ETM+ data stream is separated into two formats. Format 1 (channel, also referred to as channel I, contains bands 1-6; format 2 (channel 2, also referred to as channel Q, contains bands 6, 7, and 8 (PAN). Each format is transferred at 75 Mbps to a switching unit where the data are modulated and either (1) downlinked in real-time to a Landsat Ground Station (LGS) via an X-band link at a combined aggregate rate of 150 Mpbs, or (2) recorded on the SSR.

The data recorded on the SSR can be played back using one or two 150 Mbps bitstreams and downlinked to a LGS via the X-band link. When the spacecraft flies over a LGS, it downlinks two 150 Mbps data streams, either 1 real-time and 1 playback, or 2 playbacks. Therefore, when the data are transmitted to the LGS, it is a combined rate of 300 Mbps: a 150 Mbps bitstream from the ETM+ and a separate 150 Mbps bitstream from the SSR or two 150 Mbps bitstreams from the SSR.

The primary receiving station is at the US Geological Survey's (USGS) EROS Data Center (EDC) in Sioux Falls, South Dakota, USA. All substantially cloud-free, land and coastal scenes will be acquired by EDC through the real-time downlink or by playback from the solid state recording device. ***The capacities of the satellite, instrument and ground system will be sufficient to allow for continuous acquisition of all substantially cloud-free scenes at EDC.*** In addition, a world-wide network of receiving stations will be able to receive real-time, direct downlink of image data via X-band. Each station will be able to receive data only for that part of the ETM+ ground track where the satellite is in sight of the receiving station.

Initial Events

Landsat 7 was launched on April 15, 1999. Just three days later, on Sunday, April 18, the ETM+ instrument acquired its first scene (primary focal plane only). The ETM+ out-gassing process was successfully completed by April 30. The cool-down period, which started upon completion of out-gassing, was completed over the next 48 hours. Initial thermal analysis of the cold focal plane indicates that it is stable at 91 Kelvin (its design specification).

A Landsat 7 underflight of Landsat 5 was successfully completed during the period of June 1-3, 1999. This project was collected Landsat 5 and Landsat 7 data simultaneously to cross-calibrate the two Landsat systems. Several ground station operators (Australia, Argentina, Brazil, Canada, ESA, South Africa, and Saudi Arabia) participated by collecting Landsat 5 data. In addition, Space Imaging collected Landsat 5 data of Canada, USA, and Mexico. These data were sent to the EROS Data Center for processing and analysis. The NASA Landsat 7 Project Science Office has responsibility for analyzing these data to cross-calibrate between ETM+ and the Landsat 5 Thematic Mapper. Results of these analyses will be distributed as they become available.

By June 28, 1999, Landsat 7 was positioned in its nominal operational orbit at an altitude of 705 kilometers. The final maneuvering process placed Landsat 7 in an orbit consistent with and eight paths to the east of Landsat 5. This results in a Landsat 7 and Landsat 5 overflight of the same location eight days apart during routine operations.

When the nominal orbit was achieved, the Landsat 7 program entered into a pre-operational phase during which Landsat 7 acquired data according to the nominal duty cycle. The first 16-day cycle was completed on July 14, 1999.

The On-orbit Initialization and Verification, conducted over a 90 day period, was completed on August 2, 1999. This process stabilized the ETM+, positioned the spacecraft in the correct orbit, and allowed the on-board and ground systems to interact and undergo appropriate testing. ***Performance of both the Landsat 7 spacecraft and the ETM+ instrument met or exceeded specifications for almost all system requirements.***

Summary of the
Orbital characteristics of the Landsat Family

Landsat 1-3

- altitude :	907-915 km
- inclination :	99.2°
- orbit :	Near-polar, sun synchronous
- equatorial crossing time :	0930 AM (descending node)
- period of revolution :	103 minutes
- repeat coverage :	18 days

Landsat 4-5

- altitude :	705 km
- inclination :	98.2°
- orbit :	Near-polar, sun synchronous
- equatorial crossing time :	0930 AM (descending node)
- period of revolution :	99 minutes
- repeat coverage :	16 days

Landsat 7

- altitude :	705 km
- inclination :	98.2°
- orbit :	Near- polar, sun synchronous
- equatorial crossing time :	1000 AM (descending node)
- period of revolution :	99 minutes
- repeat coverage :	16 days

10. LANDSAT 7 DATA POLICY

October 31, 1994
Revised: September 19, 1997

INTRODUCTION

Section 105 of Public Law (P.L.)102-555, The Land Remote Sensing Policy Act of 1992, states, "The Landsat Program Management (LPM), in consultation with other appropriate United States Government agencies, shall develop a data policy for Landsat 7...". The law also identifies goals for the policy. This document, in accordance with the law, establishes a data policy for Landsat 7 that covers the acquisition, processing, archival, distribution, and pricing policy for Landsat 7 system development and operations are contained in the Management Plan for the Landsat Program.

As required by P.L. 102-555, this Data Policy is designed to achieve the following:

1. Ensure that unenhanced data are available to all users at the cost of fulfilling user requests;

2. Ensure timely and dependable delivery of unenhanced data to the full spectrum of civilian, national security, commerical, and foreign users and the National Satellite Land Remote Sensing Data Archive (NSLRSDA);

3. Ensure that the United States retains ownership of all unenhanced data generated by Landsat 7;

4. Support the development of the commerical market for remote sensing data;

5. Ensure that the provision of commercial value-added services based on remote sensing data remains exclusively the function of the private sector; and

6. To the extent possible, ensure that the data distribution system for Landsat 7 is compatible with the Earth Observing System Data and Information System (EOSDIS).

The Landsat 7 system will comprise a spacecraft carrying an Enhanced Thematic Mapper Plus (ETM+) instrument and a ground segment consisting of mission operations, data capture, ground processing, data archiving, and data product distribution elements. The ETM+ is a nadir-pointing, eight spectral band instrument designed to provide data continuity with the Thematic Mapper instruments on Landsats 4 and 5.

ACQUISITION

Data acquistion by the ETM+ on Landsat 7 will be directed the mission goal of acquiring and updating periodically a global archive of daytime, sustantially cloud-free images of land areas. In addition to the periodic global archive acquisitions, Landsat 7 will acquire every daytime scene on every pass over the United States. However, the Landsat operator will modify the acquisition schedule for the the global archive mission and the standing order for scenes of the United States to accommodate time-critical observations and other requests based on the following order of priorities:

1. Spacecraft and instrument health and safety

2. Time critical acquisitions related to national security, natural disasters, and environmental emergencies

3. Time-critical acquistions to support large campaigns and other key US Government (USG) programs

4. Acquistions critical to the global archive mission

5. Acquistion requests from individuals and commercial entities

Conflicts in the acquistion schedule will be resolved by the Landsat operator according to the priorities listed above and policy guidelines established by the Landsat Coordinating Group (LCG) acting on behalf of the Landsat Program Management. Non-time critical requests for acquisitions will by recieved by the EOSDIS Distributed Active Archive Center (DAAC) at the US Geological Survey's EROS Data Center (EDC) in Sioux Falls, South Dakota. Requests for time critical acquistions will be recieved directly by the Landsat operator.

The primary USG ground station will be located at EDC. The ground station will have the capability to capture both real-time and recorded data via direct transmission from Landsat 7. Secondary USG ground stations will be located in the Fairbanks, Alaska area, and Svalbard, Norway. The secondary station(s) will serve as backup for the primary station and ensure that the requirement for scene acquisitions is met. In addition, the Landsat 7 system will be capable of transmitting data in real-time to other, non-USG* ground station. USG ground stations will operate according to the data acquisition priorities defined in this document. Non-USG stations will receive data upon request and limited by the allocation of spacecraft assets for providing direct transmission data. These direct downlink resources will be scheduled in a balanced and equitable manner consistent with the achievement of the global archive mission goal.

The Landsat 7 operator will develop a standard ground station agreement which each non-USG operator must sign to be authorized to receive Landsat 7 data. This agreement will include conditions such as: provision for acquisition of scheduling and availability of the direct downlink; the use of non-USG ground stations as contingency backups or supplements for USG data acquisitions; retention of ownership of by USG of all unenhanced data from Landsat 7; the reception, archiving and cataloging of remotely received data; the availability of these data; exchange of metadata and image data between the non-USG ground station and the EDC-DAAC; the technical services available to the ground station; and fees associated with access to data. The Landsat 7 operator will endeavor to provide all requested coverage with the ETM+ sensor within the coverage circle of authorized ground stations, within the limits of the Landsat 7 system's resources and in accordance with conflict resolution guidelines.

Processing EDC will generate Level 0R data files, metadata, and browse images for all Landsat 7 data receieved by the Landsat 7 Ground Station at EDC. The EDC-DAAC will provide access to the Landsat 7 metadata and browse images on a nondiscriminatory basis and will generate Level 0R, Level 1R, and Level 1G data products on request (see Attachment for descriptions of the data products) for distribution to Landsat data users.

Data processing beyond Level 1 products distributed through EDC is the responsibility of the users and will be accomplished with user-owned capabilities or those available from private sector suppliers.

*Non-USG is defined as the Landsat international ground station (IGS) and other ground stations built and/or operated by government-sponsored organizations, commercial entities, or any combination therof.

ARCHIVE

EDC will archive, at a minimum, all Landsat 7 Level 0R data files, metadata, and browse images generated at EDC, and metadata and browse products provided to EDC by the Landsat 7 non-USG ground stations.

DISTRIBUTION

Landsat 7, Level 0R, Level 1R and Level 1G data products will be distributed in a timely manner on a nondiscriminatory basis, within the technical limitations of the system. The USG will impose no restrictions on subsequent use, sale, or redistribution of data from Landsat 7.

Should demand for data products exceed the daily capacity at EDC, orders will be processed based on the same priorities as data acquisition.

EDC will provide standard services associated with distribution of Landsat 7 data including distribution in defined, standard product format(s). Data will be available on physical media and via electronic transfer.

PRICING

All users will be charged standard prices for the products/ services provided. Prices will be reviewed and established by LPM once per year. It is the intent of LPM to distribute Level 0R data for no more than $500 per scene.

ATTACHMENT: LANDSAT 7 PROCESSING DEFINITIONS

METADATA

Descriptive information pertaining to the associated data files or data products. Information includes location and spatial coverage of the digital image data, acquistion date, associated file content, and data quality. Metadata are generated for the Level 0R data files and for the Level 0R, 1R, and 1G data products

BROWSE IMAGES

Sub-sampled Level 0R digital image of the Earth that can be viewed on a scene basis to quickly assess general ground area coverage, data quality, and the spatial relationships between ground area coverage and cloud coverage. A browse image provides a coarse spatial resolution image with a reduced data volume to facilitate screening of the archived Landsat 7 data.

CALIBRATION

File Parameters required to radiometrically and geometrically correct Level 0R digital image data to generate Level 1R or 1G data products. The parameters are based on calibration of the ETM+ and the Landsat 7 spacecraft.

LEVEL 0R

Data File Level 0R digital image data (see description below); payload correction data from the spacecraft including attitude, ephemeris high frequency jitter data, and ETM+ and spacecraft temperatures; mirror scan correction data; a geolocation table; and internal calibration lamp data.

LEVEL 0R

Data Product Level 0R data files packaged and formatted for distribution to Landsat 7 data users along with the associated metadata and calibration parameter file. Data products are generated on request by a data user. A user may specify a subset of a Level 0R digital image or a subset of the data files for distribution.

LEVEL 1R

Data Product A radiometrically corrected ETM+ digital Earth image along with the files containing metadata, calibration parameters, payload correction data, mirror scan correction data, a geolocation table, and internal calibration lamp data. The digital image pixels are not resampled, for geometric correction and registration. Level 1R data products are generated on request and the data are packaged and formatted for distribution to the data user.

LEVEL 1G

Data Product A radiometrically corrected and geometrically corrected ETM+ digital Earth image along with metadata, calibration parameters, and a geolocation table. The radiometrically corrected pixels are resampled for geometric correction and registration to a user-specified map projection. Level 1G data products are generated on request and the data are packaged and formatted for distribution to the data user.

4.8 SPOT Satellites

The SPOT satellite program is discussed via summary graphics and tables outlining the orbit, sensor and data - product characterisitcs of the SPOT system (see Tables 4.10- 4.11 and Figures 4.34 -4.40) .

The Next Generation: SPOT 4

SPOT 4 was launched from Kourou, French Guiana on March 24,1998. SPOT 4 has some new instrumentation in addition to all the features of the original three SPOT satellites. New features of SPOT 4 include:

- an enhanced, push-broom, multispectral imager, the HRVIR, which provides a middle infrared band (1.58-1.75µm), on-board registration of all bands and the two HRVIR imagers are programmable for independent image acquisition.

- on-board recording systems with greater storage capacity (solid state memory)

- a 5 year design life.

SPOT 4 also carries a new instrument, VEGETATION, which provides a wide swath (2,250 km), high temporal resolution, high radiometric resolution, but low spatial resolution (1.36km^2) (Table 4.11). The VEGETATION instrument features similar bands as the HRVIR instrument, as well as a blue band (B0: 0.43-0.47µm) for atmospheric correction and water penetration.

TABLE 4.10 SPOT SATELLITE CHRONOLOGY

- SPOT 1: launched 2/22/86
  retired 12/31/90
  re-used in 1997

- SPOT 2: launched 1/22/90

- SPOT 3: lauched 9/25/93
  lost 11/14/97

- SPOT 4: lauched 3/24/98

TABLE 4.11 SPOT 4 VEGETATION INSTRUMENT

• Wide field -of- view, 4-band imaging radiometer

- swath width = 2,250 km
  - @ latitude $\geq$ 35° = daily coverage
  - equatorial zone = every other day coverage

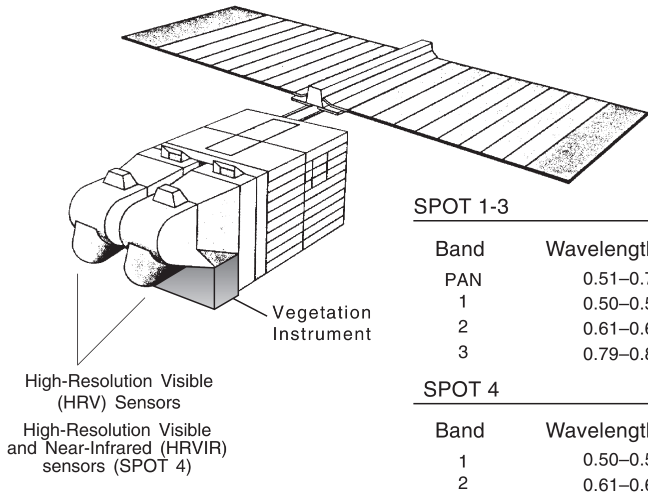
• Spectral Resolution	Band No.
- blue (0.43 - 0.47 mm)	0
- red (0.61 - 0.68 mm)	2
- NIR (0.78 - 0.89 mm)	3
-MIR (1.58 - 1.75 mm)	4

• Spatial Resolution = 1.36 km^2 (1.165 x 1.165 km)

• Radiometric Resolution = 10-bit (DN range 0-1023)

SPOT 1–4

4.34



SPOT 1-3

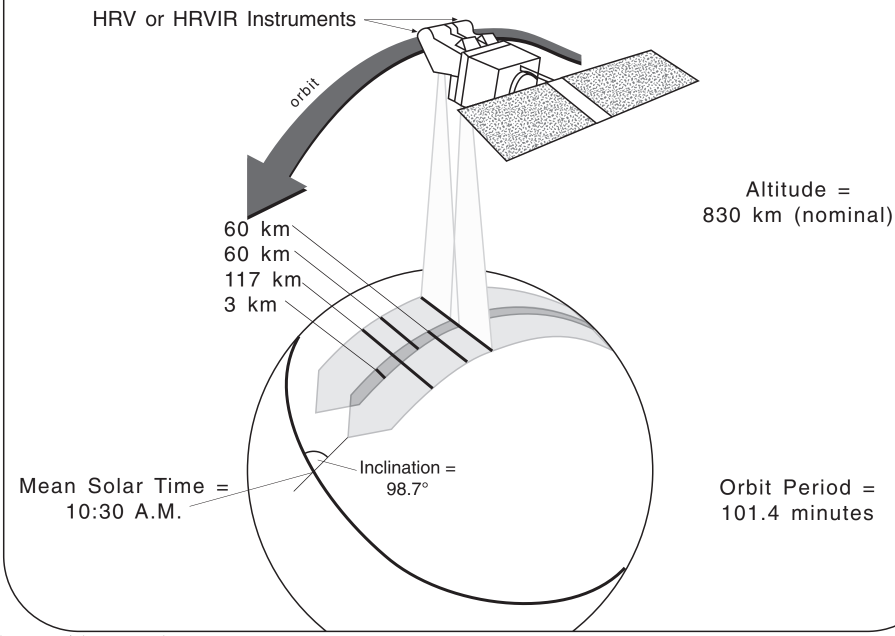
Band	Wavelength (µm)	Pixel Size (m)
PAN	0.51–0.73	10 m
1	0.50–0.59	20 m
2	0.61–0.68	20 m
3	0.79–0.89	20 m

SPOT 4

Band	Wavelength (µm)	Pixel Size (m)
1	0.50–0.59	20 m
2	0.61–0.68	10 m
3	0.79–0.89	20 m
4	1.58–1.75	20 m

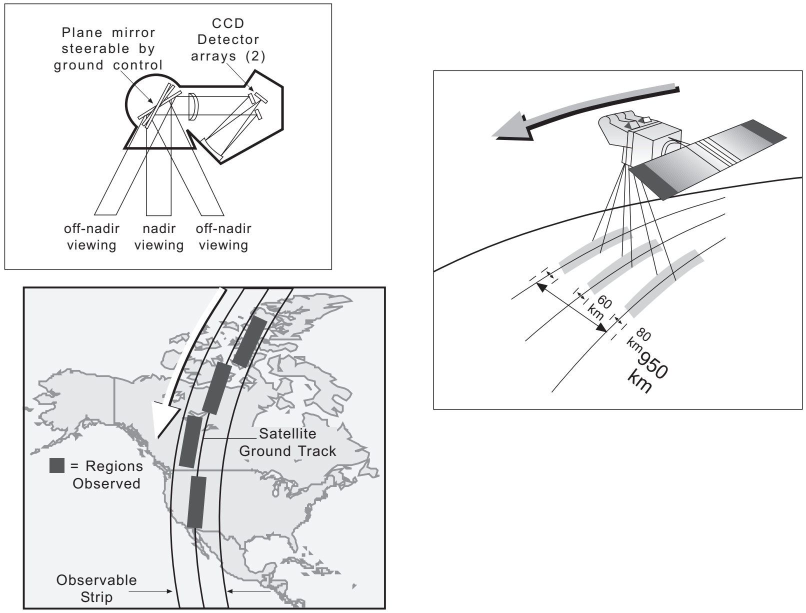
SPOT Orbital Mechanics

4.35



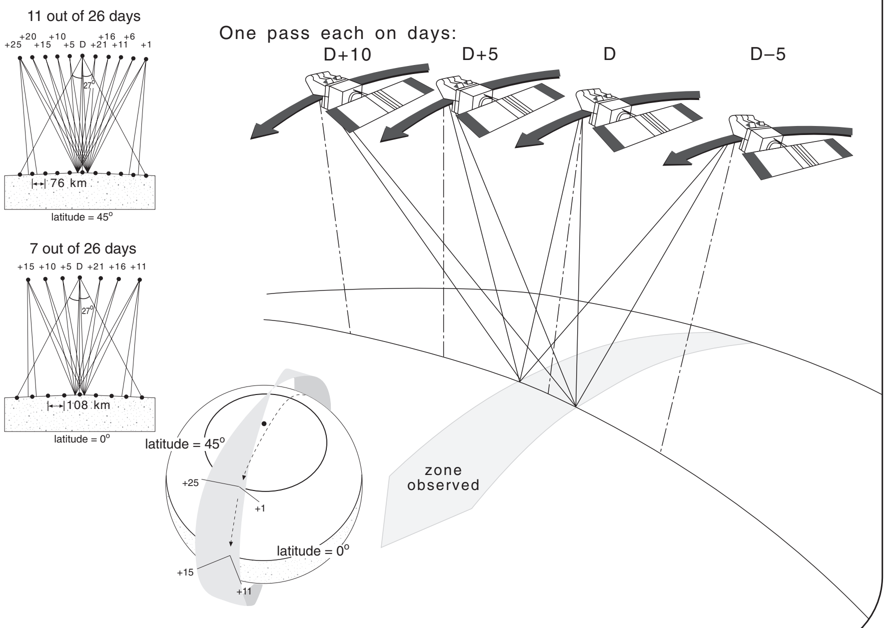
SPOT Off–Nadir Viewing

4.36



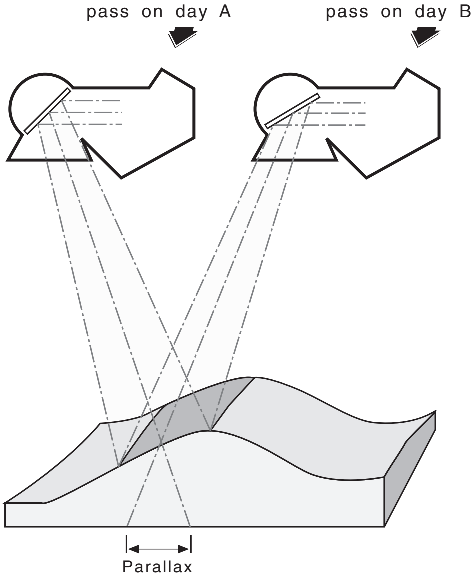
SPOT Revisit Capabilities

4.37



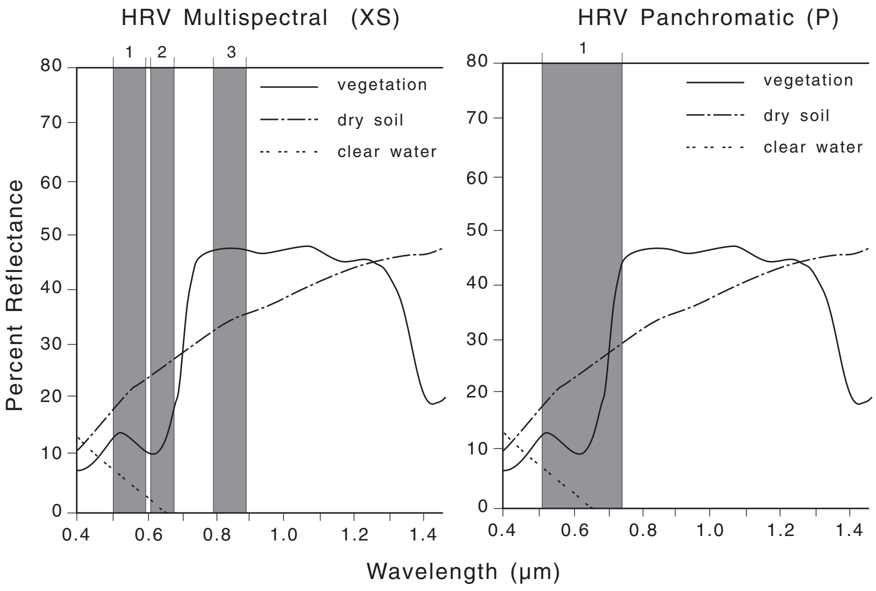
SPOT–Stereoscopic Capabilities

4.38



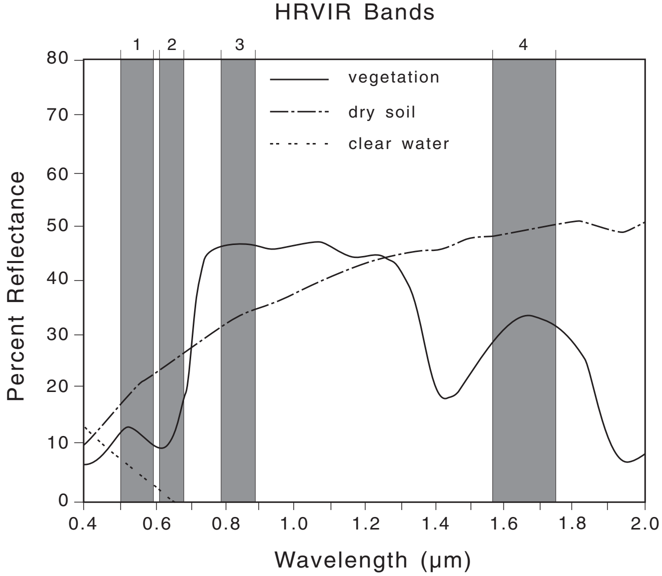
SPOT 1-3 HRV Bands

4.39



SPOT 4 HRVIR Bands

4.40



4.9 AVHRR

The U.S. National Oceanic and Atmospheric Administration (NOAA) operates a series of polar-orbiting satellites for meteorological applications. Known as the NOAA polar-orbiting satellite program, there are currently two satellites operating (NOAA-14, and -15), each carrying six major instruments (Table 4.12). Of concern to remote sensing studies is the Advanced Very High Resolution Radiometer (AVHRR). This instrument has been built in three versions: a 4-, 5-, or 6-channel scanning radiometer with sensitivity in the visible (0.58-0.68µm), near-infrared (0.73-1.10 µm), middle-infrared (1.58-1.64 µm), and different sectors of the thermal infrared (Figure 4.41) region. The AVHRR instrument has a ground resolution of 1.1 km with a swath width of about 2700 km (Figure 4.42, Table 4.13).

Figure 4.43 summarizes the spatial and spectral differences between the Landsat MSS and TM instruments, the SPOT HRV sensor, and the NOAA AVHRR radiometer.

Table 4.12 NOAA Polar-Orbiting Satellites

Presently Active	Launch Date	Data Available From
NOAA - 14	12-30-94	12-30-94 to Present
NOAA - 15	5-13-98	5-13-98 to Present

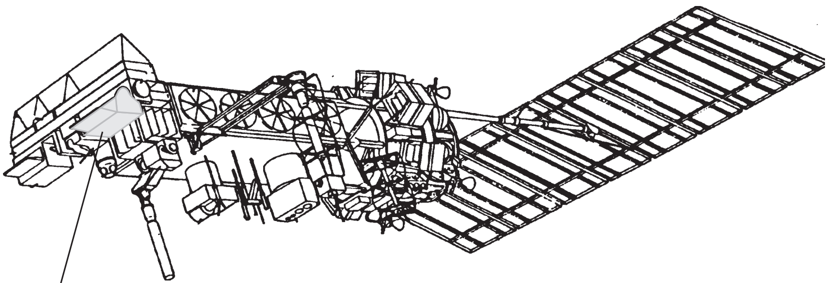
Decommissioned	Launch date	Data Availability Range
TIROS - N	10-13-78	10-19-78 to 1-30-80
NOAA - 6	6-27-79	6-27-79 to 3-5-83
NOAA - 7	6-23-81	8-19-81 to 6-7-86
NOAA - 8	3-28-83	6-20-83 to 7-12-84 7-1-85 to 10-31-85
NOAA - 9	12-12-84	2-25-85 to 11-7-88
NOAA - 10	9-17-86	11-17-86 to 9-17-91
NOAA - 11	9-24-88	11-8-88 to 9-13-94
NOAA - 12	5-14-91	9-1-91 to 12-15-94
NOAA - 13	8-9-93	8-9-93 to 8-21-93

Orbit Characteristics

Altitude	833 km (NOAA-6, 8, 10, 12 and 15) 870 km (TIROS-N; NOAA-7, 9, 11, 13, and 14)
Period of orbit	101.5 min (833 km altitude) 102.3 min (870 km altitude)
Orbit inclination	98.9°
Orbits per day	14.2 (833 km) or 14.1 (870 km)
Distance between orbits	25.5° (approx. 2,700 km)
Overpass times	

NOAA - 14 1330 (ascending) and 0130 (descending) LST
NOAA - 15 1930 (ascending) and 0730 (descending) LST

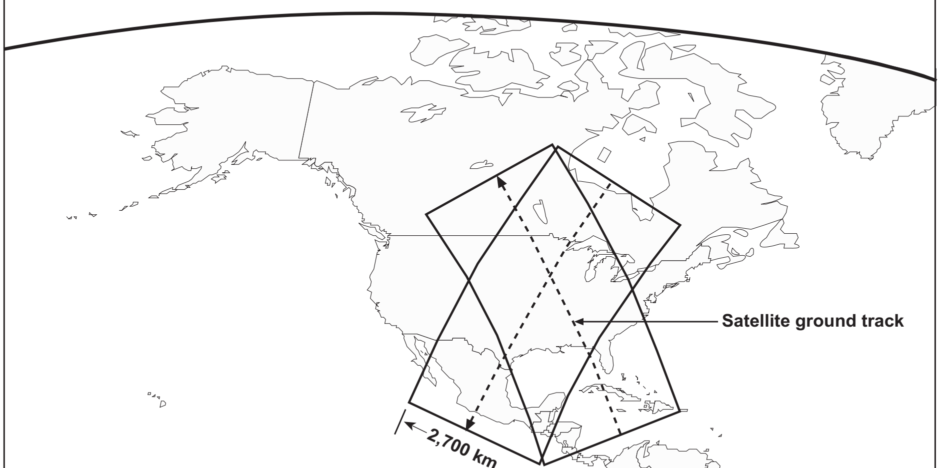
NOAA Polar Orbiter 4.41



AVHRR Spectral Channels

NOAA–6, –8, and –10	NOAA–7,–9,–11, –12 and –14	NOAA–15
1 0.58—0.68	1 0.58—0.68	1 0.58—0.68
2 0.72—1.10	2 0.72—1.10	2 0.725—1.00
-----	-----	3A 1.58—1.64
3 3.55—3.93	3 3.55—3.93	3B 3.55—3.93
4 10.5—11.5	4 10.3—11.30	4 10.30—11.30
-----	5 11.5—12.50	5 11.50—12.50

Swath Width and Orbit Types of the AVHRR Instrument 4.42



Orbit Type:
- Ascending = S Hemisphere to N Hemisphere
- Descending = N Hemisphere to S Hemisphere

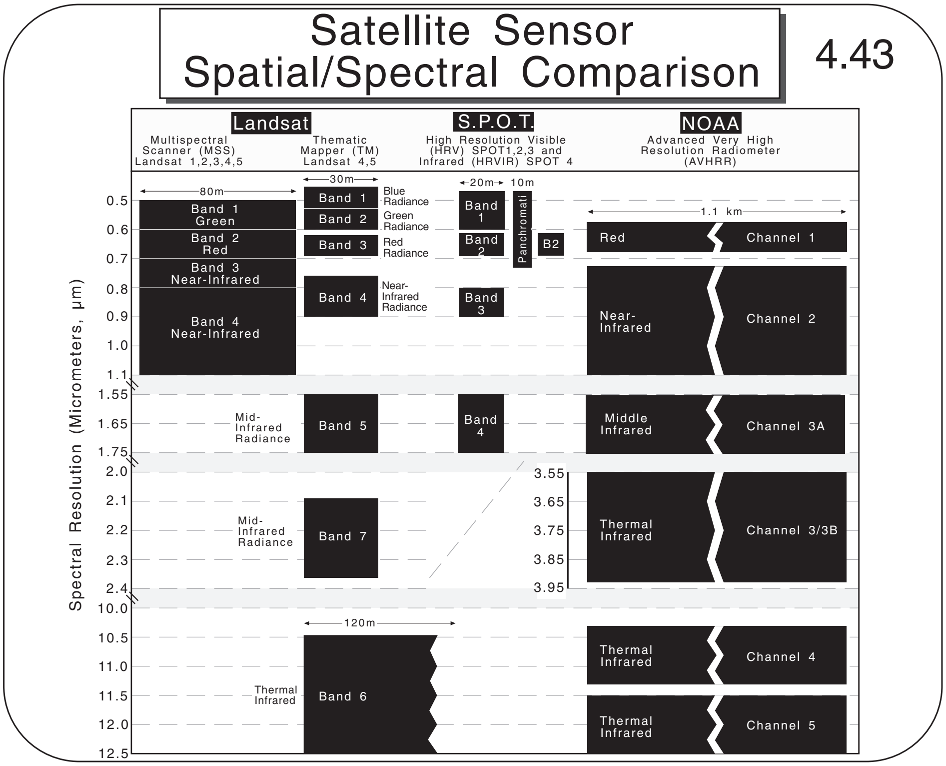

Satellite Sensor Spatial/Spectral Comparison
4.43
Landsat
Multispectral Scanner (MSS) Landsat 1,2,3,4,5
Thematic Mapper (TM) Landsat 4,5
S.P.O.T.
High Resolution Visible (HRV) SPOT1,2,3 and Infrared (HRVIR) SPOT 4
NOAA
Advanced Very High Resolution Radiometer (AVHRR)
Spectral Resolution (Micrometers, µm)
80m
Band 1 Green
Band 2 Red
Band 3 Near-Infrared
Band 4 Near-Infrared
30m
Band 1
Blue Radiance
Band 2
Green Radiance
Band 3
Red Radiance
Band 4
Near-Infrared Radiance
Mid-Infrared Radiance
Band 5
Mid-Infrared Radiance
Band 7
120m
Thermal Infrared
Band 6
20m
10m
Band 1
Band 2
Band 3
Band 4
Panchromati
B2
1.1 km
Red
Channel 1
Near-Infrared
Channel 2
Middle Infrared
Channel 3A
Thermal Infrared
Channel 3/3B
Thermal Infrared
Channel 4
Thermal Infrared
Channel 5
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.55
1.65
1.75
2.0
2.1
2.2
2.3
2.4
10.0
10.5
11.0
11.5
12.0
12.5
3.55
3.65
3.75
3.85
3.95

Table 4.13 AVHRR Characteristics

Scan angle from nadir	+/- 55.4^o
Optical FOV	1.3 mr
IFOV, at nadir	1.1 km
IFOV, off-nadir maximum	
along track	2.4 km
across track	6.9 km
Swath width	2700 km
Repeat coverage	Every 12 hr

Spectral Channels

NOAA-6,8 and 10	NOAA-7, 9, 11, 12, and 14	NOAA-15
1 0.58-0.68	1 0.58-0.68	1 0.58-0.68
2 0.72-1.10	2 0.72-1.10	2 0.725-1.00
-----	-----	3A 1.58-1.64
3 3.55-3.93	3 3.55-3.93	3B 3.55-3.93
4 10.5-11.5	4 10.3-11.3	4 10.3-11.3
-----	5 11.5-12.5	5 11.5-12.5

4.10 Earth Observing System

The Earth Observing System (EOS) is a series of Earth-orbiting satellites which will provide global observation of the land surface, atmosphere, and oceans over 15 years or more. EOS is part of NASA's Earth Science Enterprise (formerly Mission To Planet Earth) program which provides measurement systems and research initiatives to further the acquisition and synthesis of environmental data to address scientific issues related to global change and Earth system science.

Complete information and details on the satellites and instruments included in EOS can be found in the *MTPE/EOS Reference Handbook*. This document can be directly accessed at the following Internet address:

http://eospso.gsfc.nasa.gov/eos_reference/TOC.html

EOS is complemented by missions and instruments from international partners, including Japan, Brazil, the European Space Agency (ESA), and ESA member countries. Together, these NASA and international programs form the basis for a comprehensive International Earth Observing System (IEOS).

The first EOS-sponsored satellite, the polar-orbiting TERRA spacecraft (formally known as EOS AM-1) is scheduled for launch on October 4, 1999 (Figure 4.44). Its descending node equatorial crossing will be 10:30 AM. TERRA will fly four instruments:

ASTER - Advanced Spaceborn Thermal Emission and Reflection Radiometer (Figure 4.45, Table 4.14)

A three-radiometer sensor package with three vis/NIR, six SWIR, and five thermal IR channels with 15, 30, and 90 m resolution, respectively, and a 60 km swath.

MISR - Multi-angle Imaging Spectrometer

Thirty-six channel instrument; nine pushbroom cameras with discrete view angles (up to +/- 70°) in four spectral bands (0.443 to 0.865 µm) with resolution fo 275 m to 1.1 km.

MODIS - Moderate Resolution Imaging Spectrometer (Figure 4.46, Table 4.15)

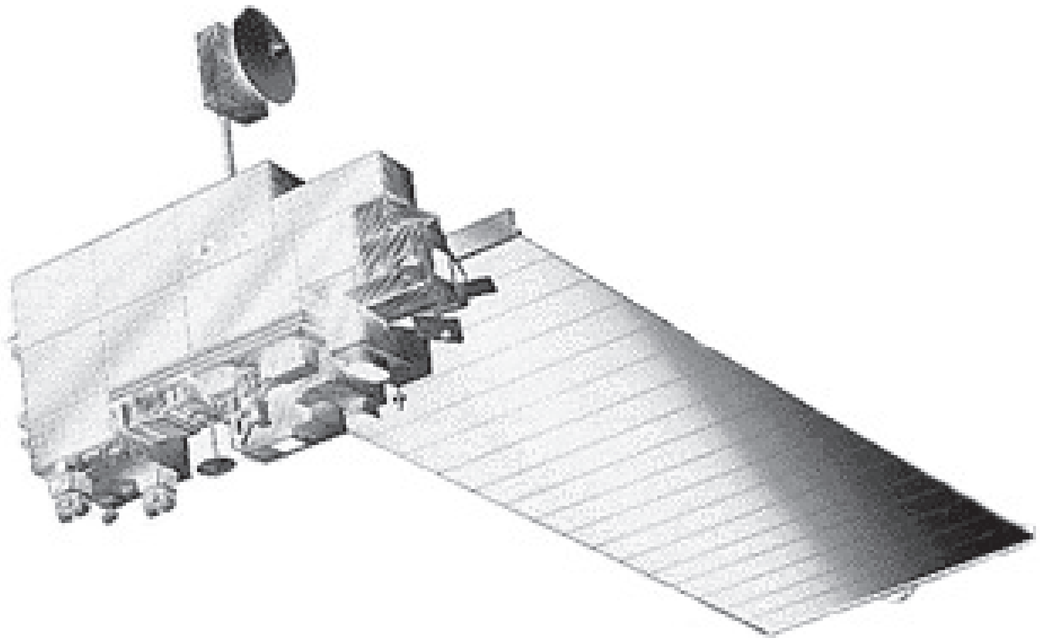
Thirty-six channel imaging radiometer (0.7 µm to 14.3 µm) with 250 m, 500 m, or 1 km resolution and 2,300 km swath width.

MOPITT - Measurement of Pollution in the Troposphere

Eight channel, cross-track scanning, gas correction radiometer operating at three wavelengths (2.2, 2.3, and 4.7 µm)

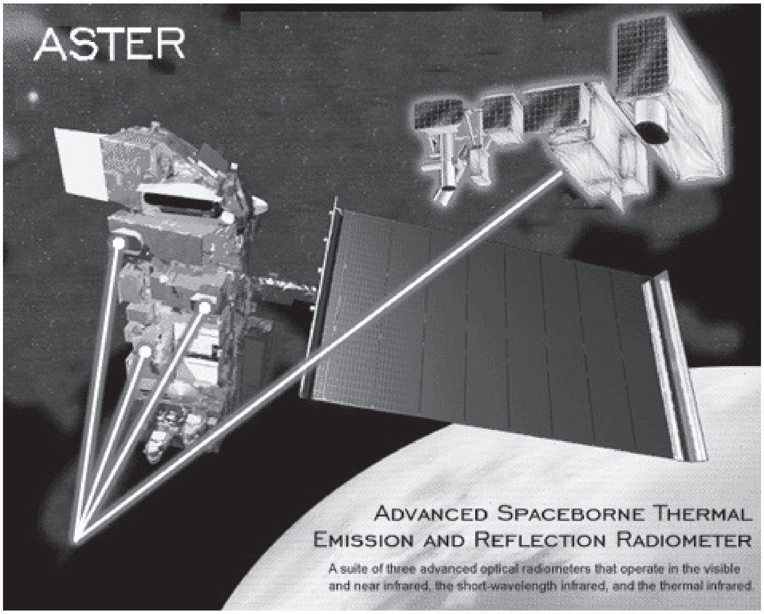
EOS TERRA

4.44



ASTER Instrument

4.57



MODIS Instrument

4.58

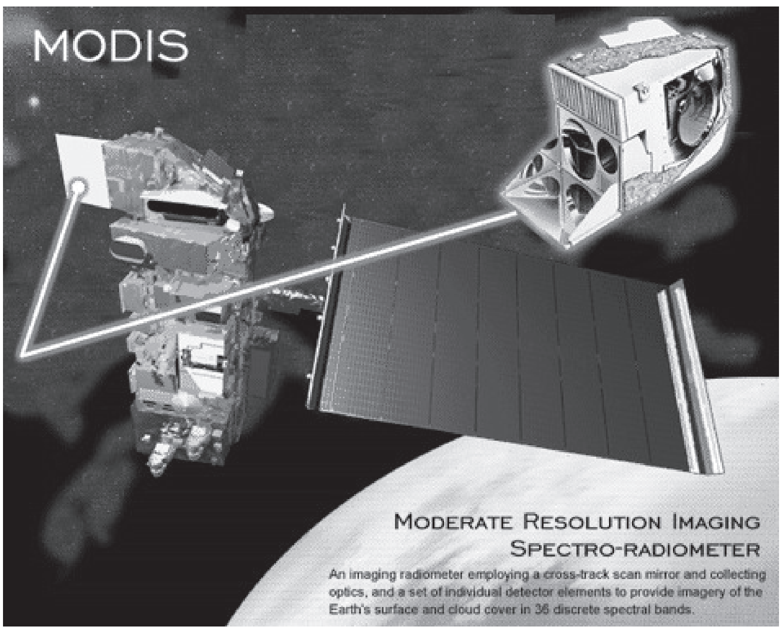


TABLE 4.10 ASTER INSTRUMENT SPECTRAL CHARACTERISTICS

	VNIR	SWIR	TIR
	Band 1: 0.52 - 0.60 mm Nadir looking	Band 4: 1.600 - 1.700 mm	Band 10: 8.125-8.475 mm
	Band 2: 0.63 - 0.69 mm Nadir looking	Band 5: 2.145 - 2.185 mm	Band 11: 8.475 - 8.825 mm
	Band 3: 0.76 - 0.86 mm Nadir looking	Band 6: 2.185 - 2.225 mm	Band 12: 8.925 - 9.275 mm
	Band 3: 0.76 - 0.86 mm Backward looking	Band 7: 2.235 - 2.285 mm	Band 13: 10.25 - 10.95 mm
		Band 8: 2.295 - 2.365 mm	Band 14: 10.95 - 11.65 mm
		Band 9: 2.360 - 2.430 mm	
Ground Resolution:	15 m	30 m	90 m

TABLE 4.11 MODIS INSTRUMENT SPECTRAL CHARACTERISTICS

Band#	Bandwidth (nm)	Primary Uses
1	620 - 670	Land/Cloud Boundaries
2	841 - 876	
3	459 - 479	Land/Cloud Properties
4	545 - 565	
5	1230 - 1250	
6	1628 - 1652	
7	2105 - 2155	
8	405 - 420	Ocean Color/Phytoplankton/ Biogeochemistry
9	438 - 448	
10	483 - 493	
11	526 - 536	
12	546 - 556	
13	662 - 672	
14	673 - 683	
15	743 - 753	
16	862 - 877	
17	890-920	Atmospheric Water Vapor
18	931 - 941	
19	915 - 965	

TABLE 4.11 Cont'd

Band#	Bandwidth (μm)	Primary Uses
20	3.660 - 3.840	Surface/Cloud Temperature
21	3.929 - 3.989	
22	3.929 - 3.989	
23	4.020 - 4.080	
24	4.433 - 4.498	Atmospheric Temperature
25	4.482 - 4.549	
26	1.360 - 1.390	Cirrus Clouds/Water Vapor
27	6.535 - 6.895	
28	7.175 - 7.475	
29	8.400 - 8.700	
30	9.580 - 9.880	Ozone
31	10.780 - 11.280	Surface/Cloud Temperature
32	11.770 - 12.270	
33	13.185 - 13.485	Cloud Top Temperature
34	13.485 - 13.785	
35	13.785 - 14.085	
36	14.085 - 14.385	

Chapter 5 | Thermal Infrared Remote Sensing

Contents

5.1 Objectives

- List the portions of the electromagnetic spectrum used for thermal sensing.
- Explain the difference between apparent and kinetic temperatures.
- List several sources of distortion in thermal IR imagery.
- Describe the characteristics of clouds and smoke on thermal IR data.
- Describe the diurnal temperature cycles of vegetation, soil, and water.
- List several applications of thermal IR data.
- List the spatial, spectral, and revisit characteristics of the thermal data from Landsat TM, ETM+ and NOAA AVHRR.

5.2 Introduction

A brief introduction to thermal infrared energy is presented along with the defintion of pertinent terms. Thermal infrared detectors are described before thermal sensing is presented. A section on interpreting thermal infrared imagery is presented next.

Definitions

Heat

The kinetic energy of the random motion of particles of matter causing collisions that result in changes of energy state and the subsequent **emission of electromagnetic radiation** (Radiant Flux).

Amount of heat

Measured in calories (one calorie = the amount of heat required to raise the temperature of one gram of water one ^{o}C)

Concentration of heat

Measured by temperature

Kinetic Temperature

Concentration of kinetic heat as measured by a thermometer in contact with the object.

Radiant Temperature

Concentration of radiant flux; it can be sensed remotely. Also known as Apparent Temperature. The total exitance ($W\ m^{-2}$) is proportional to the fourth power of kinetic temperature times emissivity. **Thermal infrared radiation is sensed remotely by electronic detection means rather than by photochemical means (i.e. film).**

Conduction

The transfer of heat through a material by molecular interaction.

Convection

The transfer of heat through the physical movement of heated matter.

Radiation

The transfer of heat in the form of electromagnetic waves. Unlike conduction and convection, radiative transfer of heat can occur through (or within) a vacuum.

Thermal Conductivity

A measure of the ease of heat transfer; a measure of the rate at which heat will pass through a material: ($W\ m^{-1}\ K^{-1}$).

Thermal Capacity

The ability of a material to store heat energy; calculated as the product of density and specific heat (cal $cm^{-3}\ {}^{o}C^{-1}$).

Blackbody Radiation

Stefan - Boltzmann Law for a Blackbody:

$$W = \sigma T^4$$

W = total radiant exitance ($W\ m^{-2}$)

σ = Stefan - Boltzmann constant
($5.6697 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$)

T = temperature of the blackbody (K)

Wien's Displacement Law

$$\lambda_{max} = \frac{2{,}898\ \mu m\ K}{T\ (Kelvin)}$$

note: λ_{max} is inversely proportional to temperature

Planck's Blackbody Law

$$M_\lambda = \frac{3.74151 \times 10^8}{\lambda^5 \left[e^{\left(1.43879 \times 10^4 / \lambda T\right)} - 1 \right]}$$

Radiation From Real Materials

A blackbody is a theoretical, perfect absorber and perfect emitter. Real materials are not blackbodies so their emitting ability is less than perfect. The emitting ability of a material is called ***emissivity*** **(ε):**

$$\varepsilon_\lambda = \frac{\text{exitance of an object at T}}{\text{exitance of a blackbody at T}}$$

ε ranges from 0 to 1:

Blackbody	$\varepsilon = 1$
Graybody	$\varepsilon < 1$, but constant at all wavelengths
Selective Radiator	$\varepsilon < 1$, but varies with wavelength

Kirchhoff's Law

$$\varepsilon_\lambda = A_\lambda$$ (under conditions of thermal equilibrium)

"Good emitters are good absorbers"

As discussed in Chapter 2,

Absorptance + Reflectance + Transmittance = 1 (1)

Kirchhoff's Law states that **Absorptance = Exitance** (2)

So, **Exitance + Reflectance + Transmittance = 1** (3)

Since most objects of remote sensing observation are opaque to thermal infrared wavelengths,

Transmittance = 0

and Eq. 3 above becomes: **Exitance + Reflectance = 1** (4)

This relationship states that Emissivity and Reflectance of thermal infrared wavelengths are **inversely related** to one another. The greater an object's Reflectivity, the lesser its Emissivity is. That's why blackbodies are black -- as the perfect emitter, a blackbody, according to Eq. 4, ***must*** also be the the perfect absorber (i.e. no reflectance). Note that Reflectivity and Emissivity must be compared at the same wavelengths.

Stefan - Boltzmann Law applied to real materials:

$$W = \varepsilon \sigma T^4$$

Emissivity varies with different materials. Two objects with the same **kinetic temperature** can have very different **exitances** (i.e. **apparent temperature**).

Thermal IR sensors detect **radiant temperature** (T_{rad}); most users are interested in **kinetic temperature** (T_{kin}).

$$T_{rad} = \varepsilon^{.25}\, T_{kin}$$

Thermal IR sensors detect thermal radiation from the **surface** of objects (about 50 µm in depth). This surface layer may have a different temperature compared to the internal bulk temperature (e.g. evaporative cooling of a soil surface).

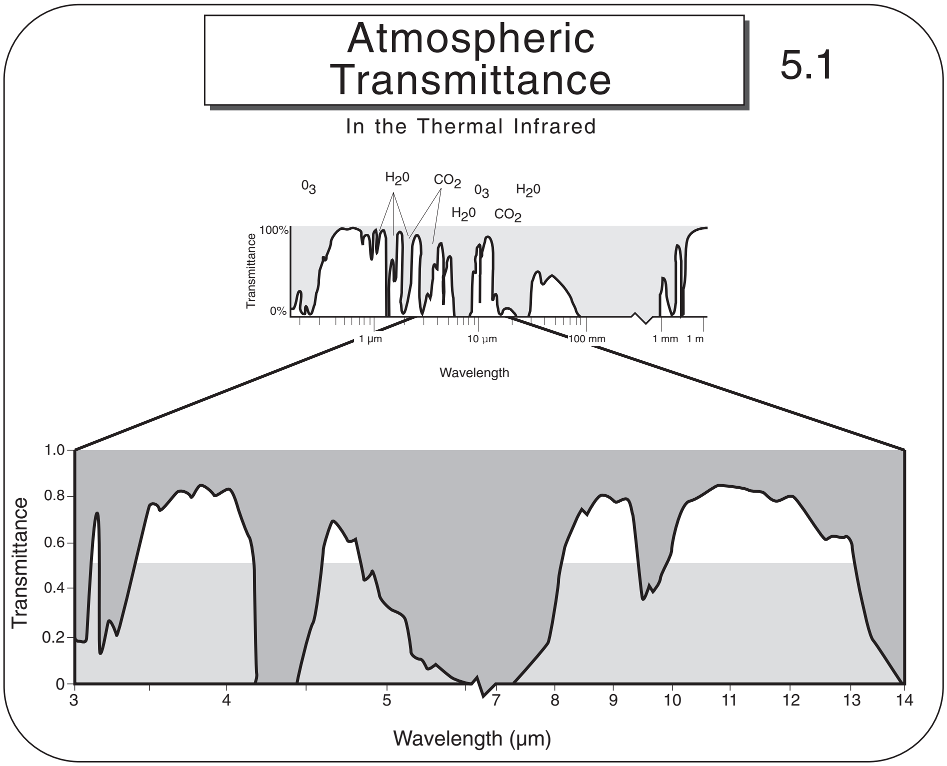
Atmospheric Effects

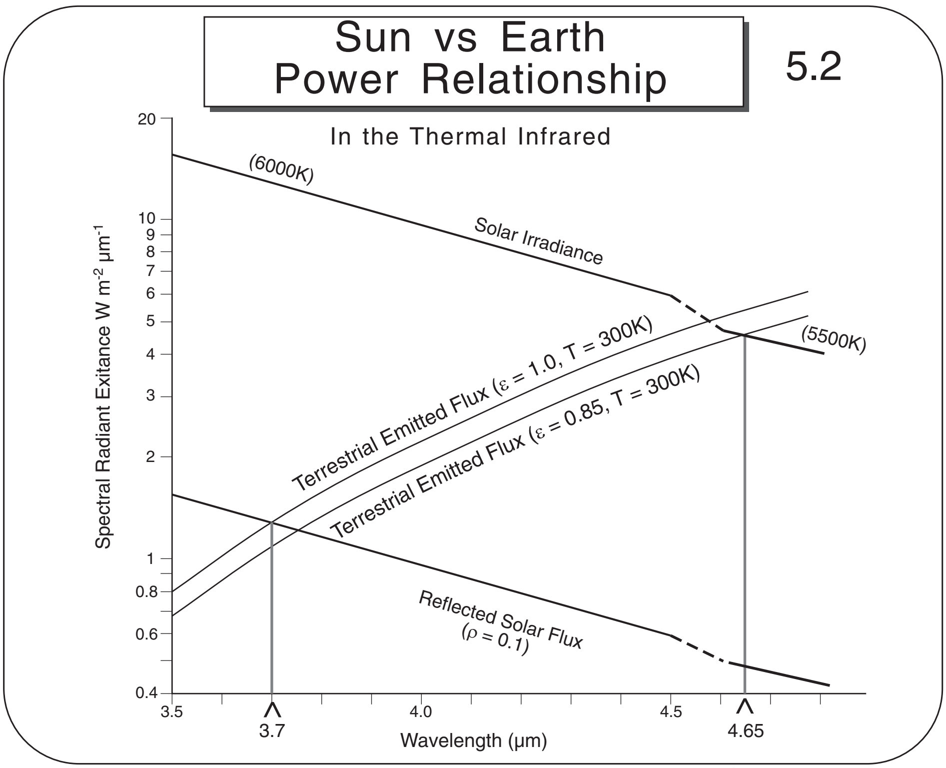
Two major (and two minor) atmospheric windows (> 50% transmission) occur in the thermal IR portion of the spectrum (Figure 5.1):

short wavelength	3.4 - 4.2 µm
thermal window	4.6 - 4.8 µm
long wavelength	8.1 - 9.4 µm
thermal window	9.8 - 13.2 µm

For certain applications, it is important to note that the short wavelength thermal bandpass is subject to "contamination" from reflected solar infrared, whereas the long wavelength thermal bandpass is not (Figure 5.2).

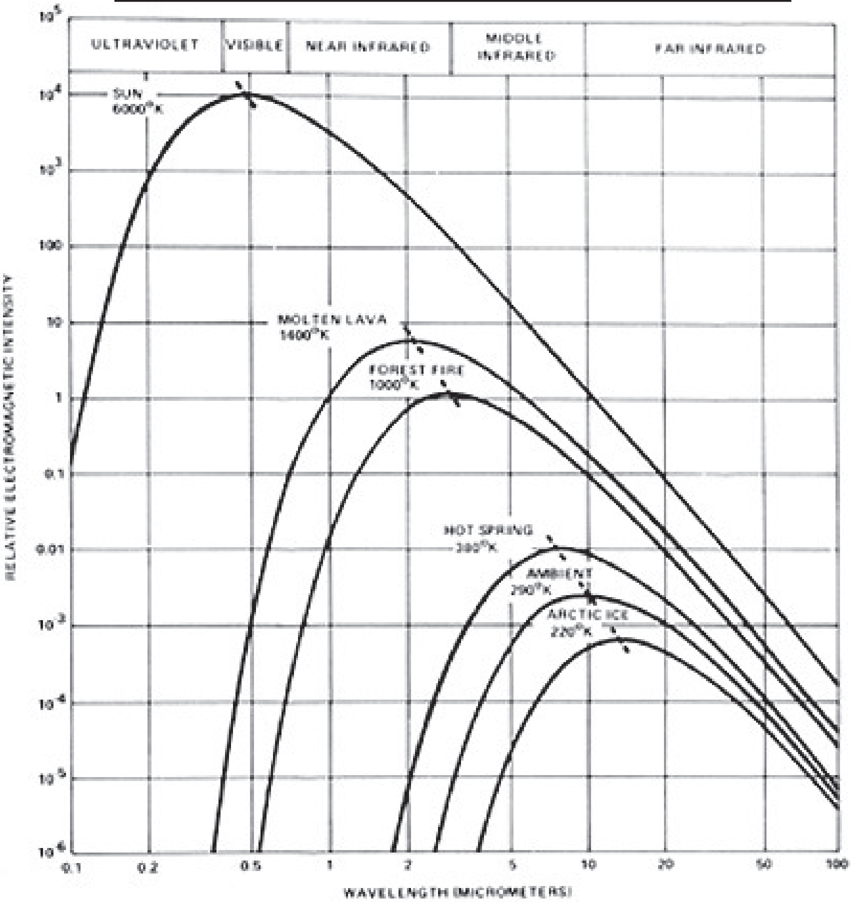
Consult the blackbody curves shown in Figure 5.3. It appears that the earth (ambient, 290 K), even at its peak wavelength, emits considerably less radiation than the sun does. In fact, at its peak wavelength, the sun emits greater than 3 million times more radiation per micrometer than the earth emits at its peak wavelength. Comparing the radiant output from the sun and the earth at the earth's peak wavelength, we can observe that the sun emits almost 450 times more radiant flux per micrometer than the earth does.


Atmospheric Transmittance
5.1
In the Thermal Infrared
03
H20
CO2
03
H20
H20
CO2
100%
0%
Transmittance
1 µm
10 µm
100 mm
1 mm
1 m
Wavelength
1.0
0.8
0.6
0.4
0.2
0
Transmittance
3
4
5
7
8
9
10
11
12
13
14
Wavelength (µm)


Sun vs Earth Power Relationship
5.2
In the Thermal Infrared
20
10
9
8
7
6
5
4
3
2
1
0.8
0.6
0.4
Spectral Radiant Exitance W m-2 µm-1
(6000K)
Solar Irradiance
(5500K)
Terrestrial Emitted Flux (ε = 1.0, T = 300K)
Terrestrial Emitted Flux (ε = 0.85, T = 300K)
Reflected Solar Flux
(ρ = 0.1)
3.5
4.0
4.5
3.7
4.65
Wavelength (µm)

Blackbody Emittance Curves

5.3



On the basis of these facts, you might conclude that thermal infrared sensing during the daytime would be dominated by reflected solar radiation rather than emitted earth radiation and, therefore, would be useless for recording terrestrial temperature data. Such a conclusion is **not correct**; daytime thermal IR sensing can be effectively done, ***if*** the correct bandpass is used. The apparent contradiction between Figure 5.3 and the above statement that daytime thermal IR sensing can be accomplished results from the faulty assumption that all of the radiant power emitted by the sun reaches the earth. **It doesn't!**

The sun is a sphere of gas nearly 1.4 million kilometers in diameter which is heated by continuous nuclear reactions at its center. The spectral radiant flux from the sun is complicated by the tremendous temperature variations which occur along its radius. Another complication is the opacity of the solar atmosphere to certain wavelengths. Stated simply, the effective, blackbody temperature of the sun is wavelength dependent. Measurements of solar irradiance from outside the earth's atmosphere provide the data presented in Table5.1.

At its peak exitance wavelength (0.487 µm), the sun can best be approximated by a blackbody source at 5950 K (Table 5.1). Using Planck's Blackbody Law, the spectral radiant exitance of the sun's surface can be calculated to be:

$$\mathbf{M_\lambda = 9.59 \times 107\ W\ m^{-2}\ \mu m^{-1}}$$

at $\lambda = 0.487\ \mu m$ and $T = 5950$ K

At the top of the earth's atmosphere, some 150 million kilometers away from the sun, solar irradiance has been measured to be:

$$2{,}072.2\ W\ m^{-2}\ \mu m^{-1}$$

Obviously, much less radiation reaches one square meter of the earth's upper atmosphere than left one square meter of the sun's surface. The reduction factor (F) by which radiant flux emitted from the solar surface is decreased by the time it reaches the top of earth's atmosphere is:

$$F = \frac{9.59 \times 10^7\ W\ m^{-2}\ \mu m^{-1}}{2072.2\ W\ m^{-2}\ \mu m^{-1}} = 4.63 \times 10^4$$

Table 5.1 Effective blackbody temperatures of the sun as a function of wavelength.

Bandpass (µm)	Effective Blackbody Temperature (K)
0.20 - 0.25	5000
0.26 - 0.34	5500
0.35 - 0.44	5700
0.45 - 0.47	5900
0.48 - 0.49	5950
0.50 - 0.54	5900
0.55 - 0.64	5800
0.65 - 0.94	5700
0.95 - 1.29	5800
1.30 - 4.50	6000
4.60 - 5.90	5500
6.00 - 20.0	5000

This reductions factor (F) applies at any wavelength and is dimensionless. The spectral radiant exitance of the sun at 9.6 µm (the wavelength of the earth's peak spectral exitance) can be calculated in a similar fashion. At 9.6 µm, the sun is best approximated by a blackbody temperature of 5000K (Table 5.1).

$$\mathbf{M_\lambda = 1.31 \times 10^4\ W\ m^{-2}\ \mu m^{-1}}$$

at $\lambda = 9.6$ µm and T = 5000 K

Applying the reduction factor (F), yields:

$$\frac{1.31 \times 10^4 \text{ W m}^{-2} \mu\text{m}^{-1}}{4.63 \times 10^4} = 0.28 \text{ W m}^{-2} \mu\text{m}^{-1}$$

For the earth, assuming an ambient temperature of 300 K, Planck's Blackbody Law gives:

$$\mathbf{M_\lambda = 31.2 \text{ W m}^{-2} \mu\text{m}^{-1}}$$

at $\lambda = 9.6$ µm and T = 300 K

These calculations show that at 9.6 µm, the earth's emitted radiation is more than 100 times more powerful than the incoming solar infrared irradiance. Figure 5.2 shows the "cross-over" region of the spectrum, where the earth becomes the more powerful radiator compared to the sun, to be 3.70 - 4.65 µm.

5.3 Thermal Energy Detectors

Thermal Detectors (Bolometers)

These devices change their own temperature in response to incident thermal radiation and usually their electrical resistance is a function of their temperature.

Advantages:
- very accurate
- response is not wavelength dependent

Disadvantages:
- incapable of rapid response
- lower thermal sensitivity

Photon (or Quantum) Detectors

Incident radiation excites electrical charge carriers within the detector material which change an electrical characteristic of the responsive element. This process is carried out without any significant temperature change in the responsive element.

There are two types of photon detectors:

1. Photoconductive - Change in incident radiation causes a change in the electrical resistance of the detector. Requires a bias voltage supply; the electronic noise of the supply limits the detector performance.

2. Photovoltaic -Change in incident radiation causes a change in the output voltage of the detector. These detectors have a better signal-to-noise ratio (SNR) than the photoconductive types, but only a limited number of materials are available:

Silicon (Si)
Indium Antimonide (InSb)
Germanium (Ge)

Advantage of Photon Detectors:

- very rapid (< 1 μsec) response time

Disadvantages of Photon Detectors:

- narrow spectral sensitivity
- necessity for cooling in order to improve SNR

5.4 Thermal Sensors

Thermal Radiometers

A **non-imaging** device; the basic form of radiant temperature sensor. For any such device, the ground resolution of the instrument at any given flying altitude is a function of the *Instantaneous Field Of View (IFOV).*

Diameter of the ground resolution cell = H ß

where H = flying height above terrain
ß = IFOV (cone angle) in radians

Thermal Scanners

Imaging devices which produce a two-dimensional record of surface radiant temperature. Aircraft scanners typically use a rotating mirror and usually have a large angular acceptance angle (90^o - 120^o). The data are most often recorded on magnetic tape, although some instruments provide in-flight imagery (CRT display or black & white strip photos).

5.5 Interpreting Thermal Imagery

Interpreting Thermal Imagery

- The diurnal cycles of radiant temperatures for vegetation, soil, and water are shown in Figure 5.4

- Polished metals have very high reflectance in the thermal IR, so their emissivity is very low (< 0.10) [Kirchhoff'f Law].

- Water has very low reflectance in the thermal IR, so its emissivity is very high (> 0.95).

- Water has the highest thermal capacity of any substance: 1.00 @ 15° C

  dry air = 0.24
  sandy soil = 0.24
  moist clay soil = 0.35

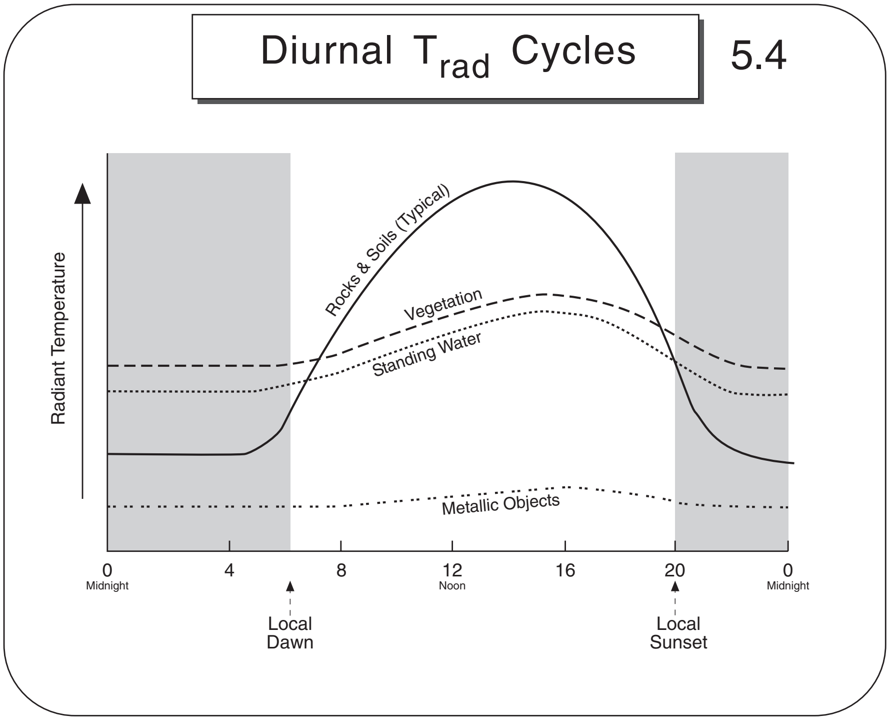
- The thermal inertia of water is similar to that of many soils and rock types:

  water = 0.037
  soils = 0.024 - 0.042
  shale = 0.034
  sandstone = 0.054

- By day, water presents a cooler radiant temperature compared to the surrounding landscape, while at night water presents a warmer radiant temperature compared to its surroundings. Why?

  1. Water has the highest thermal capacity (ability to store heat) of all landscape substances. So in the daytime, water bodies stay cooler than terrestrial objects because water can absorb a lot of energy with very little temperature change. It takes about four times as much energy to change the temperature of a shallow water body by 1° C compared to that required to change the temperature of rocks or soil by the same amount.

  2. Radiation losses (at night) from the free water surface causes cooling. Cooler water is slightly more dense that warmer water causing convection currents to set up which mix the water layers. This helps water bodies to maintain a relatively warm radiant temperature at night.


Diurnal T_{rad} Cycles
5.4
Radiant Temperature
Rocks & Soils (Typical)
Vegetation
Standing Water
Metallic Objects
0
Midnight
4
8
12
Noon
16
20
0
Midnight
Local
Dawn
Local
Sunset

Note that convection does not operate to transfer heat in soils and rocks (their heat must be conducted to the surface and earth materials are generally poor conductors).

- Moist soil is generally cooler than dry soil due to evaporative cooling and the large heat capacity of water.

- Vegetation is cooler than dry soil during the day due to transpiration; it's warmer than dry soil at night because there is no transpiration and the high thermal capacity of the *in vivo* moisture maintains the absorbed heat of the day.

- Thermal images containing clouds record the radiant temperature of their constituents: water droplets or ice particles. In most cases, due to their altitude in the atmosphere, clouds exhibit a cold to very cold signature (usually dark grey to black).

- Smoke plumes are usually invisible on thermal imagery. Hence, the thermal signatures of the surface features beneath the smoke plumes are recorded. This makes thermal imagery, particularly real time data, very useful for forest fire control work.

- Apparent thermal inertia (ΔT_{rad})

Thermal inertia cannot be measured by remote sensing methods because the three parameters needed to calculate it, conductivity, density, and thermal capacity, must be measured by contact techniques. But the maximum and minimum radiant temperature can be measured and for corresponding pixels (i.e. the same ground area): $T_{rad}max - T_{rad}min = \Delta T_{rad}$. Since the area is the same, $\boldsymbol{\varepsilon}$ is the same and ΔT_{rad} is approximately equal to $\Delta T_{kinetic}$

ΔT_{rad} is low for materials with high thermal inertia

ΔT_{rad} is high for materials with low thermal inertia

$$\text{Apparent Thermal Inertia} = \frac{1 - \text{Albedo}}{\Delta T_{rad}}$$

Chapter 6	Color Theory Applied To Image Interpretation

Contents

6.1 Objectives

- List the additive and subtractive primary colors
- Given the color continuum chart, determine the compliment of any primary color
- Given a set of generalized spectral reflectance curves, predict the color that each feature will form in both a (NIR, R, G) false-color composite and a (SWIR, NIR, R) false-color composite
- Define the vegetation index concept and describe its use.
- Define the moisture index concept and describe its use and limitations.

6.2 Introduction

The theory of color science is briefly discussed, especially with respect to additive and subtractive color formation. Satellite imagery is illustrated with respect to the formation of colors from various earth surface features portrayed in three different types of color composites.

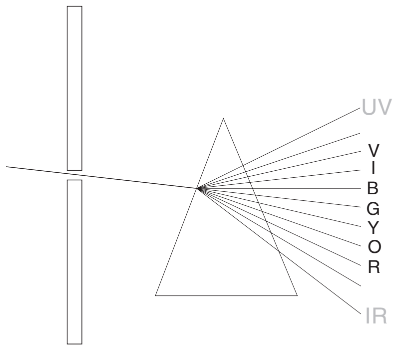
6.3 Color Science

In 1666, Sir Isaac Newton laid the foundation of color science when he discovered that white sunlight was composed of a mixture of all colors of the spectrum (Figure 6.1). The visible region of the electromagnetic spectrum extends from about 400 to 700 nanometers wavelength. EMR of these wavelengths produce a psychophysical response through the normal human eye called “color”. All spectral colors from violet to deep red are “contained” in the visible region of the EMS. Sir William Herschel is credited with the discovery of the infrared portion of the electromagnetic spectrum (Figure 6.2).

The visible light spectrum can be visualized as consisting of three main parts. The portion containing wavelengths longer than about 580 nm includes all the reddish light; wavelengths between 490 and 580 nm contain greenish light; and wavelengths shorter than 490 nm include all the bluish light. The full range of colors can be produced from a beam of white light by varying the proportions of the reddish, greenish, and bluish parts independently.

Visible Electromagnetic Radiation

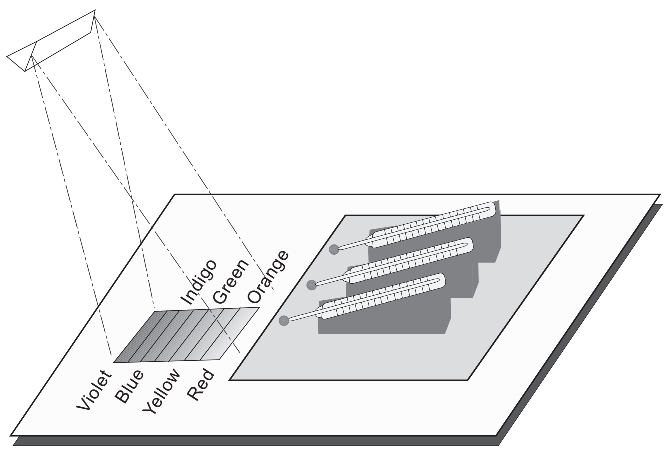
6.1



Wavelength (nm)		Apparent Color
400-430	400-490 bluish	Violet
430-475		Blue
475-510	490-580 greenish	Cyan
510-560		Green
560-590		Yellow
590-620	580-700 reddish	Orange
620-700		Red

Discovery of Infrared

6.2



Sir William Herschel (1738–1822)

There are two methods used to reproduce color:

- additive color formation using the additive primaries

  blue
  green
  red

- subtractive color formation using the subtractive primaries

  cyan
  magenta
  yellow

These six primary colors are only points on the continuum of spectral colors, but they are the compliments of one another (Figure 6.3).

6.4 Color Formation Exercise

Objective. Predict the color that common earth-surface features will form in both a (R, G, B) true-color composite and a (NIR, R, G) false-color composite.

Materials. Ten generalized spectral reflectance curves and a glossary of color terms; three color composites of a Landsat TM scene extract from the vicinity of Manaus, Brazil.

One of the complicating factors which inhibits our understanding of the false-color rendition of landscape targets is the nearly unlimited number of subtle reflectivity differences in the various wavelengths which can, and do, affect the appearance of the landscape on three-band digital displays. However, we must come to grips with at least a few "standard" color/target relationships if we expect to become proficient image interpreters.

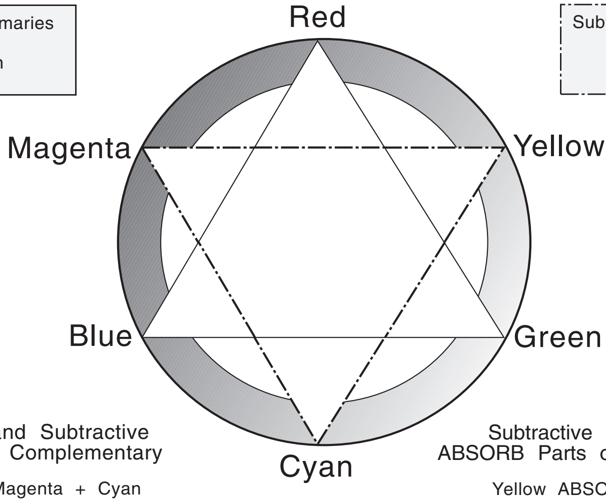
In the following exercise, you will gain experience in interpreting both true-color and false-color renditions of reflectance data. In order to maintain our perspective on multispectral reflectance, very generalized spectral reflectance curves in the wavelength range of 0.4 to 0.9 μm are presented. These curves simulate real objects, but their identity is not labeled in order that, for the present, we may concentrate solely

Color Formation

6.3

Additive Primaries
Blue
Green
Red

Subtractive Primaries
Yellow
Magenta
Cyan



Additive and Subtractive Colors are Complementary

Blue = Magenta + Cyan
Green = Yellow + Cyan
Red = Yellow + Magenta
Yellow = Red + Green
Magenta = Blue + Red
Cyan = Blue + Green

Subtractive Primaries ABSORB Parts of White Light

Yellow ABSORBS Blue

Magenta ABSORBS Green

Cyan ABSORBS Red

on spectral reflectance without reference to other image interpretation clues (e.g. texture, pattern, association or location).

In order to simplify reality, this exercise assumes that reflectance exists only in one of four magnitudes. These are shown on the Y-axes of the graphs as **L** - very little reflectance, **M** - moderate reflectance, **H** - high reflectance or **VH** - very high reflectance. Four bands will be considered on the x-axes:

Blue band: 0.4 - 0.5 µm

Green band: 0.5 - 0.6 µm

Red band: 0.6 - 0.7 µm

NIR band: 0.7 - 0.9 µm

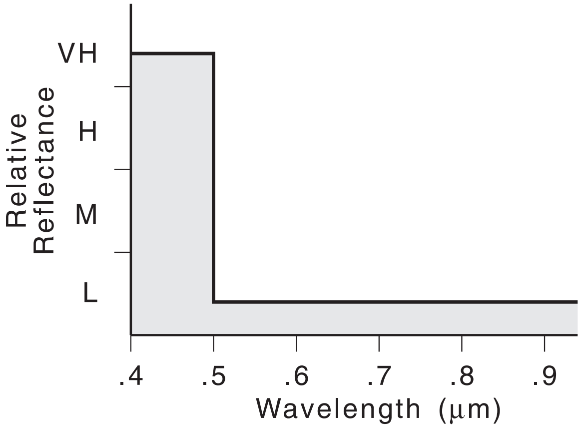
Any three of these four bands may be displayed on either the red (**R**), green (**G**) or blue (**B**) channels of a computer color display. If we assign Red, Green and Blue bands, respectively, to the R, G, B color space we can make a true-color composite. The "standard" false-color composite (one that simulates the appearance of a color infrared airphoto, is made be displaying the NIR, Red and Green bands, respectively, on the R, G, B display channels.

For the band numbering scheme of Landsat TM and ETM+, the true-color composite is the 3,2,1; the "standard" false-color composite (FCC) is a 4,3,2; and a popular high-contrast composite is the 5,4,3. For the SPOT HRVIR, no true color composite can be made directly from the available bands since no blue reflectance is measured. The HRVIR "standard" FCC is the 3,2,1, while the high-contrast FCC is the 4,3,2.

Your task is to record the relative amount of reflectance in each band in the spaces provided to the right of each graph. Make a mental judgement of the color that this arrangement will form in the two cases (i.e. the true-color composite and the "standard" FCC). Then consult the color glossary provided at the end of the exercise to see what the correct answer is, based on the relative amounts of Red, Green and Blue light in the display. All correct answers are contained in the glossary, but not all glossary entries are correct answers for this exercise.

Write the color name beneath the R,G,B column for each composite.

Question 1.



TRUE COLOR

(R) ____________

(G) ____________

(B) ____________

____
Display Color

ST'D FCC

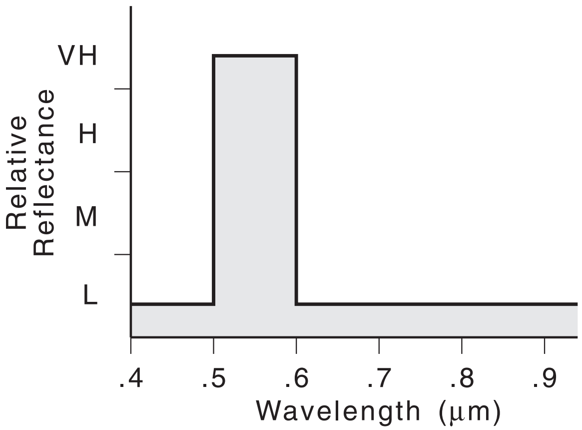
(R) ____________

(G) ____________

(B) ____________

____
Display Color

Question 2.



TRUE COLOR

(R) ____________

(G) ____________

(B) ____________

____
Display Color

ST'D FCC

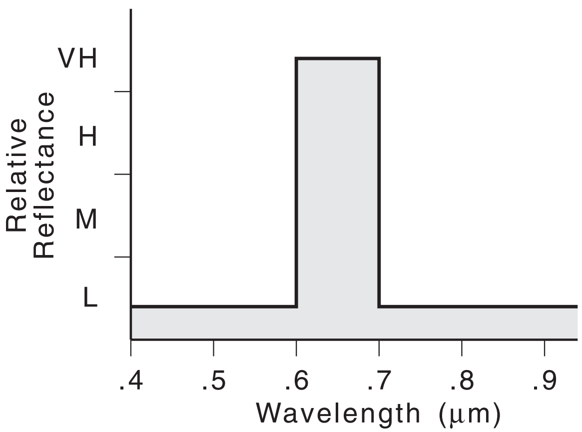
(R) ____________

(G) ____________

(B) ____________

____
Display Color

Question 3.



TRUE COLOR

(R) ____________

(G) ____________

(B) ____________

____
Display Color

ST'D FCC

(R) ____________

(G) ____________

(B) ____________

____
Display Color