Geo/SAT 2

REMOTE SENSING: LANDSAT PROGRAM

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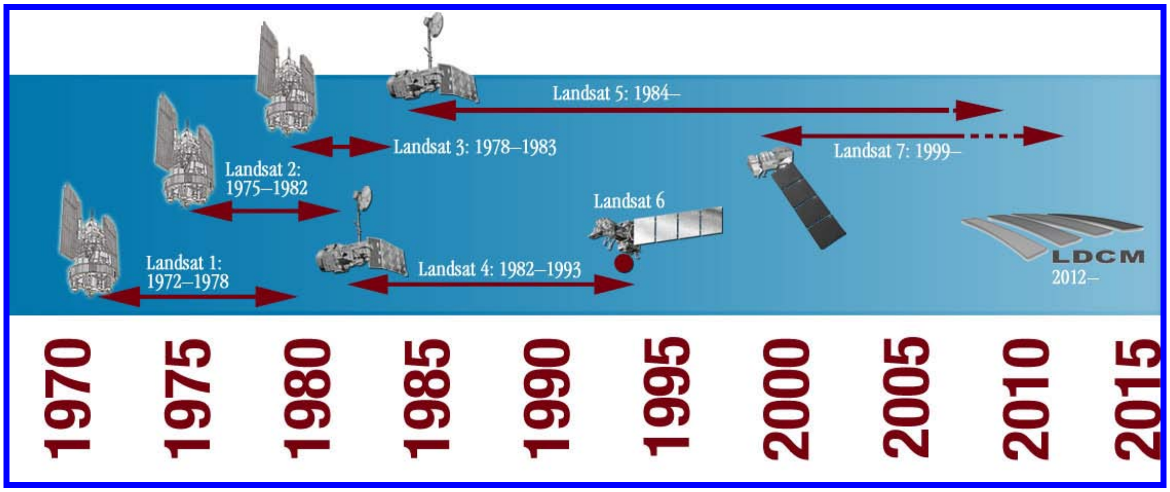


FIGURE 1: Landsat Timeline.

The Landsat program offers the longest continuous global record of the Earth's surface (Figure 1). It continues to deliver visually stunning and scientifically valuable images of our planet. In 1975, NASA Administrator Dr. James Fletcher predicted that if one space age development would save the world, it would be Landsat and its successor satellites. Since the early 1970s, Landsat has continuously and consistently archived images of Earth; this unparalleled data archive gives scientist the ability to assess changes in Earth's landscape.

"It was the granddaddy of them all (other satellite systems), as far as starting the trend of repetitive, calibrated observations of the Earth at a spatial resolution where one can detect man's interaction with the environment," Dr. Darrel Williams, the Landsat 7 Project Scientist, states about Landsat.

Landsat sensors have a moderate spatial-resolution. One cannot see individual houses on a Landsat image, but one can see large man-made objects such as highways. This is an important spatial resolution because it is coarse enough for regional coverage, yet detailed enough to characterize human-scale processes such as urban growth.

"The Landsat program was created in the United States in the heady scientific and exploratory times associated with taming the atom and going to the Moon," explains Dr. John Barker. In fact, it was the Apollo Moon-bound missions that inspired the Landsat program. During the early test bed missions for Apollo, photographs of Earth's land surface from space were taken for the first time. "This photography has been documented as the stimulus for Landsat," explains Dr. Paul Lowman, who proposed the terrain photography experiment for the last two Mercury missions, the Gemini missions, and the Apollo 7 and 9 missions.

In 1965, director of the U.S. Geological Survey (USGS), William Pecora, proposed the idea of a remote sensing satellite program to gather facts about the natural resources of our planet. Pecora stated that the program was “conceived in 1966 largely as a direct result of the demonstrated utility of the Mercury and Gemini orbital photography to Earth resource studies.” While weather satellites had been monitoring Earth’s atmosphere since 1960 and were largely considered useful, there was no appreciation of the Earth’s surface from space until the mid-1960s.

When Landsat 1 was proposed, it met with intense opposition from the Bureau of Budget and those who argued high-altitude aircraft would be the fiscally responsible choice for Earth remote sensing. Concurrently, the Department of Defense feared that a civilian program such as Landsat would compromise the secrecy of their reconnaissance missions. Additionally, geopolitical concerns existed pertaining to photographing foreign countries without permission. In 1965, NASA began methodical investigations of Earth remote sensing using instruments mounted on planes. In 1966, the USGS convinced the Secretary of the Interior, Stewart L. Udall, to announce that the Department of the Interior (DOI) was going to proceed with its own Earth-observing satellite program. This savvy political stunt coerced NASA to expedite the building of Landsat. But, budgetary constraints and sensor disagreements between application agencies (notably the Department of Agriculture and DOI) again stymied the satellite construction process. Finally, by 1970 NASA had a green light to build a satellite. Remarkably, within only two years, Landsat 1 was launched, heralding a new age of remote sensing of land from space.

LANDSATS 1-3

Landsat 1

Landsat 1 was launched on July 23, 1972 (Figure 2). Initially the satellite was known as the Earth Resources Technology Satellite (ERTS). It was the first Earth-observing satellite to be launched with the express intent to study and monitor our planet’s landmasses. To perform the monitoring, Landsat 1 carried two remote sensing instruments: a camera system built by the Radio Corporation of America (RCA) called the Return Beam Vidicon (RBV), and the Multispectral Scanner (MSS) built by the Hughes Aircraft Company. The RBV was supposed to be the prime instrument, but the MSS data were found to be superior. In addition, the RBV instrument was the source of an electrical transient that caused the satellite to briefly lose altitude control. It became necessary to shut down the RBV instrument in order to maintain the operation of the satellite. Only a small number of images were recorded using the RBV.

FIGURE 2: Landsat 1 Satellite

The MSS instrument was flown as the secondary and highly experimental instrument. “But once we looked at the data, the roles switched,” relates Stan Freden, Landsat 1

Project Scientist. In the foreword of the U.S. Geological Survey's "ERTS-1 A New Window on Our Planet," published in 1976, then-director of the USGS, Dr. V. E. McKelvey, wrote: "The ERTS spacecraft represent the first step in merging space and remote-sensing technologies into a system for inventorying and managing the Earth's resources." Landsat 1 operated until January 1978, outliving its design life by five years. The Landsat 1 MSS system acquired over 300,000 images providing repeated coverage of the Earth's land surfaces. The quality and impact of the resulting information exceeded all expectations.

Landsat 2

Landsat 2 was launched on January 22, 1975 (Figure 3), two and a half years after Landsat 1. The second Landsat was still considered an experimental project and was operated by NASA. Landsat 2 carried the same sensors as its predecessor: the RBV and the MSS systems. The RBV instrument was primarily used for engineering evaluation purposes and RBV imagery was obtained, mainly for cartographic uses in remote areas. The MSS continued to systematically collect images of Earth. Despite having a design life of one year, Landsat 2 operated for over seven years. Finally in 1982 it was decommissioned.

FIGURE 3: Landsat 2 – Artist's View

Landsat 3

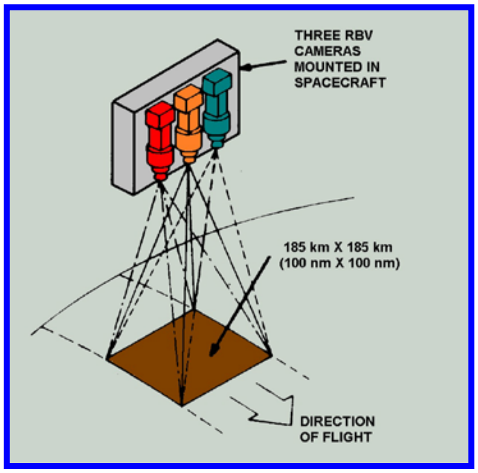
Landsat 3 was launched on March 5, 1978 (Figure 4), three years after Landsat 2. The third Landsat was still considered an experimental project and was operated by NASA until 1979. Because of the Landsat program's technical and scientific success, it was declared operational in 1979 and operational responsibility shifted from NASA (a research and development agency) to the National Oceanic and Atmospheric Administration (NOAA), the agency charged with operating the weather satellites.

FIGURE 4: Landsat 3 in the cleanroom

Landsat 3 carried the same sensors as its predecessor: the RBV and the MSS systems. However, the RBV instrument had an improved 30 m ground resolution and used two RCA cameras which both imaged in one broad spectral band (green to near-infrared; 0.505–0.750 µm) instead of three separate bands (green, red, infrared) like its predecessors.

The MSS continued to systematically collect images of Earth using four spectral bands. A fifth band, thermal infrared, was also part of the Landsat 3 MSS, but this band failed shortly after launch. In March of 1983, Landsat 3 was decommissioned.

RETURN BEAM VIDICON



The RBV camera system was designed to obtain high resolution television pictures of the Earth. Three cameras were used to take pictures simultaneously in three different spectral bands. The cameras were similar except for the spectral filters contained in the lens assemblies to provide separate spectral regions. Camera 1 covered the visible blue-green portion of the spectrum, Camera 2 the visible orange-red portion, and Camera 3 the red-near-infrared portion. They were designated Bands 1-3.

FIGURE 5: Three RBV Camera System

The three RBV cameras on Landsats 1 and 2 were aligned to view the same square ground area (Figure 5). The three Earth-oriented cameras were mounted on a common base, structurally isolated from the spacecraft to maintain accurate alignment. When the cameras were shuttered, the images were stored on the RBV photosensitive surfaces, and then scanned to produce video signal output. Video data from the RBV were transmitted in both real-time and tape-recorder modes.

On Landsat 3, two RBV cameras were used (Figure 6). The two cameras provided side-by-side images. Each camera operated independently allowing for single frame or continuous coverage. They each had the same broad-based spectral range (yellow to near IR) at 505 to 750 nanometers. These changes were made to provide increased ground resolution for mapping the Earth surface.

The RBV camera systems on Landsats 1-3 failed to perform successfully and created electronic operational problems for the satellites. The RBV systems were not used again.

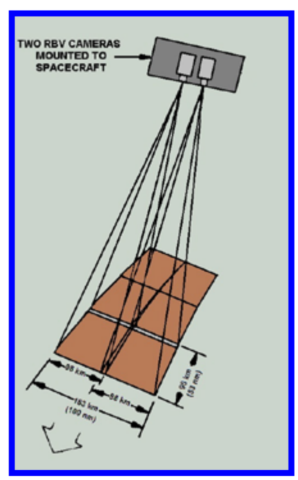


FIGURE 6: Two RBV Camera System

MULTISPECTRAL SCANNER

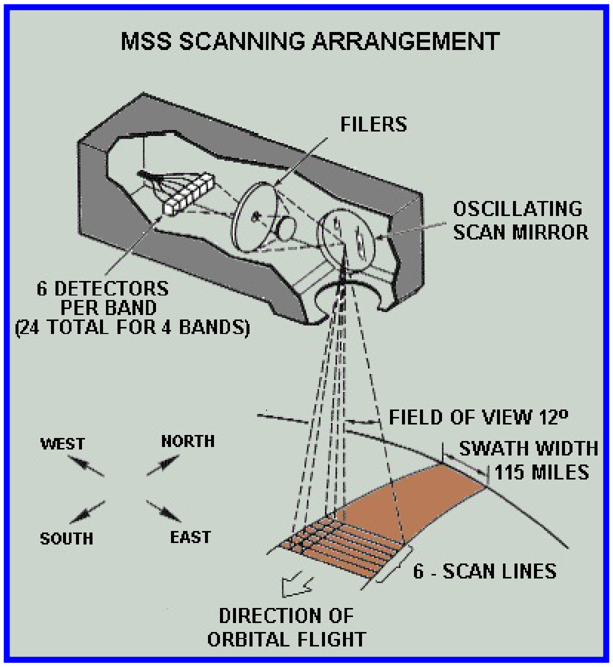


FIGURE 7: Multispectral Scanner System

The MSS sensor (Figure 7) was a line scanning devices observing the Earth perpendicular to the orbital track. The cross-track scanning was accomplished by an oscillating mirror; six lines were scanned simultaneously in each of the four spectral bands for each mirror sweep (Figure 8). The forward motion of the satellite provided the along-track scan line progression.

The first five Landsats carried the MSS sensor which responded to Earth-reflected sunlight in four spectral bands. On Landsats 1-3 these bands were numbered 4-7 since the three RBV bands were 1-3 (Table 1). On Landsats 4-5 the MSS bands were identified as 1-4. Landsat 3 carried an MSS sensor with an additional band, designated band 8, that responded to thermal (heat) infrared radiation.

An MSS scene had an Instantaneous Field Of View (IFOV) of 68 meters in the cross-track direction by 83 meters in the along-track direction (223.0 by 272.3 feet respectively). To understand this concept, consider a single, rectangular ground point that is 68 by 83 meters in size. The scan monitor sensor ensures that the cross-track optical scan is 185 km (115 mi.) at nominal altitude regardless of mirror scan nonlinearity or other perturbations of mirror velocity.

Crosstrack image velocity was nominally 6.82 meters (22 ft.) per microsecond. After 9.958 microseconds, the 83 by 83 meter image has moved 67.9 meters. The sample taken at this instant represented 15 meters (49 ft.) of previous information and 68 meters (223 ft.) of new information.

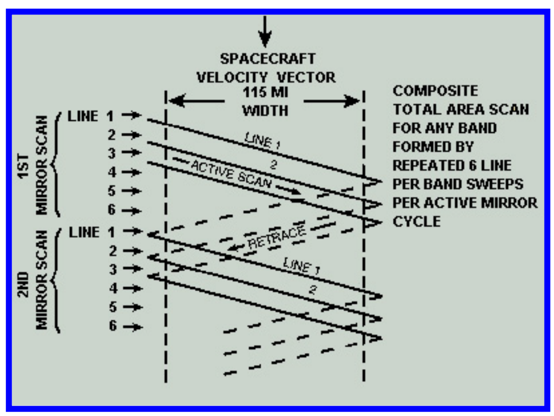


FIGURE 8: Scan Track Direction

Therefore, the effective IFOV of the MSS detector in the cross-track direction was considered to be 68 meters which corresponds to a nominal picture element (pixel) ground area of 68 by 83 meters at the satellite nadir point. Using the effective IFOV in area calculation eliminates the overlap in area between adjacent pixels.

Table 1: Landsats 1-3 RBV and MSS Specifications.

Satellite	Sensor	Band No.	Wavelength (µm)	Geo. Resolution
Landsats 1-2	RBV	1	0.48 to 0.57	80 x 80m
		2	0.58 to 0.68	80 x 80m
		3	0.70 to 0.83	80 x 80m
	MSS	4	0.50 to 0.60	56 x 79m
		5	0.60 to 0.70	56 x 79m
		6	0.70 to 0.80	56 x 79m
		7	0.80 to 1.10	56 x 79m
Landsat 3	RBV	1	0.505 to 0.75	40 x 40m
	MSS	4	0.50 to 0.60	56 x 79m
		5	0.60 to 0.70	56 x 79m
		6	0.70 to 0.80	56 x 79m
		7	0.80 to 1.10	56 x 79m
		8	10.4 to 12.6	240 x 240m

The radiometric resolutions on the first three Landsats MSS bands 1-3 were 0-127 or 128 discrete numerical levels. The resolution on the fourth band was 0-63 or 64 levels. With respect to a computer byte, a resolution of 0-127 required only 7 bits of an 8-bit byte. A resolution of 0-63 took 6 bits. During this period a byte of 8 bits was not the computer industry standard. In fact, the industry dominated by large mainframe companies such as IBM and Univac vacillated between a 7-bit byte and a 9-bit byte.

LANDSATS 4-5

Landsat 4

Landsat 4 was launched on July 16, 1982 (Figure 9). The Landsat 4 spacecraft was significantly different than that of the previous Landsats. First, it did not carry the RBV instrument. Second, in addition to the MSS sensor, Landsat 4 carried a new scanning sensor with improved spectral and spatial resolution. The new scanner could see a wider (and more scientifically-tailored) portion of the electromagnetic spectrum and could view the ground in greater detail. This new scanner was known as the Thematic Mapper (TM).

FIGURE 9: Landsat 4

The Landsat 4 TM instrument had seven spectral bands. Data were collected from the blue, green, red, near-infrared, mid-infrared (2 bands) and thermal infrared portions of the electromagnetic spectrum.

Within a year of launch, Landsat 4 lost the use of two of its solar panels and both of its direct downlink transmitters. So, the downlink of data was not possible until the Tracking and Data Relay Satellite System (TDRSS) became operational; Landsat 4 could then transmit data to TDRSS using its Ku-band transmitter and TDRSS could then relay that information to its ground stations.

When Landsat 5 became operational, Landsat 4's functional Ku-transmitter was limited to downloading acquired international data via the TDRSS. This arrangement continued until 1993, when Ku-band transmitter also failed on Landsat 4. Landsat 4 was kept in orbit for housekeeping telemetry command and tracking data (which it downlinked via a separate data path, known as the S-band) until it was decommissioned in 2001.

Landsat 5

On March 1, 1984, NASA launched Landsat 5, the agency's last originally mandated Landsat satellite. Landsat 5 was designed and built at the same time as Landsat 4 and carried the same payload: the MSS and TM sensors.

In 1987, the Landsat 5 TDRSS transmitter (Ku-band) failed. This failure made downlinking data acquired outside of the U.S. data acquisition circle (i.e., range of U.S. ground receiving antennas) impossible; Landsat 5 has no on-board data recorder to record acquired data for later downlink.

The MSS instrument was turned off in August of 1995. The TM instrument is still in operation, nearly three decades after its planned design life. Data are regularly acquired at stations in the U.S. and Australia for entry into the U.S. archive. A number of International Ground Stations download data for their local acquisition area.

In November 2005, Landsat 5 TM operations were suspended after problems with the solar array left the satellite unable to properly charge its on-board batteries. Working together, USGS and NASA engineers were able to devise a new method of solar array operations. And, on January 30, 2006 Landsat 5 resumed normal operations.

THEMATIC MAPPER

The Thematic Mapper (TM) is an advanced, multispectral scanning, Earth resources sensor designed to achieve higher image resolution, sharper spectral separation, improved geometric fidelity and greater radiometric accuracy and resolution than the MSS sensor. TM data are sensed in seven spectral bands simultaneously (Table 2). Band 6 senses thermal (heat) infrared radiation. Landsat can only acquire night scenes in band 6. A TM scene has an Instantaneous Field Of View (IFOV) of 30 square meters in bands 1-5 and 7 while band 6 has an IFOV of 120 square meters on the ground. The TM radiometric resolution is 0-255 or 256 discrete numerical levels. The MSS instruments on both Landsat 4 and 5 also have radiometric resolutions of 0-255.

Table 2: Landsats 4-5 MSS and TM Specifications.

Sensor		Band No.	Wavelength (µm)	Geo. Resolution
MSS	Green Visible	1	0.50 to 0.60	82m
	Red Visible	2	0.60 to 0.70	82m
	Near IR	3	0.70 to 0.80	82m
	Near IR	4	0.80 to 1.10	82m
TM	Blue Visible	1	0.45 to 0.52	30m
	Green Visible	2	0.52 to 0.60	30m
	Red Visible	3	0.63 to 0.69	30m
	Near IR	4	0.76 to 0.90	30m
	Mid IR	5	1.55 to 1.75	30m
	Thermal IR	6	10.4 to 12.5	120m
	Mid IR	7	2.08 to 2.35	30m

Landsats 1-3 were designed mainly to determine if satellites could provide an effective means for observing, measuring, and analyzing conditions on the Earth's surface. Emphasis was placed on developing a successful operating system that involved putting a stable platform in space, testing and evaluating two different remote sensing instruments, and downloading the imagery from the instruments. Less emphasis was given to selecting the spectral and spatial characteristics of the bands. Once Landsat 1 became operational, NASA provided imagery to several hundred scientists throughout the world. The imagery came mainly from the MSS system and included not only digitally based photographs but also the digital data downloaded from the system. These scientists, representing a wide range of disciplines, were to evaluate how effective the imagery might be in studying the Earth. To deal with the digital data, they needed to develop software that would allow the enhancement of the data, mathematically combining data from two or more bands, and classifying statistically the data. This evaluation process was done during a time when mainframe computers dominated the digital world and computer graphics were barely known. The main graphics output device of the time was the line printer, which was good for printing numerical reports but very crude with respect to displaying imagery. Within the context of this environment, the scientists started identifying better spectral band levels and ranges and better spatial (geometric) resolution to study the Earth. This work culminated in the designing the Thematic Mapper.

Table 3 identifies the main tasks that each band is especially adept at doing. These spectral bands were selected after reviewing the work done by the scientific community. Emphasis was placed on detecting various vegetation and water conditions.

Table 3: TM Spectral Band Applications.

Band	Principal Applications
1	Coastal Water Mapping, Soil Vegetation Differentiation, Deciduous/Coniferous Differentiation
2	Green Reflectance by Healthy Vegetation
3	Chlorophyll Absorption for Plant Specifies Differentiation
4	Biomass Surveys, Water Body Delineation
5	Vegetation Moisture Measurement, Snow Cloud Differentiation
6	Plant Heat Stress Measurement, Other Thermal Mapping
7	Hydrothermal Mapping

Additionally, having the three visible bands, Bands 1-3, allowed for true color composites to be generated, something not possible with the MSS bands. With true color composites one could compare what the human eye would normally see versus what the eye would view in the various false color combinations. Band 6, thermal infrared, recorded emitted energy in comparison to the other bands that dealt with reflected energy. Band 6 not only provided a different energy condition but allowed for nighttime recording of the Earth’s surface. It also brought about other applications such as separating fire from smoke in forest fires, measuring urban heat loss, and detecting evapotranspiration conditions over irrigated agricultural fields. The TM’s higher spatial resolution provided by the reflective bands has aided significantly in picking out features whose minimum dimension is usually on the order of 30 m (98 ft). Thus, TM imagery can often discern large buildings, not detectable in MSS imagery.

LANDSATS 6-7

Landsat 6

On October 5, 1993 Landsat 6 (Figure 10) failed at launch after not reaching the velocity necessary to obtain orbit. The satellite did not achieve orbit because of a ruptured hydrazine manifold. The separation from the booster rocket occurred properly; however, the ruptured rocket fuel chamber prevented fuel from reaching the apogee kick motor. This failure resulted in the spacecraft tumbling instead of accumulating enough energy to reach its planned orbit.

Landsat 6 carried an Enhanced Thematic Mapper (ETM). The ETM sensor would have collected data in the same seven spectral bands and at the same spatial resolutions as the TM instrument on Landsats 4 and 5. The ETM instrument also included an eighth band with a spatial resolution of 15 m. The eighth band was known as the sharpening band or panchromatic band. It was sensitive to light from the green through near infrared wavelengths of the electromagnetic spectrum. The MSS system was discontinued after Landsat 5.

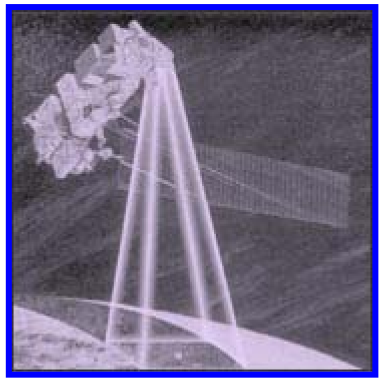


FIGURE 10: Landsat 6 – Artist's View

Landsat 7

Landsat 7 was successfully launched on April 15, 1999 from the Western Test Range of Vandenberg Air Force Base, California. The Earth observing instrument on Landsat 7, the Enhanced Thematic Mapper Plus (ETM+) (Figure 11), replicates the capabilities of the highly successful Thematic Mapper instruments on Landsats 4 and 5. The ETM+ also includes additional 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. These features are: 1.) a panchromatic band with 15m spatial resolution, 2.) on-board, full aperture, 5% absolute radiometric calibration, 3.) a thermal IR channel with 60m spatial resolution, and 4.) an on-board data recorder.

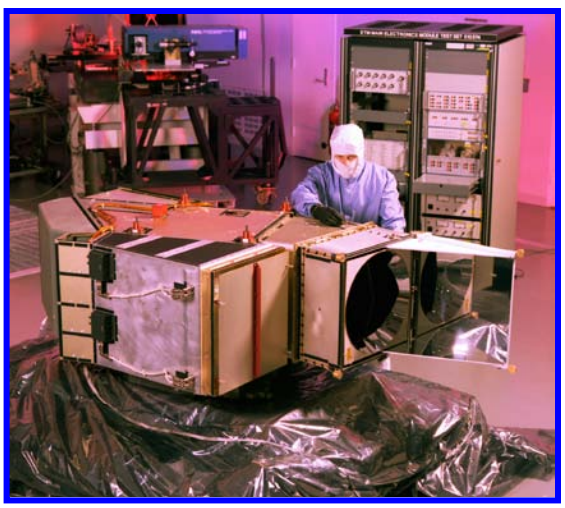


FIGURE 11: Engineer with the Landsat 7 ETM+ instrument.

Table 4: Landsat 7 ETM+ Specifications.

Sensor		Band No.	Wavelength (µm)	Geo. Resolution
ETM+	Blue Visible	1	0.45 to 0.52	30m
	Green Visible	2	0.52 to 0.60	30m
	Red Visible	3	0.63 to 0.69	30m
	Near IR	4	0.76 to 0.90	30m
	Mid IR	5	1.55 to 1.75	30m
	Thermal IR	6	10.4 to 12.5	60m
	Mid IR	7	2.08 to 2.35	30m
	Panchromatic	8	0.50 to 0.90	15m

Landsat 7 is a well calibrated Earth-observing satellite, i.e., its measurements are extremely accurate when compared to the same measurements made on the ground. Landsat 7's sensor has been called "the most stable, best characterized Earth observation instrument ever placed in orbit." Landsat 7's rigorous calibration standards have made it the validation choice for many coarse-resolution sensors.

The Landsat 7 mission went flawlessly until May 2003 when a hardware component scan line corrector (SLC) failure left wedge-shaped spaces of missing data on either side of Landsat 7's images. Six weeks after suffering the loss of SLC, the ETM+ resumed its global land survey mission resulting in only a short suspension of its imagery acquisitions for the U.S. archive.

However, the malfunction has impacted the imagery of Landsat 7. Specifically, the ETM+ optics contain the Scan Mirror and SLC assembly among other components. The Scan Mirror provides the across-track motion for the imaging, while the forward velocity of the spacecraft provides the along-track motion. The SLC assembly is used to remove the "zigzag" motion of the IFOV produced by the combination of the along- and across-track motion. Without an operating SLC, the ETM+ line of sight now traces a zigzag pattern across the satellite ground track.

In this SLC-Off mode, the ETM+ still acquires approximately 75 percent of the data for any given scene. The gaps in data form alternating wedges that increase in width from the center to the edge of a scene. The remainder of the ETM+ sensor, including the primary mirror, continues to operate, radiometrically and geometrically, at the same high-level of accuracy and precision as it did before the anomaly; therefore, image pixels are still accurately geolocated and calibrated.

To fulfill the expectations of the user community for full coverage single scenes, data from multiple acquisitions are being merged to resolve the SLC-off data gaps. In all cases, a binary bit mask is provided so that the user can determine where the data for any given pixel originated. The USGS is continuing to research other methods of providing better merged data products, and will continue to provide information resulting from this work as it becomes available.

LANDSAT DATA CONTINUITY MISSION

The Landsat Data Continuity Mission (LDCM), a collaboration between NASA and the U.S. Geological Survey, will provide moderate-resolution (15 m–100 m, depending on spectral frequency) measurements of the Earth's terrestrial and polar regions in the visible, near-infrared, mid infrared, and thermal infrared. LDCM will provide continuity with the 38-year long Landsat land imaging data set. In addition to widespread routine use for land use planning and monitoring on regional to local scales, support of disaster response and evaluations, and water use monitoring, LDCM measurements directly serve NASA research in the focus areas of climate, carbon cycle, ecosystems, water cycle, biogeochemistry, and Earth surface/interior. The LDCM is scheduled to become operational in 2012.

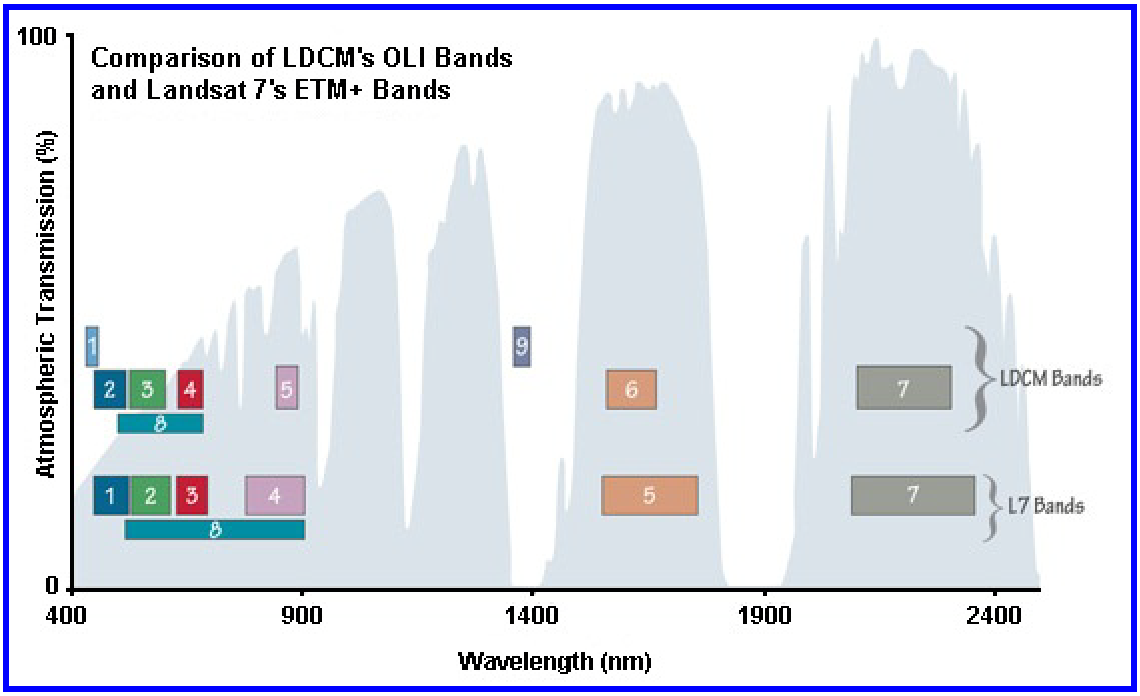


FIGURE12: Comparison of OLI and ETM+ Bands

The LDCM satellite payload will consist of two science instruments—the Operational Land Imager (OLI) and the Thermal InfraRed Sensor (TIRS). These two sensors will provide seasonal coverage of the global landmass at a spatial resolution of 30 meters (visible, NIR, MidIR); 100 meters (thermal); and 15 meters (panchromatic). The spectral coverage and radiometric performance (accuracy, dynamic range, and precision) are designed to detect and characterize multi-decadal land cover change in concert with historic Landsat data. Coordinated calibration efforts of USGS and NASA will again be part of the LDCM calibration strategy. The LDCM scene size will be 185-km-cross-track-by-180-km-along-track. The nominal spacecraft altitude will be 705 km. Cartographic accuracy of 12 m or better (including compensation for terrain effects) is required of LDCM data products. LDCM includes evolutionary advances in technology and performance. The OLI provides two new spectral bands, one tailored especially for detecting cirrus clouds and the other for coastal zone observations, and the TIRS will collect data for two more narrow spectral bands in the thermal region formerly covered by one wide spectral band on Landsats 4–7. Additionally, LDCM is required to return 400 scenes per day to the USGS data archive (150 more than Landsat 7), increasing the probability of capturing cloud-free scenes for the global landmass.

The Operational Land Imager (OLI) (Figure 13) is being built by the Ball Aerospace and Technologies Corporation. The Ball contract was awarded in July 2007. OLI improves on past Landsat sensors using a technical approach demonstrated by a sensor flown on NASA's experimental EO-1 satellite. OLI is a push-broom sensor with a four-mirror telescope and 12-bit quantization. OLI will collect data for visible, near infrared, and mid infrared spectral bands as well as a panchromatic band. It has a five-year design life. Figure 12 compares the OLI spectral bands to Landsat 7's ETM+ bands.

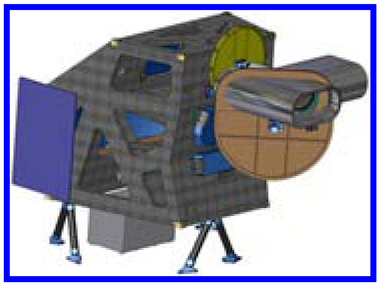


FIGURE 13: Operational Land Imager

The OLI will collect data for two new bands, a coastal band and a cirrus band, as well as the heritage Landsat multispectral bands. Additionally, the bandwidth has been refined for six of the heritage bands. The Thermal Instrument (TIRS) will carry two additional bands (not shown in Figure 14).

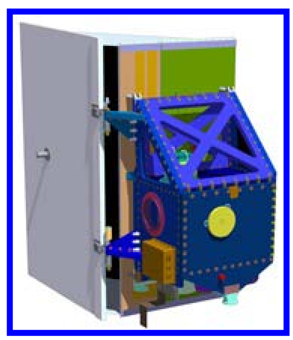


FIGURE 14: Thermal InfraRed Sensor

The Thermal InfraRed Sensor (TIRS) (Figure 14) was added to the LDCM payload to continue thermal imaging and to support emerging applications such as evapotranspiration rate measurements for water management. TIRS is being built by NASA GSFC and it has a three-year design life. The 100 m TIRS data will be registered to the OLI data to create radiometrically, geometrically, and terrain-corrected 12-bit (0-4095) LDCM data products.

ORBIT

Landsats 1-3 moved in an almost perfectly circular orbit at the altitude of 917 km (570 mi.) inclined at 98.2^{o} relative to a plane passing through the Equator (Figure 16). This near polar orbit was also sun-synchronous, crossing the Equator on the day side of the Earth 14 times each day at approximately 9:45 a.m. local time in each transit. Each successive orbit shifted westward 2875 km (1785 mi.) at the Equator. On the following day the next 14 orbits paralleled those on the previous day but each orbit was offset westward by about 159 km (99 mi.). Images obtained for any two adjacent orbits showed about 7 percent sidelap at the Equator. This sidelap increased to about 84 percent near the poles (Figure 15). All parts of a large land mass such as a continent could be imaged during the succession of shifted orbits in a cycle lasting 18 days. Thus, in principle, any area could have been imaged every 18 days, but in practice, cloud cover usually reduced the coverage to some simple multiple of 18, which depended on geographic location and time year (a typical case in the eastern United States would have been 54 days, but this varied with season).

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

FIGURE 15: Image Sidelap of Adjacent Swaths.

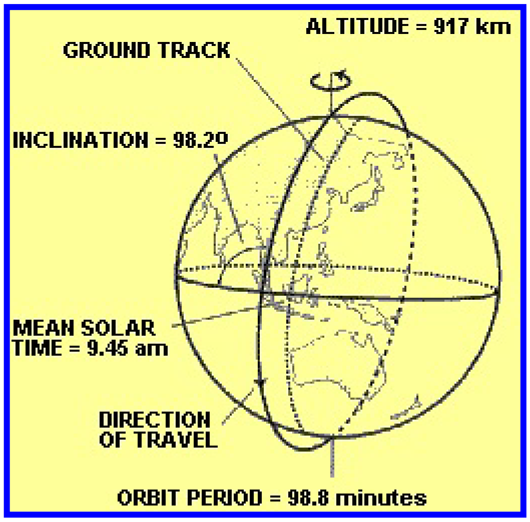


FIGURE 16: Landsat Orbit.

WORLDWIDE REFERENCE SYSTEM

The Worldwide Reference System (WRS) (Figure 17) is a global notation system for Landsat data. It enables a user to inquire about satellite imagery over any portion of the world by specifying a nominal scene center designated by PATH and ROW numbers. The WRS has proven valuable for the cataloging, referencing, and day-to-day use of imagery transmitted from the Landsat sensors.

The Landsat 1-3 WRS-1 notation assigns sequential path numbers from east to west to 251 nominal satellite orbital tracks, starting with number 001 for the first track which crosses the equator at 65.48 degrees west longitude. A specific orbital track can vary due to drift and other factors; thus, a path line is only approximate. The orbit is periodically adjusted after a specified amount of drift has occurred in order to bring the satellite back to an orbit that is nearly coincident with the initial orbit.

Row refers to the latitudinal center line of a frame of imagery. As the satellite moves along its path, the observatory instruments are continuously scanning the terrain below. The instrument signals are transmitted to Earth and correlated with telemetry ephemeris data to form individual framed images. During this process, the continuous data are segmented into individual frames of data known as scenes. Landsats 1-3 scene centers are chosen at approximately 25-second increments of spacecraft time in either direction from the equator with each scene equal to approximately 163 km (101 miles) on the Earth's surface plus about 10 percent in-track overlap (5 percent for Landsat 3) added by the ground processor. A total of 119 Landsats 1-3 daylight scenes are possible along one descending satellite path. A complete orbit of 6196 seconds, when divided by 25 seconds, yields 247.84 intervals; 248 scenes per complete orbit (descending and ascending) were selected as the standard.

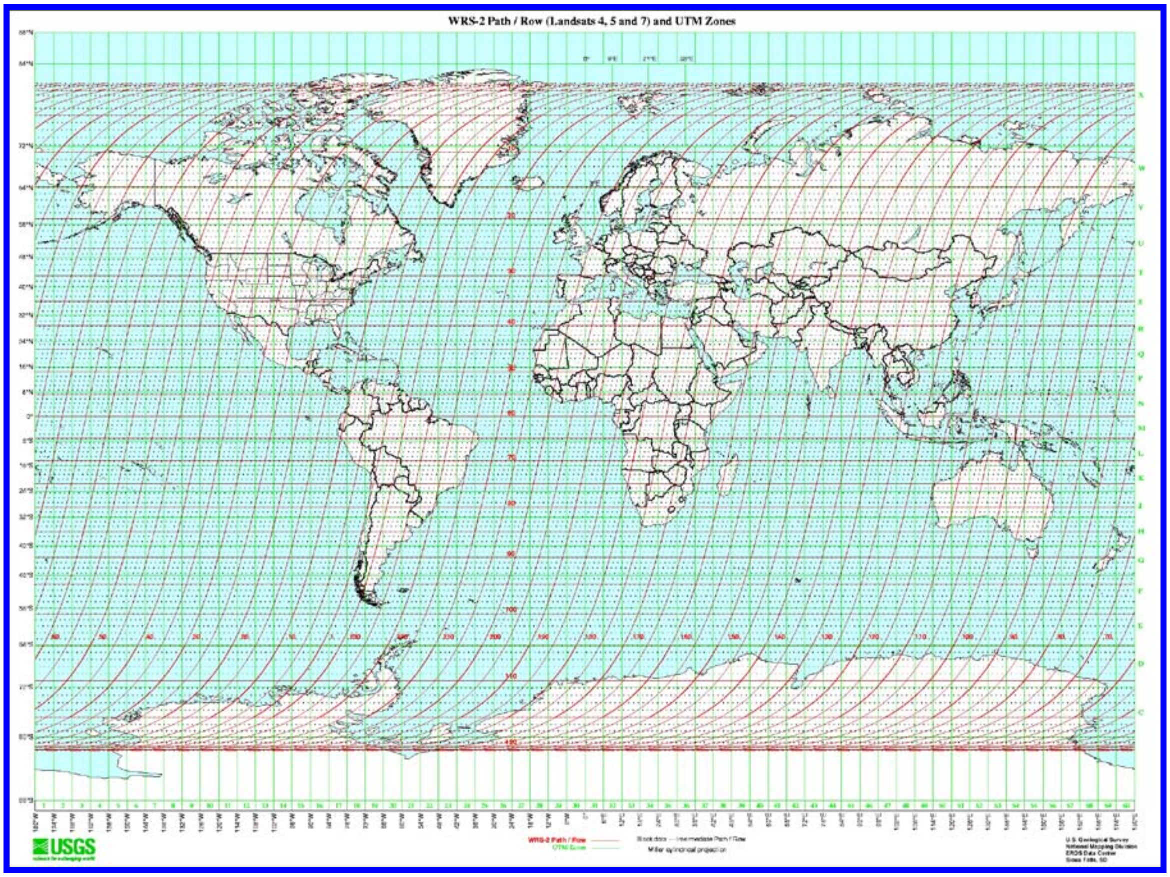


FIGURE 17: Worldwide Reference System-2 Map.

The framing is uniform for each orbit. The adjacent east-west scenes have scene center locations at the same nominal latitude. A notation of Row numbers can, therefore, be applied to identify all scenes occurring at the same latitude. Row 060 corresponds to latitude 0 (equator). Row 059 is immediately north of this, and the progression continues to latitude 80 degrees, 1 minute and 12 seconds north, which is Row 001. Row 119 is at latitude 80 degrees, 1 minute and 12 seconds south.

The combination of a Path number and a Row number uniquely identifies a nominal scene center (Figure 18). The Path number is always given first, followed by the Row number. The notation 127-043, for example, relates to Path number 127 and Row number 043.

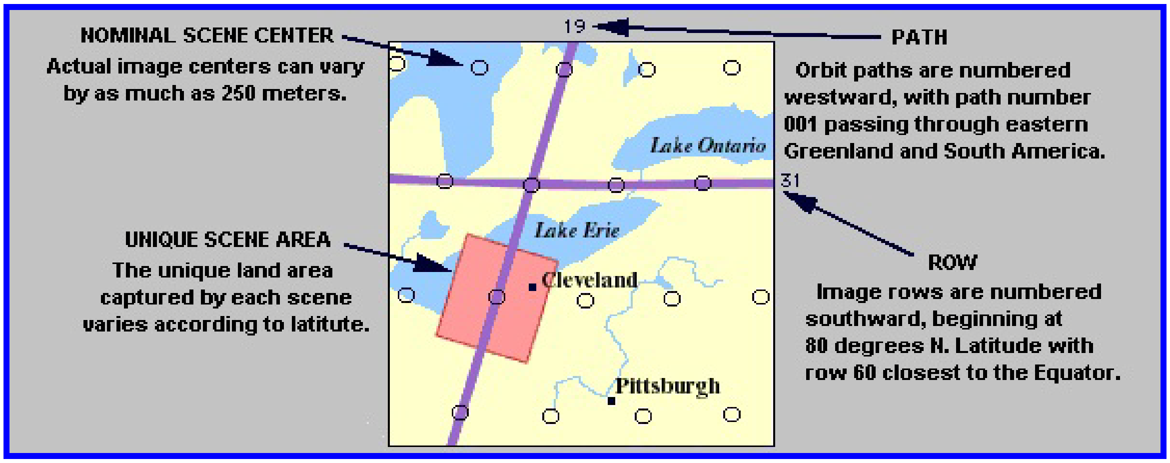


FIGURE 18: WRS Path/Row Numbering Scheme.

Landsats 1-3 orbital parameters cause each consecutive daily track to be shifted west 25.8 degrees of longitude at the equator, corresponding to 2872 km (1784 miles). Each succeeding day of Landsat 1-3 coverage overlapped the coverage of the preceding day. This constitutes one complete coverage cycle, consisting of 251 orbits, taking exactly 18 days and providing complete global coverage between 82 degrees north latitude and 82 degrees south latitude. The consecutive day sidelap resulted in a minimum of 14 percent at the equator to nearly 85 percent at extreme latitudes. A combination of data processing and orbital adjustment keep the error in the individual framed image centers of any geographical area on the Earth within 37 km (23 miles) in the across-track direction and 30 km (19 miles) in the along-track direction.

Landsats 4, 5 and 7 have Earth coverage similar to Landsats 1-3. However, the lower altitude results in a different swathing pattern. Landsat 5 and 7 (and Landsat 4 prior to its decommissioning) operate in a repetitive, circular, sun-synchronous, near-polar orbit at a nominal altitude of 705.3 km (438.4 miles) measured at the equator. The descending orbital node time is 9:45 AM +/- 15 minutes at the equator with an orbital period of 98.9 minutes, completing 14 9/16 orbits per day and viewing the entire Earth every 16 days. Each consecutive daily track is spaced 2752 km (1709 miles or 24.7 degrees) west of the previous orbit at the equator. Each succeeding day's track is shifted at the equator to the west 10.8 degrees of longitude corresponding to 1204 km (748 miles).

Coverage sidelap of adjacent orbits for the Landsat 4 and 5 MSS sensors are a minimum of 7.3 percent at the equator to nearly 84 percent at extreme latitudes (see table below). Successive orbits and framing operations are controlled to assure no more than 18 km (11 miles) variation in the across-track direction.

The Landsat 4, 5, and 7 Worldwide Reference System-2 (WRS-2) is an extension of the global Landsat 1 - 3 WRS-1 and utilizes an orderly Path/Row system in a similar fashion. There are, however, major differences in repeat cycles, coverage, swathing patterns and Path/Row designators due to the large orbital differences of Landsats 4 and 5 compared to Landsats 1 through 3.

The 16-day ground coverage cycle for Landsats 4 and 5 was accomplished in 233 orbits. Thus, for Landsats 4 and 5, 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.

SUPPLEMENT READINGS

Jenson, John R. 2007. *Remote Sensing of the Environment: An Earth Resource Perspective.* Person Prentice Hall.

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Sabins Jr., Floyd F, 1978. *Remote Sensing: Principles and Interpretation.* W. H, Freeman and Company.