The Present and Future of the Landsat Program

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ABSTRACT

The Landsat 7 satellite system was designed to operate in a manner that will substantially advance the application of remote land observations to global change research. The Enhanced Thematic Mapper-Plus (ETM+) sensor aboard the spacecraft currently acquires multispectral digital image data of the Earth's land surfaces on a routine basis. The quality of the ETM+ data is excellent, meeting or improving upon pre-launch specifications. The data are transmitted to a globally distributed set of ground stations including the primary U.S. ground station at the U.S. Geological Survey EROS Data Center in Sioux Falls, South Dakota.

The U.S. Government manages the Landsat 7 satellite system A major program objective is to create an ETM+ data archive at the EROS Data Center that provides global coverage of the Earth's continental and coastal surfaces on a seasonal basis. These data are available on a non-discriminatory basis at the incremental cost of fulfilling a user request. Once purchased from the EROS Data Center, no restrictions are placed on subsequent distribution of the data. This strategy fosters the operational applications of ETM+ data while advancing studies of the Earth as a system.

- Landsat, remote sensing, Earth system science

1. INTRODUCTION

Routine civilian observations of the Earth's land areas from space began with the launch of the first Landsat satellite in 1972. The years since have seen a slow but steady increase in the launch of satellite systems used for land observations. These systems included: the following four Landsat satellites; the Landsat-like *Systeme Probatoire d'Observation de la Terre* (SPOT) and Indian Remote Sensing (IRS) satellites; the Japanese Earth Resources Satellite-1 (JERS-1), Radarsat-1, and European Remote Sensing-1 (ERS-1) satellites with synthetic aperture radars; and the NOAA Polar-orbiting Operational Environmental Satellites with the Advanced Very High Resolution Radiometer (AVHRR) sensors. Promise of a new era in land remote sensing arose in the early 1990's as NASA initiated development of its Earth Observing System (EOS) of multiple satellites and private firms announced plans for the launch of the first completely commercial remote sensing satellites. The new era is expected to bring a proliferation of data for applications and science. Realization of the promise has just begun with recent launches of the commercial IKONOS satellite by Space Imaging on September 24, 1999, the EOS Terra satellite on December 18, 1999, and the Landsat 7 satellite on April 15, 1999. Today seems an opportune time to examine the present and future role of the Landsat satellite systems in this new era.

2. BACKGROUND

The Landsat program has wandered a twisted path since 1972. Landsat 1 was developed by the National Aeronautic and Space Administration (NASA) as an experimental system for research into Earth observations from space. The value of the data from Landsat 1, particularly the digital image data acquired by the Multispectral Scanner System (MSS), quickly became apparent for a broad range of applications and scientific investigations. Landsat evolved in practice from an experimental program to an operational program as NASA developed and launched Landsat 2 in 1975 and Landsat 3 in 1978, both with MSS sensors. During these years, NASA and the Department of the Interior shared responsibility for acquiring and distributing the MSS data in the U.S. The three satellites also transmitted MSS data to international ground receiving stations, sharing the data with much of the world.

The Carter Administration recognized the evolution of the Landsat program when it issued a presidential directive in 1979. The directive transferred responsibility for operating the Landsat satellites from NASA, a research and development agency, to the National Oceanic and Atmospheric Administration (NOAA), the agency responsible for weather satellite operations within the Department of Commerce. Although satellite operations transferred to NOAA, NASA retained responsibility for building and launching Landsat 4 and Landsat 5. Each of these satellites carried an advanced sensor, a Thematic Mapper (TM), in addition to an MSS. The TM sensors provided data at a better spatial resolution (30m for the TM compared to 80m for the MSS) and provided data for additional spectral bands (seven TM bands compared to four MSS bands) located more carefully over the visible, near infrared, shortwave infrared, and thermal regions of the spectrum. NASA launched Landsat 4 in 1982 and Landsat 5 in 1984. The presidential directive also recommended that Landsat system development and operations should utltimately be shifted to the private sector.

The Reagan Administration and Congress followed through on the Carter Administration recommendation, perhaps more rapidly than originally envisioned. Concern over the costs of the Landsat program and deliberations on the appropriate role of government in remote sensing led Congress to pass the Land Remote-Sensing Commecialization Act of 1984 (P.L. 98-365)[1]. This Act authorized the commercial operation of the Landsat satellites under contract to NOAA and with subsidies from the U.S. Government. Following a solicitation and competitive bidding process, NOAA selected the Earth Observation Satellite Company (EOSAT) to operate Landsat 4 and Landsat 5 under a ten year contract. The contract granted EOSAT the exclusive rights to market Landsat 4 and Landsat 5 data up to 10 years after the date of data acquisition. EOSAT also received the fees from the international ground stations receiving Landsat data. The contract also assigned EOSAT the responsibility for building, launching, and operating the following two Landsat satellites with government subsidization.

Some difficulties ensued in the following years of commercial Landsat operations. EOSAT's control over the conditions of data sales were constrained by provisions in the 1984 Act[2]. EOSAT could only sell unenhanced Landsat data to protect the value added vendors and could not provide favorable prices to selected customers in order to ensure nondiscriminatory access to the data. To compensate, EOSAT substantially increased Landsat data prices and severely restricted the redistribution of the data by their customers. Scientists and educators found the data difficult to impossible to afford for research and teaching. Data sales to academic institutions dropped dramatically[3]. Government subsidization of satellite operations also became uneven and uncertain in the late 1980's. Landsat 4 and Landsat 5 operations were close to termination on several occasions as operating budgets were expended[2]. Last minute budget adjustments were required to save the satellites. Additional disagreements between EOSAT, the Administration, and Congress delayed funding for next Landsat satellites[2]. The decision to fund development of Landsat 6 and only Landsat 6 was delayed until 1987. The delay led NOAA and EOSAT to plan for a 1992 launch of Landsat 6, five years beyond the three-year design life of Landsat 5.

Meanwhile, other governments launched Landsat-like remote sensing satellites and began to sell the data commercially. The French *Centre National d'Etudes Spatiales* (CNES), in partnership with Sweden and Belgium, launched the first SPOT satellite in 1986 and has subsequently launched SPOT-2 (1990), SPOT-3 (1993), and SPOT-4 (1998). The Indian Space Research Organization (ISRO) has launched five Indian Remote Sensing (IRS) satellites beginning in 1988. By 1989, revenue from the sale of SPOT data by its commercial distributor, SPOT Image, exceeded the revenue from Landsat data sales by EOSAT[3].

These problems raised concerns about the future of the Landsat program as a commercial enterprise. The concerns led the Bush Administration to release National Space Policy Directive #5 on February 05, 1992. The Directive instructed DoD and NASA to begin development of a government-owned and government-operated Landsat 7 mission. The instructions, initiatives, and goals of the Directive were enacted into law when the Land Remote Sensing Policy Act of 1992 (P.L. 102-555) was passed and signed in October, 1992.

The 1992 Act identified the continuity of Landsat data as the fundamental goal of the legislation. To that end, the Act assigned the Administrator of NASA, the Secretary of Defense, and other government officials designated by the President to "Landsat Program Management." The Act directed this group to create a management plan, assume responsibility for the Landsat Program from the Department of Commerce, procure the Landsat 7 satellite system, conduct a technology demonstration program, and assess options for a successor land remote sensing system[1]. The Act also mandated the delivery of data to all users at no more than the incremental cost of fulfilling a user request.

Landsat Program Management was restructured several times during the development of the Landsat 7 system. Initially, the Department of Defense (DoD) took responsibility for procuring and launching the Landsat 7 satellite while NASA accepted responsibility for developing the ground system for data acquisition, archival, processing and distribution[1]. DoD proceeded

in December, 1992, to contract with GE Astro (later Martin Marietta Astro Space and now Lockheed Martin Missiles and Space) for the build and launch of the Landsat 7 spacecraft with an Enhanced Thematic Mapper Plus (ETM+) sensor and an option for a second sensor called the High Resolution Multispectral Imager (HRMSI). This arrangement did not last. The costs associated with accommodating HRMSI on the spacecraft and building a ground system capable of receiving data from both the ETM+ and HRMSI became an issue between DoD and NASA[2]. The issue was exacerbated by the failure of the Landsat 6 satellite to achieve orbit when launched in September, 1993. As a result, DoD asked to withdraw from Landsat Program Management in December, 1993[1,2].

The DoD request led to a reorganization of Landsat Program Management as specified in a presidential decision directive (PDD) from the Clinton Administration, PDD/NSTC-3 dated May 5, 1994. The directive transferred responsibility for building and launching Landsat 7 to NASA, left NASA responsible for developing the ground system, and assigned NOAA the responsibility of operating the spacecraft and ground system after launch with the cooperation of the Department of Interior U.S. Geological Survey (DoI/USGS) for data archival and distribution. DoD transferred the spacecraft contract with Martin Marietta Astro Space to NASA. NASA dropped HRMSI as a payload option and took direct responsibility for the ETM+ development contract with Hughes Santa Barbara Remote Sensing (now Raytheon Santa Barbara Remote Sensing). The NASA Goddard Space Flight Center (GSFC) was assigned management of the NASA responsibilities and the USGS EROS Data Center was designated as the principal U.S. facility for receiving, archiving, and distributing Landsat 7 ETM+ data.

The NASA/NOAA/USGS partnership remained in effect almost until the launch of Landsat 7. During 1998, however, USGS and NOAA mutually agreed that the collection of information on the land surface was more closely aligned with the mission of the USGS. USGS accepted the transfer of responsibility for post-launch satellite and ground system operations from NOAA. A letter signed by NASA, NOAA, and the USGS was sent to the President's National Science and Technology Council on November 18, 1998, to request approval.

Despite the many twists and turns in the history of program management, the Landsat program remains viable, even robust. Landsat 7 was successfully launched on April 15, 1999, and is currently providing unprecedented coverage of the earth's land surfaces. Landsat 5 continues to acquire TM data 16 years after its launch and 13 years beyond its three year design life. The current program is productively adding to the longest record of land surface observations from space.

3. CURRENT LANDSAT PROGAM MANAGEMENT

Landsat Program Management has evolved into a partnership between NASA and the USGS. The Director of the USGS and the Associate Administrator for Earth Sciences, NASA, recently signed a "Management Plan for the Landsat Program," dated December 01, 1999. The plan lays out the management structure shown in Figure 1. Landsat Program Management sits at the top of the structure at the level of the NASA Administrator and the Secretary of the Department of Interior. A Landsat Coordinating Group exists under the authority of Landsat Program Management to coordinate budget, policy, and program management at the level of the Director of the USGS and the NASA Associate Administrator of Earth Sciences. The Landsat Coordinating Group is responsible for resolving inter-agency issues. The USGS currently funds and manages ETM+ data reception, archival, processing, and distribution as well as coordination of the international ground station operators. NASA currently manages and funds the Landsat 7 Mission Operations Center (MOC) and flight operations team at the NASA GSFC. This NASA center is responsible for the health, safety, and daily operation of the spacecraft until the USGS assumes responsibility for the MOC on October 01, 2000. Formal Approval of this plan by the National Science and Technology Council is pending but is expected shortly.

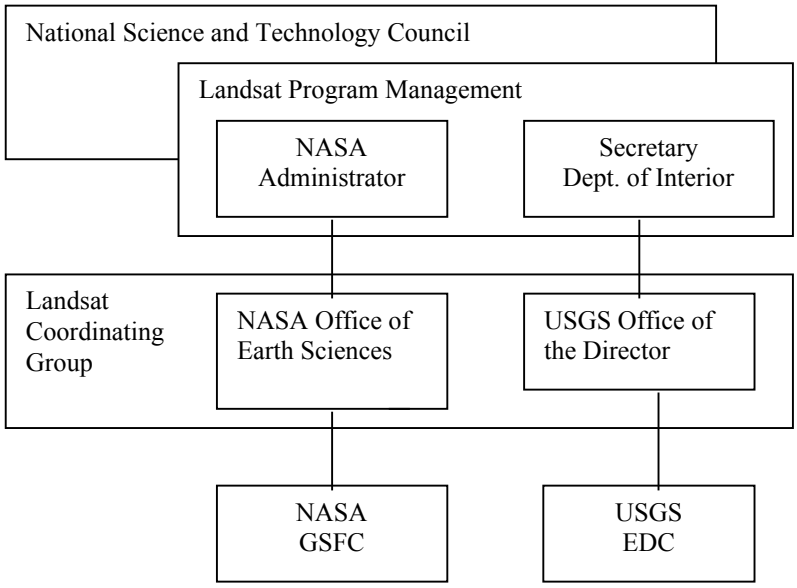

Figure 1. Landsat Program Management Structure

4. STATUS OF THE LANDSAT 5 MISSION

Landsat 5 remains in commercial operation. Space Imaging, with headquarters in Thorton, Colorado, acquired EOSAT in 1996 and took over the extended contract with NOAA for Landsat 4 and Landsat 5 operations. NOAA is in the process of formally transferring contract management to the USGS in accordance with the current Landsat Program Management structure. The contract allows Space Imaging to operate Landsat 4 and Landsat 5 at no cost to the government until the demise of the satellites and to retain data distribution rights up to five years beyond termination of operations[4]. Landsat 4 ceased acquiring data in August, 1993, due to failures of the onboard data transmitters, but the satellite is maintained in orbit. Landsat 5 continues to acquire TM data and to directly down link data to ground receiving stations through a single X-band transmitter remaining in operation. The longevity of the Landsat 5 TM and its satellite platform is truly remarkable and has preserved Landsat data continuity through the loss of Landsat 6 and on to the launch of Landsat 7.

Landsat 5 directly transmits TM data in real time to ground receiving stations distributed between 17 nations. The Space Imaging station is located in Norman, Oklahoma, and is capable of receiving TM data acquired over the coterminous U.S. and parts of Canada and Central America. The other stations are operated by international cooperators, principally national government agencies and institutions, that pay Space Imaging an annual fee for data reception and distribution rights. Each international station determines its own data distribution policies, its own data formats and storage media, its own data processing and archival practices, and its own data prices[4].

The Landsat 5 system no longer affords complete coverage of the global land surface. Each receiving station can only receive data acquired by the TM while the satellite is within view of the station's antenna. Landsat 5 carries no data storage device for the delayed transmission of data acquired outside of a stations acquisition circle. Landsat 5 does carry an antenna for transmitting data to the Tracking and Data Relay Satellite System (TDRSS), but the transmitter for this antenna failed in July, 1992. While the Landsat 5 antenna was operational, the TDRSS system could relay TM data acquired over any point on the globe back to the U.S. Since the failure, the Space Imaging station has only captured data acquired within its acquisition circle and a number of areas, including Alaska, Hawaii, central Africa, and Siberia, have lacked TM coverage due to an absence of local ground receiving stations.

5. ACCESS TO MSS AND TM DATA

The historical record of Landsat MSS and TM data is distributed between the USGS EROS Data Center, Space Imaging, and the international ground stations. The data archived within the U.S. are divided between the commercial firm, Space

Imaging, and the government facility, the EROS Data Center. Space Imaging's predecessor, EOSAT, relinquished its rights to the exclusive distribution of MSS data in February, 1993[4]. MSS data were transferred to the National Satellite Land Remote Sensing Data Archive (NSLRSDA) within the EROS Data Center where the digital data are currently provided at $200 per scene for scenes geometrically corrected without ground control (systematically corrected). NSLRSDA holds over 630,000 MSS scenes acquired from the first five Landsat satellites between 1972 and 1992[4]. A portion of these scenes are not currently accessible as the data remain stored on out-dated wideband video tapes. The EROS Data Center is currently engaged in a wideband video tape conversion project to transfer the data to modern, accessible, storage media.

Space Imaging retains the exclusive right to distribute TM data less than 10 years old to the general public at commercial prices under the in-force extension of the Landsat operations contract with NOAA. The contract extension also allows for the distribution of TM data less than 10 years old from the NSLRSDA to the U.S. government and its affiliated users at the incremental cost of fulfilling a user request. Those qualifying as U.S. government and affiliated users include U.S. Government agencies, government contractors, those involved in the U.S. Global Change Research Program, and other investigators with a cooperative agreement with the U.S. Government involving the use of TM data for non-commercial purposes[4]. Those falling within these categories require a certification from the EROS Data Center to obtain data at the incremental cost. After 10 years Space Imaging loses its exclusive data distribution rights and transfers 10 year old TM data to the EROS Data Center. The NSLRSA distributes 10 year old TM data to the general public at the incremental cost of fulfilling a user request and with no restrictions on sharing or otherwise redistributing the data. In both cases, the incremental cost is set to $475 for a systematically corrected TM scene archived by NSLRSDA. If a TM scene less than 10 years old has not previously been transferred to the NSLRSDA, the U.S. government affiliated user first requesting the scene must also pay an access fee. Space Imaging provides the scene to NSLRSDA on a high density archive tape containing multiple scenes and the access fee will equal $70 times the number of scenes on the archive tape[4]. NSLRSDA current archives over 440,000 TM scenes acquired between 1982 and the present from both the Landsat 4 and Landsat 5 satellites (Russ Johnson, EROS Data Center, personnel communication).

Both Space Imaging and the EROS Data Center provide World Wide Web based clients that allow customers to search their MSS and TM data archives, browse images, and order data via the internet. The EROS Data Center is in the process of migrating access to the data from an older client, the Global Land Information System (GLIS), to a new client, the Earth Explorer. Both organizations support their web sites with telephone access to customer service personnel . Table 1 provides contact information for the customer service desks and the web sites for both organizations.

Table 1. Contact Information for Space Imaging and the EROS Data Center

Space Imaging	EROS Data Center
12076 Grant St. Thornton, CO 80241	Customer Services U.S. Geological Survey EROS Data Center 47914 252nd Street Sioux Falls, SD 57198-0001
1-301-552-0537 1-800-232-9037	Tel: 800-252-4547 Tel: 605-594-6151 TDD: 605-594-6933 Fax: 605-594-6589 Email: custserv@edcmail.cr.usgs.gov
http://www.spaceimaging.com/search/ca.htm	http://edc.usgs.gov/webglis http://earthexplorer.usgs.gov

MSS and TM data archived by the international ground stations must be accessed either directly or indirectly from the stations. Draeger et al. provide a list of stations with their postal addresses, e-mail addresses, phone numbers, and web site URL's, where available[4]. Space Imaging and the EROS Data Center will both help customers access data from the international ground stations, but customers remain subject to the various prices, policies, and data formats of the different stations.

The Landsat Program legitimately claims the longest record of global land observations from space. The record, however, is terribly fragmented as the data are distributed amongst the international ground station operators, Space Imaging, and the

NSLRSDA at the EROS Data Center. Landsat data for long term or large scale investigations becomes exceedingly difficult to access and exploit. Investigators typically need to obtain MSS or TM data from different stations, ingest data in different formats and stored on different media, understand discrepancies in the calibration and data processing, and pay commercial prices. This situation creates a data processing overhead that is daunting and that has hindered multiple scene analyses of MSS and TM data. The Landsat 7 mission is being conducted in a manner that substantially reduces this overhead.

6. THE LANDSAT 7 MISSION

6.1. The Landsat 7 Mission Objectives

The Landsat 7 satellite system was designed and developed to meet the objectives of a global survey mission. These objectives stem from several considerations[5]. First, the Land Remote Sensing Act of 1992 identified Landsat data continuity as the fundamental goal of the Landsat 7 mission and defined continuity as data that are "sufficiently consistent (in terms of acquisition geometry, coverage characteristics, and spectral characteristics) with previous Landsat data to allow comparisons for global and regional change detection and characterization." Next, the NASA Earth Science Enterprise requires Landsat data to monitor and characterize global land cover and land use change as component of its Earth Observing System. Finally, the 28 year heritage of continuous Landsat operations has created a broad and diverse constituency of people who rely on Landsat data for a wide range of applications. This constituency includes people from the commercial, academic, government agency (federal, state, and local), national security, and international communities.

To meet the requirements of the Act, the Earth Science Enterprise, and the constituency of data users, the Landsat 7 satellite system is currently acquiring and archiving ETM+ data that provide global coverage of the Earth's continental and coastal areas on a seasonal basis. The data are entirely consistent with the TM data from Landsat 4 and Landsat 5 in terms of spectral bands and spatial resolution. Further, the ETM+ data are of high quality and are well calibrated with respect to radiometry and image geometry. Additionally, Landsat 7 is flying in formation with the EOS Terra satellite to afford near-coincident coverage of land areas from an array of sensors. Further details on the satisfaction of mission objectives are provided below.

6.2 Landsat 7 System Overview

Full appreciation of the Landsat 7 mission requires an end-to-end system perspective. Figure 2 depicts the major components of the satellite system and their interfaces. The heart of the system is the Landsat 7 satellite with its ETM+ payload. Command and control of the satellite are performed by the flight operations team within the Mission Operations Center (MOC) at NASA Goddard Space Flight Center. Daily command loads from the MOC, relayed through the Landsat Ground Network antennas, schedule ETM+ data acquisition, data storage on an on-board solid-state recorder, and data transmission to a number of U.S.-operated and international ground receiving stations. The primary U.S. station is located at the USGS EROS Data Center in Sioux Falls, South Dakota, along with the rest of the U.S. data processing system. ETM+ data received by U.S. stations are first run through the Landsat 7 Processing System (LPS). The LPS generates metadata, creates browse images, performs an automated cloud cover assessment, and packages the Level 0R (raw) ETM+ data in a format suitable for archival by the EDC Distributed Active Archive Center (DAAC), a node of the Earth Observation System Data Information System (EOSDIS). A Landsat 7 Image Assessment System (IAS) interfaces to the EDC DAAC to sample the ETM+ data for in-orbit calibrations and to asses the digital image data quality. Customers can search, browse, and order the ETM+ data stored in the EDC DAAC through a web-based client called the EOS Data Gateway (EDG), found at URL http://edcimswww.cr.usgs.gov/pub/imswelcome. Orders for Level 1 data products (radiometrically and geometrically corrected ETM+ data) are sent to the Level 1 Product Generation System (LPGS) where the corrections are performed. Level 1 data products are only generated on request and are not archived. Only the Level 0R ETM+ data remain in the EDC DAAC.

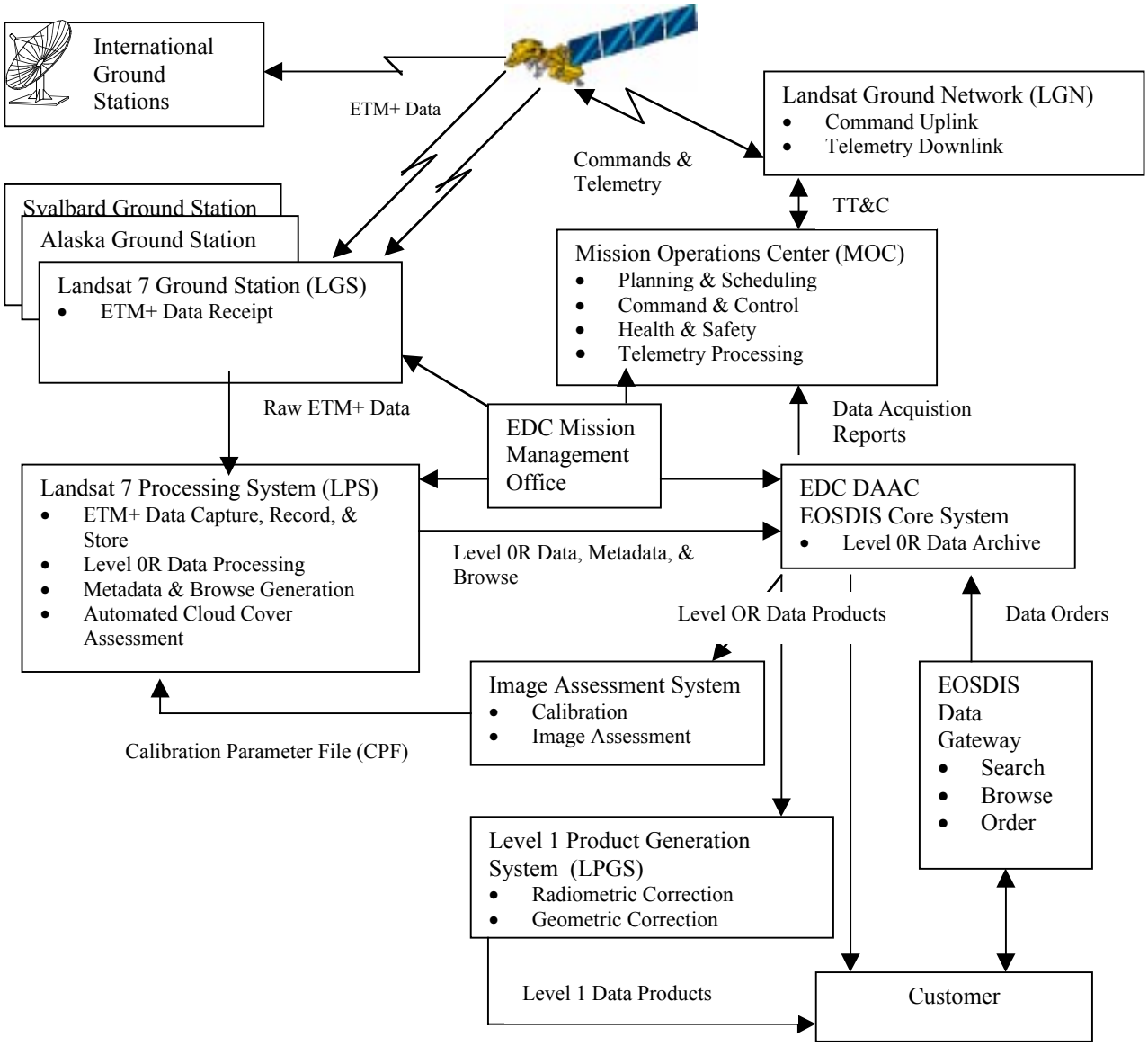

Figure 2. Schematic of the Landsat 7 Satellite and Ground System

6.3 The Landsat 7 Spacecraft and Its Orbit

The Landsat 7 spacecraft was built by Lockheed Martin Missiles and Space, Valley Forge, Pennsylvania, under contract to NASA. The spacecraft was launched on April 15, 1999, from Vandenberg Air Force Base, California, by a Boeing Delta II 7920-10 two-stage expendable launch vehicle. The spacecraft is 4.3 m long with a diameter of 2.8 m and a mass of approximately 2200 kg (Figure 3). The principal payload is the ETM+; all other spacecraft subsystems are there to keep this instrument in orbit and to provide for the acquisition and transmission of its data. In particular, the spacecraft carries a solid state recorder (SSR) with 378 gigabytes of memory. This amount of memory can concurrently hold 42 minutes of ETM+ data (approximately 100 scenes) and 29 hours of housekeeping telemetry. ETM+ data are transmitted via three directional X-band antennas where each antenna transmits at a rate of 150 Mbps. Each antenna can transmit data played back from the SSR or directly transmit ETM+ data in real time.

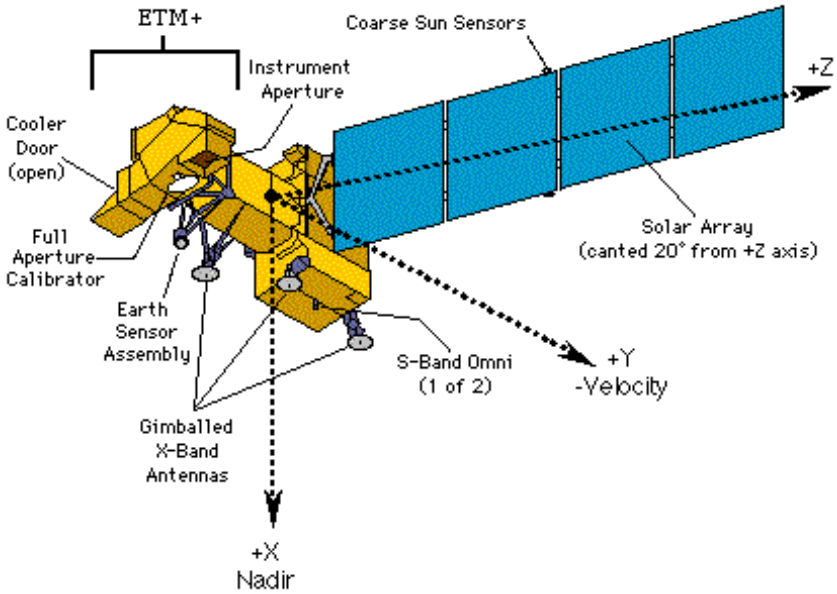

Figure 3. The Landsat 7 Spacecraft

Following launch, the satellite orbit was gradually adjusted until it reached the operational orbit. This orbit is circular and sun synchronous with an altitude of 705 km, an inclination of 98.2 degrees, and an equatorial crossing time of 10:00 a.m. in the descending node. The satellite requires 99 min to circle the Earth with each circle tracing a ground path that corresponds with a world wide reference system (WRS) of 233 ground paths. The satellite orbits over each of these paths once every 16 days in a repetitive cycle. The satellite will be maintained in this orbit for the life of the mission with periodic adjustments of its inclination and velocity. The Landsat 5 satellite is maintained in an orbit that follows the same sequence of 233 WRS paths, but the Landsat 7 satellite is situated eight days out-of-phase relative to Landsat 5. The Landsat 7 satellite first reached its operational orbit on June 29, 1999.

6.4 The Enhanced Thematic Mapper Plus (ETM+)

The ETM+ was built by Raytheon Santa Barbara Remote Sensing, Santa Barbara, California, under contract to NASA. The ETM+ design derives directly from the design of the TM sensors aboard Landsat 4 and Landsat 5 and the Enhanced Thematic Mapper (ETM) aboard the lost Landsat 6 satellite[6]. Like the earlier sensors, the ETM+ operates as a wiskbroom scanner and acquires data for the same seven visible, near infrared, shortwave infrared, and thermal infrared spectral bands (Table 2). The ETM+ ground sampling distance remains at 30 m for the reflective bands, but improves to 60 m for the thermal band (compared to 120 m for the TM thermal band). The ETM+ also acquires data for a new panchromatic band (Band 8) with a 15 m ground sampling distance. The ETM+ scans a 185 km cross-track swath as it travels along the orbital paths as do the TM sensors.

Table 2. ETM+ Spectral Bands

	1	2	3	4	5	6	7	8
Band Width (μm)	0.45 - 0.52	0.53 - 0.61	0.63 - 0.69	0.78 - 0.90	1.55-1.75	10.4 - 12.5	2.09 - 2.35	0.52 - 0.90
Ground Sampling Distance (m)	30	30	30	30	30	60	30	15

The ETM+ incorporates three devices for on-board radiometric calibration. An internal calibration lamp illuminates the ETM+ detectors at the end of each scan. A partial aperture calibrator reflects solar illumination off of reflective facets into the sensor aperture every orbit just prior to the sunrise terminator near the North Pole. In practice, the ETM+ data generated in response to the illumination from the partial aperture calibrator are captured once per day. A third device, the full aperture

calibrator, consists of a painted panel that is normally stowed out of the ETM+ field of view. Once every six weeks the panel is deployed into a position immediately in front of the ETM+ aperture obscuring the view of the Earth. In this position the panel diffusely scatters solar illumination into the ETM+ aperture as the Landsat satellite passes the sunrise terminator in the vicinity of the North Pole. The panel is retracted into its stowed position after the ETM+ data for the illuminated panel are acquired. In-flight radiometric calibration is based on the response of the ETM+ detectors to the illumination from these three devices. The Landsat 4 and Landsat 5 TM sensors incorporated only internal calibration lamps for in-flight calibration.

6.5 Landsat 7 Operations

The Landsat 7 satellite system is operated in a manner that leads to the population of the EDC archive with sun-lit, cloud-free, calibrated ETM+ data providing global coverage of the Earth's continental and coastal surface on a seasonal basis. The worldwide reference system (WRS) for TM and ETM+ data partitions the globe into a grid defined by the 233 orbital ground paths divided into 124 rows. The rows occur every 163 km along each path. TM and ETM+ data are divided into scenes where the scene centers are located at the path/row intersections. Each scene covers 185 km cross-track and 170 km along track. Overlap in coverage occurs between adjacent scenes, both along the paths and between the paths. The WRS thus divides the world into 28,892 path/row scenes. Approximately 14,000 of these scenes contain land. On any given day Landsat 7 passes over approximately 850 of those land scenes. Limits on satellite resources constrain ETM+ data acquisition to approximately 400 scenes per day. The EDC ground data processing system is capable of ingesting 250 scenes per day. The operational strategy for the Landsat 7 mission is to optimize the daily schedule of ETM+ data acquisition to achieve the desired global coverage.

The strategy for optimizing ETM+ data acquisition is referred to as the Long Term Acquisition Plan (LTAP)[7]. This Plan identifies those path/row scenes containing land, provides a monthly record of historical cloud cover for each land scene, specifies a solar zenith angle maximum (currently 85°) for data acquisition, and gives the dates within which each scene typically undergoes seasonal change. A scheduling algorithm uses the LTAP in conjunction with daily cloud cover forecasts from the NOAA National Centers for Environmental Protection (NCEP) to select scenes for acquisition on a daily basis[8]. The algorithm assigns a numerical priority to each scene within view on at given day. U.S. scenes within view are always selected for acquisition regardless of season or cloud cover. Consequently, the EDC archive captures each U.S. scene once every sixteen days. The remaining scenes are assigned priorities based on scene location, the cloud cover forecast relative to historical cloud cover, season, past success in acquiring ETM+ data for the scene, and solar zenith angle. Those scenes receiving the highest priority are selected for acquisition and archival at the EDC. Additional scenes are selected for acquisition and direct transition to international ground stations.

Given the selected scenes, the algorithm schedules the ETM+ on-times and off-times, the storage of data by the on-board solid state recorder (SSR), the subsequent playback of the data from the SSR, and the directed transmission of data to ground receiving stations by X-band telemetry. The data are currently transmitted to a total of 11 international ground stations and to three U.S.-operated stations: the primary U.S. station at EDC; a station near Fairbanks, Alaska; and a station in Svalbard, Norway. ETM+ data acquired over the coterminous U.S. are directly transmitted to EDC in real time and data acquired over Alaska are directly transmitted to the Alaska station. All other data selected for archival by the EDC are stored on the SSR and then played back and transmitted while the satellite is within range of one of the U.S.-operated stations. Data stored on the SSR are not transmitted to the other international ground stations. These international stations only receive data acquired and transmitted in real time while the satellite is within range of the stations. The flight operations team in the MOC implements the schedule for data acquisition, storage, playback, and transmission by writing commands that are transmitted to the Landsat 7 satellite once per day via S-band telemetry.

6.6 ETM+ Data Quality and System Performance

The performance of the Landsat 7 satellite system and the quality of ETM+ data have been monitored and evaluated since launch. The organizations conducting the monitoring and evaluation include: the EDC Mission Management Office and the Image Assessment System staff within the EDC Data Handling Facility; the NASA GSFC Earth Science Mission Office operating the Landsat 7 Mission Operations Center; and the GSFC Landsat Project Science Office. Analyses and evaluations indicate that the data quality is outstanding, particularly with respect to radiometry, image geometry and geographic registration, and repetitive coverage of the global continental and coastal regions.

6.6.1 Radiometry

The ETM+ detectors have demonstrated a stable radiometric response with low noise and few artifacts since launch. The radiometric response of each reflective band detector was calibrated pre-launch as a function of incident spectral radiance using the known and independently monitored illumination from an integrating sphere. The evaluation of radiometric stability since launch is based principally upon analyses of ETM+ data acquired with the full aperture calibrator (FAC) deployed. The stability of the FAC measurements has been within 3 % in all bands during the first six months on-orbit. Further, the spectral reflectance of the panel was measured before launch and when combined with knowledge of the absolute illumination from the sun, the FAC data are used to calculate on-orbit calibration coefficients for each ETM+ detector. These on-orbit coefficients have been consistent with the coefficients derived from the prelaunch observations of the integrating sphere. Consequently, the pre-launch calibration coefficients are currently used to radiometrically correct ETM+ data and generate the Level 1R and 1G data products.

The thermal band (Band 6) radiometric response has also been stable, but some evidence of a radiometric bias has been found. The thermal band detectors have shown changes of less than 0.5% based on the internal thermal calibration system. Comparisons to two ground-based calibration experiments indicate a consistent 0.3 W m^{-2} sr^{-1} μm^{-1} bias, with the ETM+ data indicating higher radiances than the ground measurements. This error corresponds in an approximately 3° C overestimation of surface temperature from the ETM+ thermal data. Efforts are underway to remove this bias from the calibration and correction of the Band 6 data (Brian Markham, NASA Landsat Calibration Scientist, personal communication).

FAC observations are also used to assess radiometric noise. These data indicate that for illumination near the middle of the detector dynamic ranges (low gain), the six reflective bands each have a signal-to-noise ratio greater than 100, a per-pixel total noise of less than ± 1 digital number (DN), and a per-pixel relative noise of better than ± 1 %. These values meet or exceed ETM+ specifications.

Radiometric artifacts are assessed using data acquired at the end of each ETM+ mirror scan in addition to FAC observations. An oscillating arm swings in front of the ETM+ focal planes at the end of each scan. The arm provides a shutter for the acquisition of dark current data as well as a pulse of illumination from an internal calibration lamp. These data indicate an absence of certain artifacts evident in data acquired by the earlier Thematic Mapper (TM) sensors aboard Landsat 4 and Landsat 5. The ETM+ data for the reflective spectral bands do not show the memory effects or scan correlated shifts seen in TM data. The ETM+ thermal band (band 6) data may have a small memory effect. Additionally, ice was known to form on the TM cold focal plane reducing the response of the TM cold focal plane detectors and requiring periodic outgassing of the sensors. The ETM+ was designed to prevent the icing and the on-orbit data show no evidence of reduced radiometric response. Thus, the radiometric response of the ETM+ detectors appears more stable and contains fewer artifacts in comparison to TM data.

6.6.2 Image geometry and geographic registration

Level 1G ETM+ data products are created by resampling the radiometrically corrected pixels of a Level 1R image. The object is to create ETM+ images that evince band-to-band registration, that enable precise image-to-image registration for multitemporal studies, and that are registered to user-selected cartographic projections for mapping. The Level 1 Product Generation System does not use ground control points to perform geometric correction. The system uses only the attitude data contained in the Landsat 7 Payload Correction Data files, satellite ephemeris from the NASA GSFC Flight Dynamics Facility, and the sensor, focal plane, and detector alignment parameters found in the Calibration Parameter File. The alignment parameters have been updated since launch by the Image Assessment System staff using ETM+ images of selected, well-mapped geometric calibration sites. The registration performed without ground control is referred to as systematic correction.

Level 1G products are routinely evaluated to assess registration accuracy. Geometric characterization of the on-orbit band-to-band registration shows a band average root-mean-square (rms) registration of better than ±0.10 of a 30-meter pixel when averaging the registration to all other bands, except coarse 60-meter Band 6 imagery. These band-to-band rms registration errors are random errors around zero once the systematic offsets are taken out by the geometric correction software The geodetic accuracy of the systematically corrected images is better than ± 50 meters, one sigma. If two systematically corrected ETM+ images from different dates are co-registered to a map reference, they can be expected to be registered to ± 5 meters, including uncompensated jitter and non-linearity. All of these geometric performance parameters are better than ETM+ specifications[9].

6.6.3 Geographic coverage

Routine ETM+ data acquisition began on June 29, 1999, following an initial on-orbit check-out period. As of April 28, 2000, the EDC archive has captured over 62,000 ETM+ scenes. The archive provides repetitive coverage the global land surfaces. The average cloud cover in an archived scene is 34% with 38% of the scenes containing less than 10% cloud cover. Those images containing less than 10% cloud cover represent over 74% of the global land surface. The provision of global, substantially cloud-free coverage in a single archive over such a short time period is unprecedented in the Landsat program. Additionally, over 50,000 ETM+ scenes have been transmitted from the spacecraft to 11 active International Ground Stations as of December 30, 1999. These Stations maintain independent data archives and independent data distribution policies. Each international ETM+ data archive provides only local region coverage.

6.7 The U.S. ETM+ Data Policy and Data Access

The Land Remote Sensing Policy Act of 1992 instructs Landsat Program Management to develop a data policy to "ensure that unenhanced data are available to all users at the cost of fulfilling a user request." The Act specifies that geometric and radiometric corrections of sensor data are preprocessing steps and do not constitute enhancements. The Act defines the cost of fulfilling a user request as the "incremental costs associated with providing product generation, reproduction, and distribution." A "Landsat-7 Data Policy," dated February 09, 2000, has been developed and signed by both the NASA Associate Administrator for Earth Science and the Director, U.S. Geological Survey. The Policy meets the mandates of the Act and ETM+ data are provided by the EDC in accordance with the Policy.

The EDC implements the data policy in the following manner. All users are able to search, browse, and order the ETM+ data archived at the EDC on a nondiscriminatory basis. EDC provides and maintains two web-based clients for ETM+ data searching, ordering, and browsing. The first client is the EOSDIS Data Gateway (EDG) developed for the EOSDIS and found at URL http://edcimswww.cr.usgs.gov/pub/imswelcome/. This client also allows users to search the archive of data products from other EOS spacecraft and sensors. The EDC has recently created a second client called the EarthExplorer at URL http://earthexplorer.usgs.gov/. This client provides access to all of the Landsat MSS, TM, and ETM+ data archived at the EDC.

Users can choose between three levels of ETM+ data. Level 0R ETM+ data products provide raw digital image data, metadata, and the ancillary files required to geometrically and radiometrically correct the raw data. The EDC currently charges $475 per scene for Level 0R data. Radiometric corrections are applied to create Level 1R data products. The Level 1R data products include metadata, the files required for a subsequent geometric correction, and the radiometrically corrected digital image data. Level 1G data products consist of radiometrically corrected digital image data resampled for geometric correction and registration to a cartographic projection. Level 1G customers may select their preferred projection, sampling algorithm, data format, and storage media from lists of options. EDC currently charges $600 per scene for Level 1R and Level 1G ETM+ data products. Future ground system enhancements will allow users to order ETM+ data spanning multiple scenes along an orbital path. Prices have not yet been determined for multiple scene products. No constraints are placed on the redistribution of ETM+ data purchased from the EDC. Customers may share the ETM+ data or derived image products without restriction.

7. FUTURE OF THE LANDSAT PROGRAM

The Land Remote Sensing Policy Act of 1992 also directs Landsat Program Management to assess options for a satellite system to succeed Landsat 7. The Act lays out four system development and management options for assessment: (1) "private sector funding and management," (2) an international consortium, (3) funding and management by the United States Government, and (4) "a cooperative effort between the United States Government and the private sector." A preference for a private sector system is expressed in the Act. NASA and the USGS are jointly exploring these options at this time. The agencies clearly recognize the preference for strong private sector involvement and are exploring strategies that ensure the continuity of Landsat 7 performance and data policies from a privately managed satellite system.

The successor program will likely exploit more advanced sensor technologies regardless of the development and management strategies. The Landsat 7 ETM+ is derived from the sensor technologies developed in the late 1970's for the Landsat 4 and Landsat 5 TM sensors. The TM and ETM+ sensors have proven to be robust, reliable, and long-long lasting, but strong incentives exist to minimize the cost of a successor system by reducing the size, weight, power consumption, and

mechanical complexity of the next sensor. The multispectral linear array technologies applied to the Advanced Land Imager (ALI) aboard the NASA Earth Observing-1 (EO-1) spacecraft are likely candidates for incorporation into any sensor aboard a successor system[10]. The EO-1 spacecraft is currently scheduled for launch in October, 2000.

SUMMARY

The Landsat program has taken us from the birth of land remote sensing into a new era of proliferating remote sensing systems. The proper role of the government and the private sector in the program has been a topic of continuing debate over these years. Program management has changed hands several times and the program has often faced threats to its continuation. Despite the many uncertainties, at least one Landsat satellite has remained in operation at all times since the 1972 launch of Landsat 1, continuously providing multispectral digital images of the Earth's continental and coastal regions.

The latest incarnation of the Landsat program, the Landsat 7 satellite system, has been a tremendous success. The ETM+ is acquiring high quality, well calibrated data. The system is operated in a manner that finally allows the program to achieve a global survey mission, populating the data archive at EDC with the data needed to monitor land cover and land use change on a global basis. Investigators now have, for the first time, ready access to affordable, quality, 30m, multispectral data for large region and global studies. Landsat 7 is establishing standards for performance, calibration, and operation that should serve as a model for successor systems.

The furture of the Landsat program depends on maintaining a vital role for Landsat 7 and its successor systems in this new era. Clearly, continuing the 28-year Landsat record of land cover and land use change is critical to understanding all aspects of global change. Providing the global perspective at a 30 m resolution appears to be a unique and vital task that the Landsat program will need to perform for years to come. Landsat Program Management, the USGS and NASA, are dedicated to maintaining this vital role by continuing Landsat 7 operations and by initiating the planning for successor systems.

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