The Landsat 7 Mission: Terrestrial Research for the 21st Century

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Abstract

The Landsat Earth observation approach introduced in 1972 created a new way of monitoring land cover and land use globally. The Landsat 7 mission, successfully launched on April 15, 1999 continues those observations and reflects significant progress in precise numerical radiometry, spectral differentiation and seasonally repetitive monitoring. Substantial improvements in calibration procedures, both prior to launch and during normal operations, have also been accomplished to ensure long-term stability in the acquired spectral radiometry. Landsat 7 data acquisitions are being driven by a long-term data acquisition plan that was designed to ensure that substantially cloud-free, seasonal coverage would be recorded and archived in the US for all land areas of the globe. NASA competitively selected a Landsat Science Team, consisting of representatives from US universities and government agencies, to exploit the Landsat 7 record for global change research. This team is addressing the technical and analytical means to process and analyze the core of this observation record, and for the first time in the history of the Landsat mission, the technical and operational aspects of the mission are being driven by the goals of the US science community. The expected outcome of these efforts is a rapid improvement in understanding the Earth system, as well as conceptual knowledge that will underpin significant advancements in the application of this technology for commercial, educational and research purposes. Pathways to achieve effective Landsat continuity in the early decades of the 21st century are also being given careful attention, and there is no question that the lessons learned from the Landsat 7 mission will strongly influence these next-generation sensor systems.

Introduction

The launch of Landsat 7 on April 15, 1999 from Vandenberg Air Force marked a significant advance in Landsat's more than quarter century mission to monitor the Earth's land areas. Begun in 1972, Landsat observatories pioneered the use of space platforms for systematic collection of land images (Short et al. 1976). These measurements produced a virtual revolution in earth science research, revealing the importance of remotely sensed images for monitoring the patterns and processes that define the Earth's land areas. In fact, the science and technology introduced by the continuing Landsat mission have served as a primary stimulus for current interest in Earth System Science and global change investigations, in particular the role of land conditions and dynamics in the Earth system.

The tremendous success of Landsat 7 has become clear during the last year. As of June, 2000, over 75,000 images had been transmitted to the U.S. archive at the USGS EROS Data Center (EDC), with nearly 40% of this total being cloud-free (< 10% cloud cover). In addition, the quality of the imagery, in terms of geodetic navigation, radiometric calibration, and signal-to-noise characteristics, has been superb, and represents a major advance over previous Landsat missions. Taken together, these early results suggest that Landsat 7 has emerged as a cornerstone for the U.S. remote sensing program.

Landsat Mission Heritage

The success of Landsat 7 belies the troubled and confused history of US Landsat operations during the last three decades (Marshall 1989a; Marshall 1989b; National Research Council 1995; Goward 1989). Much of the confusion centers on unrealized assumptions concerning possible commercial development of Earth imaging as well as misunderstandings concerning the information content and thus the scientific and applications potential of a Landsat-type observatory. From 1972 to 1982, the Landsat mission was sustained as a NASA experimental activity, directed toward demonstrating the potential of these observations in studying the Earth's land areas (Blair and Baumgardner 1977; Freden and Gorden 1983; Williams et al. 1984; Sheffner 1994). In 1982, a transition to the commercial sector was initiated. The EOSAT Corp. took over the Landsat program, under the direction of the National Oceanic and Atmospheric Administration, in an effort to develop the commercial potential of the mission. This business experiment ceased in 1992 as a result of a congressional act, the "1992 Land Remote Sensing Act" (Sheffner 1994). Based on this act, the Landsat program, beginning with Landsat 7, returned to Federal Government management. Initially the Department of Defense, NASA and NOAA shared management responsibility for Landsat 7. Over the last 5 years this management structure has changed with the mission now being shared between NASA and the US Geological Survey (USGS).

The return of Landsat operations to government management reflected not simply concerns with the success of the commercial efforts. During this time period a new emphasis on global change science placed Landsat-type observations in a central role for evaluating the status and potential changes of Earth's land areas (IGBP 1992; Bretherton 1988; National Research Council 1993). Both NASA and USGS are committed to exploiting Landsat 7 as a basic component of their contributions to the US Global Change Research Program (USGCRP) (Committee on Earth Studies 1990).

Landsat 7 Era

Landsat-type observations fill an important niche between the highly repetitive but coarse spatial resolution observations from the NOAA AVHRR, NASA EOS MODIS and French VEGETATION instruments and the ultra-high spatial resolution, local observatories such as the IKONOS instrument operated by the Space Imaging Corporation. Landsat provides systematic global coverage at a frequency sufficient to capture seasonal variations and at a spatial resolution where land cover dynamics, under the influence of natural processes and human activities, is clearly evident. If indeed we are to link global change to local environmental conditions, then Landsat-type observations will remain a fundamental requirement.

With Earth System Science clearly in mind, NASA incorporated Landsat 7 into its Earth Observation System (EOS) plans in 1994 and established a Landsat Project Science Office at the NASA Goddard Space Flight Center (GSFC). During 1995, the agency solicited proposals to form a Landsat Science Team to oversee science and application interests in the mission. This team was selected and funded in 1996. These activities reflected NASA's renewed interest in Landsat as a fundamental component of their earth science goals.

In keeping with this global change science interest, several aspects of the Landsat 7 mission were given particular attention, to ensure that this observatory would strongly support its new EOS role, as well as to better serve the broader applications community. Specific items given attention by the NASA Landsat Project Science Office included instrument characterization and calibration, development of an Image Assessment System (IAS), and an automated Long Term Acquisition Plan (LTAP) to ensure that a US archive of calibrated, global observations is compiled on an annual basis (Goward et al. 1999). The Landsat Science Team has periodically reviewed these activities in their capacity as representatives of the scientific user community. This is the first time in the history of the Landsat program when such a focussed interchange between the NASA managers and the US science community has been undertaken, a process that has laid the groundwork for this revolutionary Landsat 7 era.

Landsat 7 capability to acquire high quality, global imagery has stimulated the science community to find new ways of processing and analyzing these data. Various members of the Landsat Science Team are pursuing research activities that are directed toward exploiting large volumes of the observations. To achieve this goal they have

proposed advanced computational approaches for automated pre-processing, data storage, and analysis procedures. This research draws upon the 28-year heritage of Landsat research and well as novel concepts that have resulted from preparations for the NASA Terra mission. The team supports an initiative to develop a large-capacity computational facility to analyze a significant proportion of the Landsat 7 observations. Such a facility should be configured to handle at least 10,000 Landsat scenes per year, with the objective of answering key land science questions, such as the role of global forest dynamics in the Earth's carbon balance. A prototype of such a facility, the Research Environment for Advanced Landsat Monitoring (REALM) has been implemented at the University of Maryland to demonstrate the technical feasibility of achieving this critical mission goal (Masek et al. 2000).

Future of the Mission

Recent efforts by NASA to plan future earth science missions have revealed strong support for continuation of the Landsat mission. Among the several missions that were proposed under NASA's 1998 Request for Information on future activities (see NASA report "Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions"), a Landsat-type follow-on mission received high priority from the earth science community. Anticipating such interest, the upcoming NASA Earth Observing-1 mission is dedicated to testing advanced sensors and related hardware for possible deployment in future missions. In addition, active consideration for a Landsat-type follow-on, for deployment in the 2005 time period is now underway. The pathways to achieve effective Landsat continuity in the early decades of the 21st century are being given careful attention. The lessons learned from the Landsat 7 mission will strongly influence these next-generation sensor systems.

The Science Context

The unique contribution of Landsat observations to terrestrial research lies beyond simply its spectral radiometry. The entire observatory was designed to map and monitor the Earth's land areas at a level of spatial detail and sufficient repeat frequency to capture the essence of land dynamics under the influence of natural processes and human activities (Goward and Williams 1997). The TM instrument 30m spatial resolution, 185 km swath width and 16 day repeat cycle, were intentionally specified to detect the local patterns of change that characterize the Earth's land processes. These technical capabilities, combined with the 28-year archive, provide the underpinning for addressing science questions with Landsat data.

Terrestrial Patterns and Dynamics

Within the Earth system, land areas are the most slowly changing component. Whereas the atmosphere and oceans mix rapidly through turbulent, fluid motions, the terrestrial environment changes slowly, on time scales ranging from months (seasonal shifts) to centuries (biome migrations). As a result of this relatively stable structure, land

areas are characterized by fine-scale heterogeneity, with strongly contrasting land-cover types often existing in close proximity. The asymmetry of ecosystems in mountain regions, the presence of riparian forests in semi-arid regions, and fragmented vegetation around US suburban developments are all typical of the Earth's land areas. Thus, land areas pose the unique problem of monitoring at relatively high spatial resolution while requiring reasonable temporal repeat frequency to capture seasonal dynamics of vegetation and hydrology. The Landsat systems, particularly when combined with the complementary sensors (MODIS, MISR and ASTER) on the EOS Terra platform, provide sufficient spatial and temporal differentiation to detect and monitor the Earth's land dynamics(King and Greenstone 1999).

The operational plan for Landsat 7 achieves the long-held promise of the Landsat observatory: true multi-temporal, high spatial resolution monitoring. The reduction in price of the data ($475-600 per scene) combined with routine global coverage as driven by the long term data acquisition plan, allows researchers to assemble seasonal and inter-annual time series for almost all parts of the globe. Such data access permits true realization of the mission concept, seasonal differentiation of land cover patterns to discriminate inter-annual patterns of land cover change. Research conducted with Landsat since its beginning has repeatedly shown that multi-temporal observations, collected at differing times during the vegetation growth cycles, are critical for distinguishing land cover types (Hall and Badwar 1987; Justice et al. 1985; Townshend et al. 1987; Mauser 1989). The capacity of the Landsat mission to repeatedly view each region of the Earth through the growing season is a key element of the mission strategy.

Land Cover Change: Disturbance, Trends and Hazards

The primary science goal of the Landsat 7 mission is to characterize inter-annual changes of Earth's land cover and particularly the state of the land biosphere. As an example, land-cover change plays a major role in controlling the atmospheric carbon budget. Tropical deforestation alone is contributing some 1.6 GtC/yr to the atmospheric reservoir (Schimel 1995). At the same time, isotopic studies suggest that reforestation in the Northern Hemisphere may be absorbing some of this atmospheric carbon. While MODIS will monitor photosynthetic changes in the world's vegetation regimes (e.g., the response to CO_2 fertilization), Landsat is essential for quantifying the fine-scale changes in land-cover caused by disturbances, such as fire, flooding, storm damage and most particularly, human activity. Combined, the Landsat and MODIS measurements should be able to isolate and quantify the key aspects of the terrestrial carbon budget, leading to improved understanding of the Earth's carbon cycle. Changes in land-cover also have profound implications for local ecosystems and habitability. Agricultural and urban expansion, while vital for sustaining human populations, have strained hydrologic and ecological resources around the world. Landsat offers the potential for routine monitoring of human impacts on land-cover conditions, and ultimately leading to an understanding of how these changes affect local habitability(Sellers et al. 1995; Houghton et al. 2000).

Longer term changes in climate conditions (whether of natural or anthropogenic origin) also feed back to the terrestrial environment, thus providing a second major science objective for Landsat. Gradual changes in land characteristics revealed by inter-annual Landsat observations can be read as diagnostic indicators of climate change (DeFries and Townshend 1999). For example, the retreat and advance of alpine glaciers integrate variability in both local temperature and precipitation, and can be monitored globally with Landsat(Bindschadler and Dowdeswell 2000). Similar observations applied to desertification, changes in growing seasons, changes in rates of burning, and shifts in biome geography may record early responses to regional and global climate changes. Such responses are important for understanding exactly how global changes in climate may affect local areas and ecosystems.

Assessing and mitigating natural hazards provides a third major emphasis for Landsat science. Volcanic eruptions, floods, droughts, and landslides can all be monitored with ETM+, and (in some cases) mitigation strategies may be implemented. For example, using the ETM+ SWIR-TIR bands, it is possible to map the subsurface "plumbing" of volcanoes, potentially giving an indication of which areas are most likely to erupt in the future (Harris et al. 1998). In fact, natural hazards research is part of a larger question examining the interactions between the natural environment and human populations. The resolution of Landsat allows us to monitor both sides of this relationship, the human and the natural, to better understand the dynamic between them.

THE LANDSAT 7 MISSION Configuration

Landsat 7 System Overview

Full appreciation of the Landsat 7 mission requires an end-to-end system perspective. Figure 1 depicts the major components of the satellite system and their interfaces. The heart of the system is the Landsat 7 satellite with its ETM+ instrument payload. The flight operations team within the Mission Operations Center (MOC) at NASA's Goddard Space Flight Center performs the command and control functions for the satellite. 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. Two additional U.S.-operated stations are located near Fairbanks, Alaska and Svalbard, Norway. ETM+ data acquired over the coterminous U.S. are directly transmitted to EDC in real time, while data acquired at the Alaska and Norway stations are recorded on tape and shipped to EDC.

All 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) samples the ETM+ data for in-orbit calibrations and to assess 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.

The Landsat 7 Spacecraft and Its Orbit

Lockheed Martin Missiles and Space, Valley Forge, Pennsylvania under contract to NASA built the Landsat 7 spacecraft. 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 2). 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.

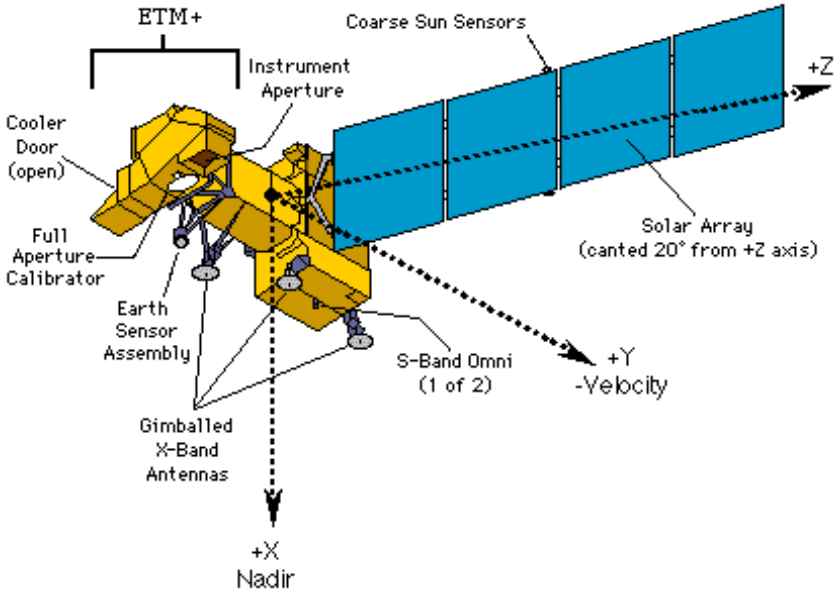

Figure 2. The Landsat 7 Spacecraft

Following launch, the satellite orbit was gradually adjusted until it reached its circular, sun synchronous operational orbit at an altitude of 705 km, an inclination of 98.2 degrees, and a nominal equatorial crossing time of 10:00 a.m. in the descending node.

The satellite requires 99 min to circle the Earth with each orbit tracing a ground path corresponding to a world-wide reference system (WRS) of 233 ground paths. The satellite orbits over each of these paths once every 16 days. The satellite will be maintained in this orbit for the life of the mission with periodic adjustments of its inclination and velocity. While Landsat 7 and Landsat 5 follow identical ground tracks, and both use the same WRS system, 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.

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 TM sensors aboard Landsat 4 and Landsat 5 and the Enhanced Thematic Mapper (ETM) aboard the lost Landsat 6 satellite (Mika 1997). Like the earlier sensors, the ETM+ operates as a whiskbroom scanner and acquires data for the same seven visible, near infrared, shortwave infrared and thermal infrared spectral bands (Table 1). 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 183-km cross-track swath as it travels along the orbital paths.

Table 1. 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 solar calibrator, consists of a panel painted with a special diffuse white paint that is normally stowed out of the ETM+ field of view. Once every six weeks this 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. By comparison, the Landsat 4 and Landsat 5 TM sensors incorporated only internal calibration lamps for in-flight calibration.

Landsat 7 Operations

The Landsat 7 is configured to populate the EDC archive with sun-lit, cloud-free, calibrated ETM+ data, providing global coverage of the Earth's continental and coastal surfaces on a seasonal basis. The worldwide reference system (WRS) divides the world into 28,892 path/row scenes, each of which covers 183 x 170 km. Approximately 14,000 of these scenes contain land and 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, while 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 global coverage within the duty cycle and processing limitations of the system.

The strategy for optimally acquiring ETM+ imagery is referred to as the Long Term Acquisition Plan (LTAP) (Arvidson et al. 2000; Arvidson et al. 2000; Gasch 2000)). The LTAP factors predicted cloud-cover, seasonal vegetation state, and the past history of acquisitions to generate a daily acquisition plan. Specifically, the algorithm assigns a numerical priority to each scene within view on any 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 NOAA NCEP cloud cover forecast relative to ISCCP climatological 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.

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; the GSFC Landsat Project Science Office, and the Landsat Science team. 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.

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 pre-launch 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 to 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.

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 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 such icing and the on-orbit data show no evidence of reduced radiometric response due to icing. Thus, the radiometric response of the ETM+ detectors appears more stable and contains fewer artifacts in comparison to TM data.

Image geometry and geographic registration

Level 1G ETM+ data products are created by re-sampling 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 multi-temporal 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 the coarser 60-meter Band 6 data. These band-to-band rms registration errors are random errors around zero once the geometric correction software takes out the systematic offsets. 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 (Storey and Choate 2000).

Geographic coverage

Routine ETM+ data acquisition began on June 29, 1999, following an initial on-orbit checkout period. As of May 31, 2000, the EDC archive has captured over 75,000 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, nearly 99,000 ETM+ scenes have been transmitted from the spacecraft to 11 active International Ground Stations as of May 31, 2000. These Stations maintain independent data archives and independent data distribution policies. Each international ETM+ data archive provides only local region coverage.

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(Drager et al. 1997).

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 permit 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.

Future Prospects

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 (Williamson 1997).

The successor program will likely exploit more advanced sensor technologies regardless of the development and management strategies (Irons et al. 1996). 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 (Ungar 1997). The EO-1 spacecraft is currently scheduled for launch in October, 2000.

Conclusions

The Landsat 7 mission achieves both the promise conceived by early visionaries who designed this Earth land observatory as well as the experience and wisdom of scientists and engineers who have spent the better part of 30 years exploring its potential. Indeed there is a remarkable convergence between well-understood science information needs and technical capabilities which has been achieved with this 7th spacecraft in this series. Both the technical qualities of the mission and the science drivers that have determined its operations and, ultimately, the analysis of the observations, reflect the maturity of our understanding on how to observe the Earth's land areas from space. We are now within a few steps of achieving a reliable and precise terrestrial monitoring system.

At the beginning of this new 21st century, the need for such an Earth observatory is quite obvious. Our increasing populations, with compounding technical and economic power, are placing ever-greater demands on the natural resources and environmental qualities, which sustain our well being. Satellite remote sensing alone will not address all the uncertainties we need to explore but these observations move us a long way toward better understanding the Earth as an environmental system capable of sustaining human existence.

The primary reason for the success of the Landsat 7 mission is the long-term dedication of numerous, highly motivated scientists, engineers and administrators who believe in, and are earnestly dedicated to, achieving the science goals of the Landsat program. The quality of results produced to date by the Landsat 7 observatory exceeds both the original technical design specifications and the expectations of the science user community. Given the various hard lessons learned over the 30 year life of the Landsat program, we hopefully can now move toward a future of continued quality observatories based on the skills and experience of the engineering and research communities which have brought us to this stage of success.

Current discussions of follow-on missions beyond Landsat 7 show a strong interest for continuation of this series. From the technical perspective, the pathway is clear and obvious. More than two decades of technical advances have occurred since the Thematic Mapper design was first developed. The current prototype ALI sensor to be flown on the NASA EO-1 spacecraft is clearly better and lower cost than the ETM+ instrument. What other interesting innovations might be considered is not yet fully explored but some possibilities include coincident atmospheric measurements and even better geographic positioning information. More novel innovations not doubt will arise over the next few years.

Administratively how a follow-on mission will be achieved is less clear. There is considerable pressure to pursue mission continuation through private sector, commercial vendors. Previous experience with Landsat commercialization leaves most of the engineering and science community skeptical and nervous. Under ideal circumstances the best interests of scientists and businesses should intersect where the same qualities that achieve global change science goals also stimulate a market place for high quality measurements to achieve economic goals. Under this scenario everyone ends up a winner because the economic demands for the observations should reduce the cost of the observations for scientific uses. To date there is scarce evidence that such a commercial market place exists, at least for the basic, original observations. On the other hand there does appear to be a growing market for value-added information derived from the original observations. The observations have critical value in scientific investigations of the Earth and there may well be a secondary market place for derived information. Can a Landsat observatory be sustained solely based on economic market forces? After 30 years, we still do not know the answer to this question.

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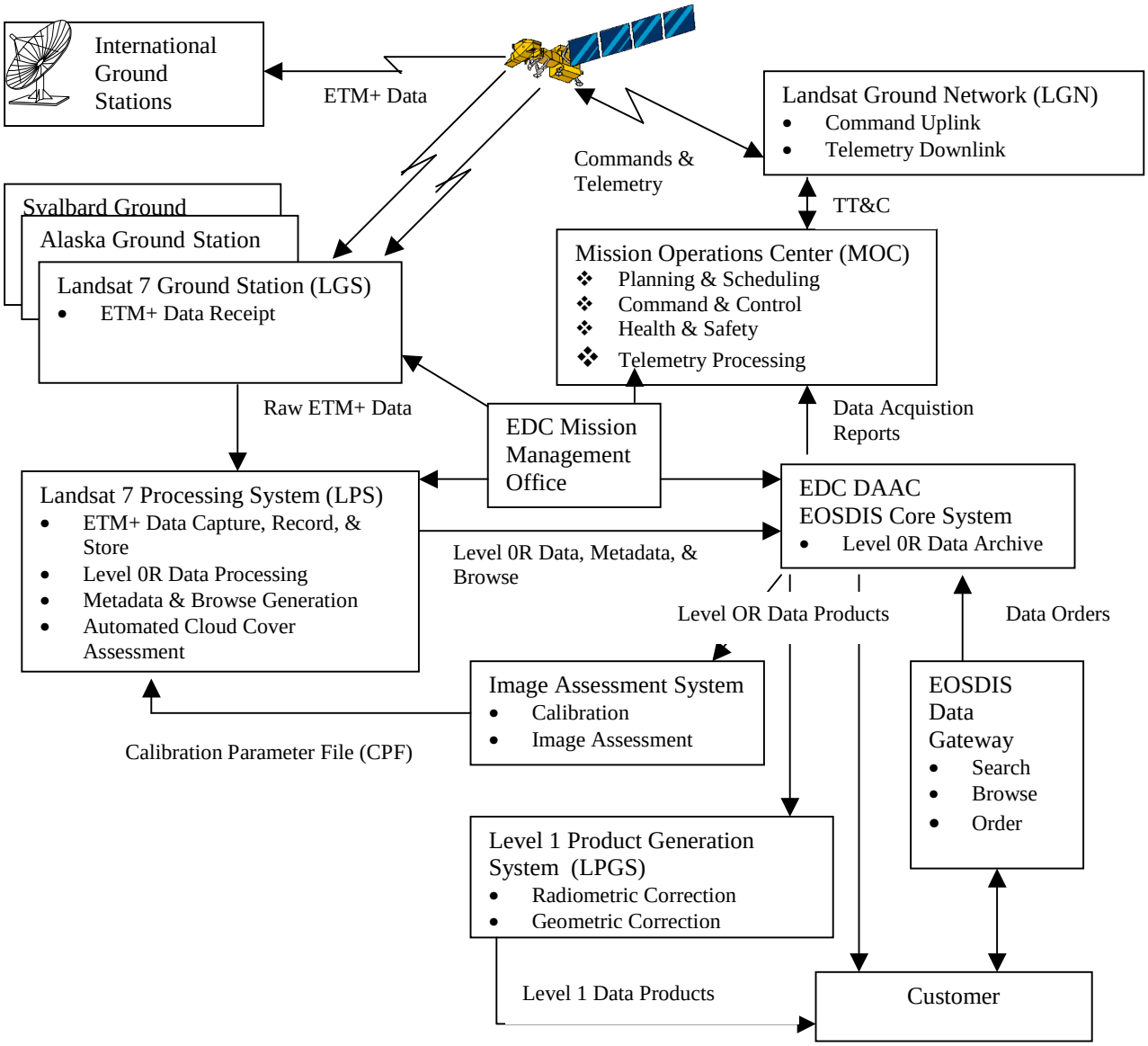

Figure 1. Schematic of the Landsat 7 Satellite and Ground System