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Landsat 7 (L7) Data Users Handbook

Version 2.0

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USGS
science for a changing world

Landsat 7 (L7)
Data Users Handbook

November 2019

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Executive Summary

The Landsat 7 Data Users Handbook is prepared by the U.S. Geological Survey (USGS) Landsat Project Science Office at the Earth Resources Observation and Science (EROS) Center in Sioux Falls, SD, and the National Aeronautics and Space Administration (NASA) Landsat Project Science Office at NASA's Goddard Space Flight Center (GSFC) in Greenbelt, Maryland.

The purpose of this handbook is to provide a basic understanding and associated reference material for the Landsat 7 Observatory and its science data products. In doing so, this document does not include a detailed description of all technical details of the Landsat 7 mission but focuses on the information needed by the users to gain an understanding of the science data products.

This handbook includes various sections that provide an overview of reference material and a more detailed description of applicable data user and product information. This document includes the following sections:

- Section 1 describes the background for the Landsat 7 mission, as well as previous Landsat missions
- Section 2 provides a comprehensive overview of the Landsat 7 concept of operations, the Observatory, including the spacecraft, the Enhanced Thematic Mapper Plus (ETM+) instrument, the Landsat 7 ground system, as well as various institutional services
- Section 3 provides information on radiometric and geometric instrument calibration, as well as a description of the Calibration Parameter File (CPF)
- Section 4 includes information about the Landsat 7 Long-Term Acquisition Plan (LTAP) and documents the changes in data acquisition scheduling since launch
- Section 5 includes a description of Level 1 data products and product generation, as well as conversion of Digital Numbers (DNs) to physical units
- Section 6 provides an overview of data search and access using various online tools
- Appendix A contains a list of known issues associated with Landsat 7 data
- Appendix B includes information about the CPF content
- Appendix C contains historical information pertaining to Landsat 7 ETM+ and Landsat 5 Thematic Mapper (TM) cross-calibration
- Appendix D includes historical information about Level 0 Reformatted (L0R) and Level 1 Reformatted (L1R) data products
- Appendix E details the differences between Level 1 Product Generation System (LPGS) and National Land Archive Production System (NLAPS) products

This document is under Land Satellites Data Systems (LSDS) Configuration Control Board (CCB) control. Please submit changes to this document, as well as supportive material justifying the proposed changes, via a Change Request (CR) to the Process and Change Management Tool.

Note: This document contains information specific to Landsat 7 ETM+ Pre-Collection data only. Landsat 7 ETM+ Pre-Collection data is no longer available from USGS EROS. As of October 1, 2017, Landsat Collection data is the standard Landsat Level 1 data product available from USGS EROS. While Landsat Pre-Collection and Collection data share basic foundational qualities, there are important differences between the datasets that users must be aware of. For up-to-date information on Landsat Collection data, visit the Landsat Missions Website.

Document History

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Section 1 Introduction

1.1 Foreword

The Landsat Project has provided calibrated high-quality moderate spatial resolution data of the Earth's surface to a broad and varied user community since 1972. Landsat images provide information that meets the broad and diverse needs of agribusiness, global change researchers, academia, state and local governments, commercial users, national security agencies, the international community, decision-makers, and the public.

The mission of the Landsat Project is to provide repetitive acquisition of moderate-resolution multispectral data of the Earth's surface on a global basis. Landsat represents the only source for global, calibrated, moderate spatial resolution measurements of the Earth's surface that are preserved in a national archive and freely available to the public. Data from the Landsat spacecraft constitute the longest record of the Earth's continental surfaces as seen from space. It is a record unmatched in quality, detail, coverage, and value.

Launched in 1999, the Landsat 7 satellite has contributed to an uninterrupted multispectral record of the Earth's land surfaces. Landsat 8, launched in 2013, orbits in an eight-day offset with Landsat 7. Landsat 7's space-borne data acquisition combines with the U.S. Geological Survey's (USGS) archival and distribution systems, which includes the data processing techniques required to render Landsat 7 data into a scientifically usable format. With Landsat 7, special emphasis has been placed on periodically refreshing the global data archive, maintaining an accurate instrument calibration, providing data in accordance with national policy directives, and ensuring there is a data processing system that creates publically accessible products of superior quality.

The Landsat satellites carry a variety of components, including remote sensing systems, data relay systems, attitude-control and orbit-adjustment subsystems, a power supply, and receivers and transmitters for ground station communications.

The Landsat 7 Observatory offers these features:

- **Data Continuity**: Landsat 7's launch in 1999 continued the unbroken series of land remote sensing satellites, which began in 1972 with the launch of the Earth Resources Technology Satellite (ERTS-1, later renamed Landsat 1). Landsat 7's Enhanced Thematic Mapper Plus (ETM+) provides seamless temporal continuity between Landsat 5 (launched in 1984) and Landsat 8 (launched in 2013).

- **Global Survey Mission**: Landsat 7 data are acquired systematically to build and periodically refresh a global archive of sun-lit, substantially cloud-free images of Earth's landmasses.

- **Free Standard Data Products**: Landsat 7 data products are available through the USGS EROS Center at no charge since 2008.

- **Absolute Radiometric and Geometric Calibration**: Data from the Landsat 7's ETM+ will be calibrated to better than five percent uncertainty, providing an on-orbit standard for other missions.

- **Responsive Delivery**: On average, products are generated within 24 hours of receipt of the data at the USGS EROS and are then available for download online.

The continuation of the Landsat Project is an integral component of the U.S. Global Change Research Program. Landsat 7 was the continuation of a joint initiative between the USGS and NASA. It was initially part of a global research program known as NASA's Earth Sciences Enterprise, an evolving long-term program studying changes in Earth's global environment. The goal of Earth Sciences Enterprise was to provide a better understanding of natural and man-made environmental changes. In the Landsat Project's long tradition, Landsat 7 is an important component of NASA's Earth Observing System (EOS) and the USGS National Land Imaging Program (NLIP), and continues to provide critical information to those who characterize, monitor, manage, explore, and observe the land surfaces of the Earth over time.

1.2 Background

1.2.1 EOSAT Era and Basis in Law for Landsat

In the mid-1980s, U.S. Government agencies, including NASA and the National Oceanic and Atmospheric Administration (NOAA), were directed to attain their commercial space objectives without the use of direct federal funding by entering into appropriate cooperative agreements with private sector corporate entities to encourage and advance private sector basic research, development, and operations.

The implementation of this policy required the transfer of government-developed space technology to the private sector in such a manner as to protect its commercial value, which included retention of technical data rights by the private sector. Commercial sector space activities developed under this mandate were to be supervised or regulated by federal agencies only to the extent required by law, national security, international obligations, and public safety.

With the passage of Public Law 98-365, the Land Remote Sensing Commercialization Act of 1984, NOAA was directed to delegate management of the Landsat 4 and Landsat 5 satellites and their data distribution to the private sector. In addition, NOAA was to pursue procurement of future remote sensing products and services, including Landsat from the private sector.

In 1985, NOAA solicited bids to manage the existing Landsat satellites in orbit and to build and operate future systems. The Earth Observation Satellite Company (EOSAT), a joint venture between the Radio Corporation of America and Hughes Aircraft, later called Space Imaging Corporation, won the competitive bidding process in August 1984 and took over operation of the Landsat system on September 27, 1985.

From 1985 to 1994, EOSAT retained exclusive sales rights to all Landsat 4 and Landsat 5 Thematic Mapper (TM) data until July 1994, at which time it was planned that Landsat data over ten years old would become available from the National Archive at USGS EROS (now called the National Satellite Land Remote Sensing Data Archive (NSLRSDA)). This agreement between Landsat Project management and EOSAT Corporation defined cost and reproduction rights for Landsat 4 and Landsat 5 TM data. EOSAT also won the competition to produce the next satellite in the series, Landsat 6.

By 1992, it had become clear that the high cost of commercially provided Landsat data had greatly restricted its use in research and other public sector applications. In response, the U.S. Congress passed H.R. 6133, the Land Remote Sensing Policy Act of 1992, into law in September of that year. This law established a new national land remote sensing policy that:

- Abandoned full commercialization of the Landsat Project
- Returned management of the Project to the Government
- Established a data policy of distributing Landsat data at the Cost of Fulfilling a User Request (COFUR*) (*superseded in 2008)
- Directed that preliminary work begin on a new Landsat 7
- Fostered development of advanced land remote sensing systems and opportunities for commercialization

The loss of Landsat 6 during its launch in October 1993, and the ages of Landsat 4 and Landsat 5, suddenly made the new Landsat 7 mission imperative. In May 1994, a Presidential Decision Directive (National Science and Technology Council, NSTC-3) defined the original Landsat 7 Data Policy, as well as program management strategies and implementation guidelines. Subsequent NASA and NOAA memoranda in the summer of 1994 brought the current Landsat 7 mission into existence.

Additional legislation relevant to Landsat history:

- HR1275 Short title: “Civilian Space Authorization Act, Fiscal Years 1998 and 1999”
- HR1278 Short title: “National Oceanic and Atmospheric Administration Authorization Act of 1997”
- HR1702 Short title: "Commercial Space Act of 1998"

1.2.2 Previous Missions

Landsat satellites have been providing multispectral images of the Earth continuously since the July 23, 1972, launch of Landsat 1. A data record of Earth’s land surface now exists and is used across disciplines to achieve improved understanding of the planet’s land surfaces and the impact of humans on the environment. Landsat data have been utilized in a variety of government, public, private, and national security applications. Examples include land and water management, global change research, oil and mineral exploration, agricultural yield forecasting, deforestation monitoring, land surface change detection, and cartographic mapping.

The first Landsat satellite was launched in 1972 with two Earth-viewing imagers — a Return Beam Vidicon (RBV) and an 80-meter MSS. Landsat 2 and Landsat 3, launched in 1975 and 1978 respectively, were similarly configured. In 1982, Landsat 4 was launched with the MSS and a new instrument called the Thematic Mapper (TM). Instrument upgrades included improved ground resolution (30 meters) and three new spectral channels or bands. In addition to using an updated instrument, Landsat 4 made use of the Multi-Mission Modular Spacecraft (MMS), which replaced the Nimbus-based spacecraft design employed for Landsat 1-3. Landsat 5, a duplicate of Landsat 4, was launched in 1984 and after providing data for almost 28 years, well beyond its five-year design life, was decommissioned in 2013. Landsat 6, equipped with a 15-meter panchromatic band and an Enhanced Thematic Mapper (ETM) sensor, was lost immediately after launch in 1993. Landsat 7's ETM+ instrument is an improved version of Landsat 6's ETM sensor.

Table 1-1 lists key mission characteristics of the Landsat Project while Table 1-2 compares the sensors carried aboard these satellites. Details on the Landsat Project Timeline are also available.

Satellite	Launch (End of Service)	Sens.	Res. (m)/Type	Communication	Alt. (km)	Rep. (days)	Data (Mbps)
Landsat 1	07/23/1972	RBV	80/ms	Direct downlink	917	18[1]	15
	(01/06/1978)	MSS	80/ms	+ recorders			
Landsat 2	01/22/1975	RBV	80/ms	Direct downlink	917	18[1]	15
	(07/27/1983)	MSS	80/ms	+ recorders			
Landsat 3	03/05/1978	RBV	40/pan	Direct downlink	917	18[1]	15
	(09/07/1983)	MSS	80/ms	+ recorders			
			240[1]/ther				
Landsat 4	07/16/1982	MSS	80/ms	Direct downlink	705	16[2]	85
	(06/15/2001[1])	TM	30/ms	+ TDRSS			
			120[1]/ther				
Landsat 5	03/01/1984	MSS	80/ms	Direct downlink	705	16[2]	85
	(06/05/2013[2])	TM	30/ms	+ TDRSS			
			120[1]/ther				
Landsat 6	*10/05/1993*	*ETM*	*15/pan*	*Direct downlink*	*705*	*16[2]*	*85*
	(10/05/1993[3])		*30/ms*	*+ recorders*			
			120[1]/ther				
Landsat 7	04/15/1999	ETM+	15/pan	Direct downlink	705	16[2]	150
			30/ms	+ SSR			
			60[1]/ther				

Satellite	Launch (End of Service)	Sens.	Res. (m)/Type	Communication	Alt. (km)	Rep. (days)	Data (Mbps)
Landsat 8	02/11/2013	OLI	15/pan	Direct downlink	705	16[2]	X-Band: 384
			30/ms	+ SSR			S-Band: 260
		TIRS	100[1]/ther				

Table 1-1. Key Landsat Project Mission Characteristics

- End of service date (satellite decommissioned; [1] science data downlink capability ended in 1993; [2] TM data ended in 2011, MSS data ended in 2013; [3] *lost during launch)*
- Sens. = Sensor(s) (RBV = Return Beam Vidicon; MSS = Multispectral Scanner; TM = Thematic Mapper; ETM = Enhanced Thematic Mapper; ETM+ = Enhanced Thematic Mapper Plus; OLI = Operational Land Imager; TIRS = Thermal Infrared Sensor)
- Res. = Nominal visible wavelength spatial resolution (meters); [1] thermal bands of Landsat 3-8 collected at various spatial resolutions and resampled to match the multispectral resolutions.
- Type = Sensor type (pan = panchromatic, ms = multispectral, ther = thermal)
- Communication = Data transfer and handling options (TDRSS = Tracking and Data Relay Satellite System; SSR = Sold State Recorder)
- Alt. = Nominal altitude on orbit
- Rep. = Landsat revisit interval (WRS = Worldwide Reference System, [1]WRS-1, orbit inclined at 99.2°; [2]WRS-2, orbit inclined at 98.2°)
- Data = Data transfer rate (Megabits per second)

Satellite	Sensor	Band (Wavelength (µm))	Resolution (m)
Landsat 1,2	**RBV**	1 (0.48 – 0.57)	80
		2 (0.58 – 0.68)	80
		3 (0.70 – 0.83)	80
	MSS	4 (0.5 - 0.6)	80
		5 (0.6 - 0.7)	80
		6 (0.7 - 0.8)	80
		7 (0.8 - 1.1)	80
Landsat 3	**RBV**	1 (0.505 - 0.75)	40
	MSS	4 (0.5 - 0.6)	80
		5 (0.6 - 0.7)	80
		6 (0.7 - 0.8)	80
		7 (0.8 - 1.1)	80
		8 (10.4 - 12.6)	240[1]
Landsat 4,5	**MSS**	4 (0.5 - 0.6)	80
		5 (0.6 - 0.7)	80
		6 (0.7 - 0.8)	80
		7 (0.8 - 1.1)	80
	TM	1 (0.45 – 0.52)	30
		2 (0.52 – 0.60)	30
		3 (0.63 – 0.69)	30
		4 (0.76 – 0.90)	30
		5 (1.55 – 1.75)	30
		6 (10.4 – 12.5)	120[2]
		7 (2.08 – 2.35)	30

Satellite	Sensor	Band (Wavelength (µm))	Resolution (m)
Landsat 7	**ETM+**	1 (0.450 – 0.515)	30
		2 (0.525 – 0.605)	30
		3 (0.630 – 0.690)	30
		4 (0.775 – 0.900)	30
		5 (1.550 – 1.750)	30
		6 (10.40 – 12.50)	60[2]
		7 (2.080 – 2.350)	30
		8 (0.520 – 0.900)	15
Landsat 8	**OLI**	1 (0.435 – 0.451)	30
		2 (0.452 – 0.512)	30
		3 (0.533 – 0.590)	30
		4 (0.636 – 0.673)	30
		5 (0.851 – 0.879)	30
		6 (1.566 – 1.651)	30
		7 (2.107 – 2.294)	30
		8 (0.503 – 0.676)	15
		9 (1.363 – 1.384)	30
	TIRS	10 (10.60 – 11.19)	100[2]
		11 (11.50 – 12.51)	100[2]

Table 1-2. Landsat Sensor Characteristics

- Sensor = Sensor used; (RBV = Return Beam Vidicon; MSS = Multispectral Scanner; TM = Thematic Mapper; ETM+ = Enhanced Thematic Mapper Plus; OLI = Operational Land Imager; TIRS = Thermal Infrared Sensor)
- Band (Wavelength (µm)) = Detector wavelength in micrometers measured at Full Width at Half Maximum (FWHM)
- Resolution = Approximate maximum spatial resolution per band (in meters); *[1] Landsat 3 included a thermal band, but the channel failed shortly after launch. [2] Landsat 4-8 thermal bands collected at various resolutions but resampled to match multispectral band resolutions.*

1.2.3 Operations and Management

The Landsat 7 project management structure changed repeatedly from 1992 through 1998, from NASA / United States Air Force / USGS to NASA / NOAA / USGS to a bi-agency NASA / USGS partnership. As described in the Landsat 7 Management Plan, NASA was responsible for the development and launch of the Landsat 7 satellite and the development of the ground system. The Landsat 7 Project Office at GSFC managed these responsibilities, with Hughes Santa Barbara Remote Sensing (SBRS) building the sensor and Lockheed Martin Missiles and Space developing the spacecraft. The USGS is responsible for operation and maintenance of the satellite and the ground system for the life of the satellite. In this role, the USGS captures, processes, and distributes the data and is responsible for maintaining Landsat 7 data within the remote sensing image archive at USGS EROS.

The NASA GSFC Landsat 7 Project was responsible for development of the Landsat 7 system. Specifically, this involved designing, developing, and testing the Landsat 7 spacecraft, the ETM+ instrument, and the end-to-end ground system. NASA was also responsible for the satellite launch and performing a 60-day in-orbit check out before handing operations to the USGS. The USGS, collaborating with NASA and the Landsat

Science Team, is responsible, decades after launch, for verifying data processing integrity and assuring high image quality.

USGS EROS manages the overall Landsat 7 mission operations. In this capacity, USGS EROS directs on-orbit flight operations, implements mission policies, directs acquisition strategy, and interacts with International Ground Stations (IGS). USGS EROS receives Landsat 7 data from various ground receiving stations and performs pre-processing, archiving, product generation, and distribution functions. USGS EROS also provides an accessible public interface into the archive for data searching and ordering.

1.3 Landsat 7 Mission

The primary Landsat 7 mission objective is to provide timely, high-quality, visible-, infrared-, and thermal-wavelength data of all land and near-coastal areas on Earth, and to thereby continually refresh the existing Landsat archive. Newly acquired data are required to be sufficiently consistent with currently archived data in terms of acquisition geometry, calibration, coverage, and spectral characteristics to allow comparison for global and regional change detection and characterization.

The Landsat Project also continues to make all Landsat data available at no charge for U.S. civil, national security, and private sector use as well as academic, foreign, and commercial uses. An additional goal of the Landsat Project is to expand the uses of such data.

1.3.1 Overall Mission Objectives

Landsat 7 has a design lifetime of five years, however, as of 2019, it is in its 20th year of operations. The overall objectives of the Landsat 7 mission are:

- Provide data continuity with previous Landsat missions
- Offer 16-day repeat coverage of the Earth's surface
- Build and periodically refresh a global archive of sunlit, substantially cloud free, land area and coastal images
- Make data widely and freely available. As of 2008, Landsat data with standard processing are available to download at no charge through digital access
- Support Government, international, and commercial communities
- Play a vital role in NASA's EOS by promoting interdisciplinary research via synergism with other EOS observations. (In particular, by orbiting in tandem with NASA's Terra satellite to obtain near coincident observations.)

1.3.2 Initial System Performance Requirements

Some of the initial specific requirements for the Landsat 7 ETM+ sensor included the following; updates to these requirements that reflect current operations are listed in Section 1.3.3.

- Acquire, capture, and archive the equivalent of 250 scenes per day
- Produce browse and metadata for all full and partial scenes acquired

- Produce the equivalent of 100 Level 0 Reformatted (L0R) products and 100 Level 1 products per day, with phased expansion capabilities to handle an increased processing load
- Accept data acquisition and product requests from users
- Provide rapid turnaround of priority acquisitions and processing
- Supply data to users at COFUR
- Provide communications downlinks for data capture by fixed and transportable X-Band ground stations using the [Consultative Committee for Space Data Systems (CCSDS)]() standard protocol for communication of data

1.3.3 Current System Capabilities

The Landsat 7 ETM+ system design currently includes the following capabilities:

- As of 2008, the entire Landsat archive is available for download at no charge
- Acquisitions average 450 scenes per day
- All acquisitions are processed to Level 1 products and archived
- Acquisition requests for special circumstances are accepted
- Provides for a systematic collection of global, moderate resolution, multispectral data
- Uses cloud cover predictions to minimize acquisition of less desirable data
- All acquisitions are available for user access within 6 hours of receipt at EROS
- Provides improved access to IGS data

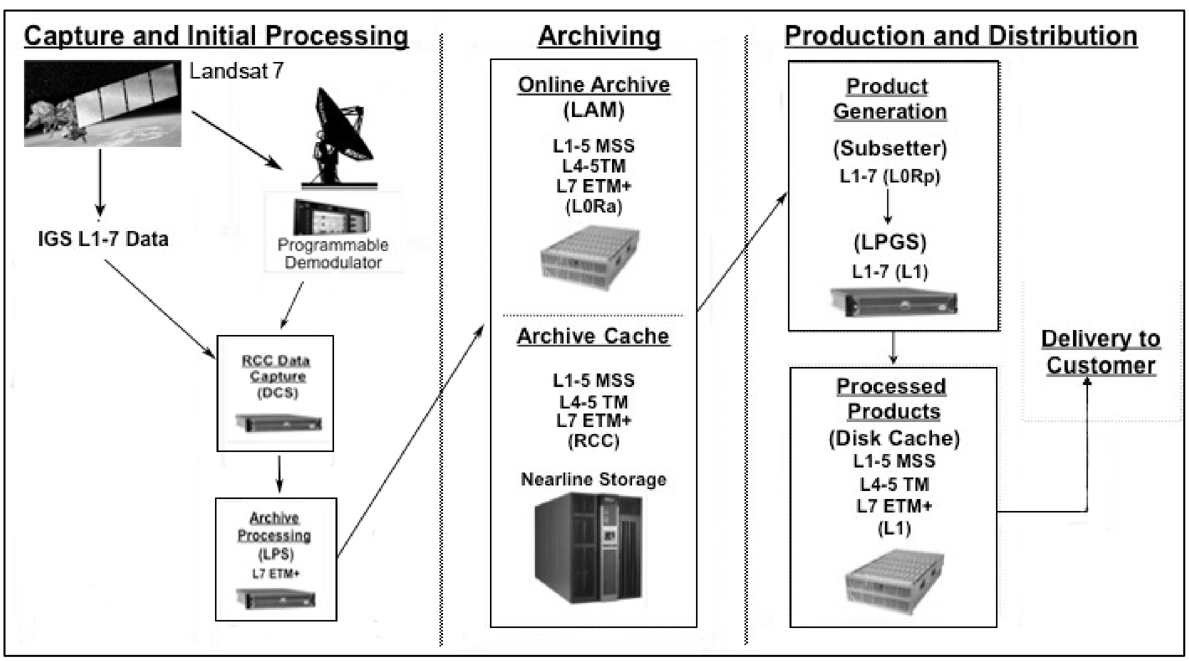

Figure 1-1. Landsat 7 Capabilities

1.3.4 Global Survey Mission

An important operational strategy of the Landsat 7 mission is to establish and maintain a global survey data archive. Landsat 7 images the Earth's landmasses systematically every 16 days utilizing the same Worldwide Reference System (WRS) used for Landsat 4, 5, and 8 (see Table 1-1).

However, unlike previous Landsat missions, Landsat 7 endeavors to systematically capture sun-lit, substantially cloud-free images of the Earth's entire land surface. A Long Term Acquisition Plan (LTAP) was developed to define the acquisition pattern for the Landsat 7 mission in order to create and periodically update this global archive. This enabled the creation of further Global Land Survey (GLS) products from ETM+ data. See Section 2 for a description of Landsat 7's WRS-2 orbit and Section 4 for additional information about the Landsat 7 LTAP.

	Landsat 7	**Landsat 8**
Scenes / Day	~450	~700
SSR Size	378 Gbits, block-based	3.14 Terabit, file-based
Sensor Type	ETM+, Whisk-Broom	OLI / TIRS, Pushbroom
Compression	No	~2:1 Variable Rice Compression
Image D/L	X-Band GXA × 3	X-Band Earth Coverage
Data Rate	150Mbits/sec × 3 Channels / Frequencies	384 Mbits/sec, CCSDS Virtual Channels
Encoding	Not fully CCSDS compliant	CCSDS, LDPC FEC
Ranging	S-Band 2-Way Doppler	GPS
Orbit	705 km Sun-sync 98.2° inclination (WRS-2)	705 km Sun-sync 98.2° inclination (WRS-2)
Crossing Time	~10:00 AM ± 15 minutes	~10:00 AM ± 15 minutes

Table 1-3. Comparison of Landsat 7 and Landsat 8 Observatory Capabilities

1.3.5 Rapid Data Availability

Landsat 7 data are downlinked and processed into standard products within 6 hours of acquisition. Level 1 and LandsatLook products are available through the USGS online interfaces. All users are required to register through the EROS Registration System (ERS) at https://ers.cr.usgs.gov/.

All Landsat data are accessible via the Internet for download at no charge via Hypertext Transfer Protocol Secure (HTTPS); there are no product media options. Available data can be viewed through a number of interfaces:

- EarthExplorer: https://earthexplorer.usgs.gov
- Global Visualization Viewer (GloVis): https://glovis.usgs.gov
- LandsatLook Viewer: https://landsatlook.usgs.gov

1.3.6 Enhanced IGS Access

Landsat 7 imagery of foreign landmasses has been directly downlinked to IGSs since early in the Landsat 7 mission. Historically, much of the data held internationally were unique, relative to each station's area of coverage, and were not duplicated in the USGS EROS archive.

This changed when the USGS Landsat Global Archive Consolidation (LGAC) effort began in 2010, with a goal to consolidate the Landsat data archives of all IGSs. Furthermore, as stipulated in the USGS-IGS Memorandum of Understanding (MOU), each IGS is now required to provide a copy of all newly downlinked Landsat 7 data to USGS EROS to support the LGAC effort.

1.4 Document Purpose

The Landsat 7 Data Users Handbook is a living document prepared by the USGS Landsat Project Science Office at the USGS EROS Center in Sioux Falls, South Dakota, and the NASA Landsat Project Science Office at NASA's GSFC in Greenbelt, Maryland.

The purpose of this handbook is to provide a basic understanding and associated reference material for the Landsat 7 Observatory and its science data products. In doing so, this document does not include a detailed description of all technical details of the Landsat 7 mission but focuses on the information needed by users to better understand the data products.

1.5 Document Organization

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Section 2 Observatory Overview

The Landsat 7 satellite was successfully launched from Vandenberg Air Force Base on April 15, 1999. The Delta II launch vehicle left the pad at 11:32 a.m. Pacific Daylight Time and performed flawlessly (see Figure 2-1). The spacecraft is a 5,000 pound-class satellite designed for a 705 kilometer (km), sun-synchronous, Earth mapping orbit with a 16-day repeat cycle. Its payload is a single nadir-viewing scanning instrument, the ETM+.

Figure 2-1. Landsat 7 Launch

Two radio frequency connections are used on Landsat 7. S-Band is used for commanding, tracking, and housekeeping telemetry operations, while X-Band is used for instrument data downlink. A 378 gigabit Solid State Recorder (SSR) can hold 42 minutes of instrument data and 29 hours of housekeeping telemetry concurrently. Power is provided by a single sun-tracking solar array (four 74" by 89.3" panels - 184 square feet) and two 50 amp-hour nickel-hydrogen batteries.

2.1 Concept of Operations

The fundamental Landsat 7 operations concept is to collect, archive, process, and distribute science data in a manner consistent with the operation of previous Landsat missions.

2.1.1 Orbit

The orbit of the Landsat 7 satellite is repetitive, circular, Sun-synchronous, and near-polar at a nominal altitude of 705 km (438 miles) at the Equator. The spacecraft crosses the Equator from north to south on a descending orbital node at 10:00 AM ±15 minutes on each pass. Circling the Earth at about 7.5 km/sec, each orbit takes approximately 99 minutes. The spacecraft completes just over 14 orbits per day thus covering the Earth between about 81 degrees north and south latitude (scene center latitude) every 16 days. Figure 2-2 illustrates Landsat's orbit characteristics.

In addition, as part of EOS, Landsat 7 and the NASA Terra satellite were launched and injected into identical 705 km, sun-synchronous orbits in 1999. This same day orbit configuration separates the satellites by about 15 minutes (i.e., equatorial crossing times of 10:00 a.m. ±15 minutes for Landsat 7 and 10:30 a.m. for Terra). A multispectral dataset having both moderate (30 meter) and medium to coarse (250 to 1000 meter) spatial resolution from Terra's Moderate-resolution Imaging Spectroradiometer (MODIS) is thereby acquired on a global basis repetitively and under nearly identical atmospheric, plant physiological, and Earth surface conditions.

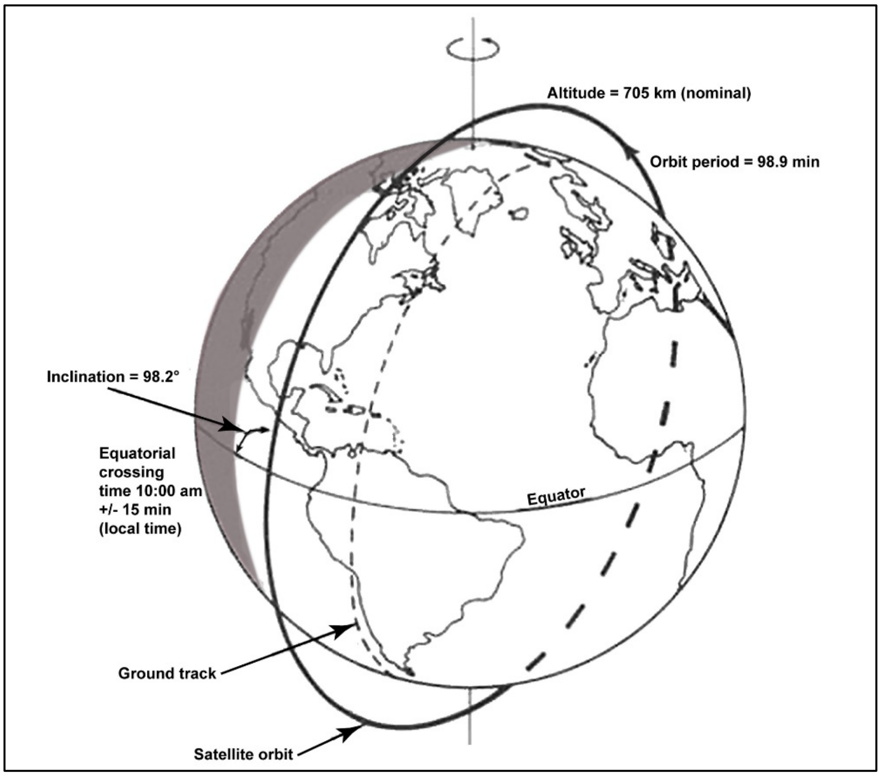

Figure 2-2. Illustration of Landsat 7 Orbit

2.1.2 Swath Pattern

Landsat 7 orbits the Earth in a preplanned ground track. The ETM+ sensor onboard the spacecraft obtains data along the ground track at a fixed width or swath as depicted in Figure 2-3. The 16-day Earth repeat coverage cycle for Landsat 7 is known as the swath pattern of the satellite. The paths scheduled for acquisition on any day can be viewed on the Landsat 7 Acquisition Calendar.

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

Table 2-1. Image Sidelap of Adjacent Swaths

At the Equator, adjacent swaths overlap at the edges by 7.3 percent. Moving from the Equator toward either pole, this sidelap increases because of the fixed 185 km swath width. This mission attribute is quite beneficial for repeat mapping of polar features such as the margin of Antarctica. Table 2-1 shows the amount of sidelap from 0 to 80 degrees latitude in 10-degree increments. Due to the ETM+ swath width, the maximum latitude limit for Landsat 7 coverage is ~82.5°.

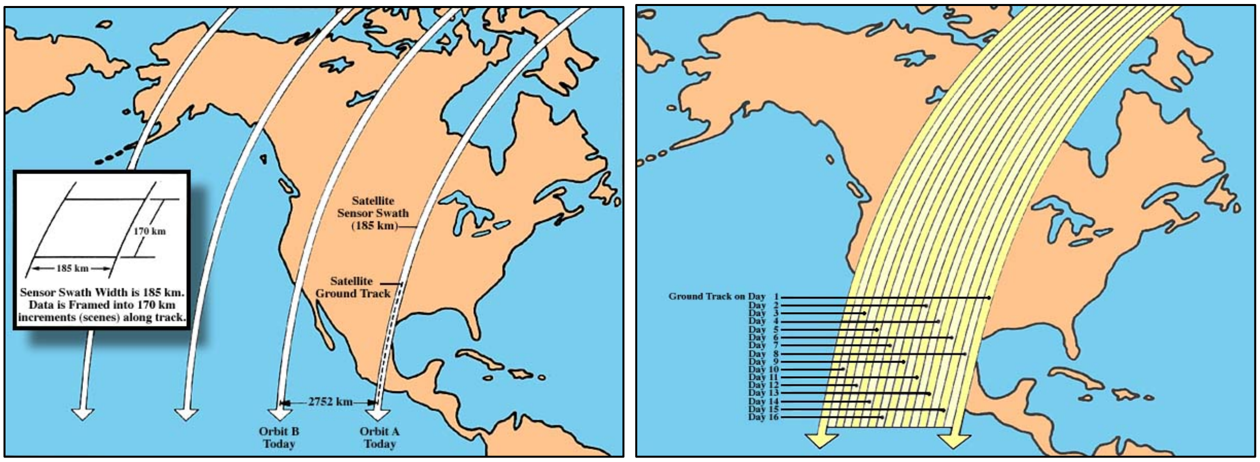

Figure 2-3. ETM+ Swath Separations for Single Day (left) and for Full 16-Day Cycle (right)

2.1.3 Worldwide Reference System (WRS)

The standard WRS-2 as defined for Landsat 4 and Landsat 5 was preserved for Landsat 7. (WRS-1 was used for Landsat 1-3, which had a higher orbit altitude and different swath pattern.) The WRS-2 indexes orbits (paths) and scene centers (rows) into a near-global grid system (for both daytime and nighttime portions of orbits) composed of 233 paths by 248 rows.

The term “row” refers to the latitudinal centerline across a frame of imagery along any given path. As the spacecraft moves along a path, the ETM+ scans the terrain below. During ground processing, the continuous data stream or subinterval of image data is framed into individual scenes that are each 23.92 seconds of spacecraft motion, resulting in 248 rows per complete orbit. The rows have been assigned in such a way that Row 60 coincides with the Equator (descending node). Row 1 of each WRS-2 path starts at 80° 46' N and the numbering increases southward to latitude 81° 51' S (Row 122). Then, beginning with Row 123, the row numbers ascend northward, cross the Equator (Row 184) and continue to latitude 81° 51' N (Row 246). Row 248 is located at latitude 81° 21' N, whereupon the next path begins. Also, there is a coverage hole at both poles where Landsat 7’s inclined orbit does not allow latitudinal coverage above -82º. Figure 2-4 graphically depicts the Landsat path/row scheme.

Successive orbits and spacecraft attitude are controlled to assure minimal variation to either side from the intended ground track. The WRScornerPoints.xls file lists the nominal latitude and longitude for the scene center and four corners of each WRS-2 scene. This includes the ascending rows that are generally not illuminated by the sun. The table uses the notation that positive latitude is north, negative latitude is south, positive longitude is east, and negative longitude is west. The table is sorted by path/row order. WRS-1 and WRS-2 path/row maps are available online in a variety of formats. The path/row number for a specific location is different in WRS-2 than in WRS-1.

The Landsat 7 Acquisition Calendar displays the acquisition dates of specific paths for Landsat 7.

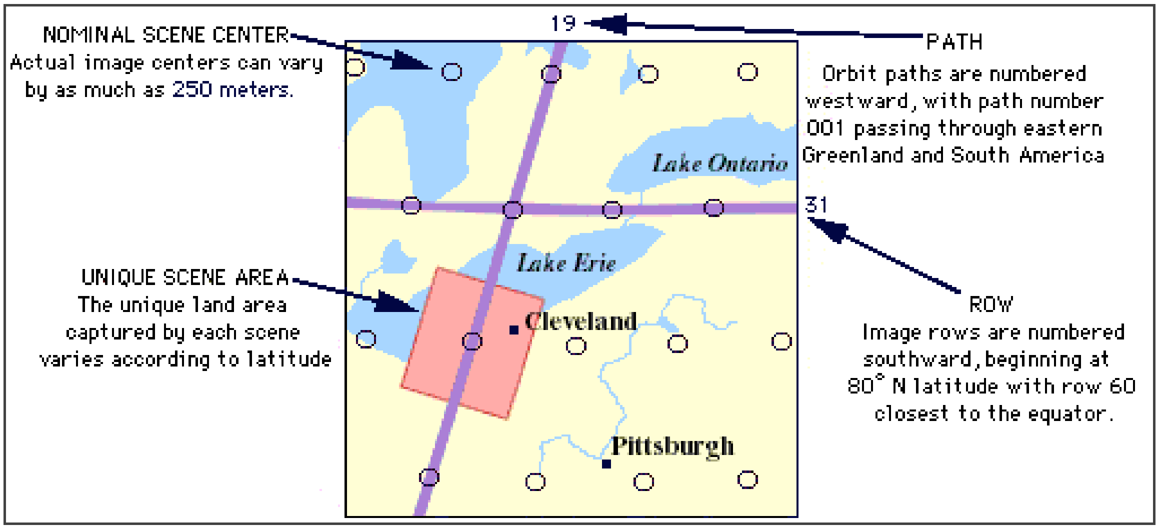

Figure 2-4. Illustration of the WRS-2 Path/Row Scheme

2.1.4 Scheduling

Planning and scheduling all satellite activities takes place in three categories: long-term planning, short-term planning, and daily scheduling.

2.1.4.1 Long-Term Planning

The primary goal of the Landsat 7 mission is to refresh the global land surface imagery archive. Because the Landsat 7 mission's orbit profile is a repetitive 16-day cycle, the LTAP (see Section 4) was designed years before the Landsat 7 satellite launch. This provided ample time for coordination with the science community, program management, international resources, and project elements. The LTAP also addresses the needs of land cover classes such as glaciers, reefs, tropical forests, and land ice. The Mission Operations Center (MOC) scheduling subsystem was built around the long-term plan and uses it to generate daily schedules of both instrument and SSR activities.

2.1.4.2 Short-Term Planning

The objectives of short-term planning are to schedule communication contacts for telemetry, tracking, and commanding services on the Landsat Ground Network (LGN). The system is designed to include special requests into the scheduling process and to generate daily reports summarizing the disposition of imaging requests and time-ordered scheduled ETM+ imaging events for the latest 37-hour period.

2.1.4.3 Daily Scheduling

On a daily basis, the MOC scheduling system generates a set of imaging, SSR activities, and X-Band downlink services based on a number of criteria including global refresh requirements, request priority, SSR or other resource availability, and cloud cover predictions. To assist in the scheduling process, the MOC receives planning aids from the flight dynamics subsystem within the MOC, cloud cover predicts from the National Centers for Environmental Prediction (NCEP) and assessed cloud cover feedback on newly archived imagery from the EROS Landsat Processing System (LPS).

2.1.5 Tracking and Spacecraft Control

The two-channel Radio Frequency (RF) communications system on Landsat 7 provides S-Band (narrowband) telemetry for housekeeping data and tracking ability. The S-Band communications are conducted through two omni S-Band antennas located on opposite sides of the spacecraft (nadir and zenith pointing). The zenith antenna is used for Tracking Data and Relay Satellite System (TDRSS) communications; the nadir antenna is used for LGN communications. Each antenna provides essentially hemispherical coverage.

Telemetry data are generated and recorded at all times and contain all of the information required to monitor and assess the health of the satellite, verify day-to-day operations, and assist in anomaly resolution. The MOC receives tracking telemetry on a daily basis that shows the position and velocity of the spacecraft. Tracking data are used to compute the actual spacecraft position and velocity for the last 61 hours and generate predicted orbit state vectors for the next 72 hours. The orbit state vectors must provide an attitude accuracy of 375 meters at 40 hours and must be uplinked daily in order to maintain the satellite within mission parameters.

The predicted orbit state vectors are compared against the old orbit state vectors in the same way the flight software makes this comparison on the satellite after the receipt of the new orbit state vectors load. Once validated, the new state vectors are up-linked to the satellite and activated. On-board software interpolates this new data to generate the positional information used for on-board navigation and contained in the Payload Correction Data (PCD).

2.1.6 Orbit Maneuvers

During the Landsat 7 mission, the MOC Operators perform three types of orbit maneuvers to ensure the safety of the satellite, as well as maintain that the satellite's orbit remains within the Landsat 7 mission parameters. The three types of orbit maneuvers are:

- In-plane maintenance
- Inclination maintenance
- Collision avoidance or risk mitigation

The in-plane maintenance maneuver, also called a drag make-up or delta-velocity maneuver, maintains the semi-major axis within an acceptable tolerance of the mission orbit semi-major axis. The semi-major axis is biased high and permitted to decay over time. The bias applied to the orbit varies with the amount of environmental drag, which is a function of solar activity. These maneuvers are performed every few weeks during a period of high environmental drag, and every few months during a period of low drag.

The inclination maintenance maneuver involves a yaw slew by approximately +/- 90 degrees. The operators perform the inclination maneuver to keep the satellite's descending node within a 30-minute box (09:45 a.m. to 10:15 a.m.). This type of maneuver was performed each fall until 2012, when it was performed in spring after an in-plane maneuver designed for a high-drag environment instead encountered low-drag and sent the spacecraft rapidly drifting out of its control box. The schedule returned to the fall the following year. In 2014 and 2015, smaller inclination maneuvers were performed in both the spring and fall, to conserve fuel and position the satellite for a long end-of-mission drift downward from the 10:15 a.m. extent of the box.

Collision avoidance or risk mitigation maneuvers are executed if the risk of a collision or close approach to space debris or another constellation is judged significantly high, based on inputs from the space debris monitoring agencies and the committee that monitors the constellations. Space debris is actively tracked, and a system has been initiated in recent years to give satellite operators notice of close approaches with debris. Additionally, the morning and afternoon Earth-observing constellations have grown over the years and occasionally there is a close approach between constellations.

The demand for orbit maneuvers is determined by the MOC flight dynamics subsystem, which uses tracking data from the Space Network (SN) and LGN stations, as well as housekeeping telemetry data to monitor the orbit, and decide when the orbit has been perturbed sufficiently to require an orbit adjust. The resulting maneuver is reviewed by the USGS Flight System Manager (FSM) and Flight Operations Team (FOT) Engineers.

Once the maneuver is approved, MOC Operators generate a set of satellite commands, which are then reviewed by the FOT Engineers. The FOT coordinates the orbit maneuver times and calculates post-maneuver position and velocity. On the day of the maneuver, the FSM makes the final decision to perform the maneuver and the FOT sends the command load to the satellite.

Following the maneuver, the MOC conducts TDRSS contacts for calculating the new orbit and evaluates the performance of the satellite components used during the orbit adjust. This information is used to calculate the remaining propellant on-board the satellite.

After many of the inclination maneuvers, imaging was performed while the ETM+ focal planes slowly returned to their nominal operating temperatures. The resulting engineering data was used to enhance the instrument calibration curves by extending them into the non-nominal operating temperature ranges.

2.2 Enhanced Thematic Mapper Plus (ETM+)

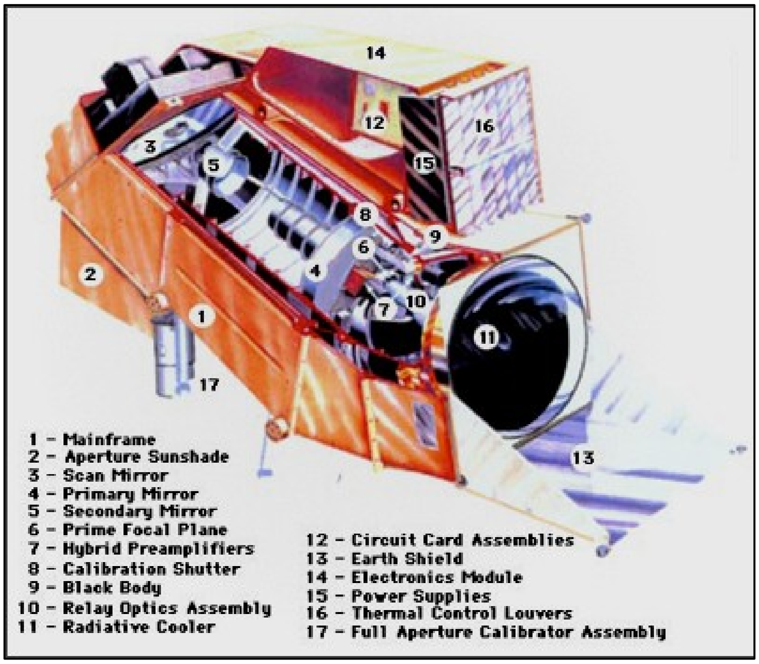

Figure 2-5. Cutaway View of ETM+ Sensor and Its Major Components

Landsat 7's sensor - the ETM+ (see Figure 2-5) - was built by Santa Barbara Remote Sensing (SBRS). The sensor is a derivative of the TM engineered for Landsat 4 and Landsat 5, but is more closely related to the ETM that was lost during the Landsat 6 launch failure. The primary performance-related enhancements of the ETM+ over the TM are the addition of two gain ranges, the panchromatic band (Band 8), the improved spatial resolution for the thermal band (Band 6), and the addition of two solar calibrators.

Reflected energy from the Earth's surface energy passes through a number of major ETM+ subsystems, depicted schematically in Figure 2-6, before the solid-state detectors at the focal plane can collect it. The bidirectional Scan Mirror Assembly (SMA) sweeps the detector's Line of Sight (LOS) in approximately west-to-east and east-to-west directions across track, while the spacecraft's orbital path provides the general north-south motion. As originally designed, a Ritchey-Chretien telescope focuses the energy onto a pair of motion compensation mirrors (i.e., Scan Line Corrector (SLC)) where it is redirected to the focal planes. The SLC is required due to the compound effect of along-track orbital motion and cross-track scanning, which would lead to significant overlap and underlap in ground coverage between successive scans, unless this is compensated for in the sensor design (see Section 2.2.3.3).

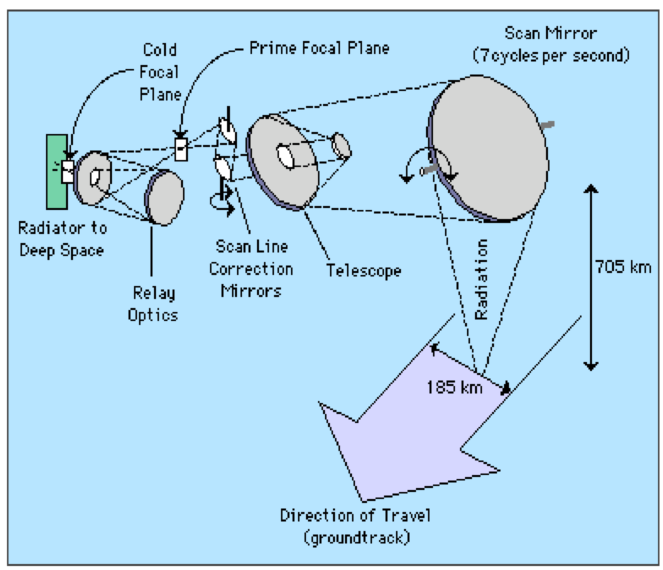

Figure 2-6. Illustration of ETM+ Optical Path from Target Area to Detectors on Focal Plane

The aligned energy encounters the Prime Focal Plane (PFP), where the silicon detectors for Bands 1-4 and Band 8 are located. A portion of the scene energy is redirected from the PFP by the relay optics to the Cold Focal Plane (CFP) where the detectors for Bands 5, 6, and 7 are located. The temperature of the CFP is maintained at a predetermined setting of 91 Kelvin (K) using a radiative cooler. The spectral filters for the bands are located directly in front of the detectors.

2.2.1 Detector Geometry

The relative position of all detectors from both focal planes with respect to their actual ground projection geometry is illustrated in Figure 2-7. The even-numbered detectors are arranged in a row normal to the scan direction while the odd-numbered detectors are arranged in a parallel row, off exactly one Instantaneous Field of View (IFOV) in the along-scan direction. This arrangement provides for a contiguous bank of 32, 16, and 8 detectors for Band 8, Bands 1-5 and 7, and Band 6, respectively. The detector arrays are swept left to right (forward) and right to left (reverse) by the scan mirror. With each sweep or scan, an additional 480 meters (32, 16, and 8 data lines at a time) of along-track image data is added to the acquired subinterval.

2.2.1.1 Band Offsets

During a scan, the actual ground observed by each band's detectors is not identical due to the horizontal spacing of detector rows within and between bands. Referring to the ground projection illustration in Figure 2-7, note the spacing between bands as measured in 30 meter or 42.5 microradian IFOVs. Taken individually, these numbers represent a band's unique leading edge preamble that occurs before coincident data are collected by a band's forward or reverse focal plane neighbor. Taken cumulatively, these numbers represent the first order zero fill offsets that LPS uses during L0R processing to achieve image registration of the raw, uncorrected data. Other factors such as detector offsets within a band and sample timing must be considered to calculate registration offsets accurately.

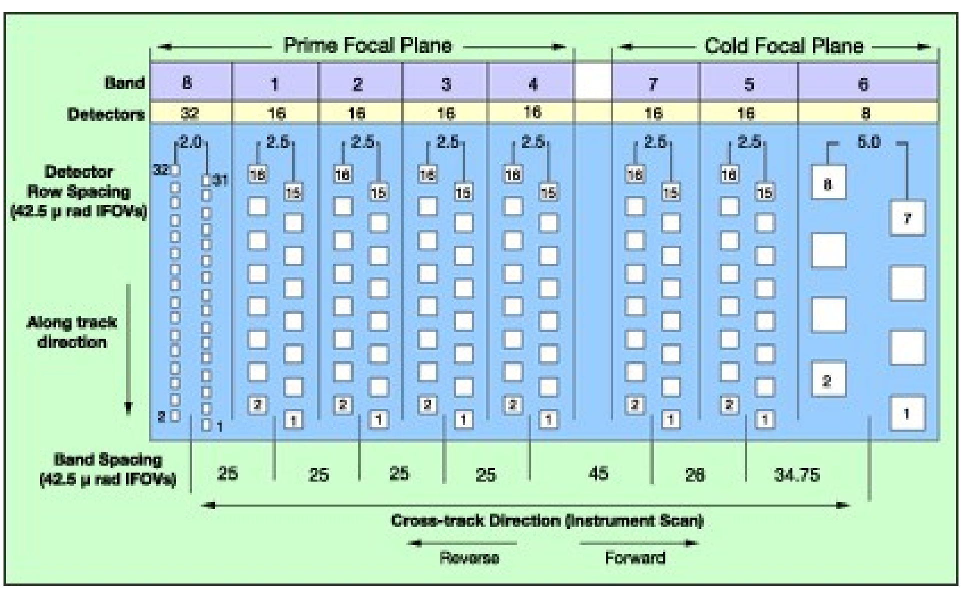

Figure 2-7. Detector Projection at ETM+ Focal Planes

2.2.1.2 Detector Offsets

Band 8 detector rows are separated by two 42.5μ IFOVs, which translate to four 15-meter samples. The Band 8 odd and even detectors are sampled simultaneously, twice per minor frame (i.e., one sample). The registration offsets for the odd and even detectors therefore always differ by four samples for both forward and reverse scans.

The detector rows within Bands 1-5 and Band 7 are separated by two and a half 42.5μ IFOVs. This design works because the multiplexer samples the even detectors one half of an IFOV later than the odd detectors within a minor frame of data. The delay effectively separates the odd and even detectors an integral multiple of IFOV's apart in sampling space. A two IFOV odd-to-even detector spacing is realized on forward scans while three IFOV spacing occurs on reverse scans. The registration offsets for forward and reverse scans always differ by these amounts.

The Band 6 odd and even detectors are separated by five 42.5μ IFOVs, which translates to 2.5 Band 6 samples. The odd and evens are sampled, however, in alternating minor frames, which separate the odd and even detectors, an integral multiple of IFOVs. A two Band 6 IFOV odd-to-even detector spacing is realized on forward scans while a three Band 6 IFOV spacing occurs on reverse scans. The registration offsets for forward and reverse scans always differ by these amounts.

2.2.1.3 Registration Offsets

Over the years, different Ground System Engineers have characterized Landsat sensor focal plane offsets in different ways that resulted in negative and positive offsets depending upon the forward and reverse scan directions and origin of the image grid. For ETM+, all shifts are declared as positive from column 1 in the 0R image buffers. These 8-bit buffers are 3300, 6600, and 13,200 elements in size for the 60-, 30-, and 15-meter bands, respectively.

2.2.2 ETM+ Sample Timing

The ETM+ data stream is composed of a continuous succession of major frames. A major frame contains the data for an entire period of one complete scan of the ETM+ scan mirror. A major frame is partitioned into minor frames—a specific pattern for organizing groups of ETM+ data words. This pattern is based on the architecture of the Landsat 7 Auxiliary Electronics Module (AEM) that samples, digitizes, and groups analog video signals from the ETM+ scanner to form scene data. The minor frame data structure is 85 words (8 bits) in length consisting of 16 separate groups of 5 words, 4 words from Band 6 along with a one-word spare.

The AEM generates the line sync code at the beginning of each new scan line and inserts it into the minor frame zero position, which is also called Scan Line Start (SLS). The time code pattern preempts all video data except Band 6 even though its data for the first minor frame is invalid. The six minor frames immediately following the SLS minor frame describe the spacecraft time code as illustrated in Figure 2-8. The Band 6 data alternate between the odd and even detectors for each successive minor frame and are synchronized to odd pixel data for the first minor frame. The first valid Band 6 data are from the even detectors and occur in minor frame two.

Scene data transmission for the other bands starts at the minor frame boundary immediately following the time code and continues until the start of the next end-of-line pattern code, which is mechanically / optically triggered. For reference, 6,313 minor frames of scene data are nominally transmitted during any given scan cycle. The digitized scene data can be organized into either of two minor frame scene data formats as depicted in Figure 2-8 and Figure 2-9. Bands 1-5 are allocated to Format 1 while Band 7 and Band 8 are allocated to Format 2. The two Band 6 data streams allocated to Format 1 and Format 2 are obtained with low gain and high gain settings, respectively.

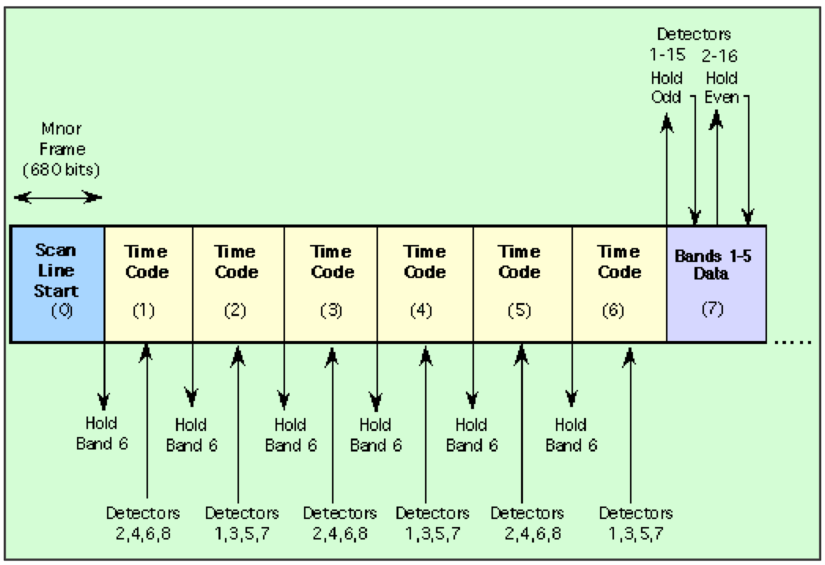

Figure 2-8. Illustration of ETM+ Sample Timing, Format 1

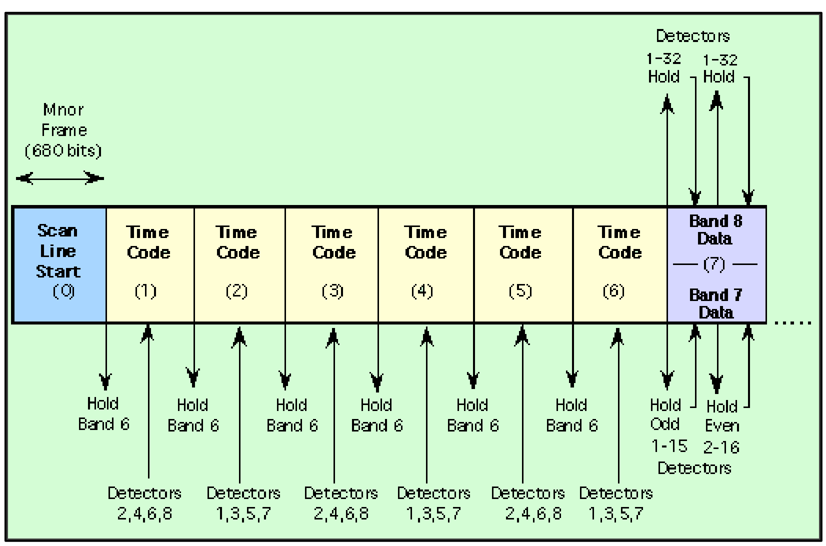

Figure 2-9. Illustration of ETM+ Sample Timing, Format 2

2.2.3 ETM+ Subsystems

2.2.3.1 Scan Mirror Assembly (SMA)

The SMA provides the cross-track scanning motion to develop a 185 km-wide scene swath. The SMA consists of a flat mirror supported by flex pivots on each side, a torquer, Scan Angle Monitor (SAM), two leaf spring bumpers, and Scan Mirror Electronics (SME). The motion of the mirror in each direction is stopped by the bumper and is boosted by precision torque pulses during the turnaround period. The SME microprocessor as determined from the SAM mirror angle pulses determine the amount of torque applied. SAM mirror angle pulses are used by the multiplexer to synchronize the detected scene data. There are two redundant sets of SMEs: SME 1 and an identical backup package, SME 2. Additionally, both SMEs have a primary SAM mode of operation and a backup Bumper Mode of operation. Table 2-2 lists the SMA characteristics.

Current Performance

Regular monitoring has revealed the ETM+ scan period is increasing with time due to growth in turnaround time, probably caused by bumper wear. However, the active scan time is showing increased variability, especially in the forward scans. The rate of growth of turnaround time, however, appears to be stable. The impact to ETM+ data is that scan gaps will gradually increase with time. Also, the scan mirror could, theoretically, lose synchronization with the calibration flag if scan time gets too long. This would effectively end the Landsat 7 mission. However, this mirror behavior is similar to what was observed in Landsat 5 TM mission's lifetime and has proven to be manageable over the Landsat 7 mission.

Parameter	Specification
Swath width at 0 degrees North	185 km
Swath width at 40 degrees North	187 km
Scan length at 0 degrees North	480 m
Scan length at 40 degrees North	484 m
Active scan amplitude	7.695 degrees
Scan period	142.925 milliseconds
Scan frequency	6.997 Hz
Active scan time	60.743 milliseconds
Turnaround time	10.719 milliseconds
Object plane scan rate	4.42191 rad/sec
Mirror scan rate	2.21095 rad/sec
30 m IFOV dwell time	9.611 microseconds
Scan Line Length (excludes turn around)	6320 IFOVs
Inertia	< 10.83 kg-cm-(sec^2)
Clear aperture	53.467 cm x 41.275 cm

Table 2-2. Scan Mirror Assembly Characteristics

Physical wear of the mirror bumpers led to growth in time to synchronize the scan mirror and calibration flag at instrument start-up. With the rate of wear rapidly increasing, the instrument warm-up time was being increased to compensate for this while the EROS product generation systems were updated to handle bumper mode processing. On April 1, 2007, the ETM+ was transitioned from the SAM mode to Bumper mode. This also impacts the scan mirror deviation correction.

The Gimbaled X-Band Antenna (GXA), when maneuvered in an across-track slew, sometimes disturbs the ETM+ scan mirror. The resulting impact to ETM+ data is a wider than normal (see Figure 2-10) variation in scan line length. Most extreme examples exceed the maximum allowable scan length leading, which leads to dropped scans. This phenomenon was not observed on earlier missions because pointable X-Band antennae are a new component on Landsat 7.

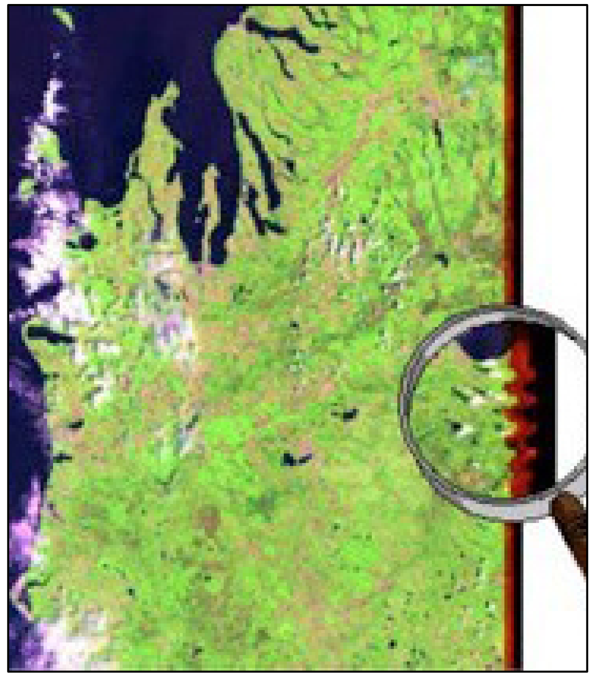

Figure 2-10. ETM+ GXA Data Anomaly caused by an X-Band Antenna Across-Track Slew Maneuver

The scan mirror may lose synchronization or, in extreme cases, restart during imaging. Such an occurrence is correlated with regions of high electron flux (see Figure 2-11) at 705 km orbital altitude particularly in Polar Regions and within the South Atlantic anomaly. The correlation was confirmed by a July 2000 solar flare, which resulted in 14 anomalies in a single day. The impact to ETM+ data is dropped scans and calibration flag incursions (see Figure 2-11) into the Earth imaging area. The scan mirror controller sees an "extra" timing pulse and thus loses synchronization with the mirror calibration flag. This phenomenon may also have occurred on Landsat 5 and impacted TM data.

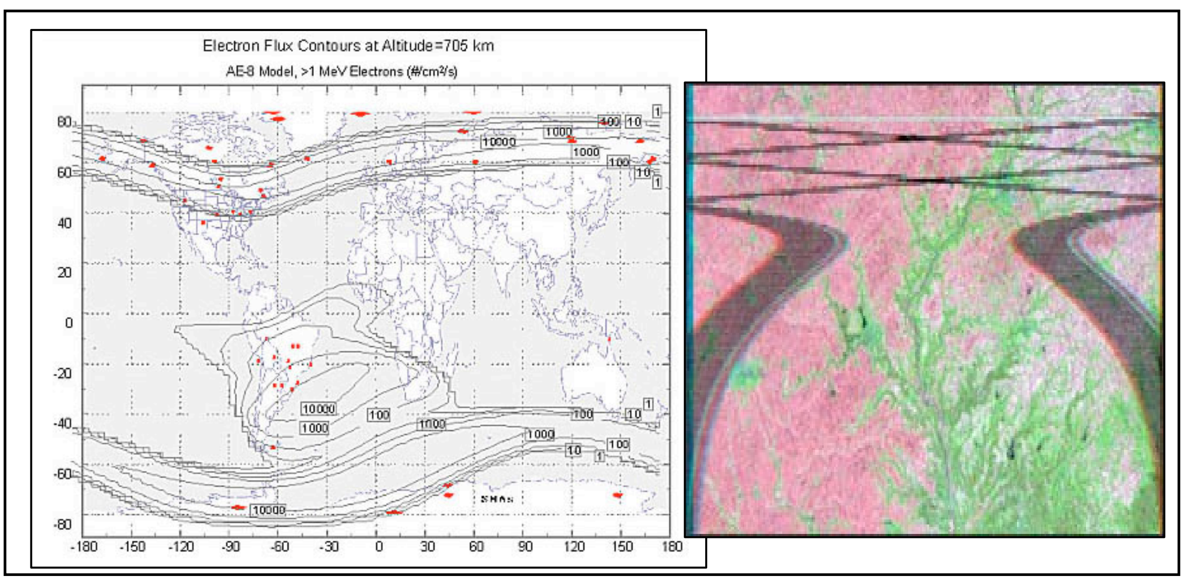

Figure 2-11 . Modeled Regions of High Electron Flux at 70 5 km (left) and GXA Anomaly in Regions of High Electron Flux (right)

2.2.3.2 Telescope

The telescope is a Ritchey-Chretien configuration with a primary and secondary mirror and baffles. Both the tube-like central baffle and the outer housing have a series of annular baffles for stray light control. The telescope structure is constructed using a graphite-epoxy laminate, which has a very low coefficient of thermal expansion and thus eliminates problems due to thermal expansion. However, the graphite-epoxy laminate is hygroscopic and can change dimensions due to moisture absorption. Table 2-3 summarizes the telescope's characteristics.

Parameter	Specification
Primary mirror clear aperture outer diameter	40.64 cm
Primary mirror clear aperture inner diameter	16.66 cm
Telescope effective clear aperture	1020 cm^2
Effective focal length	243.8 cm
f/#	6.0
Mirror material	Ultra-Low Expansion (ULE) glass
Mirror coating	Enhanced silver

Table 2-3. ETM+ Telescope Characteristics

2.2.3.3 Scan Line Corrector (SLC)

The SLC is an electro-optical mechanism composed of two parallel mirrors set at an angle on a shaft. The SLC is positioned behind the primary optics and compensates for the along-track motion of the spacecraft occurring during an active SMA cross-track scan. As a result, a rectilinear scan pattern is produced using the SLC instead of the zigzag pattern that would be produced without it (see Figure 2-12). Table 2-4 lists the SLC characteristics.

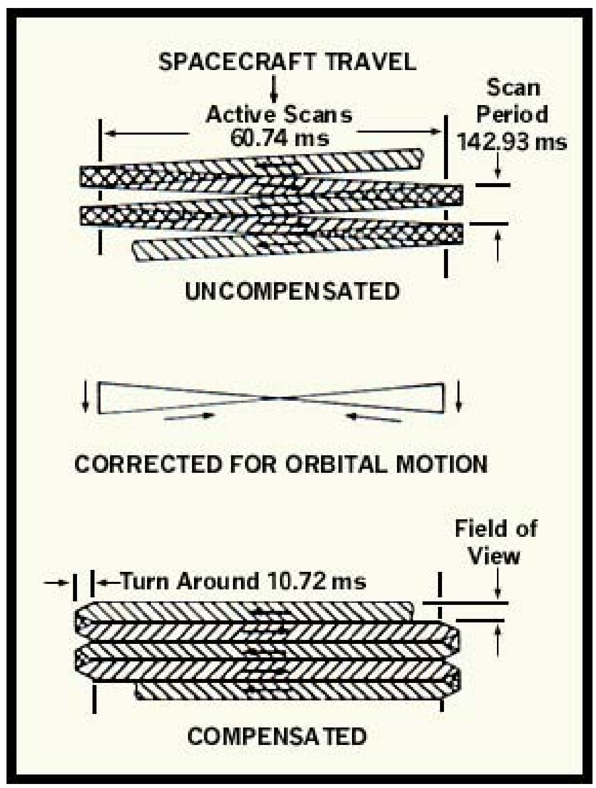

Figure 2-12 . ETM+ SLC Effect

Current Performance

On May 31, 2003, the SLC failed at approximately 21:45 Universal Time Code (UTC). Subsequent efforts to recover the SLC were not successful, and the problem is permanent for the mission. Without an operating SLC, the ETM+ LOS now traces a zig-zag pattern along the satellite ground track (see Figure 2-12) resulting in wedge shaped scan-to-scan gaps (and alternating overlap areas), which increase in magnitude away from nadir.

As a result, the imaged areas are duplicated, with a width that increases toward the edge of the scene. When the Level 1 data are processed, the duplicated areas are removed, leaving data gaps. An estimated 22 percent of any given scene is lost due to the SLC failure. The maximum width of the data gaps along the edge of the image would be equivalent to one full scan line, or approximately 390 to 450 meters and the location of the missing scan lines vary from scene to scene. Figure 2-13 shows the scan gaps in a Landsat 7 SLC-off image.

Parameter	Specification
Scan frequency	13.99 Hz
Scan period	71.462 ms
Scan rate in object space	9.610 µrad/sec
SLC rotation rate	576.6 µrad/sec
SLC linear scan angle	35.02 µrad
Linear scan angle in object space	583.7 µrad
Mirror separation	4.064 cm
Linear image displacement amplitude	0.14224 cm
Linear image displacement rate	23.4188 cm/sec
Mirror material	Nickel-plated beryllium
Mirror coating	Enhanced silver

Table 2-4. Scan Line Corrector Design Parameters

Despite this, Landsat 7 ETM+ is still capable of acquiring useful image data with the SLC turned off (SLC-off), particularly within the central portion of any given scene (see Figure 2-13). Various interpolation and compositing techniques were investigated to expand the coverage of useful data. An interpolation example can be seen in Figure 2-13, which suggests but does not fully detail the impact on image quality.

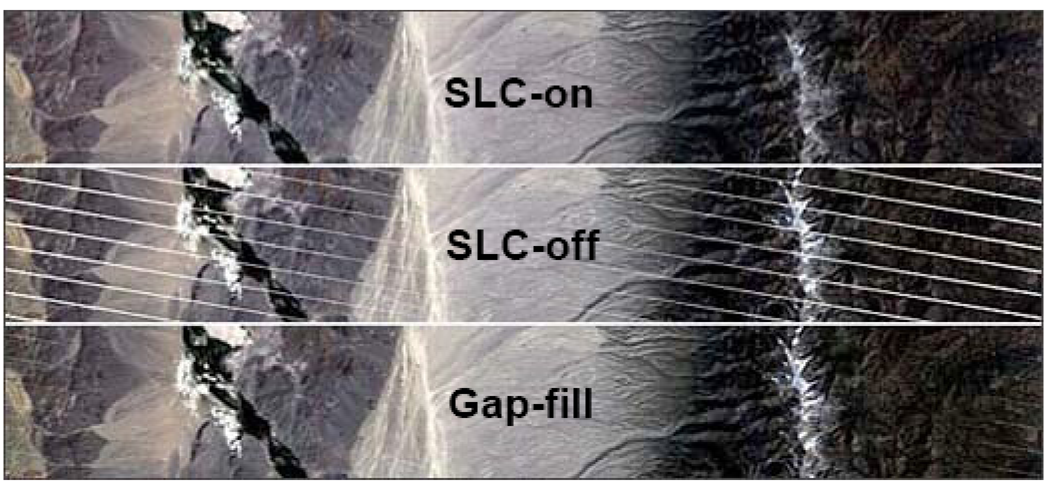

Figure 2-13. SLC-On, SLC-Off, and Gap-Fill

In Figure 2-13, the top image shows a subset of an SLC-on scene. The middle image shows a scene from the same area after the SLC failed. The bottom image shows the middle image with the SLC-off gaps largely filled by interpolation.

Besides interpolating across these unresolved areas, gap-filled products can be produced by using two methods: Phase One, which used a full Landsat 7 image (pre-

2003) to fill the gaps of the SLC-off scene (i.e., using data from the top panel in Figure 2-13 to fill in the gaps in the middle panel); and Phase Two, which incorporated more than two SLC-off scenes together to create a final product:

- Phase One: SLC-off to SLC-on - 6/1/2004 to 11/18/2004
- Phase Two: SLC-off to SLC-off - after 11/18/2004 to 2008 when the Open Data Policy was established.

To better characterize the SLC-off scenes in support of Phase Two, a gap phase statistic was added to the scene metadata to specify the location of the gap pattern relative to the scene center. This statistic is used to find another SLC-off acquisition of the same WRS-2 scene that could be used to fill in the gaps of the first image. Additionally, the browse product was modified to show the gap size, in pixels, across the width of the image. This provides the user with an idea of the gap size in their area of interest.

In part due to these efforts and the undisturbed central portion of each scene, as well as other enhancements to image processing of ETM+ data by ground systems, the USGS decided to continue the Landsat 7 mission, acquiring ETM+ image data in "SLC-off" mode since July 14, 2003.

2.2.3.4 Prime Focal Plane (PFP)

The PFP assembly consists of three major subassemblies; the Prime Focal Plane Array (PFPA) and two preamplifier stacks. The PFPA is located at the focal plane (surface) of the telescope. Table 2-5 lists its characteristics. The PFPA is a monolithic silicon focal plane made up of five detector arrays: Band 1 through Band 4 and Band 8 (panchromatic). The arrays for Band 1 through Band 4 contain 16 detectors divided into odd-even rows. The array for Band 8 contains 32 detectors also divided into odd-even rows. The system focus is optimized for Band 8, which has the highest spatial resolution. The preamplifiers are mounted on the PFP assembly and consist of two stacks of flat hybrid modules. On top of each stack is a cylindrical, black radiative cooling tower to help dissipate the heat from the preamplifiers.

Parameter	Bands 1-4	Band 8
Number of detectors	16 per band	32
Detector size	0.0103632 x 0.0103632 cm	0.0051816 x 0.0044958 cm
Detector area	10.741914 x 10^{-5} cm^2	2.50064016 x 10^{-5} cm^2
IFOV size	42.5 µrad	21.25 µrad x 18.5 µrad
Center to center spacing along track	0.0103632 cm	0.0051816 cm
Center to center spacing between rows	0.025908 cm	0.0207264 cm

Table 2-5. Prime Focal Plane Assembly Design Parameters

2.2.3.5 Relay Optics

The ETM+'s Relay Optics consist of a graphite-epoxy structure containing a folding mirror and a spherical mirror, which are used to relay the imaged scene from the PFPA to the Band 5, 6, and 7 detectors on the Cold Focal Plane Array (CFPA). Table 2-6 lists the characteristics of the Relay Optics. The Relay Optics have a magnification of 0.5. This magnification is used because of the reduced physical size of the Band 6 detectors.

Parameter	Specification
Folding mirror clear aperture outer diameter	7.9756 cm
Folding mirror clear aperture inner diameter	1.36398 cm
Spherical mirror clear aperture diameter	14.06652 cm
Magnification	0.5
f/#	3.0
Mirror material	ULE glass
Mirror coating	Aluminum, SiO overcoat

Table 2-6. Relay Optics Design Parameters

2.2.3.6 Cold Focal Plane (CFP)

The CFP assembly is mounted on the cold stage of the Radiative Cooler (RC), operates at a nominal temperature of 91.4 K, and can be controlled to one of three set points (91.4 K, 95 K, or 105 K) by a heater on the back of the substrate. The higher temperatures are backups in case the RC efficiency degrades. Table 2-7 lists the characteristics of the CFP assembly. The CFP assembly contains the detector arrays for Bands 5, 6, and 7. Each band is a separate array. The Band 5 and Band 7 arrays contain 16 detector elements. The nominal spatial resolution of Band 5 and Band 7 is the same as Band 1 through Band 4. The Band 6 array is fabricated from mercury cadmium telluride. This photoconductive array shows a significant decrease in responsivity from 90 K to 105 K. The Band 6 array contains eight detector elements.

Parameter	Bands 5-7	Band 6
Number of detectors	16 per band	8
Detector Size	0.004826 cm x 0.0051816 cm	0.0103632 cm x 0.0103632 cm
Detector Area	10.741914 x 10^{-5} cm^2	2.50064016 x 10^{-5} cm^2
IFOV size	42.5 μrad x 39.4 μrad	42.5 μrad x 85.0 μrad
Center to center spacing along track	0.0051816 cm	0.0103632 cm
Center to center spacing between rows	0.012954 cm	0.025908 cm

Table 2-7. Cold Focal Plane Design Parameters

2.2.3.7 Radiative Cooler (RC)

The RC cools the CFP by radiating internal heat out to cold space. It has a cold stage, an intermediate stage, a radiation shield, and a combination Earth shield and cooler door. Temperature-controlled outgas heaters (controlled to 318 K) are mounted on both the cold and intermediate stages to provide temporary heating of the cold surfaces should on-orbit contamination occur. The cold stage outgas heater also serves as a backup for the CFP heater. The flat rectangular corners of the RC structure that extends beyond the main circular cross section serves as radiation elements to dissipate heat from the Bands 5, 6, and 7 preamplifiers that are inside.

Table 2-8 shows the RC's characteristics.

Parameter	Specification
Horizontal field of view	160°
Vertical field of view	114°
Intermediate stage radiator area	660 cm^2
Cold stage radiator area	435 cm^2
Nominal intermediate stage temperature	134 K
Cold stage temperature	91.4 K
Cold stage minimum temperature	82 K
Outgas temperature - both temperature - both stages	318 K
Cold stage backup temperatures	95 K, 105 K

Table 2-8. Radiative Cooler Design Parameters

2.2.3.8 Spectral Filters

The nominal wavelength location of the ETM+ spectral bands and the nominal ETM+ IFOV size and associated ground resolution, for a 705-km satellite altitude, are shown in Table 2-9. The ETM+ spectral bandwidth is determined by the overall combination of all optical elements, the spectral filters, and the detector response. The spectral filters, located immediately in front of each detector array, are the dominant items that establish the optical bandpass for each spectral band. The PFPA has a filter housing that contains filters for Band 1 through Band 4 and the panchromatic band, Band 8. The CFPA has a filter housing that contains filters for Bands 5, 6, and 7.

Spectral Band	Wavelength width (µm)	IFOV Size (µm)	Resolution (m)
1	0.450 to 0.515 ± 0.005	42.5 x 42.5 ±4.3	30
2	0.525 to 0.605 ± 0.005	42.5 x 42.5 ±4.3	30
3	0.630 to 0.690 ± 0.005	42.5 x 42.5 ±4.3	30
4	0.775 to 0.900 ± 0.005	42.5 x 42.5 ±4.3	30
5	1.550 to 1.750 ± 0.010	39.4 x 42.5 ±4.3	30
6	10.40 to 12.50 ± 0.100	85.0 x 85.0 ±9.0	60
7	2.080 to 2.350 ± 0.020	39.4 x 42.5 ±4.3	30
8	0.520 to 0.900 ± 0.010	18.5 x 21.3 ±4.3	15
Detector wavelength limits have the same ± uncertainty Resolution is the nominal pixel ground spatial resolution			

Table 2-9. ETM+ Spectral Bands, IFOV Size, and Ground Resolution

2.3 Spacecraft Overview

The Landsat 7 platform provides a variety of elements necessary for mission success, including power, orbit and attitude control, telemetry and communications, and data storage and transmission capabilities for the ETM+ sensor.

The satellite attitude control uses precision mode, which is a combination of stellar and inertial guidance sensors to maintain the spacecraft platform within 0.015 degrees of Earth pointing. Narrowband communications include processing of real-time and stored commands, processing and authentication of command messages, and transmission of telemetry data, which is the collection of housekeeping and satellite processor reports.

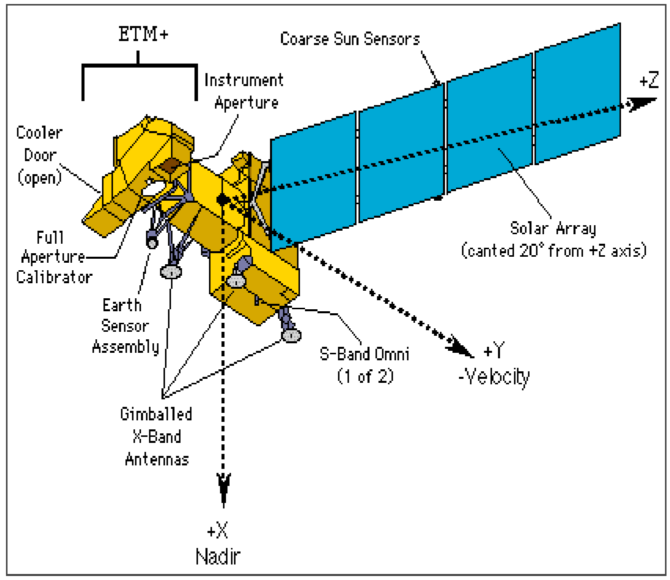

Figure 2-14 . Landsat 7 Satellite as Viewed from Sun-Facing Side

Wideband communications for payload data transmission to the ground incorporates four X-Band transmitters, switchable to three steerable antennas. Also, an on-board SSR is used to store imagery when out of view of ground stations, for subsequent transmission to the ground when the satellite is back within a ground station's view.

The on-board processor performs autonomously executed functions for wideband communications, electrical power management, and satellite control. These include attitude control, redundancy management, antenna steering, battery management, solar array pointing maintenance, thermal profile maintenance, and stored command execution. Figure 2-15 shows the current (ca. 2017) status of the individual Landsat 7 satellite subsystems.

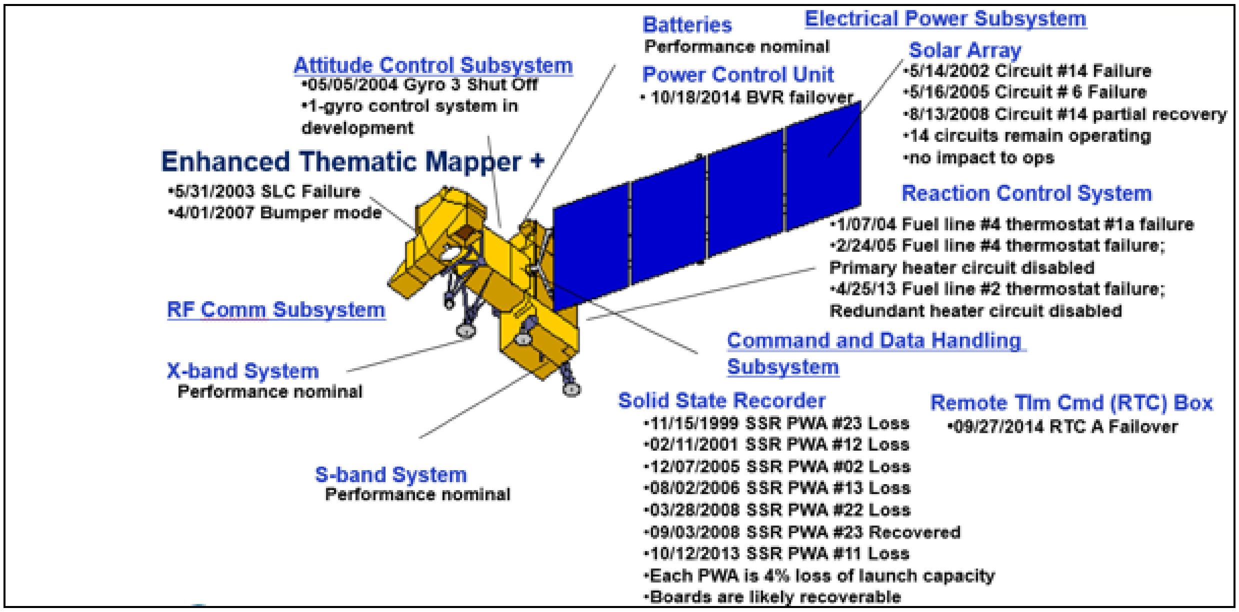

Figure 2-15. Status of Landsat 7 Spacecraft and Subsystems (ca. 2019)

2.4 Solid State Recorder (SSR)

The SSR is used to capture wideband science data from the ETM+ and narrowband housekeeping telemetry data from satellite subsystems. The SSR records and plays back data in numbered logical blocks, which are used by the MOC in commanding the recorder.

The SSR accepts two inputs from the ETM+ at 75 Megabit per Second (Mbps). The SSR was designed to hold up to 42 minutes (approximately 105 scenes) of data at 150 Mbps. Memory board shutdowns over the years, likely due to single event upsets, have reduced the capacity to approximately 84 scenes. The boards are believed recoverable, should Program Management deem it necessary to make the attempt. For now, the reduced capacity is not adversely impacting the LTAP.

The SSR records ETM+ Channel Access Data Units (CADU) as two bitstreams, each at a nominal rate of 75 Mbps. CADUs are recorded in the same order as received from the ETM+. Partial CADUs may be recorded if the ETM+ collection interval extends beyond the commanded SSR record interval, if the ETM+ is turned off before the end of the SSR data recording area is achieved, or as a result of a ground command to disable wideband recording.

During playback, the two 75 Mbps bitstreams are read out of memory and sent to the broadband switching unit. A second pair of 75 Mbps bitstreams can also be played back for a total aggregate rate of 300 Mbps. The bitstreams include the CADUs generated by the ETM+. Record intervals, each corresponding to an ETM+ collection interval, which consists of one or more Landsat scenes, may be subdivided for playback if more than one scene is collected. In this case, each resulting subinterval is defined such that data in the vicinity of each subinterval boundary are included (redundantly) with both subintervals. Each subinterval includes all of the CADU data required to process the subinterval as a separate ETM+ collection. As a result, individual subintervals may contain partial CADUs. The SSR contains error detection and a correction capability to preserve the integrity of the stored wideband and narrowband data. Reed-Solomon encoding is performed on record while Reed-Solomon decoding is performed on playback to recover data from possible dynamic Random Access Memory (RAM) list errors.

Narrowband data are captured by the SSR from the telemetry data formatter. The SSR accepts two input rates of 1.216 Kilobits per Second (Kbps) or 4.864 Kbps and plays back stored telemetry data at 256 Kbps to the S-Band transponder. The SSR is capable of either recording or playing back wideband data (but not both simultaneously) while simultaneously recording and/or playing back narrowband telemetry data. S-Band telemetry data are stored separately from wideband image data downlinked by the X-Band transponder and can be recorded when the wideband capability is shut down due to anomalies or power concerns.

2.5 Ground System

2.5.1 Overview

The Landsat 7 ground system consists of both Landsat 7 unique components as well as institutional services. The Landsat 7 unique components include the MOC, LGN, LPS, LPGS, and IAS (both explained further in Section 5), the Landsat Archive Manager (LAM), and a number of IGS.

The institutional support systems consist of the SN, the EOS Near-Earth Network (NEN), NCEP, the Land Processes Distributed Active Archive Center (LP DAAC) at EROS (used from 1999–2004), and the NASA Integrated Support Network (NISN).

The ground system context diagram in Figure 2-16 illustrates both the unique and institutional components and their data flow relationships from the satellite to the end users of the data.

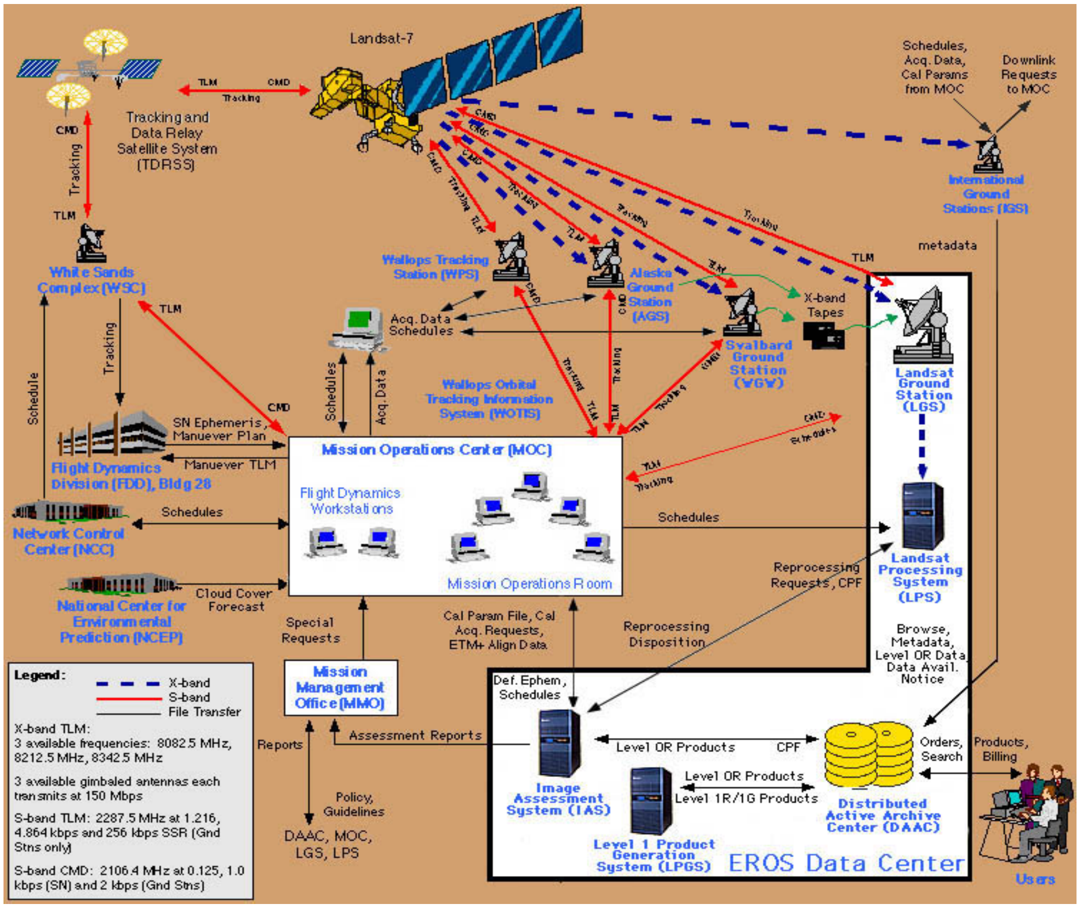

Figure 2-16 Landsat 7 End-to End Data Flow

2.5.2 Unique Landsat Ground System Components

2.5.2.1 Mission Operations Center (MOC)

The MOC, located at NASA GSFC, is the focal point for all space vehicle operations. The MOC provides the facilities, hardware, software, procedures, and personnel required to accomplish Landsat 7 planning and scheduling, to command and control the Landsat 7 space vehicle, to monitor its health and status, to analyze the performance of the space vehicle, and to maintain flight and MOC ground software. The MOC also detects, investigates, and resolves spacecraft anomalies. Flight Dynamics functions (such as maneuver planning, planning aid generation, and orbit determination) have been incorporated into the MOC systems. The MOC is staffed by the FOT, which comprises Console Analysts, Mission Planners, Flight Dynamics Engineers, Subsystem Engineers, and Supervisor / Managers.

2.5.2.2 Landsat Ground Network (LGN)

The Landsat 7 Ground Network includes four stations:

- LGS – Landsat Ground Station, Sioux Falls, South Dakota, USA
- SGS – Svalbard Ground Station, Svalbard, Norway

- ASN – Australian Ground Station, Alice Springs, Australia
- NPA – North Pole Ground Station (NPA3 and NPA4), North Pole, Alaska, USA

These ground stations are receiving sites for the X-Band downlinks of ETM+ science data from the satellite. They downlink both real-time and playback ETM+ wideband data directly from the Landsat 7 spacecraft by way of one or two 150 Mbps X-Band return links, each at a different frequency. The SGS, ASN, and NPA stations do not do any further processing but forward the downlinked data to the LGS via high-speed communication lines. The LGS separates each X-Band data into two 75 Mbps channels (I and Q) and transmits the acquired wideband data over 75 Mbps LGS output channels to the LPS where they are recorded and made available for further processing.

The LGS, NPA, and SGS stations conduct S-Band communications with the satellite, sending command and data loads, and receiving real-time and playback telemetry data. These stations also support spacecraft tracking. The ASN is capable of receiving S-Band downlinks from the satellite but is not currently used for command and data uploads or for tracking.

In addition to the ground sites, Landsat 7 uses TDRSS, operated by the SN headquartered at NASA GSFC. TDRSS enables S-Band downlink of real-time and stored housekeeping data and uplink of command data. These are used for Landsat 7 real-time command and telemetry monitoring during on-orbit operations on both a scheduled basis as well as for possible emergency operations on a call-up basis. Data rates are limited by the absence of a high-gain antenna on Landsat 7; therefore, housekeeping recorder dumps are not supported. TDRSS is also used for tracking data collection for generation of Landsat 7 spacecraft orbital state vectors for use in precision attitude control.

2.5.2.3 International Ground Stations (IGS)

The IGSs are satellite data receiving stations located around the world. They provide data reception, processing, and distribution services for their user community. They receive Landsat 7 payload data via X-Band direct downlink. The coverage areas for the IGS depict the Earth’s land areas that are regularly imaged. The X-Band direct downlink data includes the PCD required for image processing.

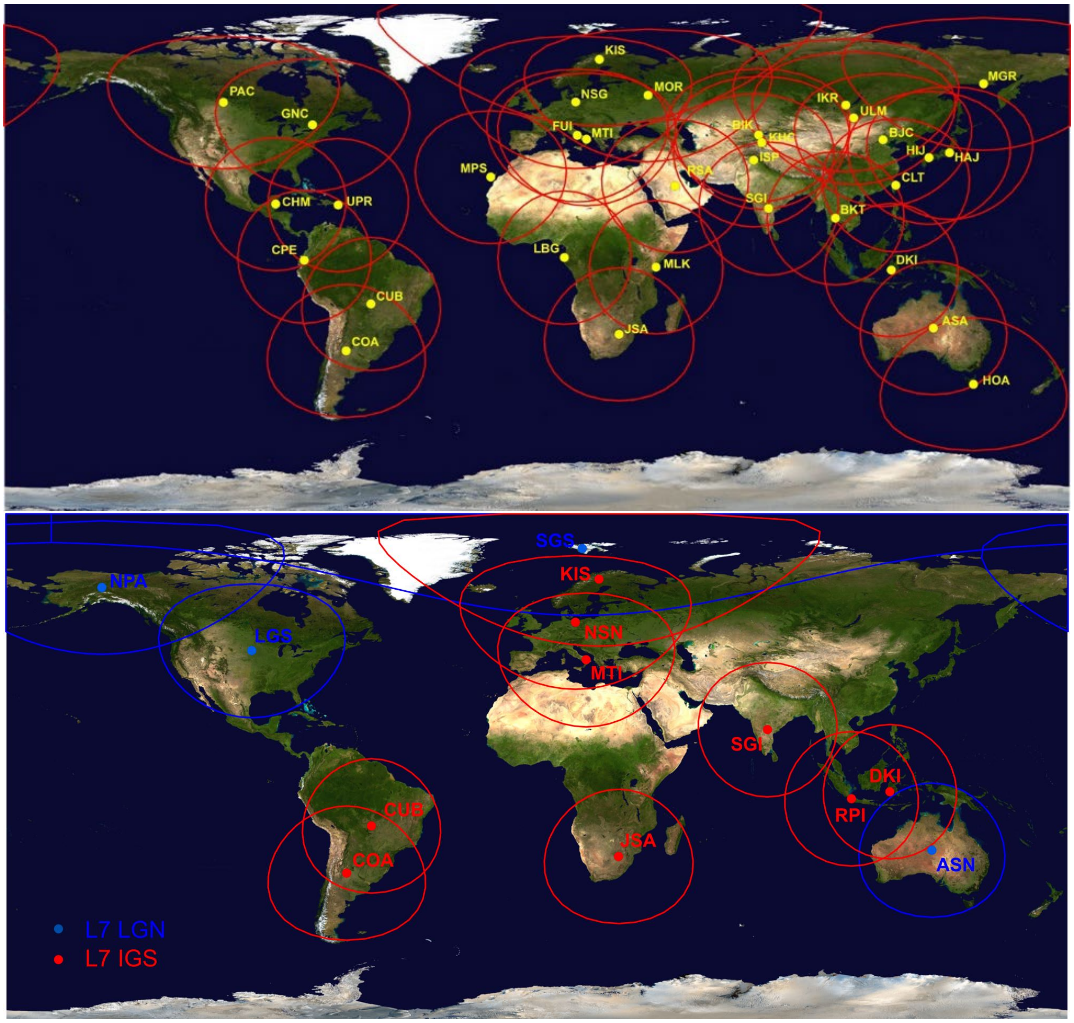

Figure 2-17. Historical International Ground Stations (above) and Active Landsat 7 Ground Stations (below)

Earlier in the Landsat 7 mission, the IGS used an online tool to submit downlink requests for the land scenes within their station view, assigning relative priorities to the scenes to aid in scheduling. Due to duty cycle considerations and the large number of participating IGSs, it was not a given that all IGS downlink requests would be scheduled; the priorities were used in the decision process for deciding which scenes to reject, if necessary. Use of the tool was discontinued in 2011, when it was determined that the low number of participating stations at that time and the amount of available duty cycle made it possible to provide full coverage scheduling for the IGS.

The IGS receives schedule and orbital element data from the MOC for their scheduled requests. After receipt of the downlink data, the IGS provides a copy of the data to EROS, where it is incorporated into the Landsat archive catalog.

Although catalogued at EROS, data downlinked to the IGS originally had to be ordered directly from these foreign stations. In 2010, the USGS began the LGAC effort to acquire as many copies as possible of these early Landsat data. See Figure 2-17 and the IGS Network webpage for a map and a current list of Landsat 7 ground stations.

2.5.2.4 Landsat Processing System (LPS)

The LPS records all wideband data, at real-time rates, into its wideband data stores. An I-Q channel pair represents a complete dataset. One channel holds Band 1 through Band 6, and the other channel holds Band 7 and Band 8 and the second gain setting from Band 6. The LPS retrieves and processes each channel of raw wideband data, at lower than real-time rates, into separate accumulations of Earth image data, calibration data, Mirror Scan Correction Data (MSCD), and PCD. Channel accumulations represented by Band 1 through Band 6 and Band 6 through Band 8 become Format 1 and Format 2, respectively. PCD and MSCD are generated twice, once for each format and their contents should be identical.

The LPS spatially reformats Earth imagery and calibration data into L0R data. This involves shifting pixels by integer amounts to account for the alternating forward-reverse scanning pattern of the ETM+ sensor, the odd-even detector arrangement within each band, and the detector offsets inherent to the focal plane array engineering design. All LPS L0R corrections are reversible; the pixel shift parameters used are documented in the Image Assessment System (IAS) CPF.

During LPS processing, Format 1 bands are duplicated, radiometrically-corrected, and used to assess cloud cover content through the Automatic Cloud Cover Assessment (ACCA) algorithm (see Section 5.6.10) and to generate a browse image. Cloud cover scores are generated on a scene and quadrant basis. Metadata are generated for the entire subinterval and on a scene basis. The image data, PCD, MSCD, calibration data, and metadata are structured into Hierarchical Data Format - Earth Observing System (HDF-EOS) for each format and sent to the LAM for long-term archival in subinterval form. The two formats of data are united when a Landsat 7 L0R product is ordered. The browse image and a subset of the metadata are used to provide online aids to ordering.

2.5.2.5 Level 1 Product Generation System (LPGS)

The LPGS at EROS uses multiple geometric algorithms to create Level 1 products from the raw L0R data. The LPGS is composed of multiple subsystems that each perform a unique function. See Section 5 for a full list of the LPGS Subsystems along with descriptions of the purpose and functions of each.

2.5.2.6 Image Assessment System (IAS)

The IAS is responsible for the offline assessment of image quality to ensure compliance with the radiometric and geometric requirements of the spacecraft and the ETM+ sensor throughout the life of the Landsat 7 mission. Section 5 provides a full description of the IAS.

2.5.2.7 Landsat Archive Manager (LAM)

The LAM at EROS was originally implemented as a backup to the LP DAAC, a part of the Earth Observing System Data and Information System (EOSDIS). In 2004, it became the primary system providing data archival and distribution functions for Landsat 7. In addition to the L0R data received from LPS, the LAM also receives and utilizes the CPF from the IAS.

2.5.3 NASA Institutional Ground System Components

2.5.3.1 Space Network (SN)

Landsat 7 uses TDRSS, operated by the SN headquartered at NASA GSFC. The SN, which includes the TDRSS and the ground terminals at the White Sands Complex, provides space-to-space and space-to-ground data relay services. TDRSS enables S-Band downlink of real-time and stored housekeeping data and uplink of command data. These are used for Landsat 7 real-time command and telemetry monitoring during on-orbit operations on both a scheduled basis, as well as for possible emergency operations on a call-up basis. Data rates are limited by the absence of a high-gain antenna on Landsat 7; therefore, housekeeping recorder dumps are not supported. TDRSS is also used for tracking data collection for the generation of Landsat 7 spacecraft orbital state vectors for use in precision attitude control.

2.5.3.2 EOS Near-Earth Network (NEN)

The EOS NEN Ground Stations include the following:

- NP3/4 – North Pole Ground Station, North Pole, AK; S-Band and X-Band
- SGS – Svalbard Ground Station, Svalbard, Norway; S-Band and X-Band
- MGS – McMurdo Ground Station, South Pole; S-Band

Figure 2-18 depicts the Svalbard Ground Station (SGS) in Norway. Since the launch of Landsat 7, the Alaska station has been at times located at Gilmore Creek, Poker Flat, and now at North Pole, Alaska.

All three stations provide S-Band services including both real-time and playback housekeeping telemetry support, command capabilities, and two-way Doppler tracking. Additionally, the SGS and both NP3 and NP4 record Landsat 7 X-Band downlinks; all stations forward recorded data to the LGS over high speed communication lines.

Figure 2-18. Svalbard Ground Station (SGS) Located on Platåberget, Spitsbergen Island, near Longyearbyen in Svalbard Archipelago

2.5.3.3 NASA Integrated Support Network (NISN)

NISN is a global system of communications transmission switching and terminal facilities that provide NASA with wide area communications services. The NISN at GSFC provides all network lines, voice communications, and ground communication interfaces among the control centers and ground stations. NISN was implemented in 2003 to serve the needs of NASA's users for the transmission of digital data, voice, and video information in the most cost-effective manner possible. This single integrated network project replaced multiple independent special purpose networks that had served individual NASA customers for several decades. NISN supports all the institutional facilities mentioned previously and provides communications between the MOC at GSFC and the LGS at EROS.

2.5.3.4 Flight Dynamics Facility (FDF)

The FDF, an institutional support element located at GSFC, provided pre-launch planning and analysis including star catalog generation and orbit injection maneuver planning; post-launch, the FDF provided orbit and attitude determination, planning and scheduling aid generations, as well as maneuver planning. Within the first year after launch, most FDF activities and responsibilities were migrated to workstations in the MOC used by the Mission Planners for orbit determination, attitude determination, ephemeris data generation, maneuver planning support, and generation of planning and scheduling aids (including in-view predictions for IGS, SN, and LGN). Today, the FDF institutional facility retains responsibility for star catalog maintenance, local oscillator frequency reporting, and SN tracking data preprocessing. They also participate in conjunction analysis and collision avoidance monitoring across all active GSFC Earth-observing missions.

Section 3 Instrument Calibration

3.1 Radiometric Characterization and Calibration Overview

A major objective of the Landsat Project is to upgrade the radiometric quality of the ETM+ data to be equivalent to the other sensors in the EOS constellation. Unlike its predecessors, a specific goal of the Landsat 7 mission is to achieve radiometric calibrations of the science data to ± 5 percent uncertainty over the planned five-year life of the satellite. Pre-launch, the mission was designed to support this requirement through sensor hardware changes, as well as pre-launch instrument characterizations. Post-launch while ETM+ is on-orbit, this five percent requirement is supported by a monitoring and calibration program, as well as the implementation of any necessary changes to ground processing of the data.

3.1.1 Radiometric Characteristics

The ground footprint, spatial resolution, and the spectral channels of sensors that were operational at the beginning of the Landsat 7 mission characterize the civilian space-based remote sensing industry around the turn of the century. On one end of the scale are the low-resolution, large footprints, multispectral sensors such as NOAA's polar orbiters that have 1 km resolution and a 2000 km swath. On the other end are high resolution, small footprint, and panchromatic sensors such as IKONOS. As depicted in Figure 3-1, Landsat 7 occupies a unique niche between these two extremes.

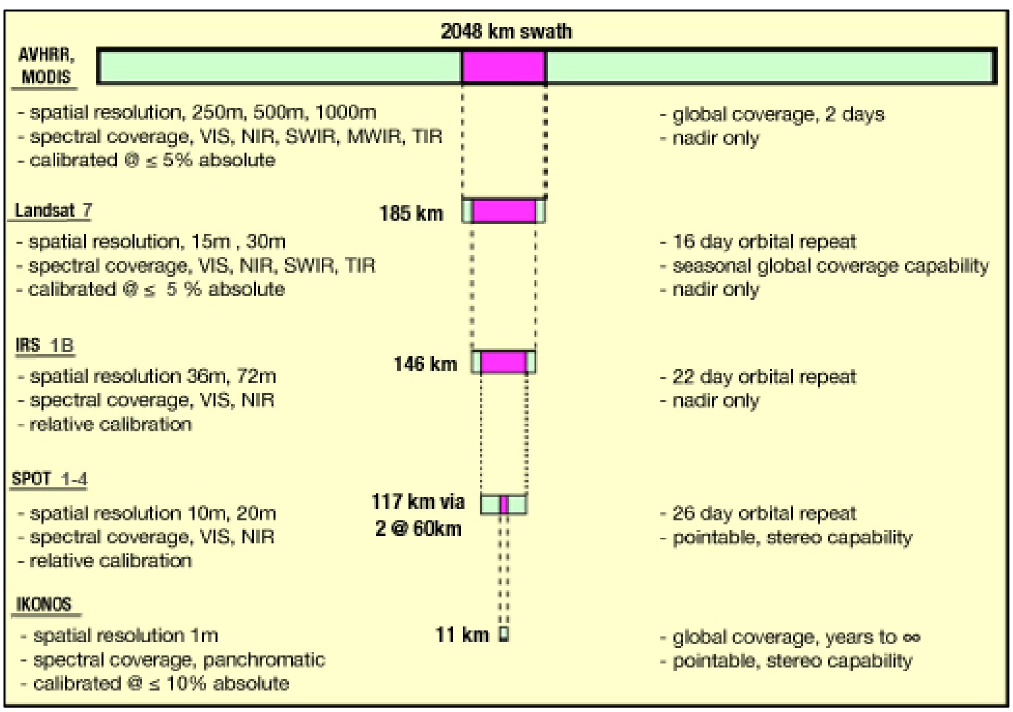

Figure 3-1. Landsat 7 ETM+ Sensor Characteristics Relative to Other Satellite Systems

The horizontal bars represent proportionately scaled footprints of the sensors on the left. Listed with each sensor are its spatial resolution, spectral coverage, and radiometric calibration accuracy. The right side of the chart lists the sensor's temporal resolution and pointing capability. No other sensor can match the characteristics of Landsat 7's ETM+, which includes repetitive, broad-area, and global coverage at moderate spatial resolution in all four passive optical regions of the electromagnetic spectrum (i.e., visible, near-infrared (IR), short-wave IR, and thermal IR), and accurate radiometric calibration. In addition, the full Landsat archive stretches back to 1972 allowing multidecadal comparisons to be made.

3.2 Pre-Launch Radiometric Characteristics

3.2.1 Spectral Characterization

The measured wavelength locations of the ETM+ spectral bands are compared to all other Landsat sensors in Figure 3-2. Exact bandpass wavelengths can be found on the Landsat Missions Website. The spectral bandwidths are determined by the combined response of all optical path mirrors (i.e., primary, secondary, SLC, scanning), the spectral filters, and the individual detectors. The spectral filters, located immediately in front of each detector array, are the dominant items that establish the optical bandpass for each spectral band. The PFPA has a filter housing that contains filters for Band 1 through Band 4 and Band 8. The CFPA has a filter housing that contains the filters for Band 5 through Band 7. See Section 2.2 for additional information on the ETM+ design.

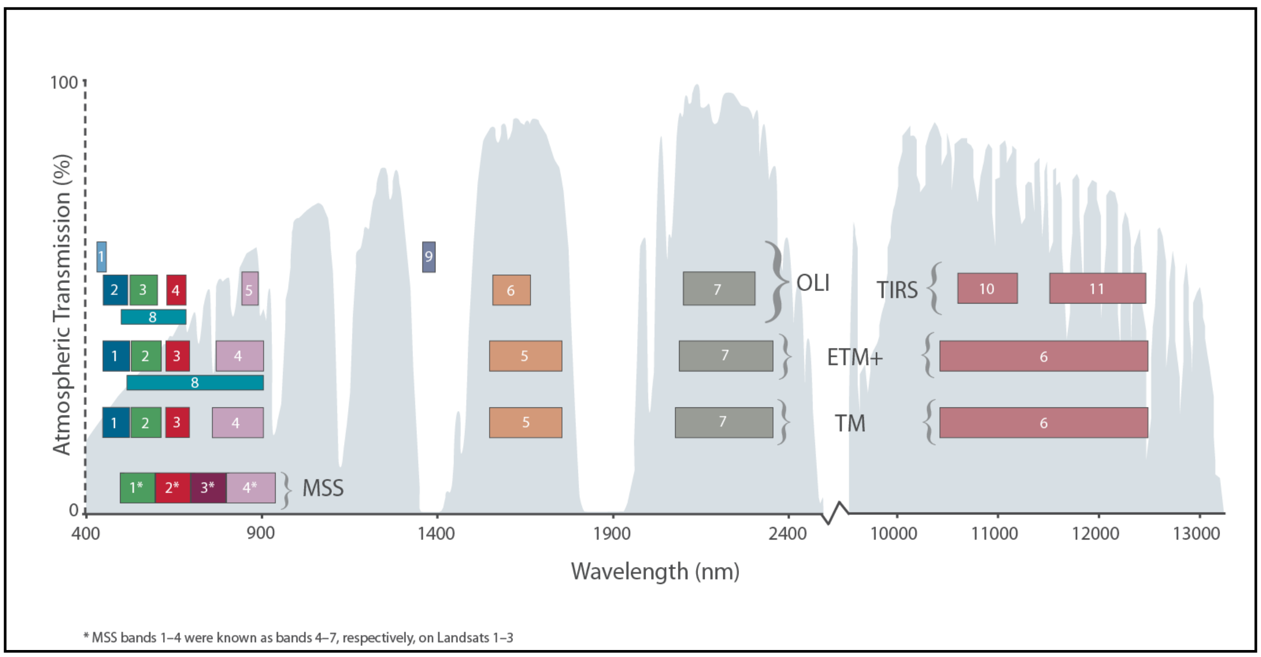

Figure 3-2.Spectral Bands and Wavelengths for Landsat Sensors

A discrete spectral shift occurred on the Landsat 5 TM sensor that has been largely attributed to filter outgassing on-orbit. The ETM+ filters were made using an Ion Assisted Deposition (IAD) process (see Section 2.2.3.8), which was designed to make the filters resistant to this phenomenon. In addition to this, the new filters have shown significant improvement in band edge responses as compared to the TM sensors on Landsat 4 and Landsat 5.

3.2.2 Radiometric Calibration

Two Spherical Integrating Sources (SIS) (see Section 3.2.3) were used to calibrate the reflective bands (Bands 1-5, Bands 7-8) of ETM+ prior to launch. The first approach used a 100 Centimeter (cm) diameter source (SIS100), which is equipped with eighteen 200-watt lamps; six 45-watt lamps and ten 8-watt lamps. This provides radiance levels covering the full dynamic range of the ETM+ instrument in all bands, and at least 10 usable radiance levels for each band for each gain state. The SIS100 was used to perform the primary radiometric calibration of the ETM+ in August 1997 and was also used for the pre-launch calibration of Terra MODIS. A second source, a 122 cm (48") SIS with six 200-watt lamps, two 100-watt lamps, and four 25-watt lamps was used for monitoring the radiometric calibration of the ETM+ five times during instrument and spacecraft level testing. During SIS calibrations, the Bench Test Cooler (BTC) was used to maintain the temperature of the CFP at 105°K. This was only one of three temperature set points for the CFP that could be obtained in ambient pressure and temperature conditions given the available ground testing facilities.

The calibration data reduction is performed as follows for the ETM+ reflective bands. The ETM+ band weighted spectral radiances, $L_\lambda(b,s)$, for band 'b' and sphere level 's' are calculated as:

$$L_\lambda(b,s) = \frac{\int RSR(b,\lambda) L_\lambda(s,\lambda) d\lambda}{\int RSR(b,\lambda) d\lambda}$$

Where:
$RSR(b,\lambda)$ is the Relative Spectral Response for band 'b' at 'λ' calculated from component level transmission, reflectance, and responsivity measurements, and
$L_\lambda(s,\lambda)$ is the measured spectral radiance of sphere level 's' at 'λ'

The quantized detector (d) responses $Q(d,b,s)$ are regressed against the integrating sphere band-weighted radiance level, $L_\lambda(b,s)$, per the calibration equation:

$$Q(d,b,s) = G(d,b) L_\lambda(b,s) + B(d,b)$$

The slopes of the resulting regression lines are the responsivities or gains $G(d,b)$ and the intercepts are the biases, $B(d,b)$. The Landsat Project Science Office at NASA's GSFC has reviewed the various integrating sphere calibrations and their effective transfer to the ETM+ and decided what calibrations should go to the IAS to be used by the pre-launch IAS.

The radiometric calibration of Band 6, ETM+'s thermal band, is fundamentally different than the reflective bands as the instrument itself contributes a large part of the signal. A model of this temperature-dependent instrument contribution has been developed by SBRS. The calibration for ETM+ Band 6 is formulated as:

$$Q_{sc}(d) - Q_{sh}(d) = G(d)(L_{\lambda,sc} - L_{\lambda,esh})$$

Where:
$Q_{sc}(d)$ is the quantized response of Band 6 detector ‘d’ to the scene
$Q_{sh}(d)$ is the quantized response of Band 6 detector ‘d’ to the shutter
$G(d)$ is the gain of detector 'd'
$L_{\lambda,sc}$ is the spectral radiance of the scene
$L_{\lambda,esh}$ is the scene-equivalent spectral blackbody radiance of the shutter:

$$L_{\lambda,esh} = L_{sh} + \sum a_j(L_{sh} - L_j)$$

and where:

L_{sh} is the blackbody radiance of the shutter, L_j is the blackbody radiance of the jth component of the ETM+ instrument, and a_j is the emissivity-adjusted view factor for the jth ETM+ component where: j = 1 for the scan line corrector; j = 2 for the central baffle; j = 3 for the secondary mirror and mask; j = 4 for the primary mirror and mask; and j = 5 for the scan mirror.

Each of these components is in front of the shutter and contributes to the apparent scene radiance when the shutter is open.

The pre-launch calibration of Band 6 was primarily a calibration of this model. The radiometric calibration of the thermal band occurs during thermal vacuum testing. During this test, the ETM+ was aligned to the Thematic Mapper Calibrator (TMC), a collimator with selectable sources at its focus. During the Band 6 calibration, blackbody sources are used in the TMC. The Band 6 detectors’ responses to combinations of various TMC blackbody and instrument temperatures were used to calibrate the instrument and to refine emitted radiance contributions from various internal ETM+ components. The results of this calibration were the nominal gains and biases for Band 6, and the emissivity adjusted view factors (a_j) for the various internal components of the ETM+ that affect the Band 6 calibration. The gains and biases were included in the CPF as pre-launch values for Band 6.

3.2.3 Spherical Integrating Source (SIS)

An SIS is a hollow sphere with the entire inner surface uniformly coated with a material that has a high diffuse reflectance. The basic concept behind the spherical shape is that light from the internal source has a chance to perform multiple bounces thereby randomizing its original direction before it exits a small aperture. A perfect diffuse reflector can behave like a perfect (i.e., Lambertian) diffuse source, which means energy is distributed in all directions equally. A Lambertian source is a source whose radiance is independent of viewing angle. Radiance is defined as the energy flux per unit projected area per unit solid angle leaving a source or a surface.

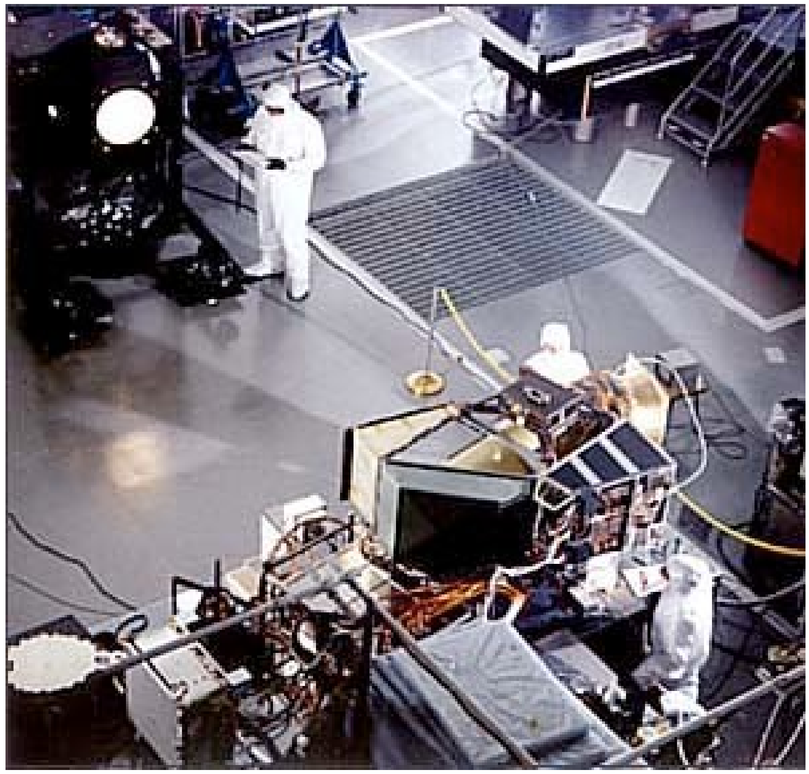

Figure 3-3. SIS (upper left) in Clean Room with ETM+ (middle right)

Each SIS is calibrated by SBRS to NIST traceable standards of spectral irradiance. In addition, EOS cross-calibration activities include comparison of the SBRS radiometric scale to the NIST, University of Arizona, NASA GSFC, and Japan's National Research Laboratory of Metrology (NRLM), now National Metrology Institute of Japan, NMIJ) radiometric scales. Lastly, the Landsat Transfer Radiometer (LXR), a visible and near-infrared radiometer designed for stability by NIST, is used to monitor the output of each sphere during each calibration and calibration check. This radiometer has also been calibrated by NIST to provide an independent check on the radiometric calibration of the two SIS sources.

3.3 Post-Launch Radiometric Characteristics

The post-launch radiometric calibration of the ETM+ is accomplished by the IAS through the regular examination of the instrument's response when illuminated by known sources designed to be relatively stable on orbit. The ETM+ has three on-board calibration devices, namely, the Internal Calibrator (IC), the Partial Aperture Solar Calibrator (PASC), and the Full Aperture Solar Calibrator (FASC). The IC is used for calibrating all ETM+ bands, while the PASC and FASC are used for the reflective bands. Changes to the ETM+ calibration have occurred since launch (see Section 3.3.5). Ground look calibrations, comparing field observations to ETM+ overpass data are occasionally performed to confirm via the analysis of the USGS Calibration and Validation Team (CVT), the accuracy of the calibration using on-board sources.

3.3.1 On-Orbit Calibration Methods

The three on-board ETM+ calibration devices are the FASC, which is a white painted diffuser panel, a PASC, which is a set of optics that allow the ETM+ to image the sun through small holes, and an IC, which consists of two lamps, a blackbody, a shutter, and optics to transfer the energy from the sources to the focal plane. Details on these devices can be found in the following sections.

The FASC is deployed in front of the ETM+ aperture approximately monthly. Based on the orientation of the panel relative to the sun and instrument, and the pre-launch measured reflectance of the panel, a calibration can be determined. The IC provides a signal to the ETM+ detectors once each scan line as well as a view of the black shutter. The shutter provides the dark reference for the reflective bands and a low temperature source for the thermal band. The lamps and blackbody provide the high radiance source for the bands. At the short wavelengths, the IC has shown both short-term and long-term instabilities. Performance of the PASC has been anomalous and results are not included here. On-orbit performance of the radiometric calibrators can be found in a paper that covers the subject in greater detail (Markham, et al., 2003).

3.3.2 Internal Calibrator (IC)

The IC consists of a shutter flag, two tungsten lamps, and a blackbody source. The shutter flag, located immediately in front of the PFP, oscillates in synchronization with the scan mirror. At the end of each scan, the shutter mechanically blocks external light to the focal planes. In addition, the shutter flag relays light from the IC lamps and blackbody, to the detectors. The two IC lamps are situated near the base of the IC flag. Light from either or both lamps is directed through optics at the pivot point of the flag, into a sapphire rod contained within the flag. This rod transfers the light up the shutter flag and splits it into separate paths for each of the spectral bands. The light is directed out of the shutter flag and onto the focal planes by additional optics in the IC flag. The light separated for each band is aligned so that it illuminates the appropriate detectors.

The IC lamps are supplied with a regulated voltage across a combination of the lamp and a resistor, resulting in quasi-constant power being supplied to the lamp. Each lamp can be commanded "on" or "off", such that four lamp states are possible (both "off" [0,0], one "on" [0,1] or [1,0] or both "on" [1,1]). The IC was designed to have each lamp produce a usable signal in all bands. Both lamps "on" saturate some bands, particularly in high gain mode. The IC blackbody is situated off the optical axis of the instrument. When the shutter flag passes in front of the PFP, radiation from the blackbody is reflected off a toroidal mirror on the flag, into the aft optics of the ETM+ and onto the Band 6 detectors. The portion of the shutter flag imaged by Band 6, exclusive of the area where the toroidal mirror is located, is coated with a high emissivity paint and acts as the second source for Band 6 calibration. This portion of the shutter flag is also instrumented with a thermistor to track temperatures over the mission lifetime to assess performance stability. The blackbody has three set point temperatures namely, 30°C, 37°C, and 46°C.

The ETM+ IC, although similar to the IC on Landsat 6, differs from the IC on Landsat 4 and Landsat 5, in several ways: (1) the ETM+ uses two lamps (four states) instead of three lamps (eight states), (2) a more compact filament results in a higher flux incident on the IC optics, though the lamps are nearly identical in terms of current and voltage ratings, (3) the control circuit for ETM+ uses voltage regulation in the primary operation mode, whereas TM used radiance stabilization in the primary mode, and voltage regulation in the backup mode, (4) ETM+ uses sapphire rods to transmit the energy from the base of the flag to the head of the shutter flag, while the TM used fiber optics in an attempt to improve the uniformity of the calibration flux at the focal plane, and (5) the ETM+ does not retain the lamp sequencer used on TM to automatically cycle through the lamp states.

When the ETM+ is operating, the shutter flag oscillates in synchronization with the scan mirror. The size of the shutter flag and its speed of movement combine to provide obscuration of the light to each detector for about 8.2 millisecond, or 750 pixels, for the 30-meter channels; the light pulse for the reflective bands has a width of approximately 40 pixels (see Figure 3-4). For Band 6, the calibration signal is similar in size to the blackbody pulse, about 20 pixels wide.

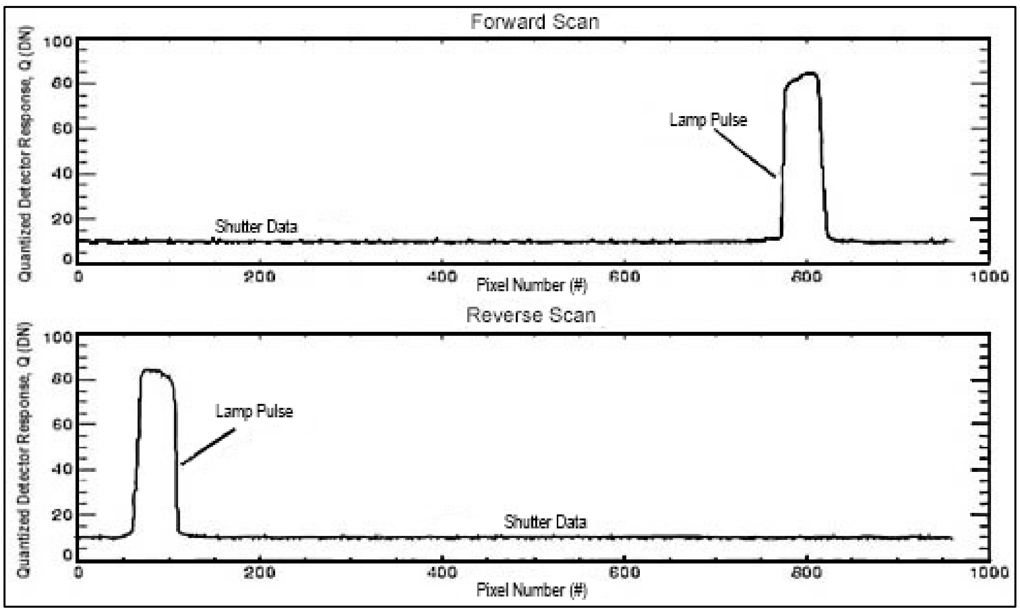

Figure 3-4. ETM+ Band 4, Detector 1, Low Gain, IC Data Acquired on 12/07/1996, using Primary Lamp

3.3.3 Full Aperture Solar Calibrator (FASC)

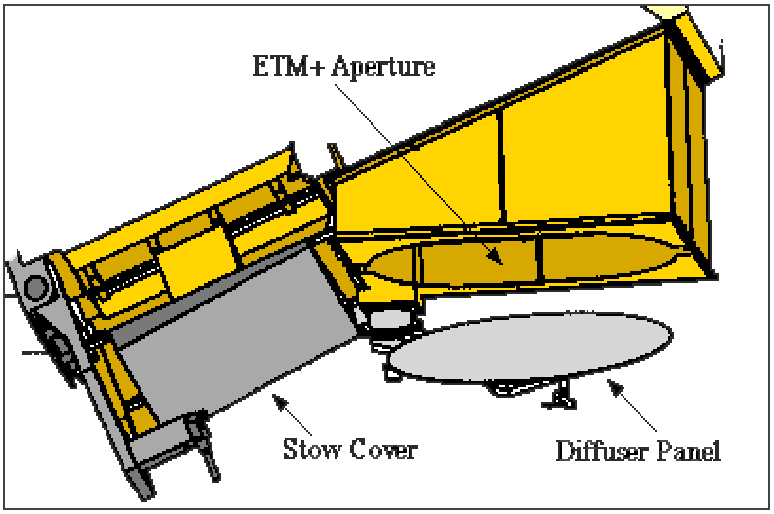

Figure 3-5. Schematic Drawing of Portion of ETM+ Sensor with FASC Deployed in Front of ETM+ Aperture

The FASC is a white painted panel deployed in front of the ETM+ aperture and diffusely reflects solar radiation into the full aperture of the instrument as illustrated in Figure 3-5. With known surface reflectance, solar irradiance and geometry conditions, this device behaves as an independent, full aperture calibrator. The device consists of an octagon shaped, aluminum honeycomb paddle on a motorized arm.

On command, the motor rotates the panel from its stowed position away from the ETM+ aperture, to an inclined position in front of the ETM+. When stowed, the panel rests adjacent to the stow cover, which reduces the exposure of the panel to contaminants and UV radiation. The center 51 cm of the FASC panel is painted with the classic formulation of YB71, an inorganic flat white paint designed for spacecraft thermal control. This paint was selected for its near Lambertian properties, high reflectance, and apparent stability in a space environment.

When the FASC is in its calibrate position, the angle between the sensor nadir vector and the panel normal, is specified to be 23.5°. In use, the panel can be illuminated by the sun from 90° zenith angle (i.e., sunrise on panel) to about 67° zenith angle. Below 67°, the instrument begins to shade the panel. Depending on the time of year, the solar azimuth angle with respect to the velocity vector of the ETM+ varies from 23° to 37°. The relative azimuth between the nadir view vector and the solar illumination varies across the same range.

ETM+ image data acquired with the FASC deployed appears to be an essentially flat field with fading cross-track edges. The image increases in brightness along-track as the Solar Zenith Angle (SZA) on the panel decreases (roughly at 1/cos(SZA)). Specifications require the FASC to fill the ETM+ aperture for the central 1000 pixels (~1/6 of each scan line); the design nominally fills the aperture for the central ~50 percent of the scan line. As the mirror scans, the view angles to the FASC panel change. If the nadir viewing pixel has the nominal 23.5° view angle and a 0° view azimuth angle, then at the extreme ends of the scan, the view zenith angle increases by about 1°, and the view azimuth angle varies by +/- 30°. Pre-launch Bidirectional Reflectance Distribution Function (BRDF) measurements indicate that the radiance change across the FASC scan should be a one percent effect across the full scan assuming the aperture is filled. Across the central 1000 pixels, this translates into a 0.1 percent effect.

The FASC calibration is performed every month. Up until mid-2015, the IAS sent FASC requests to the MOC scheduler. Now, the MOC scheduler has been enabled to independently schedule monthly FASC collections, placing them at times of low duty cycle usage to avoid impacts on regular imaging.

3.3.4 Partial Aperture Solar Calibrator (PASC)

The PASC is used for calibrating Bands 1-5, 7, and 8 and consists of a small passive device that allows the ETM+ to image the sun while viewing a 'dark earth'. It is attached to the ETM+ sunshade and permanently obscures a small portion (~0.5 percent) of the aperture. It consists of four essentially identical sets of optical elements each in a slightly different orientation. Each set (or facet) consists of an uncoated silica reflector, a 45° mirror, and an aperture plate with a precision drilled small aperture (~4 mm). The combination of the small aperture and the uncoated silica reflector reduces the signal amplitude sufficiently to bring it into the ETM+ dynamic range. The four facets are duplicated to account for angular variations of Sun position with season. They are oriented such that in any given orbit, as the satellite passes out of solar eclipse (i.e., spacecraft sunrise as it orbits from behind the Earth) in the vicinity of the North Pole, at least one facet reflect sunlight directly into the ETM+ aperture and it is able to image the sun.

Pre-launch SBRS measurements of the alignment between the PASC and scanner assembly, revealed a small design misalignment, which resulted in a nominal declination angle of the PASC (relative to spacecraft nadir) of 20 degrees, versus the prescribed 18 degrees. This increase in declination effectively forced the ETM+ to acquire PASC scenes earlier in the orbit (i.e., closer to spacecraft sunrise). Although the spacecraft solar panel undergoes a period of thermal instability during sunrise, an analysis of the resultant spacecraft jitter has shown minimal impact (< 1 percent) to the acquisition of PASC data.

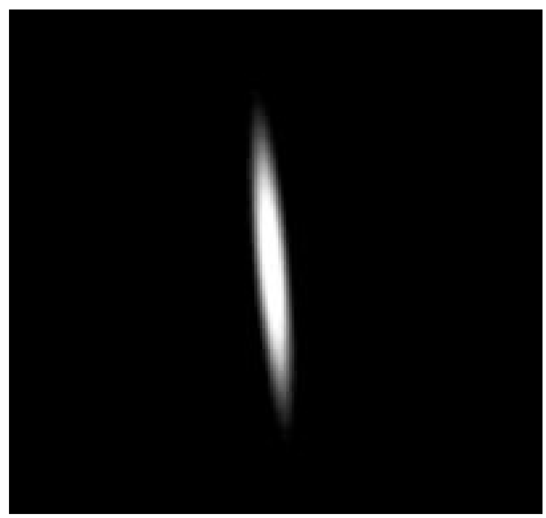

Figure 3-6. Simulated ETM+ PASC Scene Showing Reduced Resolution Image of Sun

The PASC generates a reduced resolution image of the sun with the resolution being deliberately limited by diffraction from the small apertures. This diffraction effect is wavelength dependent. For example, in Band 1 the blur extends across about 7 pixels (at the first dark ring of the diffraction pattern), and in Band 7 the extent is about 32 pixels. In addition to the blur, the image is elongated in the along-track direction. The along-track movement across the solar disk can best be expressed in terms of the spacecraft pitch rate (i.e., 360 degrees in ~100 minutes or ~3.6 degrees/minute). By comparison, the ground is normally scanned at 16 IFOVs. This equates to 0.039 degrees (16 * 0.0024 degrees) per 72 millisecond scan or ~32.5 degrees/minute. Thus, the sun image is oversampled along-track by a factor of about 9. One other contributor to the rendition of the solar image is the scanning direction, which is not perpendicular to the motion of the sun—the angle between the two can be as small at 45 degrees. The combined effects of oversampling and a non-orthogonal scan pattern produce an elongated, skewed image of the sun (see Figure 3-6).

Within a PASC processed image, it is anticipated that most uniform portions of the solar disk center will be approximately 200 pixels in width for Bands 1-5, and Band 7, 105 pixels for Band 6, and 410 pixels for Band 8. Initially, the IAS submitted PASC requests to the MOC for scheduling; within a few years of launch, the scheduler was updated to automatically schedule the PASC collects every x orbits, where x has varied over the years since launch:

- Launch to March 2007—every 17 orbits
- March 2007 to April 2007—every 34 orbits
- April 2007 to September 2007—every 17 orbits
- September 2007 to July 2015—every 25 orbits
- July 2015 to present—every 29 orbits

3.3.5 ETM+ Calibration Actions

The actions taken by the Landsat Project Science Office at NASA GSFC and the Image Assessment Team at USGS EROS to provide the best possible calibration for Landsat ETM+ imagery are listed in detail on the Landsat Missions Website.

3.3.6 Radiometric Performance

A significant improvement in the Landsat 7 system is the addition of the IAS as part of the ground processing system. The IAS has the role of monitoring the performance and calibration of the ETM+ instrument and providing updates to the CPF. The NASA GSFC Landsat Project Science Office works with the IAS (located at EROS) in analyzing the calibration information and updating the algorithms used within the IAS. Additional funding from NASA supports vicarious radiometric calibration efforts at NASA Jet Propulsion Laboratory (JPL), Rochester Institute of Technology (RIT), South Dakota State University (SDSU), and the University of Arizona. Approximately every six months, the scientists and analysts involved in characterizing ETM+ radiometric calibration meet and present their results at the Landsat Science Team Meeting. The results form the basis for updating the radiometric gain calibration parameters in the CPF.

3.3.6.1 Ground Look Calibration (GLC) Methods

There were four investigations evaluating the ETM+ radiometric calibration using GLC or vicarious methods early in the Landsat 7 mission. Each of these investigations predicted the radiance at the sensor aperture using a combination of ground- and/or aircraft-based reflectance, radiance or temperature measurements, coupled with measured and/or modeled atmospheric parameters. Two investigations were looking primarily at the reflective band calibrations: those of Helder and Thome (Thome, et al., 2001). The investigations of Palluconi and Schott were concentrating on the thermal band (Schott, et al., 2000).

3.3.6.2 Radiometric Performance Results

The combined calibration results for Bands 1-5, 7, and 8 are presented in those papers, respectively. The FASC results presented are based on the "best" portion of the FASC panel and have been adjusted based on an apparent 1° difference in the orientation of the panel from pre-launch measurements (Markham, B.L., et al., 2003). The IC results have also been included while recognizing that part of the variability present is related to the IC. In all bands, the vicarious results agree to within five percent of the FASC and pre-launch values and that the trends in the GLC results are not significant. The FASC results show significant trends, but the trends are small (less than 1.5 percent/year). The FASC trends are believed to be largely due to changes in the FASCs reflectance and not representative of the instrument. However, there is some consistency between the FASC, GLC, and IC trends (e.g., in Band 7 all are increasing). If the consistency continues and the vicarious trends become significant, a calibration update will be performed.

In Band 6, the IC is the only on-board calibration device. The slope of the responsivity, though significant, shows a change of less than 0.06 percent/year. This system is remarkably stable, particularly relative to the Landsat 4 and Landsat 5 TM thermal bands. The ETM+ instrument also appears stable relative to the vicarious measurements, though a significant bias was detected. This bias was originally measured as 0.31 (Watts/(m^2 * sr * µm)) and this correction was applied to the calibration parameter file on October 1, 2000. Updated measurements indicate the bias was closer to 0.29 (see Landsat 7 Calibration Notices). After correction for the bias, the calibrated product radiance has a scatter of about one percent around the vicarious results.

On-orbit results indicate that the Landsat 7 ETM+ absolute radiometric calibration is stable to better than 1.5 percent/year in the reflective bands and 0.1 percent/year in the thermal band. The uncertainty in the calibration is estimated at <5 percent in the reflective and ~1 percent in the thermal regions. These analyses have been continued to ensure that the ETM+ data are fully characterized through the mission lifetime and that CPFs are updated to provide accurate data processing for all acquired imagery.

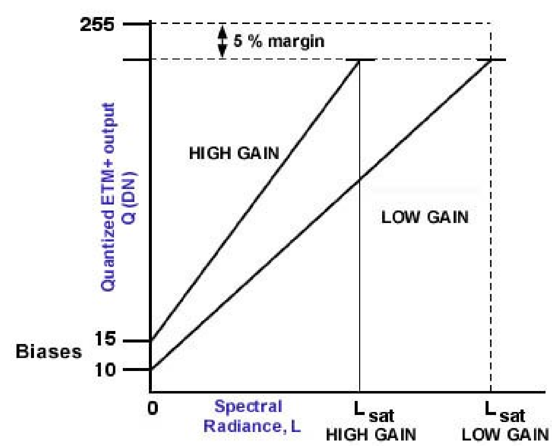

Figure 3-7. Design of High and Low Dynamic Ranges of ETM+ Reflective Bands

3.4 Additional Radiometric Characteristics

3.4.1 Gain States

The ETM+ images are acquired in either a low or high gain state (see Figure 3-7). The MOC controls gain selection for a scene and is performed by changing the reference voltage for the analog to digital convertor. The science goal in switching gain states is to maximize the ETM+'s 8-bit radiometric resolution without saturating the detectors. This requires matching the gain state for a given scene to the expected brightness conditions. For all bands, the low gain dynamic range is approximately 1.5 times the high gain dynamic range. It makes sense, therefore, to image in low gain mode when surface brightness is high and in high gain mode when surface brightness is lower. Table 3-1 lists the minimum saturation levels for all bands in both the low and high gain states.

Band	Low Gain	High Gain
	Minimum Saturation Level (W/(m² * sr * μm))	Minimum Saturation Level (W/(m² * sr * μm))
1	285.7	190.0
2	291.3	193.7
3	225.0	149.6
4	225.0	149.6
5	47.30	31.50
6	17.21	12.78
7	16.70	11.10
8	235.0	156.3

Table 3-1. ETM+ Minimum Saturation Levels for All Bands

3.4.2 At-Launch Gain Setting Strategy Rationale

The following paragraph was extracted from a paper that describes the rationale behind the at-launch gain setting strategy (Goward, et. al., 1999):

"The 8-year monthly averages of AVHRR visible and near infrared planetary reflectance measurements from the AVHRR data set, at the original 15 km spatial resolution, were used to evaluate the gain settings. Visible (Bands 1-3), near infrared (Band 4), and shortwave infrared (Band 5 and 7) gains were considered separately. The at-satellite planetary reflectance was converted to at-satellite radiance, based on the solar zenith angle at the time of satellite overpass. For each Landsat WRS-2 scene, the observed spectral radiance was subjected to the two gain states. For each gain state, an entropy statistic was calculated to determine the potential scene contrast in each setting. Where low gain was found to provide substantially greater scene contrast (e.g., glaciers in summer), this setting was selected. For all other cases the high gain was selected. This decision process will no doubt yield less than optimum results for some applications, but it was the best compromise to meet the requirement to minimize gain changes while providing generally high quality measurements".

The initial ETM+ gain settings are depicted graphically in maps, which are contained in this file. These settings were used from launch until late 2000 when the settings were updated with per band gain calculations.

The nominal gain file (American Standard Code for Information Interchange (ASCII)) contains a complete list of gain states, organized by month and WRS location, for daytime scenes.

3.4.3 Gain Settings on Orbit

The gain setting strategy for Landsat 7 scheduling has undergone several revisions since launch. On December 2, 1999, in response to feedback from data users about saturation issues with Band 4 over agricultural targets, the decision was made to acquire Band 4 data in low gain when the sun elevation angle exceeds 45 degrees. On July 13, 2000, a strategy was implemented consisting of a fixed categorization of the land cover types of the Earth, and associated gain setting rules that are land-cover and sun-angle based. Each Landsat 7 WRS-2 path/row location is categorized into one of six land cover types. The land cover types considered, and the relevant gain change rules are detailed as follows. (Within the LTAP, the gains for Bands 1-3 are always changed together, as are the gains for Band 5 and Band 7. The gains for Band 6 and Band 8 are static.)

1. Land (non-desert, non-ice):
   a. Bands 1-3 set to high gain
   b. Band 4 set to high gain except where sun elevation is greater than 45° (set to low gain) in order to avoid dense vegetation (reflectance > 0.66) saturation. (At this sun angle, high gain in Band 4 causes saturation at or above a reflectance of 0.66; therefore, switching to low gain keeps targets from saturating.)
   c. Band 5 and Band 7 set to high gain
   d. Band 8 set to low gain

2. Desert
   a. Bands 1-3 set to high gain except where sun elevation is greater than 28° to avoid bright desert target (reflectance >0.65 in Band 3, >0.66 in Band 1, >0.71 in Band 2) saturation
   b. Band 4 set to high gain except where sun elevation is greater than 45° (set to low gain) to avoid bright desert (reflectance > 0.66) saturation
   c. Band 5 and Band 7 set to high gain except where sun elevation is greater than 38° to avoid bright desert target (reflectance >0.70 in Band 5, >0.68 in Band 7) saturation
   d. Band 8 set to low gain

3. Ice / Snow and Sea Ice:
   a. Bands 1-3 set to high gain except where sun elevation is greater than 19° to avoid snow ice (reflectance > 0.95 in Band 3, >0.94 in Band 1, >1.03 in Band 2) saturation

   b. Band 4 set to high gain except where sun elevation is greater than 31° to avoid snow / ice (reflectance >0.92) saturation
   c. Band 5 and Band 7 set to high gain
   d. Band 8 set to low gain

4. Water / Coral Reefs:
   a. Bands 1-5 and Band 7 set to high gain
   b. Band 8 set to low gain

5. Volcano / Night – nighttime imaging (sun elevation angle < 0°) is only routinely performed for targets identified as "Volcano" (see Section 4.1.2).
   a. Bands 1-4 set to high gain
   b. Band 5 and Band 7 set to low gain to reduce saturation of volcanic hot spots
   c. Band 8 set to low gain

The actual saturation reflectance for daytime imagery corresponding to a given sun angle is influenced by the Earth-Sun distance, which varies by ±1.5 percent over the year, producing a ±3 percent irradiance variation. The current gain setting rules do not account for this variability. Band 8 is in low gain for all routine acquisitions as the noise level in this band is such that high gain provides very little improvement in performance. This implementation is currently under review and the Band 8 gain settings may be altered in the future.

Maps displaying the gain setting updates made in 2000 are contained in this file.

On April 20, 2001, the strategy was updated such that gain changes for scenes in northern Africa were made over the Mediterranean, so that land images were not impacted. There is a small discontinuity in the image wherein gain changes take effect, and some processing systems are not able to work through them. On May 8, 2002, the scheduler software was modified to incorporate the ability to shift gain changes, when not over the U.S., into flywheel scenes, scenes with high cloud cover predictions, or prior to the start of an imaging interval. Over the U.S., gain changes are made during the cloudiest scene prior to the scene requiring the change. In both cases, no single scene has a gain change two acquisitions in a row. Again, this was to make sure the same scenes were not impacted by gain changes and to place the changes in scenes of low priority.

3.4.4 Gain Change Timing Rationale

The gain change commands at the time of launch were issued at the start time of a scene, which due to various error accumulations was placing the gain change one to two seconds into the start of the scene. The MOC was informed that the U.S. ground processing system could not handle this band change location. A scheduler modification was subsequently made to move the gain change commanding back by four seconds, so it would occur during the trailing end of the preceding scene. This was initially incorporated between July 14 and July 26, 1999. This change was made permanent starting August 2, 1999.

The rational for setting the offset to -4 seconds was:

1. Payload command timing error: up to 1-second quantization error because the onboard computer executes commands on integer second boundaries.
2. Gain change command execution time: 0.1 second/band x 8 bands = 0.8 seconds
3. Orbital along-track position uncertainty: typically, <1.0 km, equivalent to 0.2 seconds (except on days following delta-V orbit correction maneuver, in which the along-track error could reach two seconds).
4. Scene center-to-center time variance: typically, 23.92 +/- 0.09 seconds due to orbital eccentricity.

The -4 second gain change offset exists for all scenes acquired after August 2, 1999. This is a different issue than the gain change rationale in the LTAP (see Section 4).

3.5 Geometric Calibration Overview

This section describes the geometric characterization and calibration activities performed over the life of the Landsat 7 mission using the software tools developed as part of the Landsat 7 IAS. Along with the radiometric corrections previously discussed, the IAS provides the capability to routinely perform four types of characterization to verify and monitor system geometric performance, and three types of geometric calibration to estimate improved values for key system geometric parameters.

The geometric characterizations include:

1. Geodetic accuracy assessment to measure the absolute accuracy of Level 1 Systematic (Corrected) (L1G) products
2. Geometric accuracy assessment to qualitatively and quantitatively evaluate residual internal geometric distortions within L1G images
3. Band-to-band registration assessment to measure and monitor the relative alignment of the eight ETM+ spectral bands
4. Image-to-image registration assessment to measure and monitor multitemporal image registration accuracy

The geometric calibration capabilities provided by the IAS include:

1. Sensor alignment calibration to provide improved knowledge of the geometric relationship between the ETM+ optical axis and the Landsat 7 attitude control reference system
2. Scan mirror calibration to measure and correct any systematic deviations in the ETM+ scan mirror along and across scan profiles
3. Focal plane calibration to measure and provide improved estimates of the eight band center locations on the two ETM+ focal planes relative to the ETM+ optical

axis. Techniques for measuring and estimating improved values for individual detector locations and delays are being researched and may be added to the IAS as a post-launch capability.

The most critical geometric calibration activities involved measuring and verifying the Landsat 7 ETM+ system performance during the Initial On-orbit Checkout (IOC) period that lasted until mid-June 1999. This required the use of the available geodetic, geometric, band-to-band, and image-to-image characterization capabilities, and performance of the initial sensor alignment calibration. Refining the pre-launch sensor alignment knowledge was critical to ensure that the Level 1 product geodetic accuracy specification could be met. Sufficient supporting datasets (e.g., ground control, terrain data) to perform these characterization and calibration activities had to be available at launch. The second priority during the IOC period was to verify and, as necessary, update the pre-launch focal plane, particularly band placement, as well as scan mirror profile calibrations. The results of these initial calibration activities were used to verify that the system was performing within specifications and to create the initial post-launch release of the CPF (see Section 3.10), which was used by the IAS to create Level 1 products that met the Landsat 7 geodetic accuracy requirements.

After the IOC period, ongoing calibration activities monitor the stability of the Landsat 7 ETM+ system's geometric performance and attempt to identify and characterize any systematic variations in the system's geometric parameters. This includes processing additional calibration scenes under a variety of acquisition conditions (e.g., orbital position, ETM+ time on, as instrument performance changes) to measure the system's geometric performance as a function of time, temperature, and location. The next section details the current instrument status.

3.5.1 Geometric Performance

3.5.1.1 Requirements

The geometric performance of the ETM+ is judged against three key requirements placed on the Landsat 7 system. These requirements are:

- Absolute Geodetic Accuracy
- Band-to-Band Registration
- Image-to-Image Registration

3.5.1.2 Absolute Geodetic Accuracy

This requirement ensures that geometrically corrected products be accurate to 250 meters (1 sigma), excluding terrain effects, without ground control. The geodetic accuracy is limited by spacecraft / instrument geometric model accuracy (e.g., ephemeris, attitude, alignment knowledge). Geodetic accuracy is monitored using calibration scenes containing Ground Control Points (GCPs). Scenes are first radiometrically and geometrically corrected. Control point locations are then measured on the processed imagery and compared to precisely known ground locations. Any terrain effects are removed analytically in the comparison. The product's geodetic accuracy depends on the accuracy of four data inputs. These are:

- Ephemeris data – spacecraft position and velocity
- Attitude data – spacecraft orientation (roll, pitch, yaw)
- Spacecraft clock – links image data to ephemeris and attitude
- ETM+ alignment – orientation of payload to the spacecraft

The ephemeris is estimated post-pass using satellite tracking data. On-board star trackers and gyros measure attitude. The clock performance is monitored by the Landsat 7 MOC, and the ETM+ alignment is determined by a ground processing calibration that determines the orientation of the ETM+ payload relative to the Landsat 7 spacecraft Attitude Control System (ACS) reference. Multiple scenes with ground control are used to measure the systematic biases attributable to ETM+ alignment. During the initial on-orbit calibration during the first ninety days, seven different calibration scenes were used. Periodic geodetic accuracy testing showed a slow build-up of along-track bias after July 1999. A sensor alignment calibration update was performed in June of 2000.

Twenty-four scenes acquired since July 1999 (~1 per cycle) were used to perform the initial calibration. A separate and independent set of eighteen scenes covering the same time span were used to verify the results. The ETM+ alignment shows time-varying behavior and will continue to be monitored during the course of the mission. Current trends reveal post-calibration geodetic accuracy of systematic ETM+ products of approximately 80 meters (1 sigma), which is much better than the 250 meter specification, placed on the satellite system.

3.5.1.3 Band-to-Band Registration

Band-to-band registration assessment is performed periodically throughout the mission's life. The purpose of this assessment is to measure the relative alignment of the eight ETM+ spectral bands after processing to Level 1s to verify that the 0.17 pixel band-to-band registration requirement is being met. If not, the IAS remedies the band alignment by deriving new band center locations via band-to-band registration calibration and subsequently updating the CPF.

Band registration is monitored using desert scenes because they provide the best cross-band correlation performance. The band center locations measured pre-launch were evaluated using on-orbit data and then updated using these calibration scenes during the on-orbit checkout period. The measured band registration accuracy was 0.06-0.08 pixels. However, the registration accuracy degraded slightly after July 1999. Measurements revealed that the registration offset between the PFP and CFP in the scan line direction increased to 0.08-0.10 pixels.

Band calibration analysis showed a systematic shift in the Band 5, 6, 7 locations after July 1999. The primary focal plane band centers are very stable, but the CFP band centers are much more variable with a 3-4 microradian mean shift. The CFP offsets coincided with changes in ETM+ operating temperature range, which is hotter than during the 90-day checkout period. The band center calibration was updated for data acquired after July 1999 although analysis revealed that band center estimates from individual scenes are still highly correlated with temperature telemetry. The current calibration is time-dependent pending development of a temperature dependent model. Nonetheless, registration performance (see Figure 3-8) was well within the 0.17 pixel specification early in the mission.

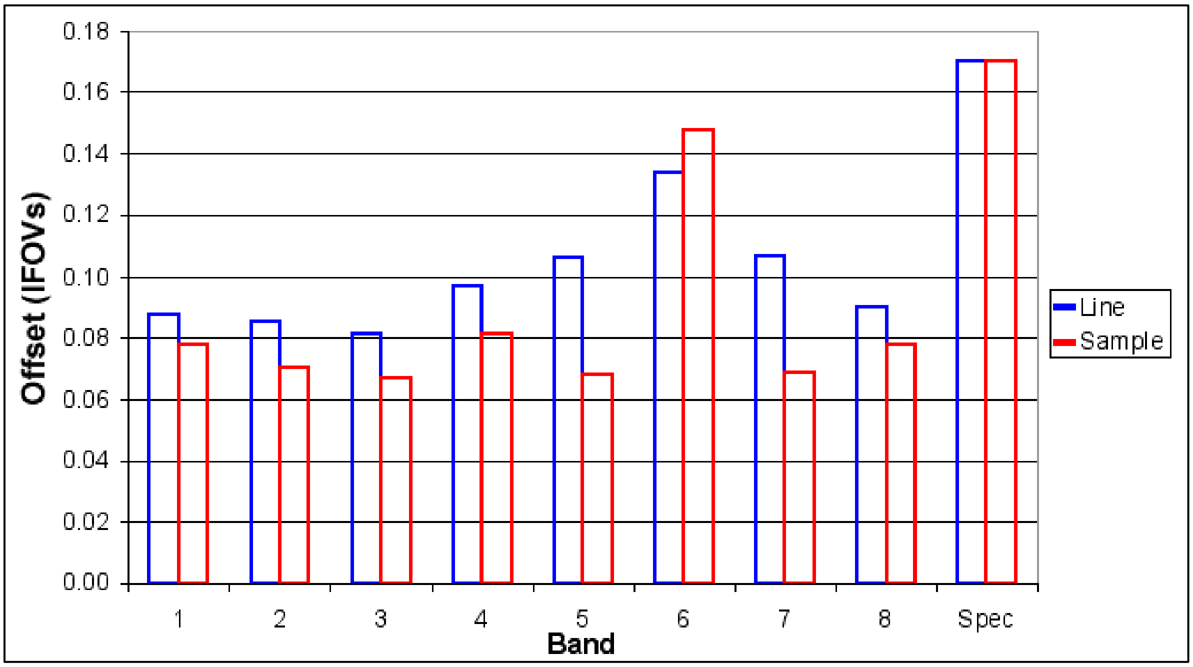

Figure 3-8. ETM+ Band Center Offsets vs. Specifications

3.5.1.4 Image-to-Image Registration

The image-to-image (or multitemporal image) registration accuracy requirement assures that geometrically corrected images from multiple dates shall be capable of being registered to an accuracy of 7.3 meters (1 sigma). This requirement was determined using cloud-free scenes of the geometric calibration "super-sites". The term "geometric super-site" is used to describe those pre-selected WRS-2 path-row locations for which ground control, digital terrain data, and reference imagery have all been collected as opposed to the more widely distributed areas with GCPs used in the previous tests. This supporting dataset makes it possible to produce precision and terrain corrected ETM+ images, and to compare them to accurately geo-registered reference images.

The required ground control, terrain models, and reference images were derived from Digital Orthophoto Quadrangle (DOQ) data (see Section 3.7). The one-meter resolution DOQs were mosaicked and reduced to the equivalent of 15-meter resolution. Five cloud-free images of two separate calibration sites were used to measure registration accuracy. The image registration assessment was performed in two ways. First, the ETM+ images were compared against the DOQ reference images. This provides a measure of image distortion relative to an absolute reference. Second, two ETM+ scenes were cross-correlated. This provides a measure of image distortion that may change from scene-to-scene although systematic calibration distortions may cancel out.

Coupled with the image registration analysis is the need to measure the ETM+ scan mirror performance to ensure the pre-launch profile and modeling is correct. The geometric calibration super-site scenes are also used for this purpose. A DOQ reference image was constructed to provide full-width coverage of a Landsat 7 scene so that measurements at all scan angles could be obtained. Mirror deviations as a function of scan angle were obtained by cross-correlating the ETM+ scene to the reference image.

No apparent problem was observed with the along-scan mirror profile. A minor adjustment to the cross-scan profiles was made to model slightly non-linear scan line corrector behavior. Also, an adjustment to the pre-launch scan angle monitor start / stop angles was made to improve image-to-image registration accuracy. The scan mirror calibration update was made to the CPF in the fourth quarter of 1999, during ETM+'s first year of operation.

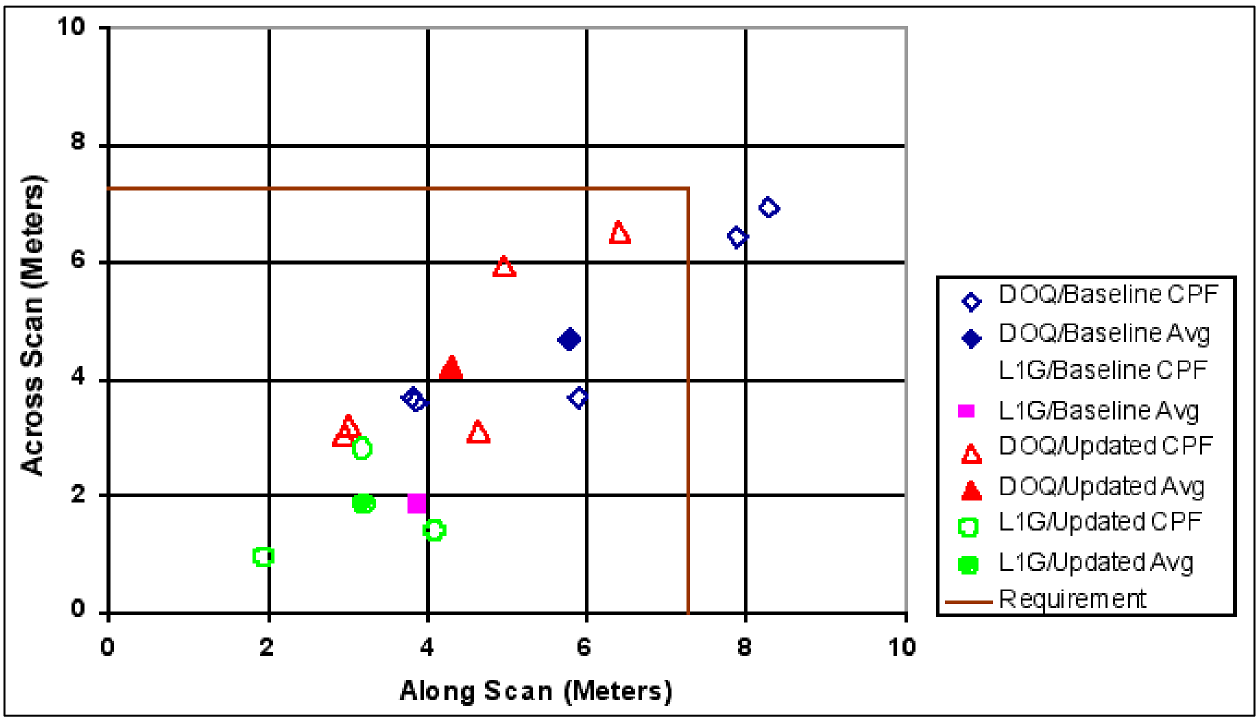

Figure 3-9. Pre- and Post-Scan Mirror Calibration Registration Accuracy

Image registration accuracy (see Figure 3-9) was measured before and after the scan mirror calibration. Results revealed that the required image registration accuracy was achieved using the baseline pre-launch scan mirror calibration parameters. Specifically:

- All-scene average registration to DOQ:

    - 5.8 meters along-scan and 4.7 meters across-scan (1 sigma)
- All-scene average ETM+ to ETM+ registration:
    - 3.9 meters along-scan and 1.8 meters across-scan (1 sigma)
- Two individual scenes fell outside specification versus DOQ

The image registration also improved using the updated scan mirror calibration parameters. Analysis yielded the following results.

- Registration to DOQ:
    - 4.3 meters along-scan and 4.2 meters across-scan (1 sigma)
- ETM+ to ETM+ registration:
    - 3.2 meters along-scan and 1.9 meters across-scan (1 sigma)
- All scenes were within specification

3.6 Sensor Alignment Calibration

The goal of the sensor alignment calibration is to improve the on-orbit knowledge of the relationship between the ETM+ instrument and the Landsat 7 navigation base reference. The IAS is required to estimate this alignment to an accuracy of 24 arc seconds (per axis) at least once per calendar quarter over the mission lifetime. This calibration uses discrete GCPs in a set of pre-defined calibration reference scenes.

The primary challenge in alignment calibration is the need to estimate the underlying alignment trend (assumed initially to be a bias or simple, static offset) utilizing a series of precision correction solutions, which measure a combination of orbit, attitude, and alignment errors. Landsat 7 has more accurate (estimated to be in the 10 to 50-meter range versus 133-meter accuracy for the ephemeris downlinked in the PCD) post-pass definitive ephemeris data available for the alignment calibration test scenes, reducing the uncertainty due to orbital errors. The GSFC FDF provides this precise ephemeris from the IAS through additional processing of the downlinked data. Multiple precision correction solutions will be integrated using a Kalman filter algorithm to estimate the best-fit systematic alignment bias. As the Kalman processes additional precision correction solutions filter, the filter’s estimates of the alignment biases improve.

Periodically, the IAS decides that the alignment knowledge has changed enough to warrant generating an updated sensor alignment matrix for inclusion in the CPF. Initially, this decision is based on the alignment bias covariance estimates generated by the Kalman filter. A new set of CPF parameters are generated as soon as the bias estimate standard deviation moves below the 24-arc second alignment accuracy requirement threshold. During normal operations, a new alignment matrix is generated whenever a new version of the CPF was scheduled for release.

As it becomes available, the Landsat 7 definitive ephemeris is used for geometrically correcting ETM+ data. Definitive ephemeris substantially improves the positional accuracy of the Level 1 product over predicted ephemeris. An ephemeris is a set of data that provides the assigned places of a celestial body (including a manmade satellite) for regular intervals. In the context of Landsat 7, ephemeris data shows the position and velocity of the spacecraft at the time imagery is collected. The position and velocity information are used during product generation within the LPGS.

The MOC receives tracking data on a daily basis that shows the position and velocity of the Landsat 7 spacecraft. This information comes from the three U.S. operated ground-receiving stations and is augmented by similar data from NASA's TDRSS. The FOT processes this information to produce a refined or "definitive" ephemeris that shows the position and velocity of Landsat 7 in one-minute intervals. Tracking data are used to compute the actual spacecraft position and velocity for the last 61 hours and to predict these values for the next 72 hours. The predicted ephemeris data are uploaded to the spacecraft daily. On-board software interpolates this data to generate the positional information contained in the PCD.

Engineers with the Landsat Project have completed a predicted versus definitive ephemeris analysis. Comparisons to GCPs demonstrated the definitive ephemeris is reliably more accurate than the predicted ephemeris. Geometric accuracy on the order of 30-50 (1 sigma) meters, excluding terrain effects, can be achieved when the definitive ephemeris is used to process the data. Level 1 products produced after March 29, 2000 use definitive ephemeris, if available. The .MTL field "ephemeris_type" in the product metadata files identifies whether a product was created with definitive or predicted ephemeris. Daily definitive ephemeris profiles have been archived since 1999 and are available for download.

3.7 Scan Mirror Calibration

The behavior of the ETM+ scan mirror is measured and, if necessary, calibrated using the IAS scan mirror calibration capability. This process compares a terrain-corrected image to a high accuracy, reference image constructed from a higher resolution source in order to detect systematic deviations of the scan mirror motion from its nominal profile. The support data used to construct the terrain-corrected image is used to generate test points, which can be related to a particular time within a particular forward or reverse scan. By comparing these test points to the reference image and analyzing the measured deviations as a function of scan direction and scan time, it is possible to estimate corrections to the pre-launch scan mirror profiles, as needed. Any significant deviations detected are folded back into the CPF through updates to the mirror profile polynomial coefficients.

Scan mirror calibration applies to both the along and across scan directions, so it detects and compensates for SLC deviations as well (see Section 2.2.3.1). In practice, SLC deviations were indistinguishable from scan mirror deviations; therefore, they were modeled as deviations of the scan mirror motion. Detecting systematic deviations that can be attributed to mirror motion requires reference points, which can be uniquely associated with individual forward and reverse ETM+ scans and provide a good distribution of data as a function of scan angle.

The current approach to acquiring such a control reference uses spatially accurate reference imagery for one or more calibration areas. The scan mirror calibration procedure compares a precision and terrain corrected ETM+ panchromatic band image with the reference image constructed from USGS DOQ data to detect within-scan mirror deviations. This involves constructing an array of points in the ETM+ scan geometry, which are mapped to the output terrain-corrected product. These points, with known scan number and time in scan coordinates are then correlated with the reference image to measure the (sub-pixel) residual distortion. The distortion patterns from many scans are analyzed to detect systematic deviations from the pre-launch forward and reverse scan mirror profiles.

On April 1, 2007, ETM+ was switched to ‘bumper operational mode’. The ETM+ was designed to have a fixed line length on every scan controlled by the SAM. However, due to the long duration of the mission, the wear on the bumpers became sufficiently large that it was no longer possible to maintain control in the SAM-mode; therefore, ETM+ was put in a backup mode where the mirror is allowed to scan at a fixed frequency of 14 Hertz (Hz) as a free pendulum. The calibration shutter is still synchronized with the scan mirror so that calibration pulse can be obtained at the end of each scan. The net result is that the variability of the scan length increases, and the geometric accuracy decreases.

3.8 Focal Plane Calibration

The focal plane calibration operations involve measuring the alignment of all eight ETM+ bands to ensure that band registration accuracy meets a 0.28 pixel requirement. If the band-to-band comparisons detect any uncompensated misalignment, the band placement calibration procedure is used to update the band center location parameters in the CPF accordingly. Detector-to-detector alignment is also monitored to ensure that image discontinuities are not introduced by using incorrect detector locations as that may cause delays in the Level 1 image resampling process.

Landsat 7 ETM+ images of focal plane calibration test sites are used to measure and calibrate the internal alignment of the detectors on the two ETM+ focal planes. These test sites are selected based on image content rather than the availability of supporting ground data. Band-to-band registration assessment requires scenes that contain significant high spatial frequency content common to all eight ETM+ bands. Although it is anticipated that scenes with long linear features would be used to assess the alignment of individual detectors, detector placement calibration techniques are still under investigation and at this time are not a part of the focal plan calibration procedure.

3.9 Modulation Transfer Function Characterization

Pre-launch modeling of the ETM+ optical system predicted that Modulation Transfer Function (MTF) performance would change on-orbit. A method was developed to monitor the along-scan MTF performance of the ETM+ sensor system using on-orbit data of the Lake Pontchartrain Causeway in Louisiana. The MTF of the ETM+ is regularly measured for comparison to the pre-launch test results and for monitoring long-term instrument performance. The MTF characterization methodology involves the analysis of cloud free scenes over the Lake Pontchartrain Bridge in Louisiana (see Figure 3-10). The bridge is a long, straight, double-spanned structure (two 10-meter wide spans, separated by 24.4 meters), is approximately aligned with the Landsat ground track (<1°), and offers high signal contrast to the waters below.

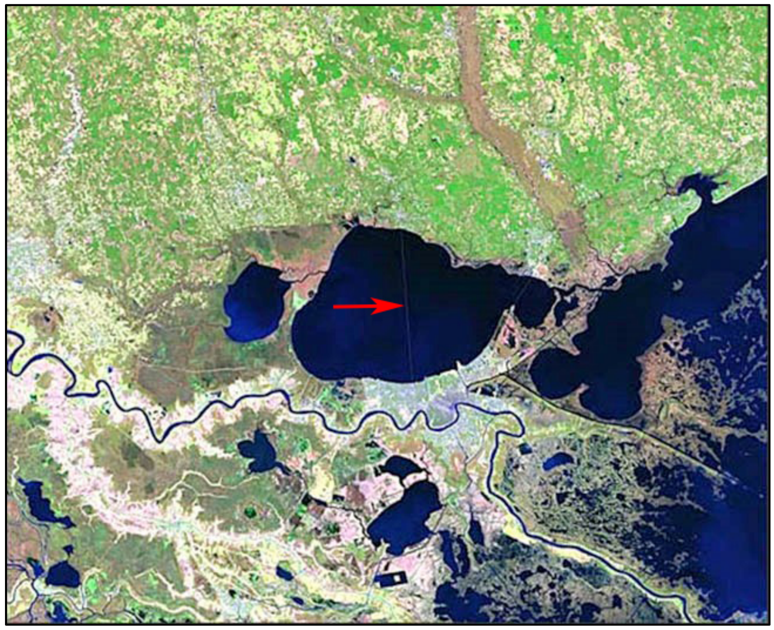

Figure 3-10. ETM+ Image of MTF Characterization Site

ETM+ image scan lines crossing the bridge are treated as multiple measurements of the target taken at varying sampling phases. These line measurements are interleaved to construct an over-sampled target profile for each ETM+ scan direction. Corresponding profiles are simulated using analytical models of the bridge and of the ETM+ system transfer function. Model parameters are adjusted to achieve the best fit between the simulated profiles and the image measurements. The ETM+ modulation at the Nyquist frequency and the full width at half maximum of the point spread function are computed from the best-fit system transfer function model.

Tracking these parameters over time has revealed apparent MTF performance degradation although this is observed mainly in the 15-meter resolution ETM+ panchromatic band. These tests confirmed the pre-launch model prediction that the panchromatic band was the most sensitive to changes in ETM+ optical performance (see Figure 3-11). The consistency between the pre-launch model, the on-orbit measurements, and the relative stability of the on-orbit measurements across the spectral bands and from date to date, suggest that the MTF estimation method is yielding useful results, and is achieving the goal of providing a means of monitoring the changing ETM+ MTF performance.

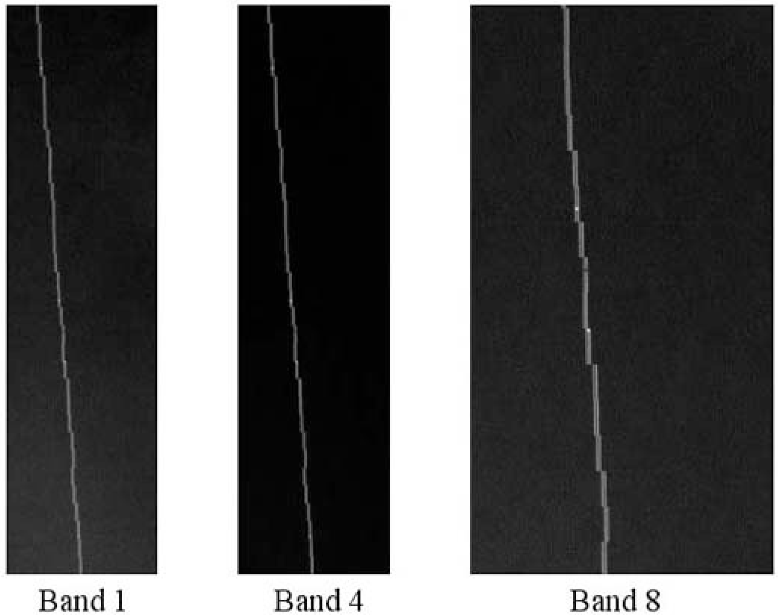

Figure 3-11. ETM+ Images of Lake Pontchartrain Bridge

3.10 Calibration Parameter Files (CPF)

3.10.1 File Description

The IAS is responsible for the sustained radiometric and geometric calibration of the Landsat 7 satellite and its ETM+ sensor and passing this knowledge to the user community. This is achieved by assessing new imagery on a daily basis, performing both radiometric and geometric calibration when needed, and developing new processing parameters for creating Level 1 products. Processing parameters are stored in the CPF, which is stamped with applicability dates and sent to EROS for storage and utilization with outbound products. As appropriate, the CPF is also sent to IGSs via the Landsat 7 MOC. The CPF provides all the radiometric and geometric calibration coefficients needed for processing raw, uncorrected Landsat 7 ETM+ image data. In addition, the IAS documents and disseminates any significant changes to CPFs through online 'Calibration Notices' as needed to alert data users to changes in ETM+ performance and/or standard processing.

3.10.2 CPF Updates

IAS updates and distributes the CPF at least every 90 days. Updates were more frequent during early orbit checkout and also occur between the regular 90-day cycles when necessary. Any irregular updates, however, do not affect the regular 90-day schedule. The timed release of a new CPF must be maintained because of the UTC Corrected (UT1) time corrections and pole wander predictions included in the file. These parameters span a 180-day interval time centered on the effective start date of the new IAS CPF. The IAS maintains a CPF archive. All Landsat CPFs are available for download from the [Landsat Calibration]() web page. Only the most recent CPFs are used in ongoing ETM+ data processing.

Prior to switching ETM+ to “bumper operational mode”, CPFs needed to be released on a regular quarterly basis, primarily because of the UT1 time corrections and the pole wander predictions included in the updated file. Following the mode switch on April 1, 2007, multiple version updates are expected during any given quarter due to a hardly predictive nature of the scanning mirror bumper parameters. The irregular (mid-quarter) updates do not affect the three month CPF release schedule.

The CPF is time stamped by IAS with an effective date range. The first two parameters in the file, “Effective_Date_Begin” and “Effective_Date_End”, designate the range and are of the form YYYY-MM-DD. The “Effective_End_Date” for the most recent parameter file is its “Effective_Date_Begin” plus 90 days. After this date, the file is without applicable UT1 time predictions. The parameter file that accompanies an order has an effective date range that includes the acquisition date of the image ordered.

Through the course of the mission, a serial collection of CPFs is generated and sent to EROS for coupling to L0R products. A distinct probability exists that a CPF will be replaced due to improved calibration parameters for a given period or perhaps due to file error. The need for unique file sequence numbers becomes necessary as file contents change. In order to generate a unique file name, the IAS uses the following file naming procedure:

L7CPF$y_1y_1y_1y_1m_1m_1d_1d_1$_$y_2y_2y_2y_2m_2m_2d_2d_2$.nn

where: L7 = Constant for Landsat 7
CPF = Three-letter CPF designator
$y_1y_1y_1y_1$ = Four-digit effectivity starting year
m_1m_1 = Two-digit effectivity starting month
d_1d_1 = Two-digit effectivity starting day
_ = Effectivity starting / ending date separator
$y_2y_2y_2y_2$ = Four-digit effectivity ending year
m_2m_2 = Two-digit effectivity ending month
d_2d_2 = Two-digit effectivity ending day
. = Ending day / version number separator
nn = Sequence number for this file (starts with 01)

As an example, suppose four calibration files were created by the IAS on 90-day intervals and sent to EROS during a given year of the mission. Further suppose that the first file was updated twice and the second and third files were updated once. The assigned filenames would be as follows:

File 1 L7CPF19980601_19980829.00
L7CPF19980601_19980829.01
L7CPF19980601_19980829.02

File 2	L7CPF19980830_19981127.01
	L7CPF19980830_19981127.02
File 3	L7CPF19981128_19990225.01
	L7CPF19981128_19990225.02
File 4	L7CPF19990226_19990526.01

The 00 sequence number assigned to the original CPF (File 1) uniquely identifies this as a pre-launch CPF. Sequence numbers for subsequent time periods all begin with 01. New versions or updates are incremented by one.

This example assumes the effectivity dates do not change. The effectivity date range for a file can change, however, if a specific problem (e.g., detector outage) is discovered somewhere within the nominal 90-day effectivity range. Assuming this scenario, two CPFs with new names and effectivity date ranges are generated for the time period under consideration. The “Effective_Date_End” for a new pre-problem CPF would change to the day before the problem occurred. The “Effective_Date_Begin” remains unchanged. A post-problem CPF with a new file name would be created with an “Effective_Date_Begin” corresponding to the imaging date when the problem occurred. The “Effective_Date_End” assigned would be the original “Effective_Date_End” for the time period under consideration. New versions of all other CPFs affected by the erroneous parameter also would be created.

Using this example, suppose a dead detector is discovered to have occurred on January 31, 1999. Two new CPFs are created that supersede the time period represented by file number three, version 2, and a new version of file number four is created. The new file names and sequence numbers become:

File 3	L7CPF19981128_19990225.01
	L7CPF19981128_19990225.02
	L7CPF19981128_19990131.03
	L7CPF19990201_19990225.03
File 4	L7CPF19990226_19990526.01
	L7CPF19990226_19990526.02

3.10.3 File Structure

All calibration parameters are stored as ASCII text using the Object Description Language (ODL) syntax developed by NASA’s Jet Propulsion Laboratory (JPL). ODL is a tagged keyword language developed to provide a human-readable data structure to encode data for simplified interchange. The body of the file is composed of two statement types:

1. Attribute assignment statement used to assign values to parameters.
2. Group statements used to aid in file organization and enhance parsing granularity of parameter sets.

To illustrate, consider the first three parameters in the file: “Effective_Date_Begin”, “Effective_Date_End”, and the “CPF_File_Name”. These three parameters form their own group, which is called “FILE_ATTRIBUTES”. The syntax employed for this collection of parameters in the CPF appears as:

```
GROUP = FILE_ATTRIBUTES
    Effective_Date_Begin = 1999-02-26
    Effective_Date_End = 1999-05-26
    CPF_File_Name = L7CPF19990226_19990526.01
END_GROUP = FILE_ATTRIBUTES
```

A description of the CPF contents is in Appendix B.

Section 4 Long-Term Acquisition Plan (LTAP)

4.1 Overview

Note: The following description was applicable to Landsat 7 operations from launch through December 2012 and is included for historical interest. In 2012, to make best use of an aging instrument, a new approach was implemented, dubbed “continental landmass scheduling”. That new approach is described in Section 4.2.

The Landsat 7 LTAP, in conjunction with the MOC Scheduling System software, automates the acquisition of Landsat scenes to periodically refresh the global archive of sunlit, substantially cloud-free land images. (From this point on, the use of “scheduler” includes both the scheduling software and the LTAP data files.) By applying a set of algorithms on a daily basis, the scheduler is designed to ensure optimal collection of Landsat 7 ETM+ imagery for scientific applications, while minimizing the effects of cloud-cover and system constraints. This section provides a brief overview of the LTAP strategy and details the specific algorithms and input files (see Section 4.1.8) used for calculating scene acquisition priorities. For a more complete review of the LTAP, including the science justification for the approach and performance results, see Goward et al. (1999), Gasch and Campana (2000), and Arvidson et al. (2001).

The ETM+ sensor does not continually acquire imagery data as it orbits the Earth. Instead, acquisitions are scheduled in advance using the LTAP data files in conjunction with a software scheduler. The WRS-2 system divides the Earth into a grid of 57,784 scenes—233 paths by 248 rows. However, due to the satellite’s slight inclination away from North-South, the Polar Regions are not completely covered. The Landsat 7 satellite is operated such that it follows the WRS-2 grid within tight tolerances, overflying the entire scene grid every 16 days. A pre-launch database of just over 14,000 scenes containing "land" was compiled for the LTAP, including continental areas, shallow coastal waters, Antarctic sea-ice, and all known islands and reefs. Within any given 24-hour period, approximately 850 of these land scenes (located along descending, sunlit paths only) are in view of the ETM+ and are candidates for acquisition. At launch, mission resource limitations restricted the daily acquisition volume for the U.S. archive to 250 scenes; improved resources now allow Landsat 7 to collect ~450 scenes per day (ca. 2017). Given the resources available initially, the mission scheduler selected the "best" 250 scenes for acquisition each day within these constraints. The scheduler automatically selected the best scenes in accordance with the LTAP, basing these decisions on cloud-cover forecasts, urgency of acquisition, and availability of resources to optimize fulfillment of the overall Landsat 7 mission goals.

From the outset of the mission, the basic scheduling approach has been to identify the candidate scenes to be considered, to raise or lower their base priority (as assigned in the LTAP data files) through consideration of several factors, to use the resulting “dynamic” priority to form a priority-ordered list, and to schedule the top ~250 (now ~450 (ca. 2017)) scenes to be collected. The factors considered during scheduling are:

1. Seasonality of vegetated regions, as well as niche-science communities with specific acquisition needs
2. Predicted versus nominal cloud-cover (forecast versus statistical assessments)
3. Solar elevation angle (especially important at high latitudes)
4. Missed opportunities for previous acquisitions
5. Quality (based on cloud-cover assessments) of previous acquisitions
6. Scene clustering (for continuity of swath observations)
7. System constraints (e.g., instrument duty cycle, ground station locations and functionality, recorder capacity)

Factors 1-6 listed above are used directly for calculating the priority of each potential acquisition, while the actual acquisition list is obtained by incorporating system constraints (Factor 7). Factor 4 requires feedback from previous scheduling runs, while Factor 5 requires feedback from cloud cover assessment of archived scenes. Each of these factors are discussed in the following sections.

4.1.1 National Centers for Environmental Prediction (NCEP)

The NCEP provides timely and continually improving worldwide forecast guidance products. NCEP, a critical part of NOAA's National Weather Service, is the starting point for many of the weather forecasts in the U.S. NCEP generates weather related products including the cloud cover predicts used by the MOC for ETM+ image scheduling.

4.1.2 Seasonality

The LTAP was designed to help the scheduling software select acquisitions more frequently during periods of land cover change, such as growth and senescence of vegetation, and less frequently during relatively stable periods, such as when full growth canopy exists or during winter quiescence. An eight-year Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) dataset was used to determine when and where change was occurring around the globe (Goward, et al., 1994, 1999). To flag seasonal change within a WRS-2 scene, a statistical test was applied to each NDVI 45 km sample mapped to that scene. Comparing each AVHRR-derived imagery sample or pixel to the same pixel two months later revealed periods of significant change in the NDVI's mean and standard deviation. This approach identified when multiple ETM+ acquisitions may be needed, versus periods of minimal change that may require only a single acquisition.

Based on this analysis, the year is broken into a set of temporal "windows" for each path-row location. During each window, a location may be labeled as "acquire once", "acquire always", or "never acquire", and this information is stored in the LTAP seasonality file. It should be noted that "acquire always" does not imply that an actual acquisition will occur for every overpass during that time window. Rather, that scene will always be a candidate for acquisition, and other factors within the scheduling process will govern whether or not an acquisition actually takes place. Conversely, "acquire once" means that once a quality, cloud-free scene is acquired, that path-row location is no longer eligible for acquisition until the next time period begins.

Niche science communities are defined as users with specific acquisition requirements that do not necessarily correlate with those derived using the NDVI approach. Basically, defining acquisitions solely through semi-monthly NDVI change does not fully capture the science and user interest in the Landsat mission. To supplement the NDVI-based seasonality metric, niche science communities have defined time windows more appropriate to their land cover and application requirements. These niche communities initially sponsored the following locations and associated time windows:

- 282 agriculture areas (acquire every season if cloud cover predict < 60%)
- 35 calibration sites (acquire "always")
- 896 reefs (acquire from 2x to 6x each year)
- 30 fire-impacted areas (acquire "always")
- 1392 land ice scenes other than Antarctica (acquire once during certain months)
- 3601 Antarctica scenes (acquire once during January-February)
- 60 oceanic islands (acquire twice each year)
- 1175 rainforest areas (acquire "always" all year)
- 352 sea ice scenes (acquire from 1x to 3x each year)
- 11 Siberia scenes (acquire "always" over 9 months)
- 72 volcanoes (acquire from 2x to 12x during year, including night)

In general, approximately 27 percent of the 250 scenes/day acquired by Landsat 7 are devoted to satisfying "niche" requests, approximately 70 percent are devoted to satisfying routine acquisitions from the seasonality file, and 3 percent are devoted to night images or special high-priority acquisitions (natural disasters, national needs, etc.). Requirements for night imaging and high-priority acquisitions, such as for disaster response, are outside the scope of the LTAP and are handled by the USGS Data Acquisition Manager (DAM) at the GSFC who may submit special requests to the MOC for inclusion in the schedule.

4.1.3 Predicted Cloud Cover

A basic goal of Landsat 7 scheduling is cloud avoidance. The scheduling software compares near-term predictions from NCEP to the historical average cloud cover for that scene for that month, to determine acquisition dynamic priorities each day. Scenes with better-than-average cloud-cover predictions are given a priority increase, while those with poorer cloud cover predictions are given a lower priority.

Global historical cloud data (climatology) are obtained from International Satellite Cloud Climatology Project (ISCCP) records (Rossow et al., 1996), which give monthly estimates of cloud-cover percentage for 2.5° grid cells from 1989 to 1993. Monthly averages over the initial five-year dataset (1989-1993) were computed and mapped to the Landsat WRS-2 grid to produce a cloud climatology. This dataset has been extended over the years. Studies have been made to evaluate replacement of the ISCCP data with a Terra MODIS dataset of assessed cloud cover data. The advantages of using MODIS data are the higher resolution and that MODIS values are computed at the same time of day as Landsat data are acquired (see Section 2.1.1), whereas the

ISCCP data was based on diurnal (24-hour) composites. The MODIS dataset under consideration is currently 13 years long; 2001–2014.

Once received from NCEP, these cloud predictions are translated to the Landsat WRS-2 coordinate system. The forecast nearest in time to a candidate acquisition is compared to the climatology value for that day to determine whether the predicted observing conditions are better or worse than typical for that location. Acquisition dynamic priority is then adjusted upward to favor the better conditions or downward to avoid the worst conditions. Cloud avoidance has so far been successful.

4.1.4 Solar Elevation Angle

Requests for high-latitude scenes are typically rejected during local winter when the solar elevation is below a certain threshold. This angle, between the scene center, the horizon, and the center of the Sun's disc, varies with time and with latitude and local elevation. This threshold was set at 5° during the initial years of the Landsat 7 mission in LTAP. On July 24, 2002, the cutoff angle was changed to 15° for the northern hemisphere because of duty cycle concerns and the fact that snow dominates scenes acquired at lower (i.e., winter) solar elevation angles. The cutoff angle remains at 5° for the southern hemisphere to avoid coverage impacts over the bottom third of Argentina and bottom half of New Zealand's South Island.

4.1.5 Missed Opportunities

An acquisition request is granted a priority increase as a function of the number of consecutive past cycles in which the opportunity to acquire the requested scene was not fulfilled. This occurs when the scene was not scheduled for acquisition due to duty cycle or other impacts, or when the acquired image fails to meet minimum quality standards, typically due to cloud cover. For example, if the last successfully acquired image of a scene was 48 days ago, then a request for this scene is granted a priority increase based on two missed opportunities from 32 and 16 days ago. In addition, all new requests submitted when an acquisition window opens are also given a priority increase to help them compete with established requests.

4.1.6 Image Quality

Image quality is determined during image processing at EROS and expressed as the amount of cloud cover assessed within the image, as well as image integrity in terms of missing data and other image artifacts (see Appendix A)—is fed back to the MOC daily. The quality of the most recently acquired image of a path/row from a previous cycle also factors into the dynamic priority for another acquisition. Taking advantage of scene overlap at high latitudes, the scheduler also considers the quality of the best image that could be spliced together as a mosaic of imagery of adjacent scenes acquired in the recent past.

A previous acquisition with a cloud cover score of 10 percent or less is considered a successful acquisition and resets the priority for another acquisition attempt back to the base value. Conversely, a previous acquisition with a cloud cover score of greater than 60 percent is considered a missed opportunity and the dynamic priority for another acquisition attempt is raised. A sliding scale is applied for values between 10 and 60 percent.

After the failure of the SLC mechanism (see Section 2.2.3.3), another quality parameter was added in 2004; a gap phase statistic. It characterizes the location of the scan gap pattern within each image relative to the scene center. This enables users to identify image pairs that when used together would fill in the gaps left by the mechanism failure. The scheduler uses the gap phase statistic to identify potential gap-closing image pairs in previous acquisitions. When a new acquisition candidate is being considered for scheduling, the existence of a good gap-closing image pair lowers the desirability of acquiring a new candidate, while lack of a good image pair raises the priority for acquiring a new candidate that might better pair with an archived acquisition.

4.1.7 Clustering

Within the Landsat 7 scheduling process, a higher priority is given to scenes that form "clusters", or contiguous groups of along-path acquisitions. Most importantly, this reduces the on-off cycling of the ETM+ power supply and prolongs instrument life. It also promotes archiving of continuous swath data.

4.1.8 Long-Term Acquisition Plan Files

The contents of the following files represent the underpinnings of the LTAP:

1. Seasonality file
2. WRS-2 land database
3. Nominal cloud cover file
4. Nominal cloud cover daylight additions file
5. Nominal gain settings file
6. Maximum solar zenith angle

1. The seasonality file specifies which WRS-2 scenes are to be acquired during which periods of time (request period), and the frequency of acquisition during those periods. Frequency of acquisition is defined as either "once" during the request period, or "all" opportunities during the request period.

The following is the warning label associated with the seasonality file:

The scheduler has many inputs and priorities that it must process during consideration of requests for scheduling, including:

- *predicted cloud cover as compared to the nominal*
- *number of missed opportunities for this request since it was opened*
- *how good the cloud cover assessment score was for the last acquisition*
- *nearness to end of the request period*
- *availability of resources including duty cycle, onboard recorder space, and station contact time*

The result of this decision process is that scenes marked with an "all" opportunities frequency are usually acquired every 4-5 cycles (64-80 days) instead of every cycle (16 days). Another outcome is that scenes marked with a "once" frequency may be acquired multiple times within the request period in an attempt to acquire an image with 10 percent or less cloud cover—the definition of a successful acquisition. As a consequence, science data users should treat the frequency assignment in the seasonality file as a guide, not a rule.

2. The WRS-2 land database identifies those WRS scenes containing land or shallow water, which is imaged at least once every year. At the end of the file are separate tables for the niche communities and special interests. These include EOS validation sites, glaciers, MODIS fire validation sites, political (disputed sites), volcanoes, and oceanic islands. A comprehensive list of coral reefs was added after the launch of Landsat 7.

3. and 4. The nominal cloud cover file reports the average cloud cover for each WRS-2 scene for each month of the year. The file spans one year and addresses the descending rows only. The nominal cloud cover daylight additions file adds those ascending rows that will be in daylight during some part of the year and therefore may be imaged. The initial set of average cloud cover for years 1989-1993 was derived from the ISCCP-D2 dataset, described in Section 4.1.3. This file is updated as subsequent years are processed; currently, it covers the period between July 1983 and June 2006. The columns in the nominal cloud cover files are: *day of the year for the first day of the month | day of the year for the last day of the month | path | row | cloud cover value.* All the cloud cover values are given for Row 1 across all paths, followed by Row 2, etc.

5. The nominal gain settings file identifies the gain settings used as defaults for each WRS-2 scene for each day of the year. This file spans one year. Although the scheduler uses the Day of Year (DOY) value, the *DD-MMM* values are also included for those who do not easily equate a DOY value of 177 with the date 25-JUN. The file contains settings of *H* for high gain and *L* for low gain for both descending and ascending rows. The order in which the settings are specified for each scene refers to bands *123456678*, where Band 6 is repeated twice, once for Format 1 and once for Format 2 (see Section 2.2.2), and Band 8 is the panchromatic band. Band 6-1 and Band 6-2 are constant at *LH* and Band 8 is constant at *L*. The other bands are changed in groupings, with Bands 1, 2, and 3 changed together, Band 4 changed on its own merits, and Bands 5 and 7 changed together. Ascending rows that are imaged at night use the following default settings: *HHHHLLHLL*. The file only contains entries showing when the default gain setting has changed from its previous setting. The default gain settings are generated using rules that take land cover type and sun angle into account. Other files influenced by these rules are:

- desert mask
- arctic mask
- monthly gain maps

6. Initially, the maximum solar zenith angle was a single value for all scenes at all times of the year. Daylight imaging was not scheduled if the angle was 85 degrees or more. (This is the same as 5 degrees or less in solar elevation angle from the Earth's surface.) In 2002, this was split into two values: 75 degrees for the northern hemisphere and 85 degrees for the southern hemisphere (15 and 5 degrees of solar elevation angle, respectively).

4.2 Continental Landmass Scheduling

In February 2014, ETM+ continental landmass scheduling was implemented to help extend the ETM+ lifetime and make best use of aging resources. These changes are partly due to the availability of Landsat 8 imagery in 2013. The primary characteristics of this approach are:

1. Only continental land (not including Antarctica) from Row 10 southward and a few major islands are imaged (not Greenland). No small islands or reefs are acquired. No night imaging occurs except by special request. This results in longer intervals and fewer ETM+ on/off cycles.
2. The daily quota of scenes acquired is essentially disabled due to these changes. Onboard resources (ETM+ duty cycle, SSR capacity) and communication link availability are the determining factors for how many scenes are acquired daily. Additional downlink opportunities were added to support increased acquisitions.
3. All daylight scenes are candidates at every opportunity; there are no longer any seasonality windows being applied.
4. Cloud avoidance is active.
5. Use of a gap phase statistic to acquire gap-filling image pairs has been disabled.

In March of 2016, the ETM+ duty cycles were relaxed by five percent to allow occasional excursions as needed to acquire the maximum scenes possible. By 2017, acquisitions under this approach were at an average of ~440 images a day, with peaks just over 500 images per day during the Northern Hemisphere summer. See Section 5.7.3.2 for an illustration of continental coverage into mid-2017.

Section 5 Level 1 Products

5.1 Overview

The geometric algorithms used by the Level 1 processing system at the EROS Center were originally developed for the Landsat 7 IAS. The overall purpose of the IAS geometric algorithms is to use Earth ellipsoid and terrain surface information in conjunction with spacecraft ephemeris and attitude data, and knowledge of the ETM+ instrument and its satellite geometry to relate locations in ETM+ image space (band, scan, detector, sample) to geodetic object space (latitude, longitude, and elevation).

These algorithms are used for purposes of creating accurate Level 1 output products, characterizing the ETM+ absolute and relative geometric accuracy, and deriving improved estimates of geometric calibration parameters such as the sensor to spacecraft alignment.

Standard processing is included with every product ordered through EarthExplorer, GloVis, and LandsatLook Viewer. As of October 2008, all Landsat data are available for download at no charge.

5.2 Level 1 Algorithms

The Level 1 processing algorithms used at EROS includes:

- PCD processing
- MSCD processing
- ETM+ / Landsat 7 sensor / platform geometric model creation
- Sensor loss of sight generation and projection
- Output space / input space correction grid generation
- Image resampling
- Geometric model precision correction using ground control
- Terrain correction

5.3 Ancillary Data

The Landsat 7 ETM+ geometric correction algorithms are applied to the wideband data (image plus supporting PCD and MSCD) contained in the raw (L0R) or radiometrically-corrected (L1R) products. Some of these algorithms also require additional ancillary input datasets and include the following:

1. Precise ephemeris from the FDF - used to minimize ephemeris error when performing sensor to spacecraft alignment calibration
2. Ground control / reference images for geometric test sites - used in precision correction, geodetic accuracy assessment, and geometric calibration algorithms
3. Digital elevation data for geometric test sites - used in terrain correction and geometric calibration
4. Pre-launch ground calibration results including band / detector placement and timing, scan mirror profiles, and attitude sensor data transfer functions (gyro and

Attitude Displacement Sensors (ADS)), to be used in the generation of the initial CPF

5. Earth parameters including static Earth model parameters (e.g., ellipsoid axes, gravity constants) and dynamic Earth model parameters (e.g., polar wander offsets, UT1-UTC time corrections) - used in systematic model creation and incorporated into the CPF

5.4 Image Assessment System (IAS)

The IAS (see Section 3.5) is responsible for the offline assessment of image quality to ensure compliance with the radiometric and geometric requirements of the spacecraft and the ETM+ sensor throughout the life of the Landsat 7 mission. In this role, the IAS orders up to 10 L0R scenes daily from the LAM and processes them to Level 1s, performing additional quality checks and trending that are not part of the standard Level 1 product generation. In addition to its assessment functions, the IAS is responsible for the radiometric and geometric calibration of the ETM+ instrument. The IAS maintains a database of calibration and quality information and trends many performance parameters and measurements. On a quarterly basis, the IAS updates the CPF, which contains the radiometric and geometric correction parameters required during Level 1 processing to create products of uniform consistency. This file is stamped with applicability dates and sent to the LPGS for use in Level 1 processing. The CPF is also made available to the IGS for their use in processing data received at their sites. Operational IAS activities occur at the EROS Center while less frequent assessments and calibration certification are the responsibility of the L7 Project Science Office at NASA's GSFC.

Detailed algorithm descriptions for the high-level processing flows for the IAS Level 1 processing algorithms can be found in the Landsat 7 IAS Geometric Algorithm Theoretical Basis Document. This document lists supporting theoretical concepts and mathematics of the IAS geometric algorithms, a review of the Landsat 7 ETM+ viewing geometry, a discussion of the coordinate and time systems used by the algorithms and the relationships between them, the mathematical development of, and solution procedures for the Level 1 processing, geometric calibration, and geometric characterization algorithms, and an examination of the estimates of uncertainty (error analysis) associated with each of the algorithms.

5.5 Landsat Product Generation System (LPGS)

The LPGS performs radiometric and geometric processing on data to generate a standard Landsat 7 Level 1 product with the following parameters:

- Standard terrain correction (L1T - precision and terrain correction) if possible; otherwise, best available (L1G - systematic or L1Gt - systematic terrain)
- Geographic Tagged Information File Format (GeoTIFF) output format
- Cubic Convolution (CC) resampling method (see Figure 5-1)
- 15-meter (Band 8), 30-meter (Bands 1-5 and Band 7), and 60-meter (Band 6) pixel sizes

- Universal Transverse Mercator (UTM) map projection (Polar Stereographic (PS) projection for scenes with a center latitude greater than or equal to 63.0 degrees)
- World Geodetic System 1984 (WGS84) datum
- North-up (NUP) image orientation

All newly acquired Landsat data are processed to a Level 1 product immediately after receipt and posted to the online disk storage from which it can be downloaded, at no charge, via EarthExplorer, GloVis, or LandsatLook Viewer web interfaces.

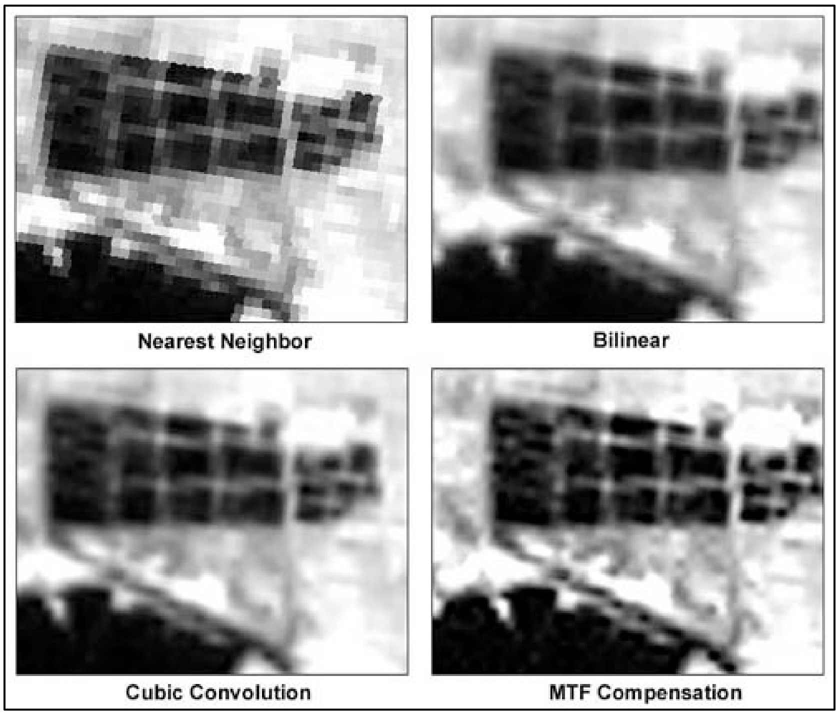

Figure 5-1. Illustration of Landsat 7 CC Resampling vs. Other Methods

5.6 Level 1 Data Products

All Landsat scenes from USGS EROS are processed to Level 1 products. The Level 1 product available to users is a high-quality, radiometrically, and geometrically corrected image. Each product is created using the best available processing level for each scene. The processing level used is determined by the existence of GCP, elevation data provided by a Digital Elevation Model (DEM), and/or data collected by the spacecraft and sensor (PCD). The LPGS uses one of three processing levels to create the Level 1 products:

- **L1T**
  Precision and Terrain Correction (L1T) provides radiometric and geometric accuracy by incorporating GCPs while employing a DEM for topographic displacement. Geodetic accuracy of the product depends on the image quality and the accuracy, number, and distribution of the GCPs.

- **L1Gt**
  Systematic Terrain Correction (L1Gt) provides systematic, radiometric, and geometric accuracy, while employing a DEM to correct for relief displacement.

- **L1G**
  Systematic Correction (L1G) provides systematic, radiometric, and geometric corrections, which are derived from PCD.

The Level 1 image is delivered in DNs. These units can easily be rescaled to spectral radiance or Top-of-the-Atmosphere (TOA) reflectance.

5.6.1 Product Components

A complete Landsat 7 Level 1 product consists of 21 total files. The breakdown of these 21 files is as follows:

- **9 individual band images - *(_B#.TIF)***
  Seven spectral bands and two thermal bands are included with the Level 1 product. Spectral bands 1-5 and 7 have a spatial resolution of 30 meters while spectral band 8 (panchromatic, grey-scale image) has a 15 meter spatial resolution. The thermal bands are collected in both low and high gain (Bands 61 and 62, respectively) for increased radiometric sensitivity and dynamic range. The band images are delivered as 8-bit images with 256 grey levels.

- **1 metadata file *(_MTL.txt)***
  Level 1 metadata are stored in a .txt file. Metadata files contain beneficial information for the systematic searching and archiving practices of data while also providing the essential characteristics of the Level 1 product.

- **1 GCP file *(GCP.txt)***
  GCPs are defined as points on the surface of the earth of known location used to geo-reference Landsat Level 1 imagery. This file contains the GCPs used during image processing.

- **1 README file *(README.GTF)***
  The README file contains a summary and brief description of the Level 1 product contents and naming conventions for the files included.

- **9 gap mask files in individual directory (SLC-off data only) *(GM_B#.TIF)***
  Landsat 7 ETM+ scenes acquired after May 2003 include gap mask files for each band. These files identify the location of all pixels affected by the original data gaps caused by the SLC failure in May 2003.

5.6.2 Product Naming Convention

The Landsat scene identifier provides valuable information about each scene. A Landsat scene ID details which satellite and sensor acquired the image, the WRS path/row location, date of acquisition, which facility obtained the transmitted data, and the archive version number. Figure 5-2 shows the scene ID naming convention along with examples of Landsat scene IDs.

Scene ID

LXSPPPRRRYYYYDDDGSIVV

L = Landsat
X = Sensor
S = Satellite
PPP = WRS path
RRR = WRS row
YYYY = Year
DDD = Julian day of year
GSI = Ground station identifier
VV = Archive version number

Examples:
LC80290302015343LGN00
LE70160392004262EDC02
LT40170361982320XXX08
LM10170391976031AAA01

Figure 5-2. Landsat Scene ID Naming Convention

5.6.3 Product Size

All available Landsat 7 Level 1 products are spatially defined by WRS-2 boundaries. Standard WRS-2 defined scenes can be downloaded from USGS EROS. Landsat 4-5 TM, Landsat 7 ETM+, and Landsat 8 Operational Land Imager (OLI) / Thermal Infrared Sensor (TIRS) follow the WRS-2. Landsat 1, 2, and 3 followed WRS-1. Figure 5-3 shows the size of an example WRS-2 path/row for Landsat 7.

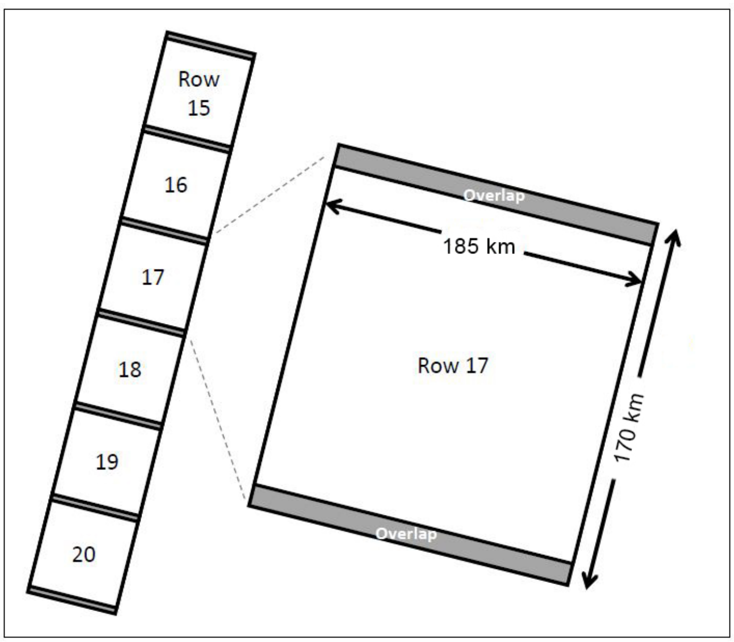

Figure 5-3. Example Landsat 7 ETM+ WRS-2 Path/Row

5.6.4 Product Format

The Landsat 7 data product is packaged as GeoTIFF. GeoTIFF is based on Adobe's Tagged Image File Format (TIFF) - a self-describing format developed to exchange raster images such as clipart, logotypes, and scanned images between applications and computer platforms. Today, the TIFF is the only full-featured format in the public domain capable of supporting compression, tiling, and extension to include geographic metadata.

The TIFF file consists of a number of labels (tags), which describe certain properties of the file (such as gray levels, color table, byte format, and compression size). After the initial tags come the image data, which may be interrupted by more descriptive tags. GeoTIFF refers to TIFF files, which have geographic (or cartographic) data embedded as tags within the TIFF file. The geographic data can then be used to position the image in the correct location and geometry on the screen of a geographic information display.

Each Landsat 7 band is delivered as its own 8-bit grayscale GeoTIFF image. A standard WRS-2 scene possessing the full band complement is comprised of nine separate GeoTIFF images or files. For detailed information regarding the Landsat 7 GeoTIFF implementation, refer to the Landsat 7 ETM+ Level 1 Data Format Control Book.

5.6.5 Conversion to Radiance

During Level 1 product rendering, image pixels are converted from DN to units of absolute radiance using 32-bit floating-point calculations. Pixel values are then scaled to byte values prior to media output. The following equation is used to convert DNs in a Level 1 product back to radiance units:

$$L_\lambda = Grescale \cdot QCAL + Brescale$$

which is also expressed as:

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{QCALMAX - QCALMIN}\right) \cdot (QCAL - QCALMIN) + LMIN_\lambda$$

where:

L_λ	= Spectral radiance at the sensor's aperture in (Watts/(m² * sr * µm))
Grescale	= Rescaled gain (the data product "gain" contained in the Level 1 product header or ancillary data record) in (Watts/(m² * sr * µm))/DN
Brescale	= Rescaled bias (the data product "offset" contained in the Level 1 product header or ancillary data record) in (Watts/(m² * sr * µm))
QCAL	= Quantized calibrated pixel value in DN
$LMIN_\lambda$	= Spectral radiance scaled to QCALMIN in (Watts/(m² * sr * µm))
$LMAX_\lambda$	= Spectral radiance scaled to QCALMAX in (Watts/(m² * sr * µm))
QCALMIN	= Minimum quantized calibrated pixel value (corresponding to $LMIN_\lambda$) in DN = 1 for LPGS products = 1 for NLAPS** products processed after 4/4/2004 = 0 for NLAPS** products processed before 4/5/2004
QCALMAX	= Maximum quantized calibrated pixel value (corresponding to

LMAX$_\lambda$) in DN
= 255

Some Landsat 4-5 TM data were processed through NLAPS. Products generated by the LPGS and NLAPS systems are similar, but not identical. This web page describes the product differences. Landsat 7 data were never processed using NLAPS.

The LMINs and LMAXs are the spectral radiances for each band at DN 0 or 1 and 255 (i.e., QCALMIN, QCALMAX), respectively. LPGS used 1 for QCALMIN. One LMIN / LMAX set exists for each gain state. These values change slowly over time as the ETM+ detectors lose responsivity. Table 5-1 lists two sets of LMINs and LMAXs. The first set should be used for LPGS Level 1 products created before July 1, 2000, and the second set for Level 1 products created after July 1, 2000. Please note the distinction between acquisition and processing dates. Use of the appropriate LMINs and LMAXs ensure accurate conversion to radiance units. Note for Band 6: A bias was found in the pre-launch calibration by two Landsat Science Team investigator groups post-launch. For data processed before December 20, 2000, the image radiances given by the above transform were 0.31 (Watts/(m² * sr * μm)) too high. The September 1, 2000 update on this page provides more information. The required radiometry constants are tabulated in this paper.

	Processed Before July 1, 2000				**Processed After July 1, 2000**			
	Low Gain		**High Gain**		**Low Gain**		**High Gain**	
Band Number	**LMIN**	**LMAX**	**LMIN**	**LMAX**	**LMIN**	**LMAX**	**LMIN**	**LMAX**
1	6.2	297.5	6.2	194.3	6.2	293.7	6.2	191.6
2	6.0	303.4	6.0	202.4	6.4	300.9	6.4	196.5
3	4.5	235.5	4.5	158.6	5.0	234.4	5.0	152.9
4	4.5	235.0	4.5	157.5	5.1	241.1	5.1	157.4
5	1.0	47.70	1.0	31.76	1.0	47.57	1.0	31.06
6	0.0	17.04	3.2	12.65	0.0	17.04	3.2	12.65
7	0.35	16.60	0.35	10.932	0.35	16.54	0.35	10.80
8	5.0	244.00	5.0	158.40	4.7	243.1	4.7	158.3

Table 5-1. ETM+ Spectral Radiance Range (Watts/(m² * sr * μm))

5.6.6 Radiance to Reflectance

For relatively clear Landsat scenes, a reduction in between-scene variability can be achieved through a normalization for solar irradiance by converting spectral radiance, as calculated above, to planetary reflectance or albedo. This combined surface and atmospheric reflectance of the Earth is computed with the following formula:

$$\rho_p = \frac{\pi \cdot L_\lambda \cdot d^2}{ESUN_\lambda \cdot cos\theta_s}$$

Where:

ρ_p = Unitless planetary reflectance

π = Mathematical constant approximately equal to 3.14159

L_λ = Spectral radiance at the sensor's aperture

d = Earth-Sun distance in astronomical units interpolated from values listed in Table 5-2

$ESUN_\lambda$ = Mean solar exo-atmospheric irradiances from Table 5-2 (View *Earth-Sun distances for every DOY*)

θ_s = Solar zenith angle in degrees

Day of Year	Distance	Day of Year	Distance	Day of Year	Distance	Day of Year	Distance	Day of Year	Distance
1	.98331	74	.99446	152	1.01403	227	1.01281	305	.99253
15	.98365	91	.99926	166	1.01577	242	1.00969	319	.98916
32	.98509	106	1.00353	182	1.01667	258	1.00566	335	.98608
46	.98774	121	1.00756	196	1.01646	274	1.00119	349	.98426
60	.99084	135	1.01087	213	1.01497	288	.99718	365	.98331

Table 5-2. Earth-Sun Distance in Astronomical Units

Band	Watts/(m² * µm)
1	1970
2	1842
3	1547
4	1044
5	225.7
7	82.06
8	1369

Table 5-3. ETM+ Solar Spectral Irradiances (generated using ChKur** solar spectrum)

***ChKur is the combined Chance-Kurucz Solar Spectrum within MODTRAN 5 (Berk et al. 2011). This spectrum has been used for the validation of the Landsat 7 ETM+ reflective band calibration and is therefore recommended for use for Landsat 7. The Thuillier spectrum (2003), previously used to calculate ESUN values presented in this document and elsewhere, has been recommended by the Committee on Earth Sciences (CEOS) to be used, where possible, as a standard. Thuillier data has not been used for the validations and there is an up to 3.5 percent difference in the integrated ESUN values using these two spectra, the largest difference being in ETM+ Band 7 data.*

5.6.7 Band 6 Conversion to Temperature

ETM+ Band 6 imagery can also be converted from spectral radiance to a more physically useful variable. This is the effective at-satellite temperatures of the viewed Earth-atmosphere system under an assumption of unity emissivity and using pre-launch calibration constants listed in Table 5-4. The conversion formula is:

$$T = \frac{K2}{\ln(\frac{K1}{L_\lambda} + 1)}$$

Where:

T = Effective at-satellite temperature in Kelvin
$K2$ = Calibration constant 2
$K1$ = Calibration constant 1
L_λ = Spectral radiance in (Watts/(m^2 * sr * µm))

Sensor	Constant 1 - $K1$ (Watts/(m^2 * sr * µm))	Constant 2 - $K2$ Kelvin
Landsat 7 ETM+	666.09	1282.71
Landsat 5 TM	607.76	1260.56
Landsat 4 TM	671.62	1284.30

Table 5-4. ETM+ and TM Thermal Band Calibration Constants

5.6.8 Radiometric Scaling Parameters for Landsat 7 ETM+ Level 1 Products

The LMINs and LMAXs are a representation of how the output Landsat ETM+ Level 1 data products are scaled in radiance units. The LMIN corresponds to the radiance at the minimum quantized and calibrated data DN (QCALMIN), which is typically "1" or "0" and LMAX corresponds to the radiance at the maximum quantized and calibrated data DN (QCALMAX), typically "255".

5.6.8.1 Reflective Bands

The LMINs are set so that a "zero radiance" scene is still on scale in the 8-bit output product, even with sensor noise included. LMIN should result in "zero" radiance being about 5 DN in low gain and 7.5 DN in high gain. The LMAXs are set so that LMAX corresponds to slightly less than the saturation radiance of the most sensitive detector. This is done so that in the output product all "pixels" saturate at the same radiance. Currently, the LMAX is set to 0.99 of the pre-launch saturation radiance of the most sensitive detector in each band.

Normally, there is no need to change the LMINs or LMAXs, unless something changes drastically on the instrument. If the sensitivity of the instrument increases, which is not expected, there is no need to change the LMIN and LMAX values. If the sensitivity decreases, the LMAX values can be increased, which in turn increases the usable dynamic range of the product (this does not occur unless the change is large). The changes that have taken place to date have been mostly due to the adoption of "improved" pre-launch gains for the instrument that have, in effect, "increased" its sensitivity. The Landsat Project Science Office also detected a few errors in the original numbers, which were corrected.

5.6.9 Definitive Ephemeris

An ephemeris is a set of data that provides the assigned places of a celestial body (including a manmade satellite) for regular intervals. In the context of Landsat 7, ephemeris data shows the position and velocity of the spacecraft at the time imagery is collected. The position and velocity information are used during product generation.

If available, the Landsat 7 definitive ephemeris is used for geometrically correcting ETM+ data. Definitive ephemeris substantially improves the positional accuracy of the Level 1 product over predicted ephemeris.

The Landsat 7 MOC receives tracking data on a daily basis that shows the position and velocity of the Landsat 7 spacecraft. This information comes from the three U.S. operated ground-receiving stations and is augmented by similar data from NASA's Tracking and Data Relay Satellites (TDRS). The FOT processes this information to produce a refined or "definitive" ephemeris that shows the position and velocity of Landsat 7 in one-minute intervals. Tracking data are used to compute the actual spacecraft position and velocity for the last 61 hours and to predict these values for the next 72 hours. The predicted ephemeris data are uploaded to the spacecraft daily. On-board software interpolates from this data to generate the positional information contained in the PCD.

Engineers with the Landsat Project have completed a predicted versus definitive ephemeris analysis. Comparisons to GCPs demonstrate the definitive ephemeris is, in fact, reliably more accurate than the predicted ephemeris. Geometric accuracy on the order of 30-50 (1 sigma) meters, excluding terrain effects, can be achieved when the definitive ephemeris is used to process the data. Level 1 products produced after March 29, 2000, use definitive ephemeris if available. The metadata (MTL.txt) field "ephemeris type" identifies whether a product was created with definitive or predicted ephemeris. Daily definitive ephemeris profiles have been archived since June 29, 1999 and are available for downloading from this page.

5.6.10 Automated Cloud Cover Assessment (ACCA)

5.6.10.1 ACCA Overview

As part of standard LPGS processing, a cloud cover assessment is provided as part of the EarthExplorer, GloVis, or LandsatLook Viewer's scene information. The Landsat 7 ACCA algorithm recognizes clouds by passing through the scene data twice (Irish, 2000). This two-pass approach differs from the single pass algorithm employed for Landsat 5. The algorithm is based on the premise that clouds are colder than Earth surface features. While true in most cases, temperature inversions do occur. Unexpected cloud cover calculations occur in these situations. This is not unusual in the Polar Regions for example.

The first pass through the data is designed to trap clouds and only clouds. Twenty-six different filters are deployed for this purpose. Omission errors are expected. The pass one goal is to develop a reliable cloud signature for use in pass two where the remaining clouds are identified. Commission errors, however, create algorithm havoc and must be minimized. Three class categories result from pass one processing - clouds, non-clouds, and an ambiguous group that is revisited in pass two.

After pass one processing, descriptive statistics are calculated from the cloud category using Band 6. These include mean temperature, standard deviation, and distribution skew. New Band 6 thresholds are developed from these statistics for use during pass two. Only the thermal band is examined during this pass to capture the remaining clouds. Image pixels that fall below the new threshold qualify. After processing, the pass one and two cloud cover scores are compared. Extreme differences are indicative of cloud signature corruption. When this occurs, the pass two results are ignored, and the cloud score reverts to the pass one result.

During processing, a cloud cover mask is created. After two passes through the data, a filter is applied to the mask to fill in cloud holes. This filtering operation works by examining each non-cloud pixel in the mask. If five of the eight neighbors are clouds, then the pixel is reclassified as cloud. The final cloud cover percentage for the image is calculated based on the filtered cloud mask.

The images in Figure 5-4 demonstrate an example of the improved power the Landsat 7 ACCA algorithm has over the Landsat 5 algorithm. In this case, clouds are successfully separated from the desert terrain below.

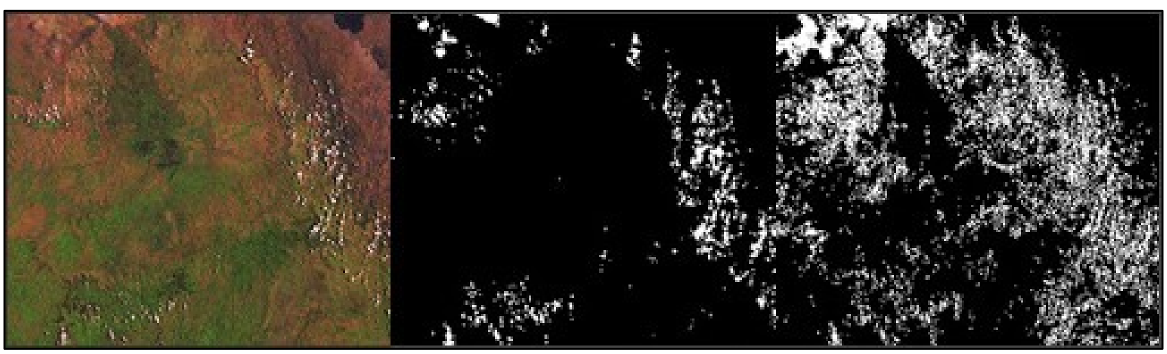

Figure 5-4. Landsat 5 and 7 Cloud Cover Mask Comparison

In Figure 5-4, this desert area in Sudan (left: Bands 5-4-2) represents terrain where the Landsat 5 algorithm misclassified rocks as clouds due to their high reflectance in Band 5 (right). In the middle example, the Landsat 7 algorithm captures clouds while recognizing rocks for what they are.

5.6.10.2 Landsat 7 ETM+ ACCA Algorithm

This section describes the operational Landsat 7 ETM+ ACCA algorithm. It has been divided into five processes:

- **A.** Pass 1 Spectral Cloud Identification (Filters 1-11)
- **B.** Band 6 Cloud Signature Development (Filters 12-16)

C. Pass 2 Thermal Band Cloud Separation (Filters 17-20)
D. Image-Based Cloud-Cover Assignments and Aggregation (Filters 21-15)
E. Nearest-Neighbor Cloud-Filling (Filter 26)

Most of the computer-intensive part of processing is in Pass 1 and therefore most of the following ACCA algorithm documentation addresses the processes within Pass 1.

A. Pass 1 – Spectral Cloud Identification

The algorithm handles the cloud population in each scene uniquely by examining the raw uncalibrated L0R image data twice. Data preparation involves converting Band 2 through Band 5 to planetary reflectance and Band 6 to apparent at-satellite radiance temperature.

For each spectral band (λ), the 8-bit observed raw uncalibrated image quantized level Q, in units of DN, is related to TOA spectral radiance (L_λ) (in Watts/(m² * sr * μm)) by

$$Q_i = G_i L_\lambda + Q_{0i}$$

Where:

G_i = Sensor responsivity (in DN per unit spectral radiance) for each detector in the band
Q_{0i} = Average zero-radiance shutter background (in DN) from the CPF

Sensor responsivity and the zero-radiance bias for each detector is maintained by the IAS and recorded in the CPF at the U.S. ground processing system at EROS. Radiometric detector normalization is applied in each spectral band. Bias-corrected image values are then given by:

$$\Delta Q_i = Q_i - Q_{0i} = G_i L_\lambda$$

Thus, TOA spectral radiances (L_λ) are related to image data by:

$$L_\lambda = \frac{\Delta Q_i}{G_i}$$

TOA planetary albedo or reflectance (ρ_λ) for Band 2 through Band 5 is related to TOA spectral radiance (L_λ) by:

$$\rho_\lambda = \frac{\pi \cdot L_\lambda \cdot d^2}{ESUN_\lambda \cdot cos\theta_s}$$

Where:

π = Mathematical constant approximately equal to 3.14159
d = Earth-Sun distance in Astronomical Units interpolated from Table 5-2.

$ESUN_\lambda$ = Exo-atmospheric solar irradiance in each spectral band in Watts/(m² * µm), which are referenced in Table 5-2
θ_s = Solar zenith angle (degrees)

At-satellite temperature for Band 6 (T) is related to TOA spectral radiance (L_λ) by:

$$T = \frac{K2}{\ln(\frac{K1}{L_\lambda} + 1)}$$

Where:

T	= The at-sensor temperature in Kelvin
$K2$	= The calibration constant 1282.71 in degrees Kelvin
$K1$	= The calibration constant 666.09 in Watts/(m² * sr * µm)
L_λ	= The spectral radiance from equation 3

The first pass through the data is designed to capture pixels that are unambiguously clouds and not something on the ground. Eight different filters are used to isolate clouds and to eliminate cloudless areas including problem land surface features such as snow and sand. The pixels of clouds from Pass 1 are used to develop a Band 6 thermal profile and thresholds for clouds for use in Pass 2 where the remaining clouds are identified. Five categories result from Pass 1 processing warm clouds, cold clouds, desert, non-clouds, and an ambiguous group of image pixels that are reexamined in Pass 2.

The Band 6 temperature profile is formulated from the observed Pass 1 cloud population if it exists. The profile is defined by the cloud populations mean, variance, and skewness, and undergoes modulation if snow or desert features are present in a scene.

A description of each filter, presented in the order implemented, follows:

- **Filter 1 - Brightness Threshold**
  Each Band 3 pixel in the scene is first compared to a brightness threshold. Pixel values that exceed the Band 3 threshold, which is set at .08, are passed to Filter 2. Pixels that fall below this threshold are identified as non-clouds and flagged as such in the cloud mask.

- **Filter 2 - Non-cloud / Ambiguous Discriminator, Band 3**
  Comparing each pixel entering this filter to a Band 3 threshold set at .07 identifies potential low-reflectance clouds. Pixels that exceed this threshold are labeled as ambiguous and are re-examined in Pass 2. Those pixels falling below .07 are identified as non-clouds and flagged as such in the cloud mask.

- **Filter 3 - Normalized Difference Snow Index**
  The Normalized Difference Snow Index (NDSI) is used to detect snow (Hall et al. 1995). The NDSI filter is expressed as:

  NDSI = ((Band 2 – Band 5) / (Band 2 + Band 5))

  This filter is designed to eliminate snow. The reflectance of clouds and snow are similar in Band 2. However, in Band 5, reflectance for clouds is high while snow is low. Hall discovered that NDSI values greater than 0.4 represent snow cover quite well. This value was initially tried for ACCA to eliminate snow, but clouds composed of ice crystals (e.g., cirrostratus) were also eliminated. The threshold was raised to 0.7 to capture potential clouds of this type. Pixels that fall between an NDSI range of -0.25 and 0.7 qualify as potential clouds and are passed to Filter 5. Pixels outside this NDSI range are labeled as non-cloud and passed to Filter 4. Snow pixels that slip through are generally trapped later.

- **Filter 4 - Snow Threshold**
  Knowledge of snow in a scene is important for Pass 2 processing; therefore, a tally of snow pixels is retained. NDSI values above a 0.8 threshold qualify as snow and are recorded as non-cloud in the cloud mask.

- **Filter 5 - Temperature Threshold**
  The Band 6 temperature (T) values are used to identify potential clouds. If a pixel value exceeds 300K, a realistic cloud temperature maximum, it is labeled as non-cloud. Pixels with a temperature value less than 300K are passed to Filter 6.

- **Filter 6 - Band 5/6 Composite**
  The low values of the product of values are sensitive to the detection of clouds. The Band 5/6 Composite is expressed as:

  *Band 5/6 Composite = (1 – Band 5) * Band 6*

  This filter works well because clouds have cold temperatures (< 300K) and are highly reflective in Band 5 and therefore have low Band 5/6 Composite values. It is particularly useful for eliminating cold land surface features that have low Band 5 reflectance such as snow and tundra. Sensitivity analysis demonstrated that a threshold setting of 225 works optimally. Pixels below this threshold are passed to Filter 8 as possible clouds. Pixel values above this threshold are examined using Filter 7.

- **Filter 7 - Non-cloud / Ambiguous Discriminator, Band 5**
  Comparing each pixel entering this filter to a Band 5 threshold set at 0.08 identifies potential low-reflectance clouds. Pixels that exceed this threshold are labeled as ambiguous and are re-examined in Pass 2. Those falling below 0.08 are identified as non-clouds (probably water) and flagged as such in the cloud mask.

- **Filter 8 - Band 4/3 Ratio for Growing Vegetation**
  This filter eliminates highly reflective vegetation and is simply Band 4 reflectance divided by Band 3 reflectance. In the near-infrared (Band 4), reflectance for green leaves is high because very little energy is absorbed. In the red region (Band 3), the chlorophyll in green leaves absorbs energy so reflectance is low. The 4/3 ratio results in higher values for vegetation than for other scene features, including clouds. A threshold setting of 2.0 is used. Pixels that exceed this threshold are labeled ambiguous and are revisited in Pass 2. Pixels with ratios below this threshold are passed to Filter 9.

- **Filter 9 - Band 4/2 Ratio for Senescing Vegetation**
  This filter eliminates highly reflective senescing vegetation and is formed by dividing the Band 4 reflectance by the Band 2 reflectance. In the near-infrared (Band 4), green leaves that are dead or dying absorb even less energy and are thus highly reflective. In the green region (Band 2), the leaves absorb less energy because of chlorophyll loss and exhibit increased reflectivity. The 4/2 ratio values are higher for vegetation than other scene features, including clouds. A threshold setting of 2.16248 works effectively. The at-launch setting was 2.16 but was changed in May of 2001 when the operational decision was made to image Band 4 in low gain mode. Pixels that exceed this number are ambiguous and revisited in Pass 2. Pixels with ratios below this threshold are passed to Filter 10.

- **Filter 10 - Band 4/5 Ratio for Soil**
  This filter eliminates highly reflective rocks and sands in desert landscapes and is formed by dividing the Band 4 reflectance by the Band 5 reflectance. Rocks and sand tend to exhibit higher reflectance in Band 5 than in Band 4, whereas the reverse is true for clouds. A threshold setting of 1.0 works effectively. Pixels that fall below this threshold are labeled ambiguous and are revisited in Pass 2. Knowledge of desert pixels in a scene is important for Pass 2 processing. Therefore, a desert pixel tally is retained. Pixels with ratios that exceed this threshold are passed to Filter 11.

- **Filter 11 - Band 5/6 Composite for Warm and Cold Clouds**
  All pixels reaching this filtering level are classified as clouds. A further separation into two classes is achieved by again using the Band 5/6 Composite filter. For each cloud pixel, the Band 5/6 Composite is compared against a threshold setting of 210. Pixels above and below this threshold are classified as warm and cold clouds, respectively. These two cloud classes are recorded in the cloud mask and used to develop two cloud signatures, one for the cold clouds and the other conjoined cloud classes.

B. Band 6 Cloud Signature Development
Pass 2 processing requires two new Band 6 thresholds against which all ambiguous pixels are compared. These thresholds are computed using the Pass 1 cloud temperature statistics. Only the cold clouds are used if snow or desert soil is present,

otherwise the cold and warm clouds are combined and treated as a single population. The cloud thermal profile developed includes key statistics including the maximum cloud temperature, mean, standard deviation, and histogram skewness.

- **Filter 12 - Snow and Desert Indicator**
  An infrared / short-wave infrared ratio is used to identify highly reflective rocks and sands in desert landscapes. Snow was previously accounted. If snow or desert rocks are present, the warm cloud class is eliminated. The desert indicator employed is simply the ratio of potential cloud pixels exiting and entering Filter 10 compared against a threshold value of 0.5. If the remaining pixels are less than 50 percent, the warm clouds are removed. The snow percentage for the scene is computed and compared against a threshold of 1 percent. If the scene is more than 1 percent snow, the warm clouds are removed.

- **Filter 13 – Pass 1 Cloud-free Indicator**
  The Pass 1 cloud tally is compared against zero. If no clouds were tallied processing ends and the scene is declared cloud-free.

- **Filter 14 – Pass 1 Cold Cloud, Desert, and Mean Cloud Temperature Indicator**
  Three conditions have to exist to continue Pass 2 processing. The cold cloud scene percentage must be greater than 0.4 percent, the Pass 1 cloud temperature mean must be less than 295K, and desert conditions must not exist. If any of these tests are not met, processing passes to Filter 22. If all three tests are met, Pass 2 processing continues at Filter 15.

- **Filter 15 - Temperature Histogram Negative Skewness**
  Prior to computing the Band 6 thresholds, a skew factor is computed from the skewness of the cloud temperature histogram. If the histogram skewness is negative, the cloud population is biased towards the left or colder tail of the distribution. No skew factor is necessary because the thresholds are set at appropriate levels for identifying clouds that skew colder. The shift factor is set to 0.0.

- **Filter 16 - Temperature Histogram Positive Skewness**
  If the histogram skewness is positive, the cloud population is biased towards the right or warmer tail of the cloud temperature distribution. Because of the upward bias in temperature, an upward threshold adjustment is necessary. The skewness becomes the skew factor if it is less than 1.0, otherwise it is set to 1.0.

C. Pass 2 – Thermal Band Cloud Separation
One of the thresholds is set low and used to generate a conservative estimate of clouds in a scene. The other is set high and used to compute a less restrictive estimate of cloud cover. The thresholds are determined from the Pass 1 cloud temperature histogram. The histogram's 97.5 and 83.5 percentiles are the starting points for the two temperature thresholds and adjustments are made if necessary. All ambiguous pixels

are tested against the two thresholds. If a pixel falls below the high threshold, it is labeled as a warm cloud. It is re-labeled cold cloud if it also falls below the lower threshold.

If a pixel temperature falls below the upper threshold, the cloud mask is flagged with a unique number that identifies a class of warmer clouds. If the pixel temperature also falls below the lower threshold, the cloud-mask value is changed to a colder cloud-class identifier.

- **Filter 17 - Threshold Shift Deployment**
  If the skew factor is positive, upward adjustments are made to compensate for the warm cloud bias. The threshold shift is the product of the skew factor and cloud temperature standard deviation. Both thresholds are adjusted by this amount. If the skew factor is 0.0, processing continues at Filter 19.

- **Filter 18 - Band 6 Maximum Threshold**
  A final check is made to see if the new upper threshold exceeds the histogram's 98.75 percentile (a threshold above or near the cloud temperature maximum is unwanted). If so, the 98.75 percentile becomes the new upper threshold and the lower threshold is adjusted by the amount of skewness compensation allowed.

- **Filter 19 - Band 6 Warm Cloud Indicator**
  Each ambiguous pixel's Band 6 temperature is tested against the higher threshold and labeled a warm cloud if it is lower. Pass 2 processing continues at Filter 20. If it is higher, it is skipped, and the next ambiguous pixel is likewise examined. The process continues until all ambiguous pixels are accounted.

- **Filter 20 - Band 6 Cold Cloud Indicator**
  Each Pass 2 warm cloud is tested against the lower threshold and is re-labeled cold cloud if it is lower. Processing continues at Filter 19 until all ambiguous pixels are accounted.

D. Image-Based Cloud Cover Assignments and Aggregation

After Band 6 is processed, the scene percentages for the warm and cold cloud classes are computed. The integrity of the two additional cloud classes is then appraised. The presence of snow or desert features, and the magnitude of the two new cloud classes are used to accept or reject one or both classes. Cloud classes that qualify as legitimate are combined with the Pass 1 clouds to form a single unified cloud class in the mask.

- **Filter 21 – Pass 2 Cloud-free Indicator**
  The Pass 2 cloud tally is compared against zero. If no clouds are tallied, an event unlikely to happen, the final scene cloud cover score reported is the cold cloud percent from Pass 1. Processing resumes at Filter 26.

- **Filter 22 – Pass 1 Cloud Temperature Mean**

This filter is used when the three Pass 1 criteria are not met in Filter 14. The cold cloud scene percentage might be less than 0.4 percent, the Pass 1 cloud temperature might be greater than 295K, and desert conditions may exist. The mean of the Pass 1 cold cloud population is again tested against the limit of 295K. If it is less, the clouds are accepted as real but with less certainty. If any of these tests are not met, processing passes to Filter 22. The final scene cloud cover score reported is the cold cloud percent from Pass 1. Processing resumes at Filter 26. If the mean is greater than 295K, then uncertainties exist. The final scene cloud cover score is set to zero and processing ends.

- **Filter 23 – Pass 1 Cloud Acceptance Indicator**
  If the snow or desert conditions determined earlier exist, the Pass 1 cloud percentage is determined using the Pass 1 cold clouds only. If the scene is free from snow and desert soil, the Pass 1 cloud percentage is determined using both the cold and warm Pass 1 clouds.

- **Filter 24 – Pass 2 Cold and Warm Cloud Acceptance**
  The temperature means and maximums are computed for the Pass 2 cold and warm cloud populations. Additionally, the percentages of the scene represented by the Pass 2 cold class and combined classes (cold and warm) are computed. The Pass 2 cold and warm clouds are united with Pass 1 if four conditions are met. The Pass 2 cold and warm cloud contribution cannot be more than 35 percent, snow cannot be greater than 1 percent of the scene, the mean temperature for combined cloud population cannot be greater than 295K, and between the combined cloud maximum temperature and the upper threshold cannot be less than 2 degrees. If these four conditions are met, all clouds identified in Pass 2 are united with the Pass 1 clouds and processing proceeds to Filter 26. If any one condition is breached, processing passes to Filter 25.

- **Filter 25 – Pass 2 Cold Cloud Acceptance**
  The Pass 2 cold clouds are used if their contribution to scene cloud percentage is less than 25 percent and their mean temperature is less than 295K. If these two conditions are satisfied, the cold clouds are united with the Pass 1 clouds and processing advances to Filter 26. If either rule is breached, the Pass 2 analysis is considered invalid and the Pass 1 cold clouds are used in computing the final scene score. Processing continues at Filter 26.

E. Nearest-Neighbor Cloud Filling
A final step involves identifying and filling cloud mask holes. This operation boosts the cloud-cover content to more accurately reflect the amount of unusable image data in a scene. Afterwards, the cloud pixels in the mask are tabulated and a final cloud cover percentage score for the scene is computed.

- **Filter 26 - Threshold Shift Deployment**
  Each non-cloud image pixel is examined and converted to cloud if at least five of its eight neighbors are clouds. Filled pixels qualify as cloudy neighbors in subsequent tests.

5.6.11 Algorithm for Calculation of Scene Quality

Besides the cloud cover assessment that is part of the standard LPGS processing, a scene quality assessment is provided as part of the EarthExplorer, GloVis, or LandsatLook Viewer's scene information. A two-digit number that separates image and PCD quality is used by the LPS for Landsat 7. The first digit represents image data quality and can range in value from 0 to 9. The second digit represents PCD quality and can range in value from 0 to 9. The formula for the combined score is:

*image score * 10 + PCD score*

The following describes how the image quality and PCD quality scores are assigned.

5.6.11.1 Image Quality Component

The image quality digit is based on the number and distribution of bad scans or equivalent bad scans in a scene. It is computed by dividing the total number of filled minor frames for a scene by 6313 (the nominal number of image data minor frames in a major frame for 30-meter bands). This gives a number of equivalent bad scans.

The distribution of filled minor frames is characterized as being either clustered or scattered. A cluster of 128 bad scans still yields a scene with a cluster of 246 good scans, which is almost 2/3 of a scene. A scattering of 128 band scans may make the entire image worthless.

It is proposed that bad scan lines are clustered if they occur within a grouping of 128 contiguous scans (approximately 1/3 of a scene). Errors are characterized as scattered if they occur outside the bounds of 128 contiguous scans. The image score is assigned according to the rules in Table 5-5.

Score	Image Quality
9	No errors detected, a perfect scene
8	≤ 4 equivalent bad scans, clustered
7	≤ 4 equivalent bad scans, scattered
6	≤ 16 equivalent bad scans, clustered
5	≤ 16 equivalent bad scans, scattered
4	≤ 64 equivalent bad scans, clustered
3	≤ 16 equivalent bad scans, scattered
2	≤ 128 equivalent bad scans, clustered
1	≤ 128 equivalent bad scans, scattered
0	> 128 equivalent bad scans, scattered (> 33% of the scene is bad)

Table 5-5. Scene Quality Score – Image Quality Component

5.6.11.2 PCD Quality Component

The PCD quality digit is based on the number and distribution of filled PCD minor frames. There are approximately 7 PCD major frames for a standard WRS scene comprised of 375 scans. Each PCD major frame consists of 128 minor frames or 16,384 bytes. Clustering of filled PCD minor frames indicates that errors are localized whereas scattering indicates that numerous or all major frames may be affected.

Each PCD minor frame has 16 jitter measurements and corresponds to 30 milliseconds or approximately 1/2 of a scan. Two minor frames correspond to a single scan while 256 minor frames (i.e., 2 PCD major frames) correspond to 128 scans or approximately 1/3 of a scene.

Like the image data, it is proposed that bad PCD minor frames are clustered if they occur within a grouping of two contiguous PCD major frames (1/3 of a scene). Errors are characterized as scattered if they occur outside the bounds of contiguous PCD major frames. The PCD score is assigned according to the rules in Table 5-6.

Score	PCD Quality
9	No PCD errors detected
8	≤ 8 bad minor frames, clustered
7	≤ 8 bad minor frames, scattered
6	≤ 32 bad minor frames, clustered
5	≤ 32 bad minor frames, scattered
4	≤ 128 bad minor frames, clustered
3	≤ 128 bad minor frames, scattered
2	≤ 256 bad minor frames, clustered
1	≤ 258 bad minor frames, scattered
0	> 256 bad minor frames, scattered (> 33% of the scene is bad)

Table 5-6. Scene Quality Score – PCD Quality Component

5.6.11.3 Scene Quality

The score calculated using the methods described is recorded in the scene level metadata under the keyword "SCENE_QUALITY". Using this scoring system, the highest possible rating for an image would be 99, and the lowest would be 00. The score treats missing image data more critically than missing or filled PCD data. For example, an image with 16 filled scans that are scattered and with errorless PCD would have a 59 score whereas an image with intact image data and a 32 filled PCD minor frames that are scattered would receive a score of 95. The rationale is that PCD is less important because missing values can always be extrapolated or interpolated to enable Level 1 processing. Missing image data cannot be retrieved and thus impacts the user more severely than missing PCD. The score construct unambiguously alerts the user to image data deterioration.

5.7 Data Properties

5.7.1 Scientific Theory of Measurements

When solar energy strikes an object, five types of interactions are possible and, in most cases, multiple interactions occur at the same time. The energy can be:

1. Transmitted - The energy passes through with a change in velocity as determined by the index of refraction for the two media in question.
2. Absorbed - The energy is given up to the object through electron or molecular reactions and the object heats up as a result of this process.
3. Reflected - The energy is returned unchanged with the angle of incidence equal to the angle of reflection. Reflectance is the ratio of reflected energy to the total amount incident on a body. The wavelength of the reflected energy (not absorbed) determines the color of an object.
4. Scattered - The direction of energy propagation is randomly changed. Rayleigh and Mie scatter are the two most important types of scatter in the atmosphere.
5. Emitted - In this case, the incident solar energy is first absorbed, and then re-emitted, usually at longer wavelengths. The object also heats up due to this process.

The Landsat 7 system is designed to collect seven bands or channels of reflected energy and one channel of emitted energy (see Table 5-7). A well-calibrated ETM+ dataset enables the conversion of the raw solar energy collected by the sensor to absolute units of radiance. Radiance refers to the flux of energy (primarily irradiant or incident energy) per solid angle leaving a unit surface area in a given direction. Radiance corresponds to brightness in a given direction toward the sensor, and is often confused with reflectance, which is the ratio of reflected versus total incoming energy. Radiance is what is measured at the sensor and is somewhat dependent on reflectance as well as environmental conditions.

Band	Wavelength (µm)	Resolution (m)
1	0.450 – 0.515	30
2	0.525 – 0.605	30
3	0.630 – 0.690	30
4	0.775 – 0.900	30
5	1.550 – 1.750	30
6	10.40 – 12.50	60*
7	2.080 – 2.350	30
9	0.520 – 0.900	15
*Band 6 is collected at 60m, then resampled to 30m to match the ETM+ reflective bands		

Table 5-7. Landsat 7 ETM+ Band Wavelengths and Resolution

The seven spectral bands of ETM+ data are designed to distinguish Earth surface materials through the development of spectral signatures. For any given material, the amount of emitted and reflected radiation varies by wavelength. These variations are used to establish the signature reflectance fingerprint for that material. The basic premise of using spectral signatures is that similar objects or classes of objects have similar interactive properties with electromagnetic radiation at any given wavelength. Conversely, different objects have different interactive properties. A plot of the collective response of scattered, emitted, reflected, and absorbed radiation at specific wavelengths of the electromagnetic spectrum should, according to the basic premise, result in a unique curve, or spectral signature that is diagnostic of the object or class of objects. A signature on such a graph can be defined as reflectance as a function of wavelength. Figure 5-5 illustrates four such signatures.

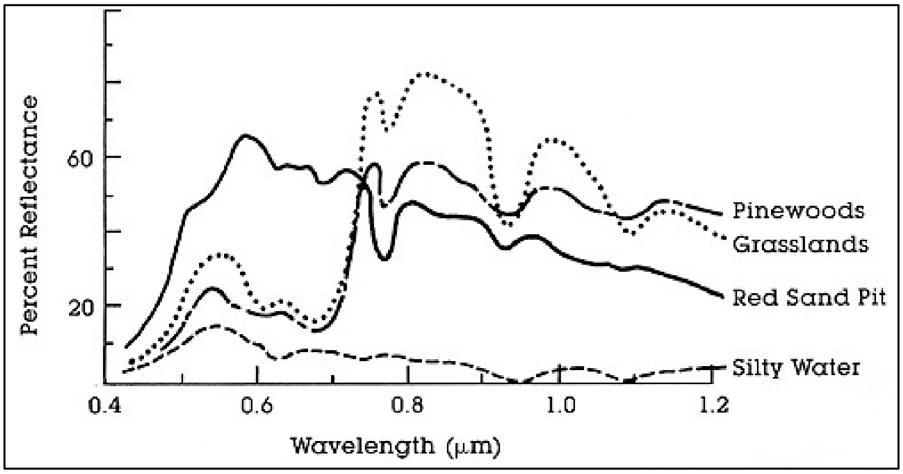

Figure 5-5. Plot of Spectral Reflectance Curves of Four Different Earth Surface Targets

ETM+ data can be used to plot spectral signatures although the data are limited to eight data points corresponding to each of the sensor's bands, which cover the spectral range of 0.45 to 12.5 µm. It is often more useful to plot the ETM+ spectral signatures in multidimensional feature space. The four Earth surface materials shown in Figure 5-5 are plotted in Figure 5-6 using just two of the ETM+ spectral bands (in this case, Band 2 versus Band 4). Using this technique, the four test surface targets (grasslands, pinewoods, red sand, and silty water) may be characterized as distinctly different by this technique.

Each of the materials has been plotted according to its percent reflectance for two of the wavelengths or spectral bands. Multidimensional plots, which use more than two wavelengths, are involved; the plots in multidimensional space tend to increase the separability among different materials. This technique of spectral separation forms the basis for multispectral analysis where the goal is to accurately define the bounds of accurately identified, spectrally-identifiable data point clusters.

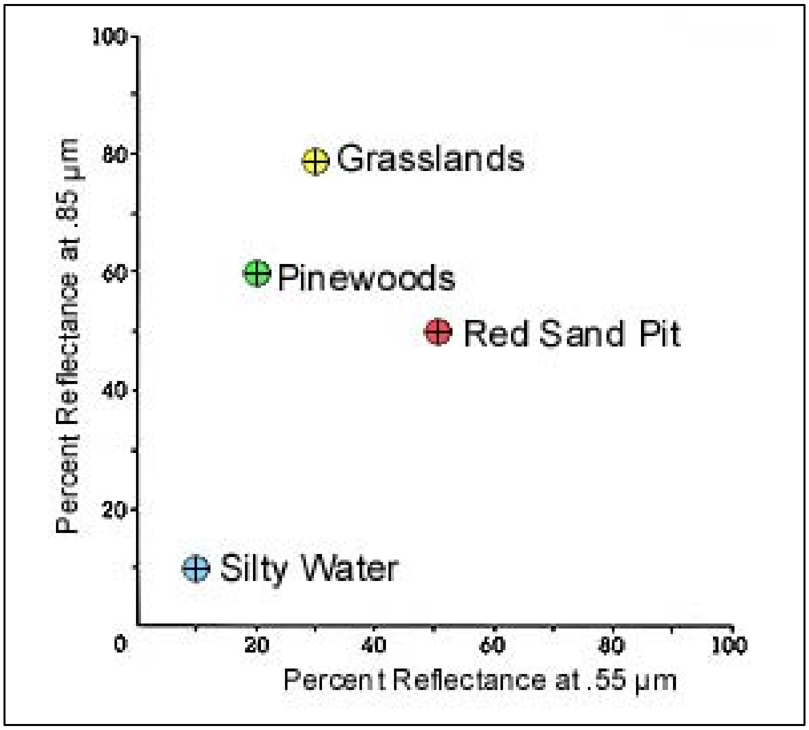

Figure 5-6. Spectral Separability of Surface Targets using Two ETM+ Bands

5.7.2 Spatial Characteristics

Spatial resolution is the resolving power of an instrument needed for the discrimination of features and is based on detector size, focal length, and sensor altitude. More commonly used descriptive terms for spatial resolution are Ground Sample Distance (GSD) and IFOV. The IFOV, a synonym for pixel size, is the area of terrain or ocean covered by the Field of View (FOV) of a single detector. The ETM+ is designed to sample the ground at three different resolutions; 30 meters for Bands 1-5 and Band 7, 60 meters for Band 6, and 15 meters for Band 8 (panchromatic) data (see Table 5-8). Figure 5-7 shows an example of a 30-meter pixel. Each 30-meter pixel is about the size of a baseball diamond.

A standard WRS-2 scene covers a land area approximately 185 km (across-track) by about 170 km (along-track). A more precise estimate for actual scene size can be calculated from the L0R product image dimensions (see Appendix D).

Band Number	Resolution (m)	Samples (columns)	Data Lines (rows)	Bits per Sample
1-5, 7	30	6,600	6,000	8
6	60	3,300	3,000	8
8	15	13,200	12,000	8

Table 5-8. Image Dimensions for Landsat 7 L0R Product

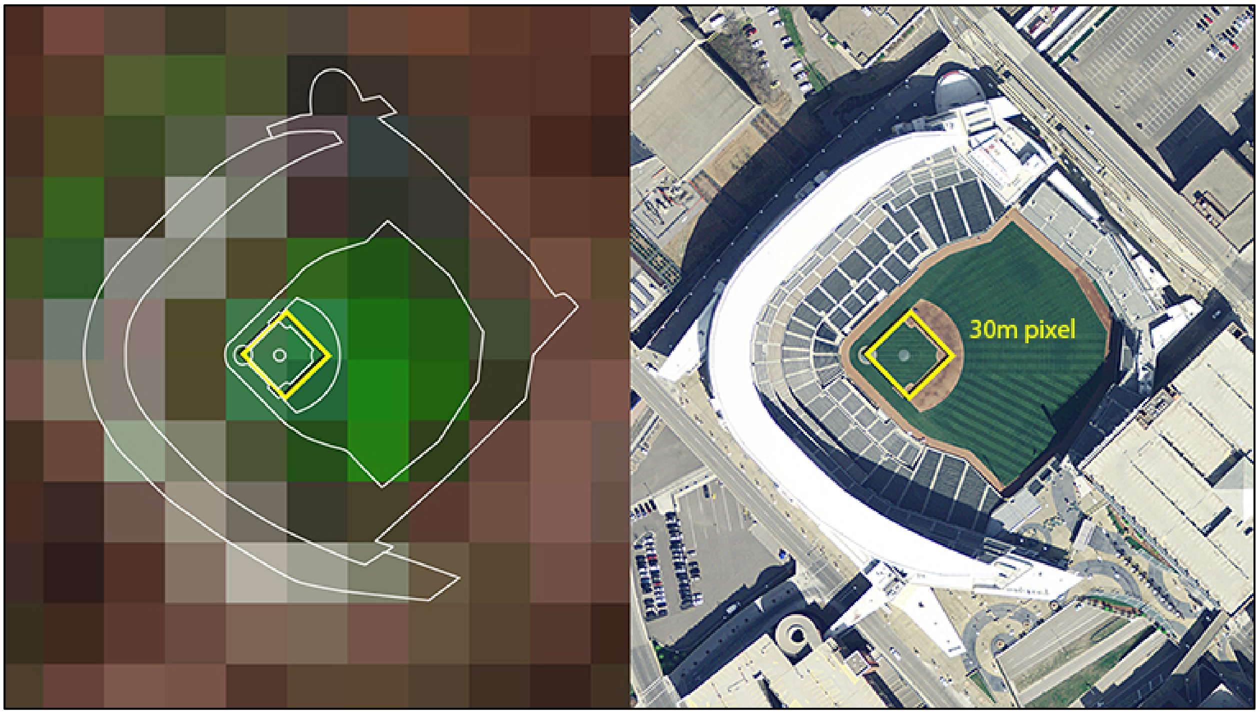

Figure 5-7. Landsat Pixel Size Relative to a Baseball Diamond

A Landsat scene's spatial extent cannot be determined simply by multiplying the rows and columns of a scene by the IFOV. This would lead to a scene width of 198 km (6600 samples * 30 meters) and a scene length of 180 km (6000 lines * 30 meters). While this calculation applies to scene length, the scene width calculation is more complicated due to the presence of image buffers and the staggered image bands in the L0R product. Left and right image buffers were placed in the L0R product to accommodate a possible increase in scan line length over the mission's life. The staggered image bands result from the focal plane design (see Section 2.2), which LPS accounts for by registering the bands during L0R processing. The end result is an increasing amount of zero-fill preamble according to the band order on the ground projected focal plane array.

The detector offsets determine the amount of zero-fill preamble for each band. These are listed in Table 5-9 and can also be found in the CPF (see Section 3.10). Coincident imagery for all 8 bands starts at pixel location 247 for the 30-meter bands. This is shown by the reverse scan odd detector offset for Band 6. This number, 116, is in 60-meter IFOVs, which translates to 232 30-meter pixels. Another 14 pixels must be added to this number to account for the seven minor frames of image data pre-empted by time code. Coincident imagery for all 8 bands ends at pixel location 6333 for the 30-meter bands. This number is determined by looking at the reverse even detector offset for Band 8. Add to this number the value 12,626 that represents the number of Band 8 pixels per line (6313 minor frames multiplied by 2). The total, 12,666, is halved to put the ending pixel number into 30-meter units. The number of coincident image pixels in a scan is therefore 6087 (6333 - 247 + 1). The nominal width for a scene is therefore 182.61 km (6087 * 30 meters).

Band Number	Forward Scan Even Detectors	Forward Scan Odd Detectors	Reverse Scan Even Detectors	Reverse Scan Odd Detectors
1	49.0	51.0	45.0	48.0
2	74.0	76.0	70.0	73.0
3	99.0	101.0	95.0	98.0
4	124.0	126.0	120.0	123.0
5	195.0	197.0	191.0	194.0
6	110.0	113.0	114.0	116.0
7	169.0	171.0	165.0	168.0
8	50.0	54.0	40.0	44.0

Table 5-9. Landsat 7 ETM+ Detector Shifts

5.7.3 Temporal Characteristics

5.7.3.1 Sun Elevation Effects

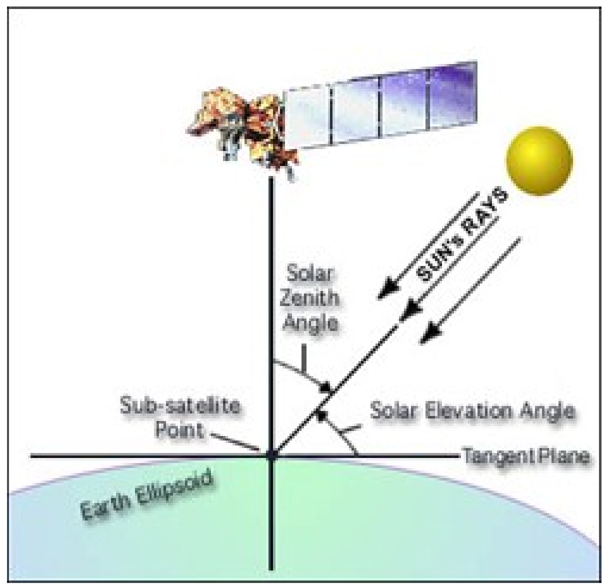

Figure 5-8. Illustration of Sun's Variable Elevation Angle Relative to Landsat 7's Nadir View

While the orbit of Landsat 7 allows the spacecraft to pass over the same point on the Earth at essentially the same local time every 16 days, changes in sun elevation angle, as defined in Figure 5-8, cause variations in the illumination conditions under which imagery is obtained. These changes are due primarily to the north-south seasonal position of the sun relative to the Earth (see Figure 5-9). The actual effects of variations in solar elevation angle on a given scene are very dependent on the scene area itself. The reflectance of sand, for example, is significantly more sensitive to variations in sun elevation angle than most types of vegetation. Atmospheric effects also affect the amount of radiant energy reaching the Landsat sensor, and these too can vary with time of year. Because of such factors, each general type of scene area must be evaluated individually to determine the range of sun elevation angles over which useful imagery can be realized (see Section 4). Depending on the scene area, it may or may not be possible to obtain useful imagery at lower sun elevation angles. At sun elevation angles greater than 30 degrees, typically all image data can be used. For the Landsat 7 mission, a minimum solar elevation angle of 5 degrees is generally accepted as the lowest angle at which some amount of ETM+ imagery can be acquired over most land cover types. However, data acquired over land ice (e.g., Antarctica, Greenland) at 2 degrees elevation does still yield useful information on surface characteristics through casted shadows but this is a rather specialized application.

Apart from the variability of scene effects, sun elevation angle is affected by a number of perturbing forces on the Landsat orbit. These include forces such as atmospheric drag and the sun's gravity. These forces have the effect of shifting the time of descending node throughout the year, which results in changes to the nominal sun elevation angle. The effects of orbit perturbations, however, can be considered minor for most applications, and are compensated for by periodic orbit maneuvers (see Section 2.1.6).

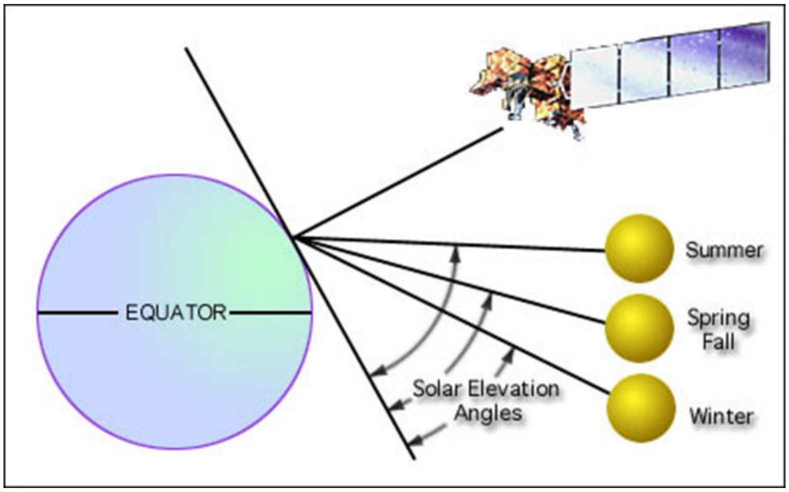

Figure 5-9. Effects of Seasonal Changes on Solar Elevation Angle for Particular Latitude

5.7.3.2 Revisit Opportunities

Repeat imaging opportunities for a given scene occur every 16 days. This does not mean every scene is collected every 16 days (see Section 4 for details). Duty cycle constraints, limited onboard recorder storage, the use of cloud cover predictions, and adherence to the LTAP make this impossible. The goal, however, is to collect as much imagery as possible over dynamically changing landscapes. Deserts do not meet this definition and thus are imaged once or twice per year. Temperate forests and agricultural regions qualify as dynamic and are imaged more frequently. Figure 5-10 illustrates over 4 million archived ETM+ scenes acquired during the mission's first 18 years (ca. 2017). More than 17,000 unique scenes are now in the Landsat 7 portion of the archive at EROS. These numbers are only from descending or daylight passes, and tens of thousands of additional scenes have been acquired during night-time passes over volcanoes and calibration / validation sites, as well as for instrument assessments.

Due to Landsat 7's maturity, coverage trends can be observed, as Figure 5-10 illustrates. The U.S., including Alaska, has been extensively covered because every imaging opportunity was exploited. South America and Australia are similarly well covered. North Africa is mostly desert and appears brown to yellow as do large portions of Earth's taiga / tundra regions. Northern Asia is mostly green and yellow due to recorder and downlink opportunity constraints.

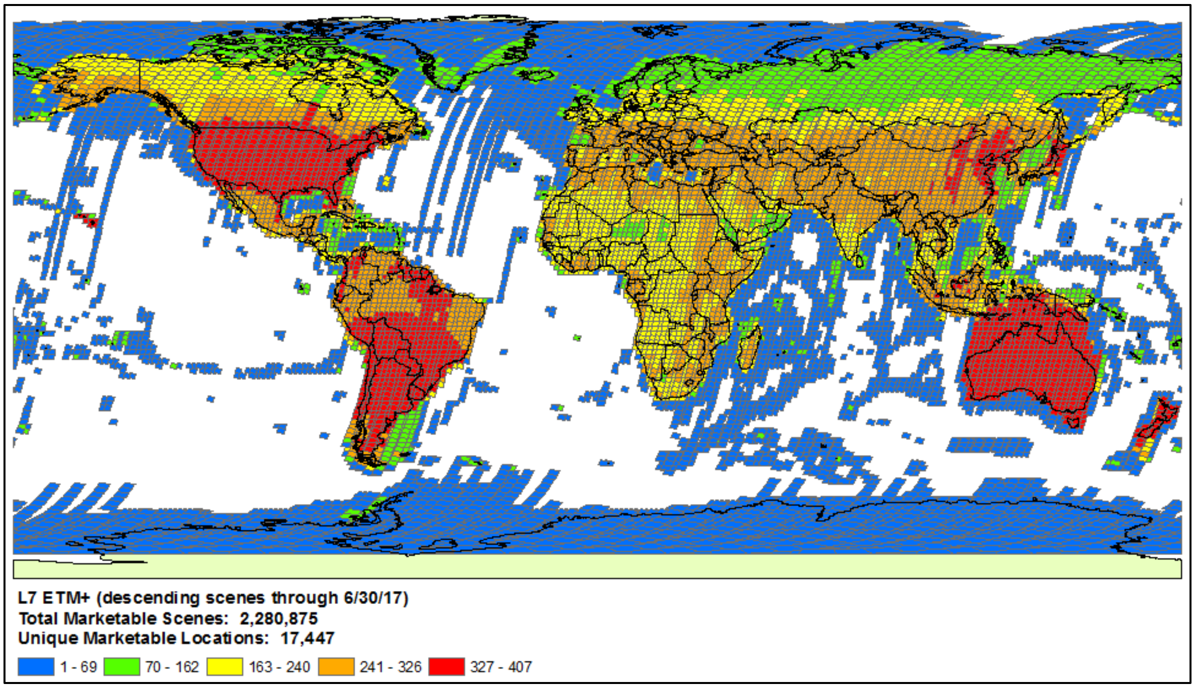

Figure 5-10. Map Showing all Landsat 7 ETM+ Data Acquired and Archived through June 30, 2017 (descending/daytime only)

The importance of repeatedly imaging dynamically changing landscapes frequently is illustrated in Figure 5-11. The dramatic color changes in the mountains to the east of Salt Lake City indicate the montane growing season is over in October. A multitemporal analysis using images such as these allows people to resolve, with greater accuracy, key landscape components such as biomass, species distribution, and phenological growth patterns.

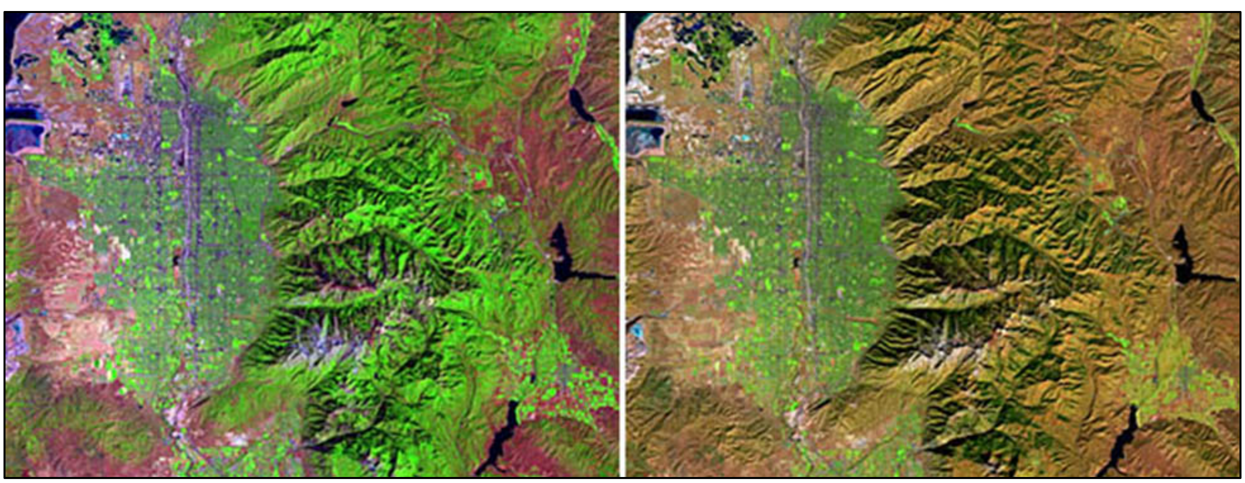

Figure 5-11. August 14, 1999, (left) and October 17, 1999, (right) Images of the Salt Lake City Area shown in Band Combination 5,4,2

Section 6 Data Search and Access

6.1 Overview

The USGS archive holds data collected by the Landsat suite of satellites, beginning in 1972 with Landsat 1. An average of 450 Landsat 7 scenes are added to the USGS archive each day and become available to all users for download at no charge using the interfaces described in this section. Current Landsat 7 Level 1 products available include:

- LandsatLook Natural Color Image - a full-resolution, 3-band JPG image
- LandsatLook Thermal Image - a full resolution, thermal (Band 6) JPG image
- LandsatLook Quality Image - a JPG image containing unsigned integers that represent bit-packed combinations of surface, atmospheric, and sensor conditions that can affect the overall usefulness of a given pixel
- LandsatLook Images with Geographic Reference - a bundle containing the Natural Color, Thermal, and Quality Images - full-resolution GeoTIFF images with geographic reference information
- Level 1 Data Product - a compressed file including all individual multispectral and/or thermal band and metadata files

6.2 Online Aids

Landsat archive searching and downloading is available through three data visualization viewers, all developed at the USGS EROS Center: EarthExplorer, GloVis, and LandsatLook Viewer.

6.2.1 EarthExplorer

EarthExplorer is the primary viewer for accessing aerial, mapping, elevation, and satellite data held in the USGS EROS archives, which includes Landsat data products. An EROS Registration System (ERS) username and password are required to download data products. Some functions of the website work only after a successful login.

https://earthexplorer.usgs.gov

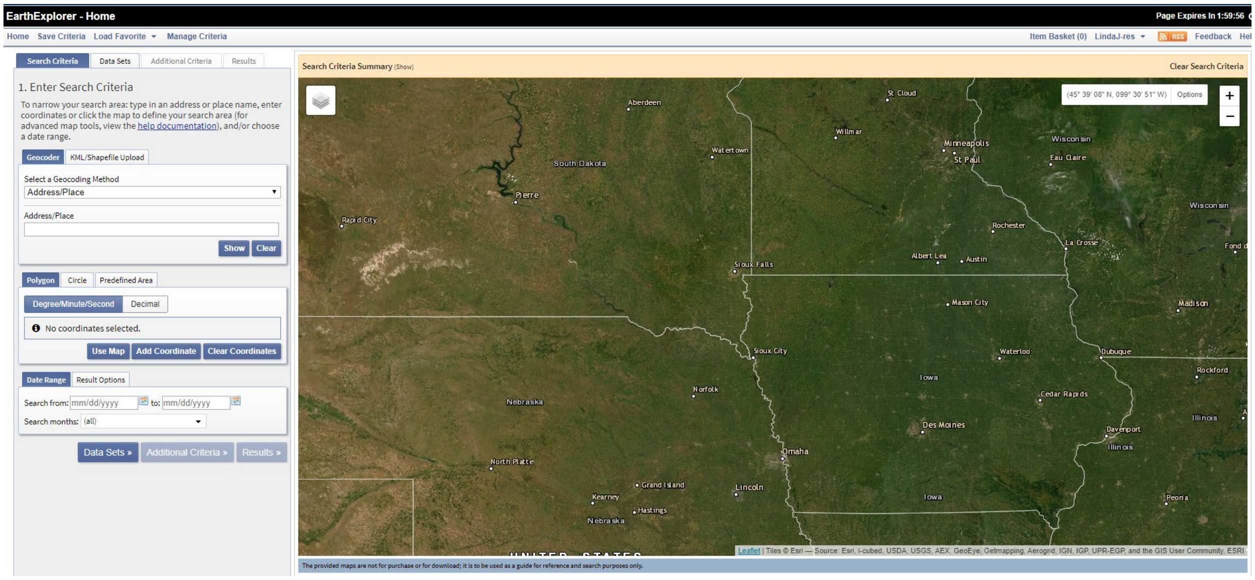

Figure 6-1. EarthExplorer Interface

The Search Criteria tab options allow users to select the geographic area of interest by entering a place name, latitude/longitude coordinates, path/row, shape file, or Keyhole Markup Language (KML) file.

On this same tab, the Date Range and Number of Results can be specified (see Figure 6-1).

The Data Set tab lists all categories of data held in the USGS EROS Archives. The Landsat section of this tab lists all Landsat datasets, which are organized by collection and processing level (see Figure 6-2).

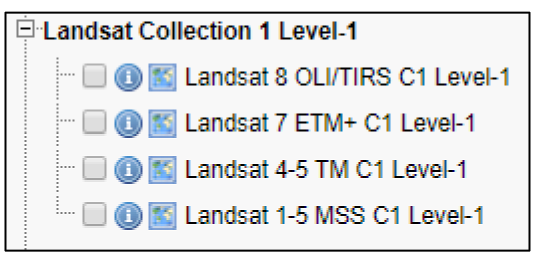

Figure 6-2. EarthExplorer Landsat Level 1 Datasets

Next to each dataset are options to link to additional information about the data and to toggle the coverage map on or off in the main viewer window.

The Additional Search Criteria tab provides the opportunity to search by specific scene ID, Path/Row, and set cloud cover limits. Users interested in searching nighttime imagery can select that option.

The Results tab allows users to view a browse image of the scene, open a subset of the metadata file, or verify the footprint of a scene on the map. The available data products can then be downloaded by clicking the Download Options button (green arrow with a grey disk). Scenes can also be added to a bulk order by selecting the box icon with a yellow arrow. The shopping cart icon is used to order Web Mapping Service (WMS) links.

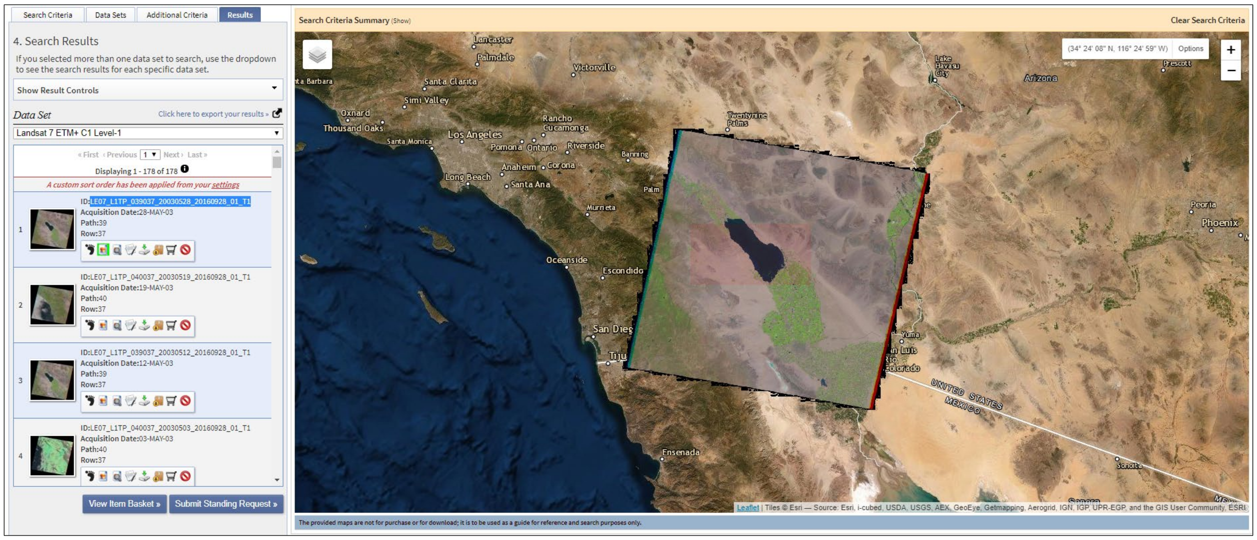

Figure 6-3. EarthExplorer Results - Browse Image Display

The Result Controls section, located above the results listing, allows users to view the footprints, browse all results, or add the results to a bulk download order (see Figure 6-4).

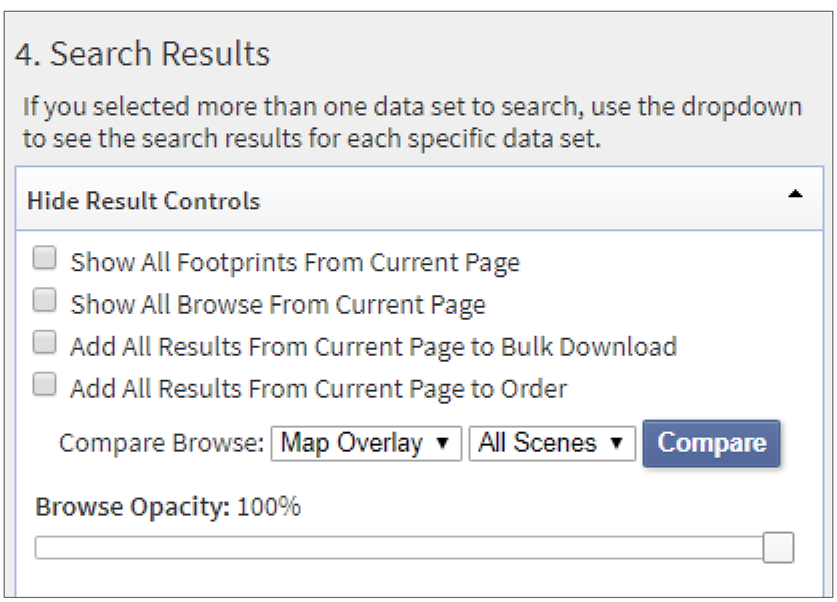

Figure 6-4. EarthExplorer Results Controls

6.2.2 Global Visualization Viewer (GloVis)

GloVis is a browse-based tool that displays all available Landsat scenes held in the USGS archives.

https://glovis.usgs.gov

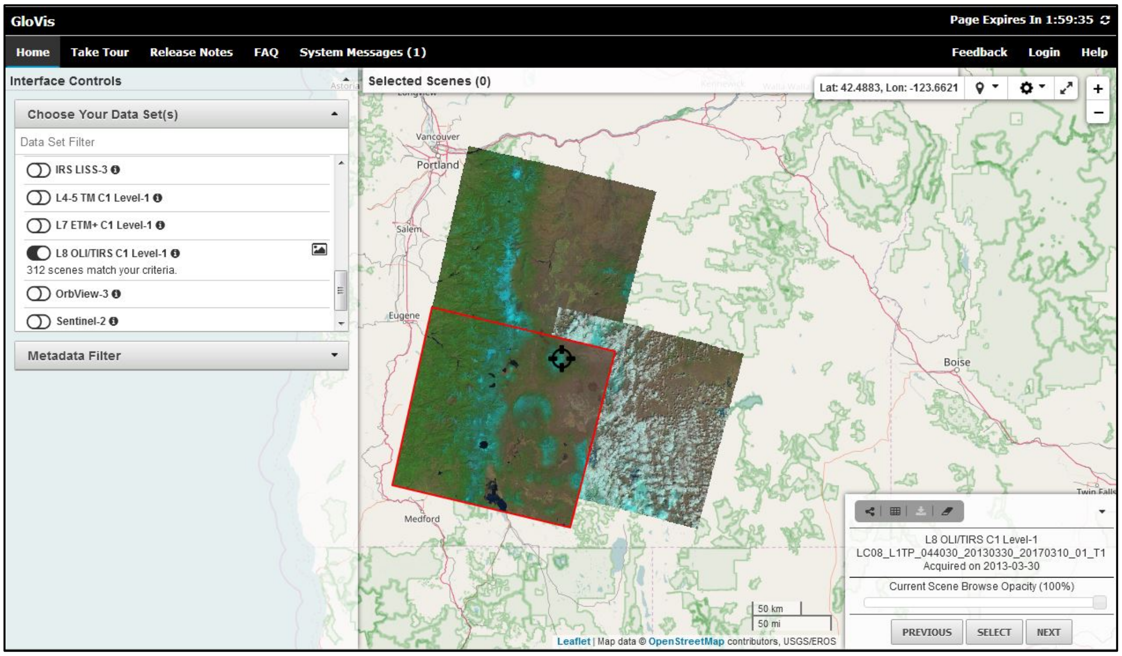

Figure 6-5. GloVis Interface

Upon opening, the viewer displays the most recent, least cloudy image over the vicinity of the USGS EROS Center. To navigate to a specific area, pan and zoom to the area of interest or use the “Jump to…” feature in the upper right to select a WRS path/row, or enter latitude and longitude coordinates. The user can change the cloud cover limits and other filters by using the faceted search options on the left side of the screen.

Scenes can be selected by using the “Select” option in the lower right corner of the viewer. Once all desired scenes have been selected, they can be viewed in the “Selected Scenes (#)” tab.

Figure 6-6. View Selected Scenes

From this tab, the user can view scene metadata, order or download scenes, show footprints, choose to bulk download, and remove scenes.

6.2.3 LandsatLook Viewer

The LandsatLook Viewer allows users to enter a place name or pan and zoom around the globe to a specific area of interest.

https://landsatlook.usgs.gov

Figure 6-7. LandsatLook Viewer

Once the desired geographic location is found, criteria (Years, Days of Year, Cloud Cover, and Landsat Sensors) can be modified to narrow the parameters of the search. This interface displays adjacent scenes more realistically mosaicked, giving a more seamless appearance to the view.

A file of the screen display can be exported as imagery or as a PDF with annotations. Full Resolution Browse (FRB) image files (LandsatLook images) or Level 1 data products can be selected and downloaded by opening the Show Metadata tab on the bottom of the screen. The ERS login screen appears when the Level 1 data products are selected. Once a user logs in, the item basket appears with options to select the WMS link (order) or add the scene to a bulk download order.

Figure 6-8. Display of Landsat Imagery

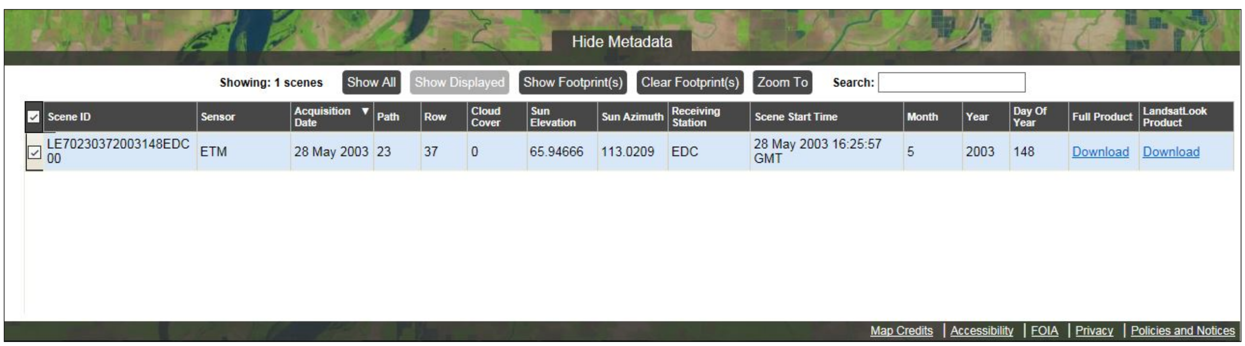

Figure 6-9. LandsatLook Viewer Show Metadata Tab Display

6.3 Landsat ETM+ Scene-Based Browse Image

The land area seen in an ETM+ browse image is not common to all bands (see Figure 6-10). The image planes have been staggered according to the following band order arrangement: 8, 1, 2, 3, 4, 7, 5, and 6. For an image collected on a descending pass, Band 8 covers more land area to the west than Band 1, while Band 1 covers more land area to the east. This band staggering effect can be seen in the browse image above. The browse image Bands, 5, 4, 3 are placed in Red, Green, Blue (RGB) color space. Band 5 reaches furthest to the east as evident by the red margin on the right side of the image. Though not as clear, a blue margin exists on the left side of the browse image due to Band 3 and its more western position (see Figure 6-10).

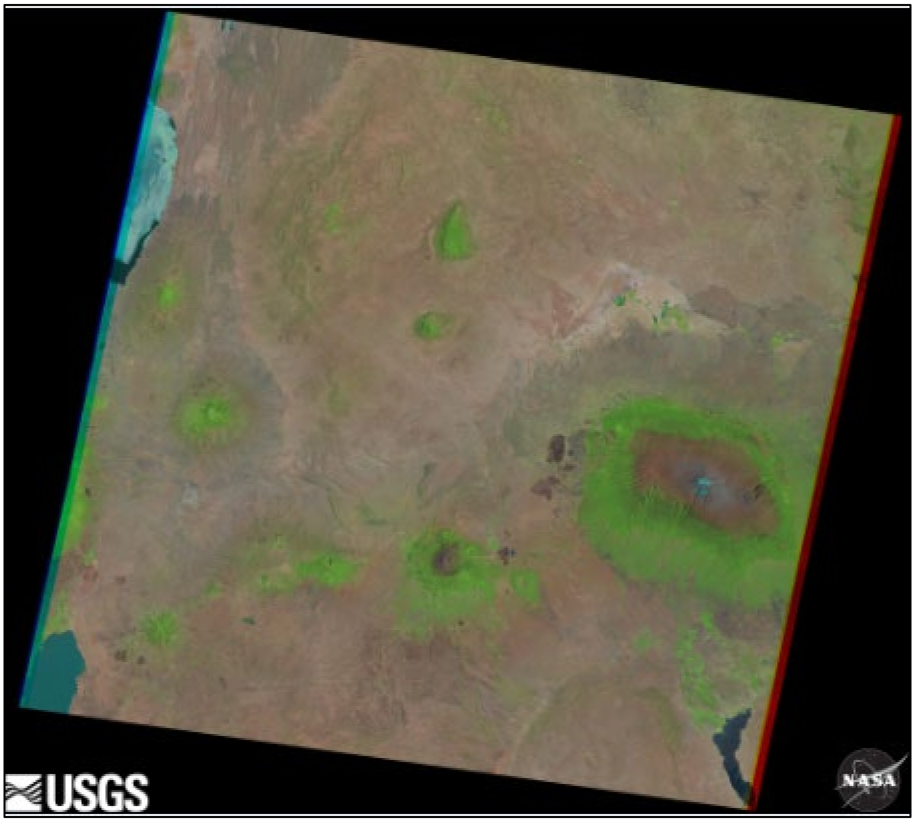

Figure 6-10. Landsat 7 ETM+ SLC-on Browse Image

When viewing a browse image for geographic coverage, it is important to keep the band staggering effect in mind. For example, the panchromatic band starts approximately 500 meters before Band 5 but also ends 500 meters earlier. Knowledge of band offsets prevent coverage surprises when examining a product for the first time.

Following the SLC failure, changes were made to the browse scenes available from EarthExplorer, GloVis, and LandsatLook Viewer. Images acquired after July 2003 display as RGB composites and show Bands 5, 4, and 3. Landsat 7 ETM+ scenes acquired from 5/31/2003 to 7/14/2003 and 9/3/2003 to 9/17/2003 are not available due to efforts to resurrect the SLC. Browse images are resampled to a pixel size of 180 meters from the original 30-meter data. The browse image shown in Figure 6-11 displays a Landsat 7 ETM+ image with the effects of the SLC-off gaps. For more information on SLC-Off data, see the Landsat Missions Website.

Each Landsat 7 scene is color-stretched based on individual scene content. This may result in an apparent mismatch of colors between scenes. The browse image previews are uncorrected images in satellite orientation and can be viewed in a separate window.

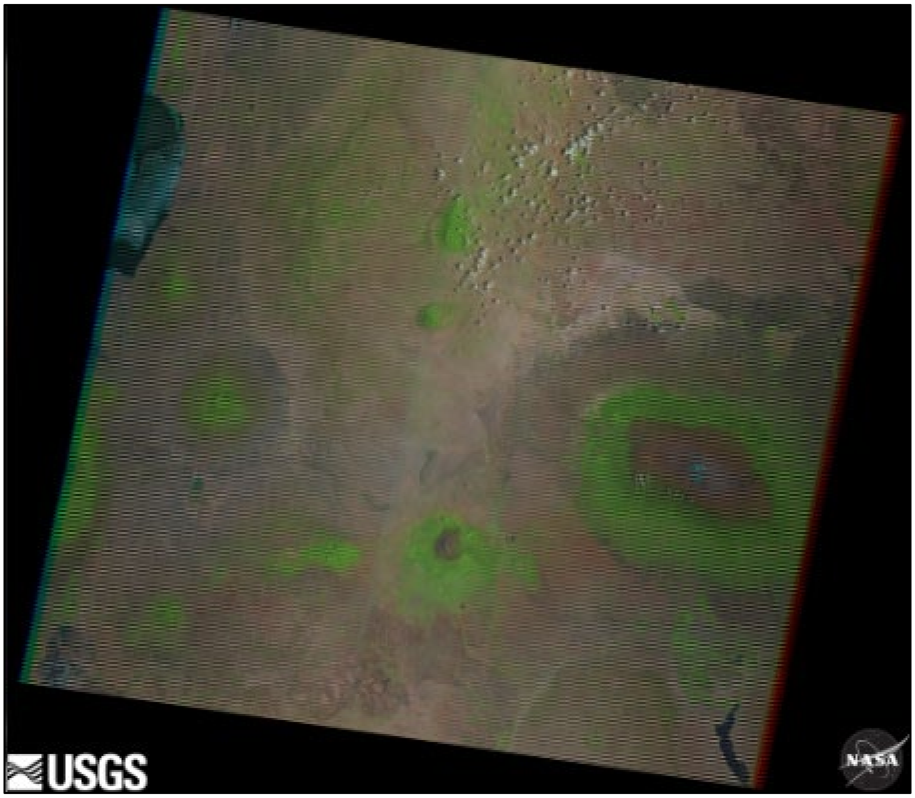

Figure 6-11. Landsat 7 ETM+ SLC-off Browse Image

6.4 IGS Landsat Data Archives

The IGS represent an evolving worldwide network of Landsat 7 data collection and product generation centers (see Figure 6-12). IGS data policies and product types may differ from those in the U.S. archive. While foreign landmasses are imaged for onboard storage and eventually downlinked to U.S.-controlled ground stations, the depth of ETM+ coverage at participating IGS was much deeper prior to the changes in the Landsat Project in 2008. Most, if not all, IGS captured every scene imaged by Landsat 7 within their respective acquisition circles.

The LGAC effort started in 2010, in order to reduce the need for direct contact with any ongoing IGS. This effort from the USGS has the goal of consolidating the Landsat archives from all stations worldwide to make all Landsat scenes, from all missions, available to users.

Consolidating the USGS Landsat record with IGS data includes several challenges:

- Various data formats and processing methods
- Unknown data formats and processing methods (stations no longer active)
- Media storage age and conditions
- Various or obsolete technologies used to ingest data

While every technological asset available will be explored, some data may be irrecoverable.

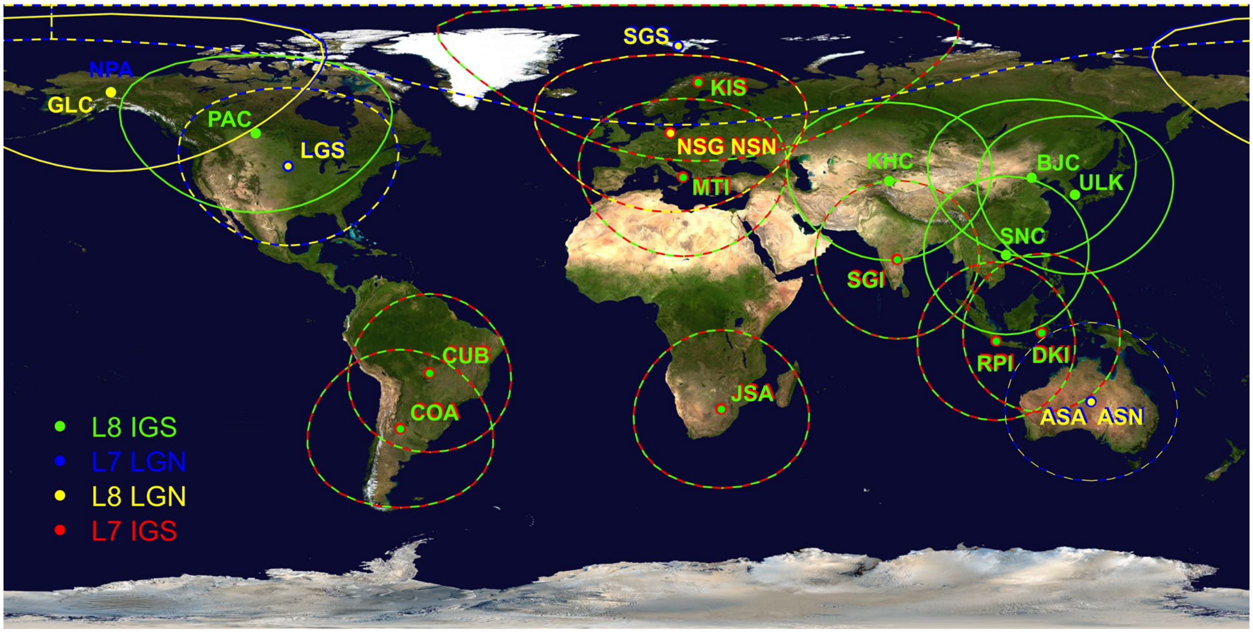

Figure 6-12. Active Landsat International Ground Stations – as of 2019

This effort to systematically acquire, reconcile, and ingest all recoverable foreign data is estimated to last a number of years. As data are successfully ingested, the Landsat scenes will become available for download at no charge from [EarthExplorer](), [GloVis](), and [LandsatLook Viewer]().

Appendix A Known Issues

A.1 Overview

Analyses performed on earlier Landsat data revealed the existence of imperfections or image artifacts caused by the instrument's electronics, dead or dying detectors, as well as downlink errors. As a descendant of the Landsat 4 and Landsat 5 TM sensor, the ETM+ was expected to generate data with similar characteristics. In the past, these anomalous effects were ignored or artificially removed using cosmetic algorithms such as histogram equalization during radiometric processing by the ground system. In keeping with the mission's goals (see Section 1), a more proactive approach was developed for Landsat 7 before launch. One of the goals of the enhanced Landsat ground system is to detect and remove image artifacts prior to radiometric processing. Remnant artifacts, if they exist, can be subsequently removed in a post-processing step using cosmetic algorithms as can be done for TM data.

Based on analyses of TM data, the ETM+ image artifacts were expected to be scan correlated shift, memory effect, modulation transfer function, and coherent noise. Dropped lines and inoperable detectors can also impact ETM+ data via decommutating (data stream synchronization) errors and detector failure, respectively. On-orbit analyses of ETM+ have also identified some impacts related to the operation of the SLC (anomalous coherent noise and detector ringing), as well as a coherent noise storm in the data that was acquired as the SLC failed. Due to one or more of these issues, remnant artifacts may exist in a given scene and can appear as banding and striping. A discussion of these effects and characterization methodologies follows in this section. Eliminating their presence from data products is addressed in Section B.4. The ETM+ SLC failure in 2003 is discussed in Section 2.2.3.3.

A.2 Scan Correlated Shift (SCS)

SCS is a sudden change in bias that can occur in all ETM+ detectors simultaneously. The bias level switches between two states and not all detectors are in phase; some are 180 degrees out of phase (i.e., when one detector changes from low to high bias, another may change from high to low). All detectors shift between these two bias states over time with the shift frequency varying from days to months. Measurement of SCS levels is affected by another instrument artifact known as Memory Effect (ME).

Characterization of possible SCS is performed at three levels. First, SCS levels are obtained for each detector in each line of the scene. This must be done to all scenes that require removal of SCS. Second, the value for the SCS levels is calculated for each detector. Third, the exact location of the transition from one SCS state to another within a scan line is determined, (assuming that a continuous flow of data from the detectors is available). SCS can be diagnosed by its random nature, by its fixed magnitude states, and by its appearance in otherwise completely dark nighttime data. On-orbit analyses of ETM+ data indicate that SCS does not exist in Landsat 7 data.

A.3 Memory Effect (ME)

TM data from Landsat 4 and Landsat 5 was rife with the artifact known as ME. It is manifested in a noise pattern commonly known as banding. It can be observed as alternating lighter and darker horizontal stripes that are 16 pixels wide in data that have not been geometrically corrected. These stripes are most intense near a significant change in brightness in the horizontal (along scan) direction, such as where a cloud (bright) and water (dark) are imaged together. Because of this, it was formerly termed 'Bright Target Saturation' or 'Bright Target Recovery.' Another artifact known as 'Scan Line Droop' was originally thought to be a separate phenomenon, but has since been shown to be simply another manifestation of ME. Because of its nature, ME impacted data have historically been the cause of significant error in calibration efforts because its effect on the Internal Calibrator (IC) data is scene dependent. It is present in TM Band 1 through Band 4 acquired at the PFP, and nearly absent in the Bands 5-7 acquired at the CFP.

ME is known to be caused by circuitry contained in the pre-amplifiers immediately following the detectors in the TM electronics. It is primarily due to a portion of a feedback circuit that contains a resistor / capacitor combination with a time constant of approximately 10 µm. This directly corresponds to time constants of 1100 minor frames (pixels) that have been derived from night scenes.

ME is characterized by both a magnitude and a time constant, which is a measure of the length of the artifact. If both values are known, ME is correctable (Helder et al., 1997). Most modern processing systems correct ME by default; thus, it usually appears only in Level 0 data or in data processed by older systems. Analysis of ETM+ data indicates that ME has never been detected in reflective band data, but insignificant amounts may exist in the thermal band. Ongoing studies will assess if it becomes a significant problem as the ETM+ sensor ages.

A.4 Coherent Noise (CN)

CN appears as a repeating pattern in satellite imagery and is most visible over dark homogenous regions (see Figure A-1). These patterns may appear in only one band or in several bands and may or may not be phase-locked to the instrument scan time. Although CN can be corrected, this correction often degrades other parts of the image; therefore, correction is performed only for very high magnitude noise sources.

Currently, the only CN correction performed for Landsat 5 and Landsat 7 is for Nyquist Noise (see Figure A-2). Nyquist frequency CN is phase-locked to the mirror scan and arises in

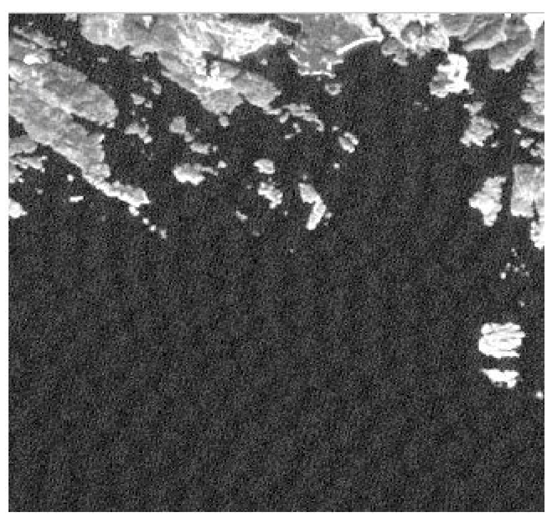

Figure A-1. Example of CN in Band 3 of Landsat 7 ETM+ Level 1

the analog / digital conversion circuits of an instrument. Nyquist noise is easily removed and usually unseen in Level 1 images.

Figure A-2. Example of Nyquist Frequency CN in Band 1 in Landsat 5 MSS Image

The other form of CN is Anomalous Coherent Noise, which appears when a CN source changes in magnitude across a single instrument scan. It has been seen in Band 1 and Band 8 on Landsat 7 ETM+. It only affects a few detectors in each band. The Landsat 7 ETM+ anomalous CN is largest in the IC region and at the edges of a scene. It drops to zero magnitude in the center of a scene.

The Anomalous Coherent Noise sources on Landsat 7 appear at 20 Kilohertz (kHz), which is the same operating frequency as the SLC. As a result, a link between the anomalous noises and the SLC has been theorized. This theory appears to have been confirmed with the failure of the SLC in June 2003. After ETM+ returned to normal operations, it was observed that the 20 kHz noises in Band 1 and Band 8 were decreased in magnitude, and the anomalous nature of CN has been greatly reduced.

Anomalous Coherent Noise is a known problem on Landsat 7. Even though it is uncorrectable, it is not a cause for concern. However, new Anomalous Coherent Noise sources require further analysis.

A.5 Dropped Scan Lines

Dropped scan lines can occur in ETM+ L0R data due to decommutating errors in the raw data stream ingested by the LPS due to transmission problems between the satellite and the receiving ground station. Because Landsat 7 data are downlinked and processed in two different data format streams, transmission-related data loss usually only affects one format—either Bands 1-5 and Band 6 low gain, or Bands 7-8 and

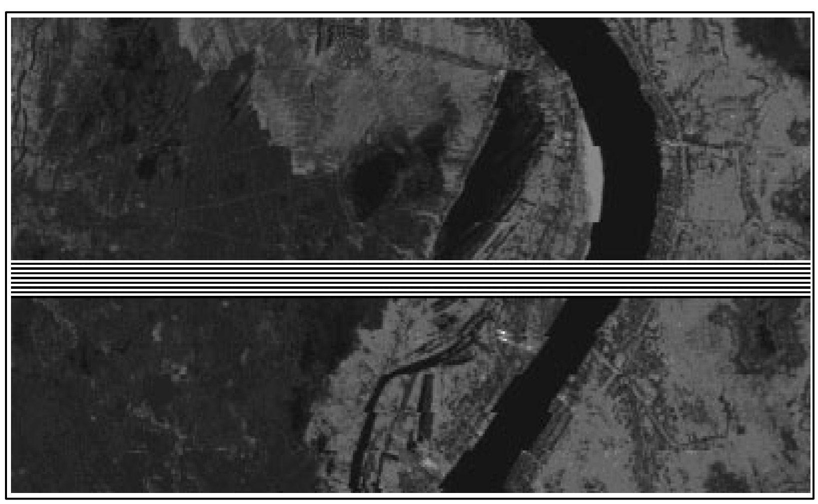

Figure A-3. Dropped Scan in Band 7 of Landsat ETM+ L0 Data

Band 6 high gain. Missing scan lines may also be caused by a temporary problem in the ETM+ main scan mirror. Figure A-3 shows an example of dropped scans in Level 0 data.

A.6 Inoperable Detectors

Also known as Detector Failure, Inoperable Detectors is a term used when transient or permanent anomalies arise in an individual detector. Detector Failure is uncorrectable, although interpolation of data from adjacent detectors can mitigate its effects. All forms of Detector Failure are matters for serious concern and may indicate progressive problems onboard the instrument.

Transient Detector Failure, also known as a “flaky detector”, occurs when a single detector undergoes a sudden and drastic change in bias. Usually, the detector slowly returns to nominal behavior over the course of several scans. The cause is unknown but is most likely due to energetic particle strikes within the detector circuitry. Transient failure has been observed once in Landsat 7 ETM+ data (see Figure A-4).

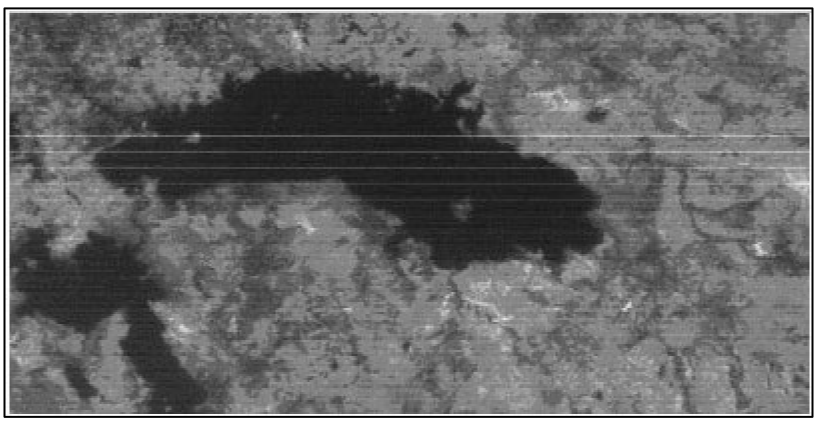

Figure A-4. Transient Failure in Landsat 7 ETM+ Level 0 Band 6, Detector 6

A Flat Detector is a permanent but partial detector failure. Either the detector’s bias values, gain values, or both, are affected, resulting in reduction in dynamic range. The detector return values may only vary within a range of a few DN values, or they may register a single constant value. Also, detector values may exhibit larger than usual random noise. Flat detectors have been seen in Side B engineering data in Landsat 7 ETM+ but should not appear in normal imagery.

Absolute, permanent detector failure is known as a Dead Detector. Dead Detectors do not return any signal and have a constant DN value of 0. Although previous Landsat instruments have exhibited Dead Detectors near the end of their operating lifetime, there are currently no Dead Detectors on any instruments aboard Landsat 7.

A.7 Banding

Banding or "scan-to-scan striping" are common terms for a visible noise pattern that affects Landsat data. Three artifacts are known to cause Banding.

SCS (see Section A.2) causes banding by forcing each band to randomly choose one of two or more bias states. This banding has a stable magnitude across each scan. Figure A-5 shows an example of SCS-caused Banding.

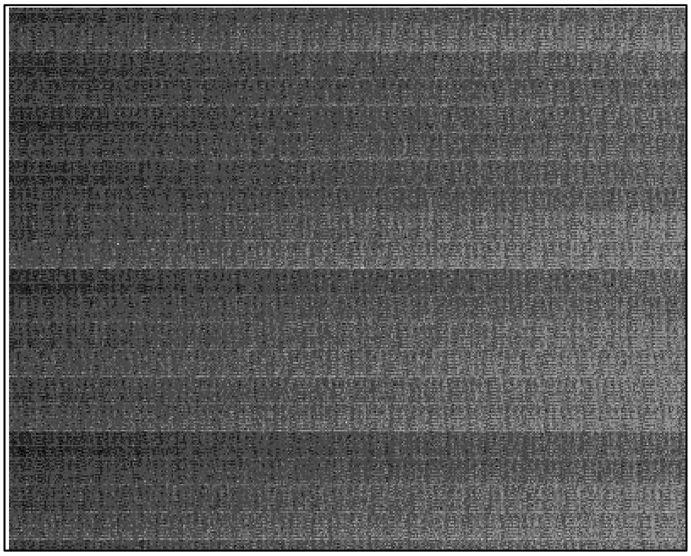

Figure A-5. Example of Banding Due to SCS

ME (see Section A.3) causes banding-like patterns that change in magnitude across a scan (see Figure A-6). This banding is caused by a large radiation transition in the scanning direction (from bright target to dark or from dark target to bright), either in the imagery or in the IC region of the data. For ME to create banding, the target is usually many scan lines in size, and if the target is in the imagery, the banding may visibly change over the bright target.

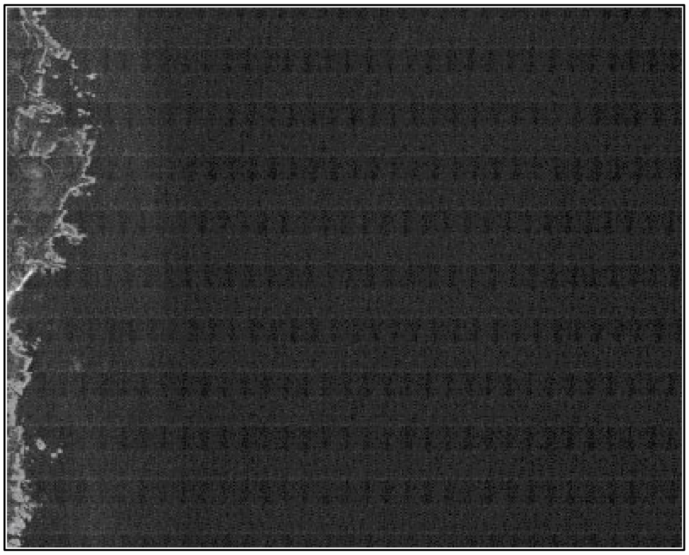

Figure A-6. Example of Banding Due to ME

The third artifact known to cause banding is Calibration Error. Also known as True Banding or Sweep Striping, Calibration Error Banding is caused by errors in calibration algorithms that treat forward scans and reverse scans separately, so that one direction of scan has a different bias than the other. Calibration Error Banding is stable across the scan and consistently alternates between high and low bias. Calibration Error Banding is rare and corrected when found.

More than one of these artifacts can affect an instrument, causing banding of a complex character that may be difficult to diagnose with a cursory visual inspection. All forms of banding are known artifacts, all correctable, and do not cause a concern.

A.8 Striping

Striping is a line-to-line artifact phenomenon that appears in individual bands of radiometrically corrected data. Its source can be traced to individual detectors that are calibrated incorrectly with respect to one another (true striping or "calibration striping"). Another form of this problem is "saturation striping", which can occur over bright snow / ice surfaces or clouds (see Figure A-7). Saturation striping is normal and expected in L1R products. Saturation striping is corrected during LPGS processing.

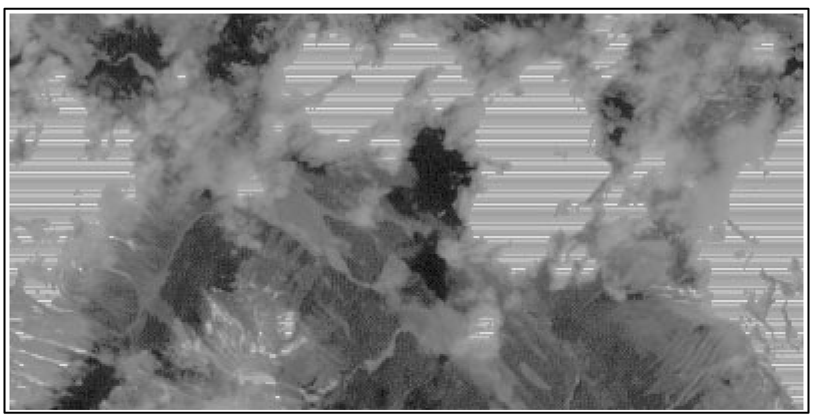

Figure A-7. Saturation Striping in Landsat 7 ETM+ L1R Band 3 Data

Saturation striping may also appear in some Landsat 7 gain-change scenes. In these scenes, part of the scene is converted from one gain setting to another. If high gain data with a small dynamic range is converted to low gain data with a large dynamic range, it may saturate at a value less than 255 DN. The processing system does not recognize it as saturated data and may cause striping in radiometric correction processing. Saturation striping in L1R or L1G gain-change scenes is expected and not a cause for concern. If saturation striping is visible in a normal Level 1 product, corrections need to be made to the calibration of the instrument.

A.9 Scan Line Corrector Failure

On May 31, 2003, the SLC aboard Landsat 7, malfunctioned. The failure of the SLC eliminated the instrument's ability to compensate for the forward motion of the satellite.

Subsequent efforts to recover the SLC were not successful, and the problem is permanent since that date. The ETM+ is still capable of acquiring useful image data with the SLC turned off, particularly within the central portion of any given scene. The center of an SLC-off scene is very similar in quality to previous Landsat 7 data. However, the scene's edges contain alternating scan lines of missing data (see Figure A-8). The precise location of the affected scan lines varies from scene to scene. See Section 2.2.3.3 for additional material on this instrument artifact.

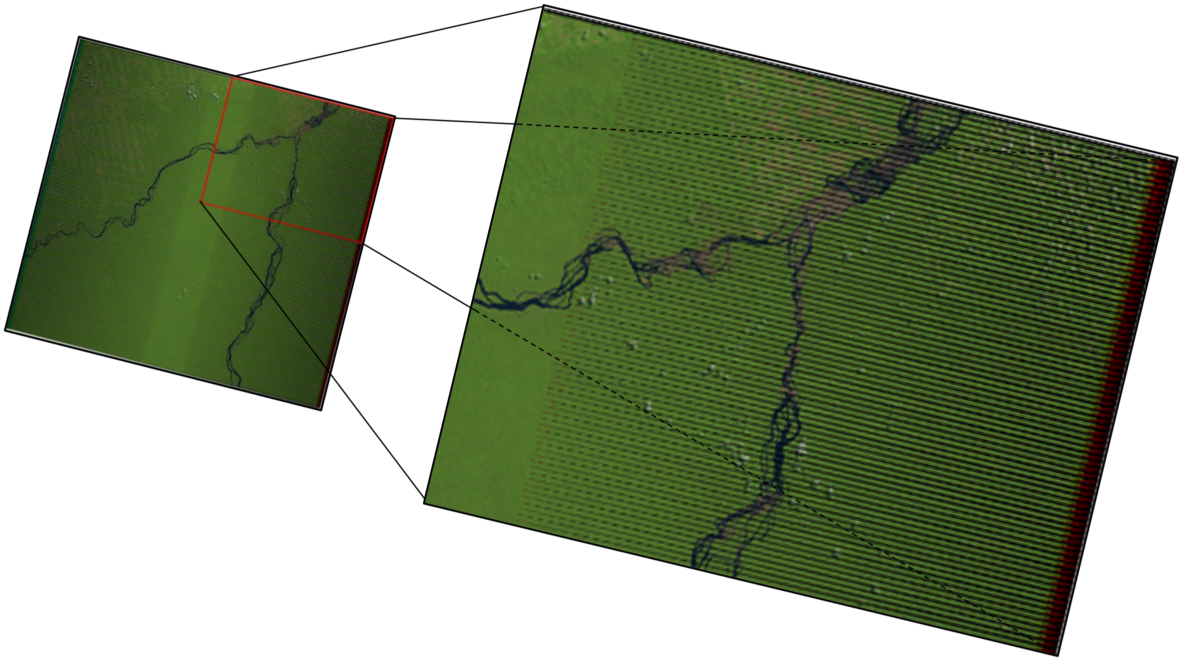

Figure A-8. A Subset of Landsat 7 ETM+ Scene Showing SLC-off Scan Gaps

Figure A-8 A Subset of a Landsat 7 ETM+ Scene Showing SLC-off Scan Gaps shows that the scan gaps increase in magnitude toward the scene edges.

Appendix B CPF Content

B.1 File Content

The CPF supplies the radiometric and geometric correction parameters required during Level 1 processing to create superior products of uniform consistency across the Landsat 7 system. Besides the file attributes, these parameters fall into one of three major categories: geometric parameters, radiometric parameters, or artifact removal parameters.

B.2 Geometry Parameters

The geometric parameters are classified into 11 first tier groups. The heading for each group is the actual ODL group name used in the CPF.

- Earth Constants
- Orbit Parameters
- Scanner Parameters
- Spacecraft Parameters
- Mirror Parameters
- Bumper Mode (April 1, 2007)
- Scan Line Corrector
- Focal Plane Parameters
- Attitude Parameters
- Time Parameters
- Transfer Function
- UT1 Time Parameters

B.3 Radiometric Calibration Parameters

The radiometric parameters are classified into 15 first tier groups. A brief description of each group and their use in various Landsat 7 systems or by an individual user follows. The heading for each group is the actual ODL group name used in the CPF.

- **Detector Status**
  The Detector Status parameters provide a five-element code that describes the current health status of each ETM+ detector. The five codes indicate detector status (live or dead), low gain signal noise, high gain signal noise, low gain dynamic range quality, and high gain dynamic range quality.

- **Detector Gains**
  Analysis of the SIS calibration transfer to the IC and output from the Combined Radiometric Model (CRaM) used by IAS results in the Detector Gain parameter set. For each detector, there is a pre-launch gain, post-launch gain, and a current gain for each of the two gain settings. The pre-launch and post-launch gains are based on the SIS calibration and remain static while the current gain is updated as a function of CRaM improvement and detector responsivity over time. The

Detector Gain parameters are used to radiometrically correct ETM+ data prior to LPS processing and derivation of the ACCA score and optionally used by LPGS as an alternative to computing gains on the fly from the IC data.

- **Bias Locations**
  The bias location parameters refer to the IC data. They specify the starting pixel location for the bias (dark current restore), the length in pixels of the bias region, and the length of useable IC data including the pulse. A set of parameters exists for each of the three band groups - reflective, panchromatic, and thermal. They are used during radiometric correction for rapid retrieval of calibration pulse and shutter data.

- **Detector Biases Band 6**
  During Level 1 processing, Band 6 biases are generally computed from the IC for the image being processed. This is a complex task and may be subject to anomalies. This parameter group is computed both pre-launch and at regular intervals over the life of the mission. These are baseline Band 6 biases and are used during Level 1 processing if the image specific IC-derived biases prove unreliable.

- **Scaling Parameters**
  The Scaling Parameter set consists of the lower and upper limit of the post-calibration dynamic range for each band in each gain state. These are the LMIN and LMAX values and are expressed in units of absolute spectral radiance. These values are used by LPGS to convert 1G products to scaled 8-bit values and by users for the reverse transformation. There is an LMIN / LMAX pair per band for each of the gain modes.

- **MTF Compensation**
  All image systems, including Landsat 7, cause a blurring of the scene radiance field during image acquisition. Accurate characterization of this blurring is referred to as the MTF. Restoration processing compensates and corrects for systemic degradations to yield greater radiometric accuracy. The MTF compensation parameters are weighting functions for each band. Five weighting parameters for both pixel and line directions were selected to best fit the optimal MTF response. These are applied to the components of the piecewise cubic convolution kernel to generate the optimal MTF reconstruction kernel.

- **Sensitivity Temperatures**
  The temperature of the detectors on the primary focal plane of the ETM+ is not controlled and tends to warm up as the instrument operates. The CFP is controlled but may operate at different set points. Most detectors show some dependence of responsivity with temperature. The sensitivity temperature parameters describe the relationship between gain change and operating temperature for each detector and are used to adjust the gains derived from

multi-calibration sources. Gains derived solely from IC data are not temperature adjusted.

- **Reference Temperatures**
  The sensitivity temperature coefficients are used to adjust gains for varying focal plane temperatures. The reference temperatures are used to normalize the gains to a stable temperature. A single reference temperature is calculated pre-launch and post-launch for each band at both gain states.

- **Lamp Radiance**
  The lamp radiance parameters contain the actual radiance of the two IC lamps in three possible configurations (i.e., lamp 1 on - lamp 2 off, lamp 1 off - lamp 2 on, lamp 1 on - lamp 2 on). For each reflective band, there are pre-launch, post-launch, and current values for the low and high gain settings. Pre-launch values are established by transferring the SIS calibration to the IC lamps within the ETM+. Post-launch is determined using PASC and FASC calibration data. The lamp radiance parameters used to compute the gains are used for converting raw ETM+ data to units of absolute radiance.

- **Reflective IC Coefficients**
  Radiance levels produced by the IC or seen by the detectors vary as a function of instrument state. Several parameters affecting instrument state are tracked and used for correcting this effect. These parameters are instrument on time, position on-orbit, and temperatures of the IC components and focal plane arrays. The reflective IC coefficients are used in the model that corrects for these effects. For each detector, there are 18 coefficients for both the low and high gain states.

- **Lamp Reference**
  The radiance levels produced by the IC or seen by the detectors vary as function of instrument state. The model that compensates for these effects requires as input 14 temperatures of the IC components and focal plane arrays. In general, these temperatures are extracted from the PCD for the image being processed. However, the IAS also performs a pre-launch calibration of the ETM+ and a post calibration using the combined radiometric model. The lamp reference parameters represent the instrument state at the time of calibration.

- **B and 6 View Coefficients**
  The Band 6 view coefficients are used in computing the actual shutter (i.e., bias) values when processing the emissive IC data. The offset algorithm takes into account radiance of the shutter flag, as well as contributions from other instrument components such as the scan mirror and SLC. Each Band 6 detector has a different view of the contributing components. The Band 6 view coefficients capture this view and are used to adjust the contributing spectral radiances accordingly.

- **Band 6 Temp Model Coefficients**
  The Band 6 temperature coefficients are used to calculate the temperature of the scan mirror. The emissive IC algorithm requires scan mirror temperature for computing Band 6 gains and offsets. The scan mirror's contribution to the Band 6 response must be calculated and accounted.

- **Lamp Current Coefficients**
  Included in the PCD are the currents for the two IC lamps. The currents are in a raw data format and require conversion to engineering units (i.e., milli-amps) prior to their use. The lamp coefficient parameters are used to linearly transform the raw counts to milli-amps. There are two coefficients for each lamp.

- **Thermistor Coefficients**
  Included in the PCD are a variety of ETM+ component temperatures. The temperatures are in a raw data format and require conversion to valid numbers prior to their use. The thermistor coefficients parameters are used for this purpose. Six conversion coefficients are supplied for each of the 28 different temperatures that accompany the PCD.

B.4 Artifact Removal Parameters

The artifact parameters are classified into 9 first tier groups. A brief description of each group and their use in various Landsat 7 systems follows. The heading for each group is the actual ODL group name used in the CPF. Not all the following issues impact ETM+ data but the CPF is designed to accommodate them if the need arises.

- **Memory Effect**
  Memory effect is a noise pattern commonly known as banding. It can be identified as alternating lighter and darker horizontal scan-wide stripes. The memory effect parameters were derived by the IAS and are static. They consist of a magnitude and time constant for each detector. These are used in an inverse filtering operation to remove the memory effect artifact.

- **Ghost Pulse**
  The ghost pulse is a faint secondary image of the IC lamp pulse. It appears in Band 5 and Band 7. The ghost pulse parameters identify the beginning and ending minor frames that bound this ghost image.

- **Scan Correlated Shift**
  Scan correlated shift is a sudden change in bias that occurs in all detectors simultaneously. The scan correlated shift parameters are derived by the IAS and are static. They consist of a bias magnitude for each detector and are used to compensate for the shift when it occurs.

- **Striping**
  Striping is defined as residual detector-to-detector gain and offset variations within a band of radiometrically corrected (L1R) data. The 1R process is intended

to remove detector-to-detector variations through the generation of relative gains and bias from histograms. These are included in the absolute gains and biases eventually applied. Nonetheless, the possibility of residual striping remains. The striping parameters are correction methodology flags. Two processing options are possible: linearly adjust the 1R data to match the means and standard deviations of each detector to a reference detector or to an average of all the detectors. There is one striping parameter per band for each of the gain modes.

- **Histogram**
  Histogram analysis estimates the relative gains and biases for all detectors by characterizing the response behavior of individual detectors in a band relative to the other detectors in a band. Results are used to adjust the gains and biases applied during radiometric correction. The histogram parameters control the algorithm by specifying detector noise, a normalization reference detector for each band, saturation metrics, and histogramming window size.

- **Impulse Noise**
  Impulse noise within a digital signal manifests itself in a sample as a departure from the signal trend far in excess of that expected from random noise. The impulse noise parameters specify a median filter width and an impulse noise threshold for each detector. The IAS employs these parameters for identifying and trending impulse noise in otherwise homogeneous data such as night scenes and FASC imagery.

- **Coherent Noise**
  Coherent noise is a low-level periodic noise pattern found in all Landsat 5 imagery and characterized by the IAS for Landsat 7. The coherent noise parameters consist of the number of noise components and a set of waveform characteristics that describe each component for each band. The waveform characteristics are the mean, sigma, minimum, and maximum for each component's frequency, phase, and magnitude.

- **Detector Saturation**
  In addition to normally observed saturation (i.e., 0, 255) two other types of detector saturation can occur. An analog to digital converter may saturate below 255 counts at the high end, or above 0 at the low end. The detector saturation parameters identify these levels for each detector. The analog electronic chain may saturate at a radiance corresponding to a level below 255 counts and above 0 counts on the low end. The detector saturation parameters also identify these levels for each detector.

- **Fill Patterns**
  LPS uses two values to fill minor frames to distinguish missing or bad band data from good data. The two fill values used are zeros for odd detectors and 255s for even detectors. The fill data are placed on a minor frame basis - if data are missing from part of a minor frame, the whole minor frame is filled. The

alternating 0/255 fill pattern was selected to unambiguously flag artificial fill from reflectance values that naturally could occur such as those caused by SLC-off.

B.5 ACCA Parameters

Each scene processed by LPS undergoes ACCA prior to being archived. The cloud cover scores become searchable metadata and can be used to filter out undesirable scenes during an archive search. The ACCA algorithm uses a variety of threshold and band indices for cloud identification. These may change during the mission and are therefore included in the CPF.

- **ACCA Biases**
  The LPS ACCA algorithm requires radiometrically corrected image data. The ACCA Biases parameter set is used in conjunction with the Detector Gains for converting raw DNs to units of absolute radiance. There is one bias parameter per detector per band for each of the two gain modes. Although ACCA uses only Band 2 through Band 6, the other band biases are included for completeness. Biases are reported in units of digital counts.

- **ACCA Thresholds**
  The LPS ACCA algorithm uses Band 2 through Band 6 in a combination of thresholds, ratios, and indices to separate clouds from land. Results are reported in metadata that are eventually used in client data searches. LPS and possibly IGS list the ACCA Threshold parameters in the CPF for use by the end user.

- **Solar Spectral Irradiances**
  The LPS ACCA algorithm converts radiometrically-corrected data to units of planetary reflectance prior to cloud filtering. This involves normalizing image data for solar irradiance, which reduces between-scene variability. The parameter values listed in Table B-1 are the mean solar spectral irradiances for Band 1 through Bands 5, 7, and 8. There is one value for each band.

Band	Watts/(m^2 * μm)
Band 1	1969.000
Band 2	1840.000
Band 3	1551.000
Band 4	1044.000
Band 5	225.700
Band 7	82.07
Band 8	1368.000

Table B-1. Solar Spectral Irradiances

- **Thermal Constants**
  ACCA converts Band 6 from spectral radiance to a more physically useful variable, namely the effective at-satellite temperatures of the viewed Earth-

atmosphere system. The transformation equation requires two calibration constants, which are listed in Table B-2.

Constant	Value	Units
K1	666.09	(Watts/(m^2 * sr * µm))
K2	1282.71	Kelvin (degrees)

Table B-2. ETM+ Thermal Constants

Appendix C ETM+ and TM Cross-Calibration (Historical)

The following information is applicable to Landsat TM and ETM+ Pre-Collection data and is included for historical interest. Starting with Collection 1, Landsat 4-8 data are all radiometrically calibrated, regardless of sensor (Micijevic, Haque, & Mishra, 2016). The historical information describes the Collection 1 cross-calibration that supersedes the old TM / ETM+ calibration.

C.1 Introduction

The entire Landsat data record is important for terrestrial remote sensing and global change research because it covers a 40+ year period during which significant anthropogenic and natural terrestrial change has occurred. In order to maximize the benefits of this data record, steps are needed to ensure that the data are self-consistent and not significantly affected by artifacts of the various Landsat sensors. For the Landsat 7 mission, renewed efforts were made to ensure radiometric calibration across the whole Landsat series of sensors, as well as with other Earth observation sensors such as Terra MODIS. A critical step in such a process is relating sensor radiometric calibration to an absolute scale, thus yielding image data at the TOA in physical units. Additional processing steps to retrieve surface parameters, such as reflectance and temperature, then become possible.

Consistency between the Landsat sensors starts with refined calibration of all individual sensors, including the development of a stable sensor (i.e., ETM+), detailed pre-launch characterization, as well as periodic on-orbit calibration. Post-launch radiometric calibrations are referenced to onboard standards and ground-based test sites with independent measurements. For Landsat 7 and ETM+, cross-calibration with earlier Landsat sensors begins by using near-simultaneous imaging of common Earth surface targets by Landsat 5's TM sensor. Typically, there is a limited overlap period when more than one of the sensors is operating. Such an overlap period with Landsat 5 was planned for the initial phases of the Landsat 7 mission. The resulting opportunity for radiometric cross-calibration between ETM+ and Landsat 5 TM during the early part of their many years of simultaneous operation is the main subject of this section. The following material was extracted and condensed from a paper that covers the subject in greater detail (Teillet, et. al., (2001)).

C.2 Tandem Configuration

The launch of Landsat 7 on April 15, 1999 placed the spacecraft temporarily in an orbit very close to that of the Landsat 5 spacecraft. During this time, the mean altitude of Landsat 7 was 699 km, 6 km below the 705-km mean altitude of Landsat 5. At this altitude, the Landsat 7 ground track drifted slowly relative to the essentially fixed Landsat 5 pattern. The key period for the tandem configuration was June 1-4, 1999, when their tracks were almost exactly the same, but with a temporal offset on the order of only 10 to 30 minutes. This unusual and valuable opportunity was specifically designed to facilitate the establishment of data consistency comparisons between the ETM+ and TM sensors. During the tandem configuration period, image sequences corresponding to 791 matching scenes were recorded by both Landsat 7 ETM+ and

Landsat 5 TM (see Table C-1). Subsequently, the Landsat 7 orbit was adjusted for regular operations such that its 16-day repeat coverage cycle became offset from that of Landsat 5 by eight days. Given cloud cover and issues with data reception and recording, the number of useful data scene pairs acquired during the tandem phase was around 400 scenes.

The cross-calibration methodology documented in Teillet, et. al. (2001) is applicable to tandem image pairs acquired at other times and between other sensor pairs although it presents specific results for two different pairs of nearly coincident matching scenes from the Landsat 5 and Landsat 7 tandem configuration period. The main results were updated TM responsivities in the six solar reflective spectral bands referenced against the well-calibrated ETM+ responsivities in its corresponding spectral bands. The analysis approach included adjustments for differences in illumination, as well as for differences in spectral response profiles between the two sensors.

C.3 Tandem Datasets Selected for Analysis

Attention was focused on two particular tandem image pairs for cross-calibration methodology development and analysis because of the availability of ground reference data. Both Landsat sensors imaged the Railroad Valley Playa (RVPN), Nevada on June 1, 1999, when a team from the University of Arizona made measurements of surface spectral reflectance and atmospheric aerosol optical depth the same day. Similarly, a team from SDSU acquired the same types of ground reference data at a grassland test site near Niobrara, Nebraska (NIOB) on June 2, 1999, the day of the tandem Landsat overpasses for that site.

Tandem Scene Coverage (June 1-4, 1999)			
Date	**Path**	**Row**	**Station**
6/3	6	21-29	GNC
6/3	6	57-71	CUB
6/3	6	67-71	COA
6/2	15	12-44	GNC
6/2	15	27-45	NOK
6/3	22	10-43	GNC
6/3	22	26-49	NOK
6/2	31	7-40	PAC
6/2	31	25-46	NOK
6/3	38	6-39	PAC
6/3	38	25-40	NOK
6/1	40	25-38	NOK
6/2	47	4-30	PAC
6/2	47	25-30	NOK
6/3	54	4-25	PAC
6/2 – 6/3	95	65-87	ASA
6/3	102	69-83	ASA
6/2	104	62-82	ASA
6/3 – 6/4	111	64-84	ASA
6/2	152	-	RSA
6/3	159	-	RSA
6/3	159	69-78	JSA

Tandem Scene Coverage (June 1-4, 1999)			
6/2	168	19-27	KIS
6/2	168	-	RSA
6/2	168	62-83	JSA
6/3	175	19-26	KIS
6/3	175	23-42	FUI
6/3	175	-	RSA
6/3	175	62-85	JSA
6/2	184	22-44	FUI
6/2	184	44-77	LBG
6/3	191	14-24	KIS
6/3	191	17-43	FUI
6/2	200	17-40	FUI
6/3	207	19-24	FUI
6/2	216	63-76	CUB
6/3	223	60-86	CUB
6/3	223	68-98	COA
6/2	232	54-85	CUB
6/2	232	66-97	COA

*Not all stations are still receiving, https://landsat.usgs.gov/igs-network
*Stations: ASA – ACRES, Alice Springs, Australia; COA – Cordoba, Argentina; CUB – INPE, Cuiaba, Brazil; FUI – ESA, Fucino, Italy; GNC – CCRS, Gatineau, Canada; JSA – Johannesburg, South Africa; KIS – ESA, Kiruna, Sweden; LBG - DLR, Libreville, Gabon; NOK – SI/EOSAT, Norman, Oklahoma; PAC - CCRS, Prince Albert, Canada; RSA – Saudi Arabia (for SI/Dubai)

Table C-1. Landsat 7 ETM+ and Landsat 5 Tandem Data Coverage

Table C-2 provides information on the characteristics of the two datasets and Figure C-1 shows both Landsat image pairs. The RVPN test site is a dry-lake playa that is very homogeneous and consists of compacted clay-rich lacustrine deposits forming a relatively smooth surface compared to most land covers. The NIOB test site is characterized primarily by grasslands grazed by cattle and by a small area of agricultural crops.

	Railroad Valley Playa	Niobrara, Nebraska
Image Date	June 1, 1999	June 2, 1999
WRS-2 Path/Row	40/33	31/30
Landsat 7 Offset from WRS	76.56 km East	18.15 km East
ETM+ Data Level	Level-0R	Level-0R
TM Data Level	Level-0	Level-0
ETM+ Solar Zenith Angle	24.28°	26.60°
TM Solar Zenith Angle	27.23°	28.67°
Terrain Elevation	1.425 km	0.760 km
ETM+ AOD_{550}*	0.1046	0.059
TM AOD_{550}*	0.1035	0.059
Area Common to ETM+ and TM	10.7 km by 4.4 km	106 km by 66km

* AOD_{550} represents aerosol optical depth at 550 nanometers

Table C-2. Characteristics of Two Tandem Datasets

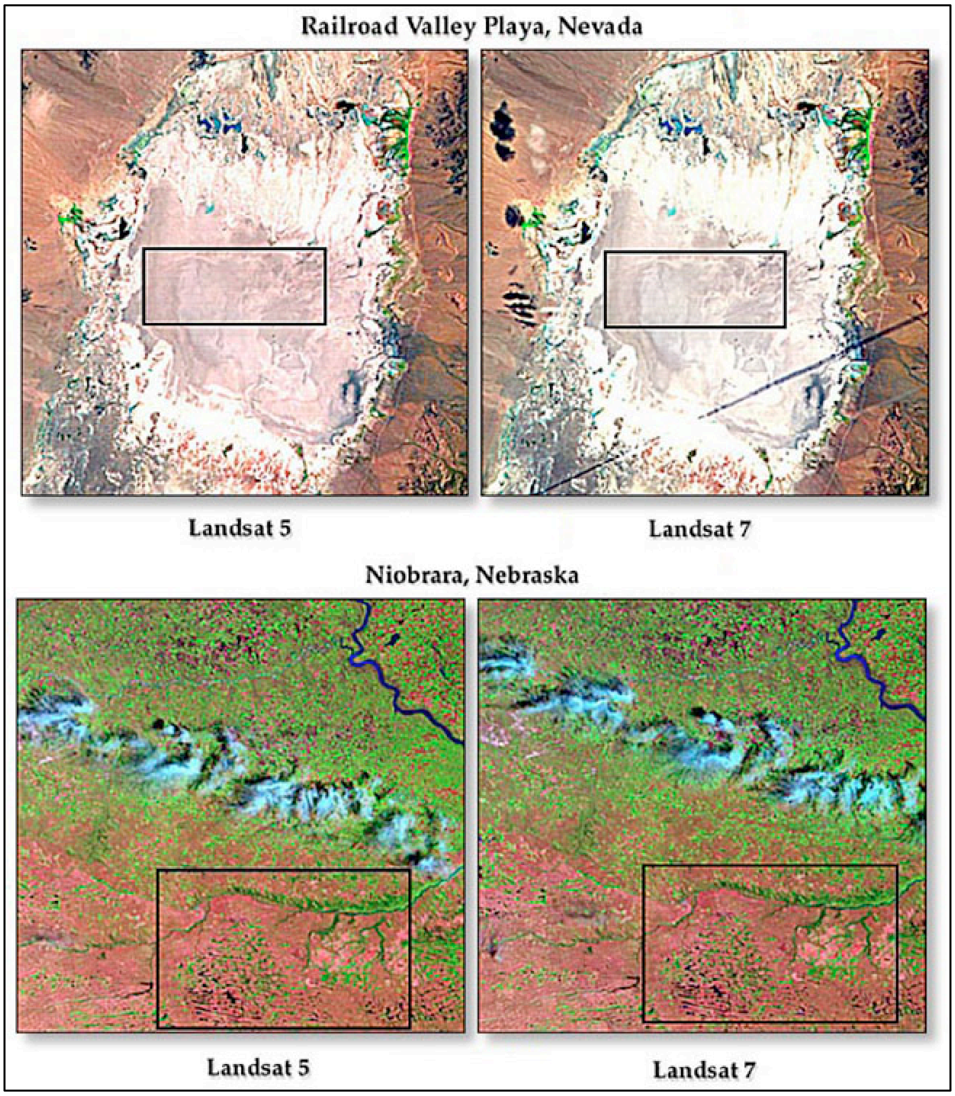

Figure C-1. Landsat 5 and 7 Cross-calibration Datasets of Railroad Valley Playa, Nevada (WRS-2 40/33) acquired June 1, 1999, and of Niobrara, Nebraska, (WRS-2 31/30) acquired June 2, 1999

Figure C-1 shows images using Band 5, Band 4, and Band 2.

C.4 Cross-Calibration Methodology

The cross-calibration methodology assumes that the Landsat 5 TM calibration is to be updated with respect to the Landsat 7 ETM+ sensor, which serves as a well-calibrated reference sensor (Barker et al., 1999). Because data acquisitions were only 10 to 30 minutes apart during the tandem configuration period, it is assumed that the surface and atmospheric conditions did not change significantly between the two image acquisitions.

Cross-calibration methodologies in general should consider adjustments as appropriate for Bi-directional Reflectance Factor (BRF) effects due to differences in illumination and observation angles. For the Landsat sensor image data pairs acquired during the tandem configuration period, the expectation is that such BRF adjustments are not necessary. The solar illumination geometries are very similar (within three degrees), satellite zenith angles are predominantly near-nadir, and relative azimuth angles between solar and satellite directions do not differ significantly from one Landsat overpass to the other. Nevertheless, it was necessary to address geometric, radiometric, and spectral differences between the sensors to account for their impacts.

Differences between the Landsat 7 and Landsat 5 sensors in their along-track and across-track pixel sampling made it difficult to establish sufficient geometric control to facilitate radiometric comparisons on a point-by-point and/or detector-by-detector basis. Therefore, the analysis approach made use of image statistics based on large areas in common between the image pairs. There are also significant differences in relative spectral response profiles between the corresponding ETM+ and TM spectral bands. The effects these spectral band differences have on measured TOA reflectance depends on spectral variations in the exo-atmospheric solar illumination, the atmospheric transmittance, and the surface reflectance.

C.5 Cross-Calibration Results

All of these challenges were overcome. As a result, detailed analyses were done on each corresponding band of data from these almost simultaneous image pairs acquired during the tandem configuration period. This allowed the use of the well-calibrated Landsat 7 ETM+ data to update the radiometric calibration of the Landsat 5 TM. The consistent results from the two field sites between their nearly coincident image pairs was encouraging. The band-to-band comparisons show negligible differences in spectral Band 4 to almost 4 percent difference in Band 7. The average difference is 1.6 percent, which, although based on only 12 spectral band cases, is a measure of the repeatability of the cross-calibration approach. Substantial differences between Landsat 5 TM’s pre-launch calibration coefficients for the visible bands on-orbit were also detected through this analysis and updated coefficients were incorporated in subsequent processing of TM data.

The work indicates that the tandem cross-calibration approach provided a valuable "contemporary" calibration update for Landsat 5 TM’s solar reflective bands relative to the excellent radiometric performance of Landsat 7 ETM+. Initial trials of the approach with two different tandem image pairs yielded repeatable results for TM responsivity coefficients that led to updated coefficients being used for processing of additional TM datasets. This effort, and other studies of sensor performance during the Landsat Project have been incorporated in the processing output products from the LPS.

Appendix D L0R and L1R Products (Historical)

The 2008 single-product data policy changes at EROS made the L0R product option obsolete. The following paragraphs are only relevant from a historical perspective.

D.1 L0R Product

Figure D-1. Simulated ETM+ L0R Image

Unlike earlier Landsat satellite systems, the Landsat 7 system was not originally designed to produce high-level (i.e., Level 1) products for users. The baseline program philosophy was to provide raw data only, which would leave the value added domain for commercial companies. A prevailing "wait and see" position by commercial vendors prompted NASA to add a systematic correction capability to ensure product availability. The primary product for users and vendors seeking higher level processing, however, is L0R data - an essentially raw data form that is marginally useful prior to radiometric and geometric correction. This is readily apparent when viewing a simulated L0R image. A Landsat 7 L0R product (see Figure D-1), however, does contain all the ancillary data required to perform these corrections including a CPF generated by the Landsat 7 IAS.

LPS spatially reformats Earth imagery and calibration data into L0R data. This involves shifting pixels by integer amounts to account for the alternating forward-reverse scanning pattern of the ETM+ sensor, the odd-even detector arrangement within each band, and the detector offsets inherent to the focal plane array engineering design. All LPS L0R corrections are reversible; the pixel shift parameters used are documented in the IAS CPF. The LPS L0R output is HDF-EOS formatted and archived.

D.1.1 Product Size

Three options, depicted in Figure D-2, existed when defining the size or spatial extent of a Landsat L0R product ordered prior to 2008 when Landsat data became freely available.

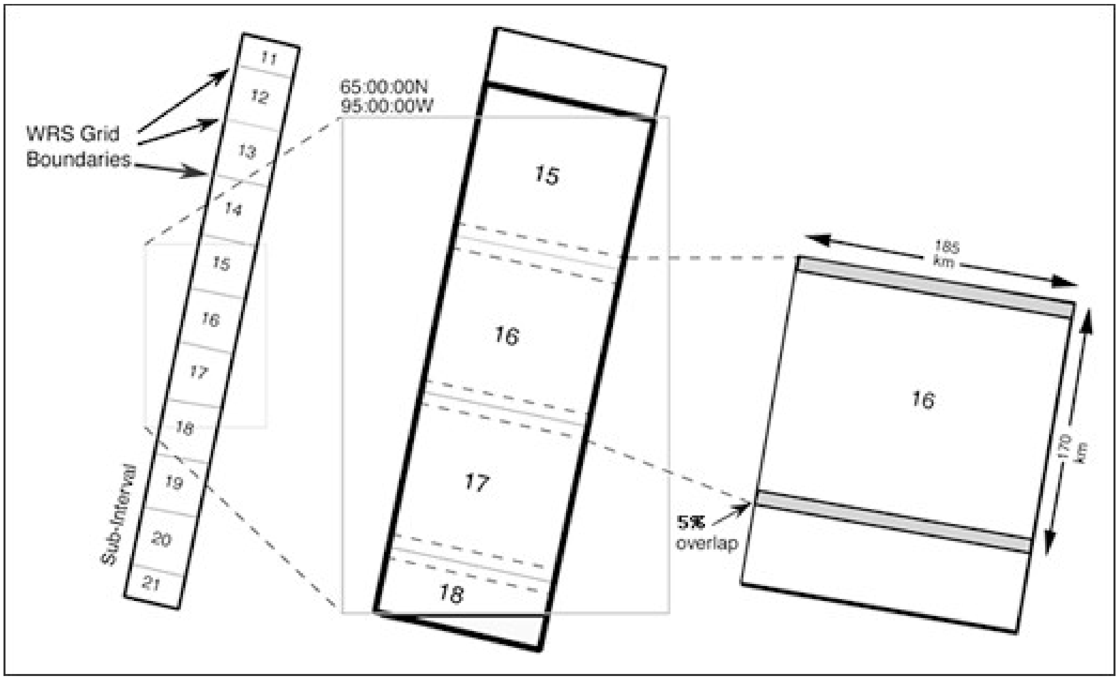

Figure D-2. L0R Product Alternatives

- **Standard WRS-2 Scene**
  The standard WRS-2 scene as defined for Landsat 4 and Landsat 5 was preserved as a product for Landsat 7. The WRS indexes orbits (paths) and scene centers (rows) into a global grid system comprising 233 paths by 248 rows. The path/row notation was originally employed to provide a standard designator for every nominal scene center and allow straightforward referencing without using longitude and latitude coordinates. The distance between WRS center points along a path is 161.1 km. A path distance of 90 km before and after a center point defines the standard scene length of 180 km. This length includes 20 scans of overlap with neighboring scenes. The standard WRS scene overlaps neighboring scenes along a path by five percent at the equator and has a width or cross-track distance of 185 km. Landsat 7 browse is framed according to WRS-2 scenes. An ordered scene covers the same geographic extent observed in the browse with the following caveat. Standard WRS scenes have 375 scans. Partial scenes (less than 375 scans) may exist at the beginning or end of a subinterval because the imaging events do not always start and end on scene boundaries. Browse and scene metadata for these occurrences accurately reflect their partial scene nature and geographic extent although partials are currently not offered due to complexities associated with Level 1 processing.

- **Subinterval**
  An interval is a scheduled ETM+ image period along a WRS path and may be from 1 to 90 scenes in length. A subinterval is a contiguous segment of raw wideband data received during a Landsat 7 contact period. Subintervals are caused by breaks in the wideband data stream due to communication dropouts

and/or the inability of the spacecraft to transmit a complete observation (interval) within a single Landsat 7 contact period. The largest possible subinterval is 35 scenes long. The smallest possible subinterval is a single ETM+ scene.

- **Partial Subinterval**
  A partial Landsat 7 subinterval could also be ordered. The partial subinterval is dimensioned according to standard WRS scene width, is at least one WRS scene in length, and can be up to 10 scenes in length if ordered in L0R form or 3 scenes in length in 1G form. A partial subinterval can float or be positioned at any scan line starting point within a subinterval. Partial subintervals are defined by either contiguous WRS locations or a bounding longitude/latitude rectangle. In the latter case, all scan lines touched by the bounding rectangle are included in their entirety.

D.1.2 Product Components

A complete scene-sized L0R product consisted of 19 datasets derived from the wideband telemetry, an IAS-generated CPF, a product specific metadata file, a geolocation index generated by EOSDIS Core System (ECS), and an HDF directory. Therefore, if a complete (i.e., all bands) scene-based L0R product was ordered, it had 23 distinct files. A brief description of each follows.

1 - 9. Earth Image Data - The unique bands of ETM+ image data comprise nine of the datasets. The data is laid out in a scan line sequential format in descending detector order (i.e., detector 16 followed by detector 15 and so on for the 30-meter bands). Band 6 is captured twice - once in low gain mode and the other in high gain mode. Under nominal satellite configuration, the low gain form of Band 6 is present in Format 1. All image samples or pixels are 8 bits in size.

10. IC data - Format 1 - IC data for Format 1 consists of scan line ordered internal lamp and shutter data for Bands 1-5 and blackbody radiance and shutter data for low gain Band 6. The data are collected once per scan and structured in a band sequential format in descending detector order (e.g., detector 16 followed by detector 15 and so on for the 30-meter bands).

11. IC data - Format 2 - IC data for Format 2 consists of scan ordered internal lamp and shutter data for Band 7 and Band 8 and blackbody radiance and shutter data for high gain Band 6. The data are collected once per scan and structured in a band sequential format in descending detector order (e.g., detector 16 followed by detector 15 and so on for the 30-meter bands).

12. MSCD - Format 1 - A logical record of MSCD exists for each data scan present in the L0R product ordered. Each logical record consists of three MSCD data values - the first half scan error, the second half scan error, and the scan line direction. This information, which applies to the previous scan, is used to compute deviations from nominal scan mirror profiles as measured on the ground and reported in the CPF. Also included in the MSCD file are scan based values such as time code, gain status, and processing errors encountered by LPS. The MSCD is trimmed to fit the product ordered, although one additional record is added to the file during the subsetting process because scan error and direction information corresponds to the prior scan.

13. **MSCD - Format 2** - A duplicate set of MSCD is generated when Format 2 is processed and kept with the product in the event Format 1 MSCD is lost or corrupted.

14. **PCD - Format 1** - The PCD for Format 1 consists of attitude and ephemeris profiles, as well as high frequency jitter measurements. PCD for the entire subinterval is included with the 0R product regardless of the size of the dataset ordered.

15. **PCD - Format 2** - A duplicate set of PCD is generated when Format 2 is processed and kept with the product in the event Format 1 is lost or corrupted.

16. **Scan line offsets - Format 1** - During LPS processing, image data are shifted in an extended buffer to account for predetermined detector and band shifts, scan line length, and possible bumper wear. The scan line offsets represent the actual starting and ending pixel positions for valid (non-zero fill) Earth image data on a data line by data line basis for Band 1 through Band 6 low gain. The left starting pixel offsets also apply to the IC data.

17. **Scan line offsets - Format 2** - During LPS processing, image data are shifted in an extended buffer to account for predetermined detector and band shifts, scan line length, and possible bumper wear. The scan line offsets represent the actual starting and ending pixel positions for valid (non-zero fill) Earth image data on a data line by data line basis for Band 6 high gain through Band 8. The left starting pixel offsets also apply to the IC data.

18. **Metadata - Format 1** - During LPS Format 1 processing, metadata is generated that characterizes the subinterval's spatial extent, content, and data quality for Band 1 through Band 6 low gain. This file, in its entirety and original form, accompanies the 0R product.

19. **Metadata - Format 2** - Format 2 metadata is similar but not identical to Format 1 metadata. The subinterval-related metadata contents are identical; the scene-related metadata is specific to Band 6 - high gain, Band 7, and Band 8. Also, the Format 2 metadata does not include cloud cover assessment data or references to browse data products. This file, in its entirety and original form, accompanies the 0R product.

20. **Metadata – ECS** - A third metadata file generated by ECS during order processing. This file contains product specific information such as corner coordinates and number of scans.

21. **Geolocation Index** - The geolocation index is also produced by ECS. This table contains scene corner coordinates and their product-specific scan line numbers for bands at all three resolutions. Its purpose is to provide efficient subsetting of a 0R product.

22. **Calibration parameters** - The IAS regularly updates the CPF to reflect changing radiometric and geometric parameters required for Level 1 processing. These are stamped with applicability dates and sent to EROS for storage and bundling with outbound 0R products.

23. **HDF Directory** - A file containing all pointers, file size information, and data objects required to open and process the L0R product using the HDF library and interface routines.

A user may order a subset of the available bands that affect the actual file count in a L0R product. In all cases, however, every product includes two PCD files, two MSCD files, three metadata files, the CPF, and the HDF directory. Only the IC, scan line offset, and Earth image file counts are affected by a product possessing less than the full complement of bands.

D.1.3 Product Format

The product delivered to Landsat 7 data users is packaged in HDF - an open standard file format selected by NASA for EOS data products. HDF is a self-describing format that allows an application to interpret the structure and contents of a file without outside information. HDF allows Landsat L0R products to be shared across different computer platforms without modification and is supported by a public domain software library consisting of access tools and various utilities.

Product users are directed to the Landsat 7 Zero-R Distribution Product Data Format Control Book for details regarding the HDF design used for the 0R product. Included are references to National Center for Supercomputing Applications (NCSA)-authored documentation.

D.2 L1R Product

The 2008 single-product data policy changes at EROS made the L1R product option obsolete. The following paragraphs are only relevant from a historical perspective.

The L1R product is a radiometrically corrected L0R product. Radiometric correction is performed using either the CRaM gains in the CPF or gains computed on the fly from the IC data. The choice is available to a user when the product is ordered. The biases used are always calculated from the IC data. Image artifacts such as banding, striping, and scan-correlated shift are removed prior to radiometric correction. Radiometric corrections are not reversible. The L1R product geometry is identical to the input L0R data.

During L1R product rendering, image pixels are converted to units of absolute radiance using 32-bit floating-point calculations. Pixel values are then multiplied by 100 and converted to 16-bit integers prior to media output. Two digits of decimal precision are thus preserved. One merely divides each pixel value by 100 to convert the L1R image data back to radiance units. The 16-bit 1R product is twice the data volume of an alike 0R product. For Band 6, a bias was found in the pre-launch calibration by a team of independent investigators post-launch. This was corrected in the LPGS processing system beginning December 20, 2000. For data processed before this, the 16- bit image radiances are 0.31 ($W/(m^2 * sr * \mu m)$) too high.

Official Announcement

In the fall of 2000, two Landsat 7 science team investigator groups discovered a Band 6 calibration bias in Level 1 ETM+ data products emanating from the LPGS at EROS. This bias apparently results from limitations in the pre-launch calibration of the ETM+. The magnitude of the correction is estimated to be 0.31 ($W/(m^2 * sr * \mu m)$) or about 3-4 percent radiance error at typical surface temperatures. This apparent systematic error in Band 6 radiance calibration translates into estimated temperatures derived from Landsat 7 ETM+ being about 3°C too high for typical Earth surface temperatures.

To remedy the situation, several changes were made to the product generation software and CPF. The Band 6 biases and instrument component view coefficients were changed in the October 1, 2000 release of the CPF. The calibration equation used by LPGS software was operationally updated on December 20, 2000. Users need to be aware of the impact these changes have on Level 1 products.

LPGS Level 1 products - pre 12/20/00

Users should subtract the bias value (0.31 ($W/(m^2 * sr * \mu m)$)) from the radiances obtained from L1R and L1G data products generated since launch by LPGS for both high and low gain Band 6 data. The changes made to the October 1, 2000 CPF effectively remove the temperature bias but only if the product generation software uses the changed CPF values. The LPGS software in place prior to December 20 does not.

LPGS Level 1 products - post 12/20/00

Users can safely use temperatures derived from Band 6 radiance values. No bias correction is necessary.

Other Systems - pre 10/01/00

If the CPF gains and biases are used, then the Band 6 radiance values should be adjusted for the bias described in paragraph three above.

Other Systems - post 10/01/00
If the CPF gains and biases are used, then no adjustments are necessary after this date. Other systems that employ a Band 6-calibration equation are outside NASA / USGS configuration and control. For accurate processing, please consult with your product provider.

D.2.1 Product Size

Two options existed for users when defining the size or spatial extent of a Landsat L1R product ordered from EROS.

- **Standard WRS-2 Scene**
  The standard WRS-2 scene, as defined above for the L0R product, could be ordered in L1R form. Partial scenes that may exist at the beginning and end of subintervals could also be ordered.

- **Partial Subinterval**
  A partial subinterval could also be ordered in L1R form. Unlike the L0R product, the L1R was limited to a maximum of three WRS scenes in size. The variably sized L1R product could float or be positioned at any scan line starting point within a subinterval. Alternatively, the product could be defined by up to three contiguous WRS-2 locations.

D.2.2 Product Components

A complete scene-sized L1R product consists of 17 datasets derived from the wideband telemetry, an IAS-generated CPF, a product specific metadata file, a geolocation index generated by ECS, and an HDF directory. Therefore, if you order a complete (i.e., all bands) scene-based L0R product, it has 21 distinct files. There are two fewer data files than an alike L0R product because the multiple PCD and MSCD files are merged into single consensus files. Please reference the L0R file product for individual file descriptions.

A user could order a subset of the available bands, which affected the actual file count in a L1R product. In all cases, however, every product included one consensus PCD file, one consensus MSCD files, three metadata files, the CPF, and the HDF directory. Only the IC, scan line offset, and Earth image file counts were affected by a product possessing less than the full complement of bands.

D.2.3 Product Format

The L1R product was delivered to users only in the HDF format. The HDF 0R and 1R formats are nearly identical. Exceptions include the united PCD and MSCD files and an enhanced product specific metadata file that reflects L1R correction characteristics.

Appendix E Level 1 LPGS and NLAPS Product Differences (Historical)

E.1 Overview

At the start of the mission, two USGS Landsat 7 Level 1 product generation systems, LPGS and NLAPS, were available to create products from ETM+ data that were similar but not identical. LPGS products were ordered through the EOS Data Gateway while EarthExplorer was used to order NLAPS products. Users of data acquired prior to 2004 should be aware of the following differences.

E.2 Scaling

After radiometric correction, the LPGS system scales the output values of the ETM+ 1G image data within the range of 1-255. The zero value is reserved for fill data. NLAPS, prior to April 5, 2004, scaled the 1G image data from 0-255 and also used 0 for fill data. After this date, NLAPS processing was changed so that all post April 5, 2004 ETM+ L1G data scales from 1-255 match LPGS processing (the output scale for TM and MSS processing remains unchanged (0-255)). This change was made to assist in identifying the potential gaps for SLC-off products. Users must be cognizant of which system was used and the date of processing if a conversion back to radiance is desired.

E.3 Gain Change Scenes

Earlier, it was reported that the LPGS and NLAPS have different scaling procedures for scenes with gain state changes. This is not the case. Both systems always utilized the low gain LMAX value when scaling the radiance of a scene. LPGS continues to utilize this value as gain settings have changed with modifications to the LTAP.

E.4 Edge Trimming

The two systems also treat the scene scan line edges differently. NLAPS trims the band offsets while LPGS does not. This distinguishing characteristic (see Figure E-1) can be used when the processing system origin is unknown.

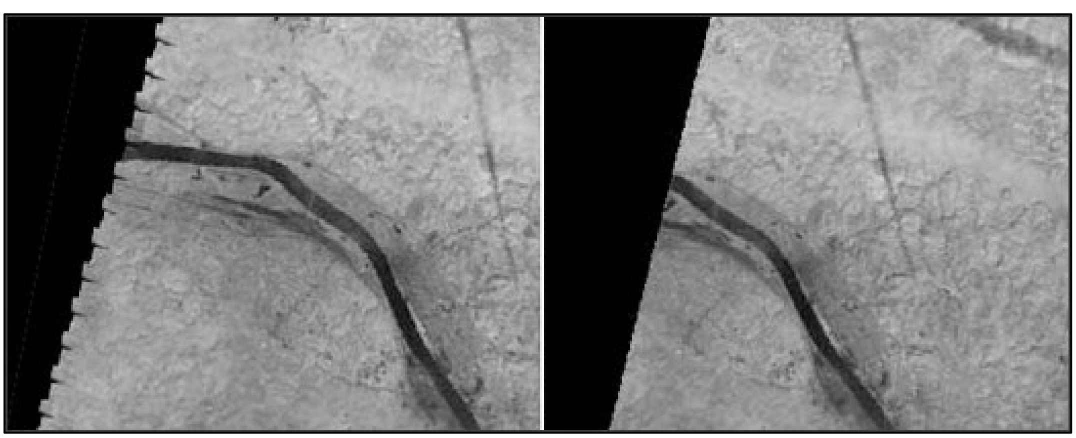

Figure E-1. LPGS (left) Did Not Trim Scan Edges Like NLAPS (right)

E.5 Map Projection Coordinates

The two systems also used slightly different output projection pixel placement schemes. LPGS products continue to have map coordinates that are pixel center based. NLAPS coordinates assigned coordinates to the upper left corner. These differences are illustrated in Figure E-2 where the upper left corner pixel is depicted for all three ETM+ band resolutions.

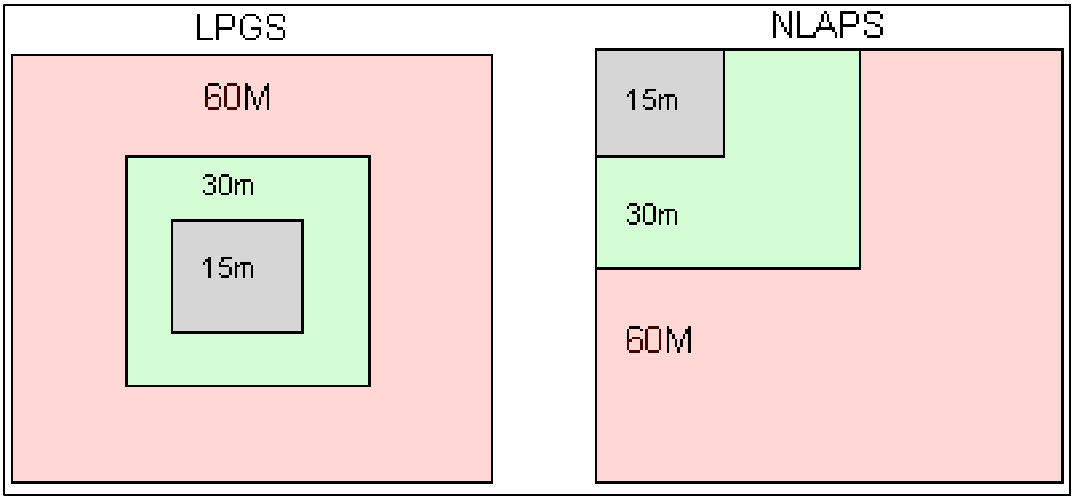

Figure E-2. Illustration of Upper Left Corner Pixel Alignment for LPGS vs. NLAPS L1G Products

E.6 GeoTIFF Header

There is also a difference in the TIFF header for GeoTIFF formatted products. Both systems have the *BitsPerSample* tag set to 8. The NLAPS product also had the *SampleFormat* tag set to an unsigned integer format. The LPGS does not use the *SampleFormat* tag for its GeoTIFF formatted products.

E.7 GXA Slewing

Data anomalies that manifest as scan line offsets can occur when the GXA is redirected from one ground station to another. Level 1 processing algorithms attempt to correct this problem but are not always successful. When not, LPGS estimates an End-of-Line (EOL) and processes the damaged scans. The scans will be offset but available. NLAPS assumes an absent EOL means no data and zero fills the affected scans.

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EarthExplorer Registration: https://ers.cr.usgs.gov/register/

GloVis Tutorial: https://lta.cr.usgs.gov/GloVisHelp/glovis_help

Landsat Data Product information: https://www.usgs.gov/land-resources/nli/landsat/product-information

Landsat 7 ETM+ Level 1 Product Data Format Control Book (DFCB)

Landsat 7 Gap Phase Statistics Algorithm Theoretical Basis Document (ATBD)

Landsat 7 Calibration Parameter File (CPF) Definition Document

Landsat 7 IAS Geometric Algorithm Theoretical Basis Document (ATBD)

Landsat Bumper Mode Scan Mirror Correction Algorithm Theoretical Basis Document (ATBD)

Landsat 7 Enhanced Thematic Mapper Plus (ETM+) Calibration Notices

Landsat 7 Overview

Documents pertaining to the Landsat 7 mission and data products can be found on https://www.usgs.gov/land-resources/nli/landsat/landsat-project-documents.

Contact USGS Landsat User Services with any questions regarding these interfaces or Landsat data products, M-F 8:00 am to 4:00 p.m. CT:

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