

The next Landsat satellite: The Landsat Data Continuity Mission
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Popular Summary

The Landsat program is one of the longest running satellite programs for Earth observations from space. The program was initiated by the launch of Landsat 1 in 1972. Since then a series of six more Landsat satellites were launched and at least one of those satellites has been in operations at all times to continuously collect images of the global land surface. The Department of Interior (DOI) U.S. Geological Survey (USGS) preserves data collected by all of the Landsat satellites at their Earth Resources Observation and Science (EROS) Center in Sioux Falls, South Dakota. This 40-year data archive provides an unmatched record of the Earth's land surface that has undergone dramatic changes in recent decades due to the increasing pressure of a growing population and advancing technologies. EROS provides the ability for anyone to search the archive and order digital Landsat images over the internet for free. The Landsat data are a public resource for observing, characterizing, monitoring, trending, and predicting land use change over time providing an invaluable tool for those addressing the profound consequences of those changes to society.

The most recent launch of a Landsat satellite occurred in 1999 when Landsat 7 was placed in orbit. While Landsat 7 remains in operation, the National Aeronautics and Space Administration (NASA) and the DOI / USGS are building its successor satellite system currently called the Landsat Data Continuity Mission (LDCM). NASA has the lead for building and launching the satellite that will carry two Earth-viewing instruments, the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). The OLI will take images that measure the amount of sunlight reflected by the land surface at nine wavelengths of light with three of those wavelengths beyond the range of human vision. TIRS will collect coincident images that measure light emitted by the land surface as a function of surface temperature at two longer wavelengths well beyond the range of human vision. The DOI/USGS is developing the ground system that will command and control the LDCM satellite in orbit and manage the OLI and TIRS data transmitted by the satellite. DOI / USGS will thus operate the satellite and collect, archive, and distribute the image data as part of the EROS archive. DOI/USGS has committed to renaming LDCM as Landsat 8 following launch. By either name the satellite and its sensors will extend the 40-year archive with images sufficiently consistent with data from earlier Landsat satellites to allow multi-decadal, broad-area studies of our dynamic landscapes. The next Landsat satellite and ground system are on schedule for a January, 2013 launch.



The next Landsat satellite: The Landsat Data Continuity Mission

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ABSTRACT

The National Aeronautics and Space Administration (NASA) and the Department of Interior United States Geological Survey (USGS) are developing the successor mission to Landsat 7 that is currently known as the Landsat Data Continuity Mission (LDCM). NASA is responsible for building and launching the LDCM satellite observatory, USGS is building the ground system and will assume responsibility for satellite operations and for collecting, archiving, and distributing data following launch. The observatory will consist of a spacecraft in low-Earth orbit with a two-sensor payload. One sensor, the Operational Land Imager (OLI), will collect image data for nine shortwave spectral bands over a 185 km swath with a 30 m spatial resolution for all bands except a 15 m panchromatic band. The other instrument, the Thermal Infrared Sensor (TIRS), will collect image data for two thermal bands with a 100 m resolution over a 185 km swath. Both sensors offer technical advancements over earlier Landsat instruments. OLI and TIRS will coincidentally collect data and the observatory will transmit the data to the ground system where it will be archived, processed to Level 1 data products containing well calibrated and co-registered OLI and TIRS data, and made available for free distribution to the general public. The LDCM development is on schedule for a December 2012 launch. The USGS intends to rename the satellite "Landsat 8" following launch. By either name a successful mission will fulfill a mandate for Landsat data continuity. The mission will extend the almost 40-year Landsat data archive with images sufficiently consistent with data from the earlier missions to allow long-term studies of regional and global land cover change.

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1. Introduction

The National Aeronautics and Space Administration (NASA) and the Department of Interior (DOI) United States Geological Survey (USGS) will build, launch, and operate the next Landsat satellite through a cooperative effort called the Landsat Data Continuity Mission (LDCM). NASA leads the development and launch of the satellite observatory consisting of the spacecraft and its sensor payload. USGS leads the development of the ground system and will assume responsibility for satellite operations following launch and an initial on-orbit checkout period. The LDCM is the follow-on mission to Landsat 7 and USGS has committed to christening the LDCM observatory as Landsat 8 once it has achieved orbit and begun nominal operations. This paper will use the current "LDCM" designation to refer to the satellite subsystems and readers are reminded here that "LDCM" and "Landsat 8" refer to the same satellite and may be used interchangeably in other papers and references.

We describe here the LDCM satellite system currently in development including the mission operations concept, the two-sensor payload, the spacecraft, the launch vehicle, and the ground system. The description includes discussions of requirements and specifications along with a presentation of some initial pre-launch test data for sensor performance. Additionally, we describe the planned LDCM data products that will be available to the public for free. This development is on schedule for a December 2012 launch with nominal system operations beginning in early 2013.

2. Background

2.1. Implementation strategy

The current development of the LDCM satellite system represents the third mission implementation strategy attempted by NASA and USGS. The Land Remote Sensing Policy Act of 1992 (U.S. Code Title 15, Chapter 82) directed the federal agencies involved in the Landsat program to study options for a successor mission to Landsat 7, ultimately launched in 1999 with a five-year design life, that maintained data continuity with the Landsat system. The Act further expressed a preference for the development of this successor system by the private sector as long as such a development met the goals of data continuity.

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In accordance with this guidance, NASA and USGS initially attempted to form a public–private partnership where the U.S. Government would procure data meeting continuity requirements from a privately owned and operated satellite. Following system formulation studies, NASA released a request for proposals (RFP) in January 2003 soliciting a private sector partner to share the risk and cost of system development in return for ownership of the satellite and data sales to the U.S. Government. NASA in consultation with the USGS subsequently declined to accept any of the proposals submitted in response to the RFP and canceled the solicitation in November 2003. NASA concluded that the proposals failed to meet the objective of forming a fair and equitable partnership leading to a reduction in the Government's cost for acquiring Landsat data. NASA and USGS adopted the name "Landsat Data Continuity Mission" for this initial implementation approach and the name has persisted to the subsequent strategies.

The Executive Office of the President convened an interagency working group in the wake of the solicitation termination to identify other options for LDCM implementation. An August 2004 memorandum from the Office of Science and Technology Policy (OSTP) directed NASA to implement the group's recommendation to incorporate Landsat-type sensors on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) satellite platforms (Marburger, 2004). The group's intent was to transition the Landsat land observation program from the NASA research and development environment to the operational environment envisioned for the NPOESS program. NASA began working with the NPOESS Integrated Program Office to specify requirements for a Landsat-type sensor, labeled the Operational Land Imager (OLI), and to identify the necessary accommodations aboard the NPOESS spacecraft. The technical and programmatic challenges of integrating a moderate resolution Landsat sensor onto a spacecraft already designed for a crowded payload of coarser resolution sensors soon became apparent. Recognition of these challenges and the impact on both the LDCM and NPOESS projects led to a final change in the LDCM strategy.

A second OSTP memorandum dated December 23, 2005 superseded the 2004 memorandum and directed NASA and the USGS to implement LDCM as a single "free-flyer" satellite (Marburger, 2005). The "free-flyer" designation provided guidance for the development and operation of a satellite system exclusively to meet LDCM requirements. NASA and USGS have since worked to implement this third strategy by developing the system described here. The strategic changes have delayed the LDCM launch to a point more than seven years past the five-year design life of Landsat 7.

2.2. LDCM requirements

The basic LDCM requirements remained consistent through the extended strategic formulation phase of mission development. The 1992 Land Remote Sensing Policy Act (U.S. Code Title 15, Chapter 82) established data continuity as a fundamental goal and defined continuity as providing data "sufficiently consistent (in terms of acquisition geometry, coverage characteristics, and spectral characteristics) with previous Landsat data to allow comparisons for global and regional change detection and characterization." This direction has provided the guiding principal for specifying LDCM requirements from the beginning with the most recently launched Landsat satellite, Landsat 7, serving as a technical minimum standard for system performance and data quality.

The 1992 Land Remote Sensing Policy Act (U.S. Code Title 15, Chapter 82) also transferred responsibility for Landsat 7 development from the private sector to the U.S. Government. An October 2000 amendment to a 1994 Presidential Decision Directive (Executive Office of the President, 2000) ultimately assigned Landsat 7 responsibility to NASA and USGS as an interagency partnership. NASA and USGS established several new practices for Landsat 7 to better serve the public relative to earlier Landsat missions (Irons & Masek,

2006). These practices included rigorous in-orbit calibration and performance monitoring of the Landsat 7 sensor, the Enhanced Thematic Mapper-Plus (ETM+), the systematic scheduling and collection of images providing coverage of the global land surface at least once per season, and the distribution of data products at a lower cost leading eventually to the current policy of distributing Landsat data for free. The interagency partnership persists intact for the LDCM and the partnership has propagated forward the practices established for Landsat 7 to the LDCM requirements.

The highest-level LDCM requirements, referred to as Level 1 requirements by NASA, are now captured in an internal NASA document called the "Earth Systematic Missions Program Plan." This Plan states the mission objectives as follows:

- collect and archive moderate-resolution, reflective multispectral image data affording seasonal coverage of the global land mass for a period of no less than five years;
- collect and archive moderate-resolution, thermal multispectral image data affording seasonal coverage of the global land mass for a period of no less than three years;
- ensure that LDCM data are sufficiently consistent with the data from the earlier Landsat missions, in terms of acquisition geometry, calibration, coverage characteristics, spectral and spatial characteristics, output product quality, and data availability to permit studies of land cover and land use change over multi-decadal periods;
- and distribute standard LDCM data products to users on a nondiscriminatory basis and at no cost to the users.

The plan goes on to specify baseline science requirements for LDCM data including the number of images collected per day, the spectral bands, the spatial resolution for each band, and the quality and characteristics of the LDCM standard data products. These objectives and requirements all flow down to lower-level specifications for the LDCM subsystems and will be discussed further below.

2.3. LDCM management

NASA and USGS have well defined roles and responsibilities for the mission. NASA leads the development of the LDCM spacecraft and its sensor payload and is responsible for the launch. NASA also leads mission system engineering for the entire system and therefore acts as the system integrator with responsibility for mission assurance efforts through an on-orbit check out period. The NASA Associate Administrator for the Science Mission Directorate (SMD) has delegated program management responsibility through the Earth Science Division within SMD to the Earth Systematic Mission Program Manager at NASA Goddard Space Flight Center (GSFC). Program management has assigned responsibility for technical implementation to the LDCM Project Office in the Flight Projects Directorate at GSFC.

USGS leads the development of the ground system, excluding development of one ground element under NASA management, and will take responsibility for LDCM mission operations after completion of the on-orbit checkout period. Mission operations will include the scheduling of data collection along with receiving, archiving and distributing LDCM data. The USGS Director for Climate and Land-Use Change leads USGS program management for LDCM through the Land Remote Sensing Program. Responsibility for ground system implementation and LDCM operations is assigned to the USGS Earth Resources Observation and Science (EROS) Center. EROS maintains the U.S. archive of data from all of the previous Landsat satellites.

3. LDCM system overview and mission operations concept

3.1. System overview

Following launch, the LDCM satellite system will consist of two major segments: the observatory and the ground system. The observatory

consists of the spacecraft bus and its payload of two Earth observing sensors, the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). OLI and TIRS will collect the LDCM science data. The two sensors will coincidentally collect multispectral digital images of the global land surface including coastal regions, polar ice, islands, and the continental areas. The spacecraft bus will store the OLI and TIRS data on an onboard solid-state recorder and then transmit the data to ground receiving stations.

The ground system will provide the capabilities necessary for planning and scheduling the operations of the LDCM observatory and the capabilities necessary to manage the science data following transmission from the spacecraft. The real-time command and control sub-system for observatory operations is known as the Mission Operations Element (MOE). A primary and back-up Mission Operations Center (MOC) will house the MOE with the primary MOC residing at NASA GSFC. A Data Processing and Archive System (DPAS) at EROS will ingest, process, and archive all LDCM science and mission data returned from the LDCM observatory. The DPAS also provides a public interface to allow users to search for and receive data products over the internet. The DPAS will become an integral part of the USGS Landsat data archive system.

3.2. Mission operations concept

The fundamental LDCM operations concept is to collect, archive, process, and distribute science data in a manner consistent with the operation of the Landsat 7 satellite system. To that end, the LDCM observatory will operate in a 716 km near-circular, near-polar, sun-synchronous orbit (728 km apogee, 704 km perigee, 705 km altitude at the equator). The observatory will have a 16-day ground track repeat cycle with an equatorial crossing at 10:00 a.m. (± 15 min) mean local time during the descending node of each orbit. In this orbit, the LDCM observatory will follow a sequence of fixed ground tracks (also known as paths) defined by the second Worldwide Reference System (WRS-2). WRS-2 is a path/row coordinate system used to catalog the image data acquired from the Landsat 4, Landsat 5, and Landsat 7 satellites. These three satellites have all followed the WRS-2 paths and all of the science data are referenced to this coordinate system. Likewise, the LDCM science data will be referenced to the WRS-2 as part of the ground processing and archiving performed by the DPAS (Irons & Dwyer, 2010). The LDCM launch and initial orbit adjustments are planned to place the observatory in an orbit close to

Landsat 5 providing an eight-day offset between Landsat 7 and LDCM coverage of each WRS-2 path.

OLI and TIRS will collect the LDCM science data on orbit. The MOC will send commands to the satellite once every 24 h via S-band communications from the Ground Network Element (GNE) within the ground system (Fig. 1) to schedule daily data collections. A Long Term Acquisition Plan (LTAP-8) will set priorities for collecting data along the WRS-2 ground paths covered in a particular 24-hour period. LTAP-8 will be modeled on the systematic data acquisition plan developed for Landsat 7 (Arvidson et al., 2006). OLI and TIRS will collect data jointly to provide coincident images of the same surface areas. The MOC will nominally schedule the collection of 400 OLI and TIRS scenes per day where each scene is a digital image covering a 185-by-180 km surface area. The objective of scheduling and data collection will be to provide near cloud-free coverage of the global land-mass each season of the year.

The LDCM observatory will initially store OLI and TIRS data on board in a solid-state recorder. The MOC will command the observatory to transmit the stored data to the ground via an X-band data stream from an all-earth omni antenna. The LDCM GNE will receive the data at several stations and these stations will forward the data to the DPAS at EROS. In addition, data will be transmitted directly from the observatory to a network of international stations operated under the sponsorship of foreign governments referred to as International Cooperators (ICs). Data management and distribution by the ICs will be in accordance with bilateral agreements between each IC and the U.S. Government.

The DPAS will ingest, store, and archive the data received from the GNE and will also generate LDCM data products for distribution. The DPAS will merge the OLI and TIRS data for each WRS-2 scene to create a single product containing the data from both sensors. The data from both sensors will be radiometrically corrected and co-registered to a cartographic projection with corrections for terrain distortion to create a standard orthorectified digital image called the Level 1T product. The interface to the LDCM data archive is called the User Portal and it will allow anyone in the general public to search the archive, view browse images, and request data products that will be distributed electronically through the internet for no charge.

4. The Earth observing sensors

The OLI and TIRS represent an evolution in Landsat sensor technology. All earlier Landsat sensors (with the exception of the little-

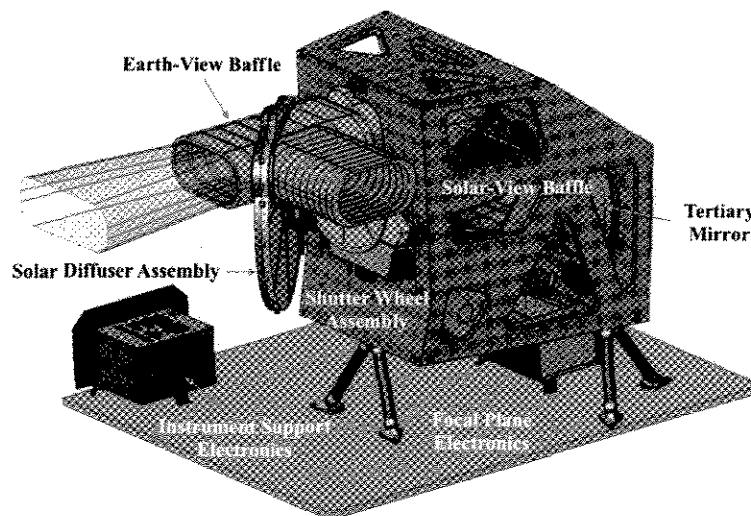


Fig. 1. Drawing of the Operational Land Imager (Courtesy of Ball Aerospace & Technologies Corporation).

used Return Beam Vidicon sensors aboard the first three Landsat satellites), the Multispectral Scanner System (MSS) instruments, the Thematic Mapper (TM) sensors, and the ETM+, were “whiskbroom” imaging radiometers that employed oscillating mirrors to scan detector fields of view cross-track to achieve the total instrument fields of view. In contrast, both OLI and TIRS use long, linear arrays of detectors aligned across the instrument focal planes to collect imagery in a “push broom” manner. This technical approach offers both advantages and challenges as shown by a “push broom” sensor called the Advanced Land Imager (ALI) flown on the Earth Observing-1 satellite (Ungar et al., 2003), a technology demonstration mission. The major advantage of the push broom design is improved signal-to-noise performance relative to a “whiskbroom” sensor. The challenges include achieving spectral and radiometric response uniformity across the focal plane with the attendant need to cross-calibrate thousands of detectors per spectral band. Co-registration of the data from multiple spectral bands also presents some difficulty.

4.1. The Operational Land Imager (OLI)

NASA released an RFP in January 2007 for an OLI to acquire visible, near infrared, and short wave infrared image data from an LDCM spacecraft. The RFP specified instrument performance rather than a specific technology although the specifications were informed by the performance of the ALI push broom sensor. NASA awarded a contract to Ball Aerospace & Technologies Corporation (BATC) in July 2007 after an evaluation of proposals. BATC conducted a successful OLI critical design review in October 2008, and proceeded to instrument assembly, integration, and test. The OLI has completed environmental testing and is scheduled to ship in August 2011 for integration onto the LDCM spacecraft. Environmental testing included vibration tests to ensure that the instrument will survive launch, electromagnetic compatibility and electromagnetic interference testing to ensure that the instrument neither causes nor is susceptible to electromagnetic disturbances, and thermal balance and thermal cycling in a thermal vacuum chamber to verify thermal control performance and to ensure that the sensor can endure the space environment.

4.1.1. OLI requirements

The OLI requirements specified a sensor that collects image data for nine spectral bands with a spatial resolution of 30 m (15 m panchromatic band) over a 185 km swath from the nominal 705 km LDCM spacecraft altitude. Key requirements include: a five-year design life; spectral band widths, center wavelengths, and cross-track spectral uniformity; radiometric performance including absolute calibration uncertainty, signal-to-noise ratios, polarization sensitivity, and stability; ground sample distances and edge response; image geometry and geolocation including spectral band co-registration; and the delivery of data processing algorithms.

The OLI is required to collect data for all of the ETM+ shortwave bands to partially fulfill the data continuity mandate. Table 1 provides the specified spectral bandwidths in comparison to the ETM+ spectral bands along with the required ground sample distances (GSDs). The widths of several OLI bands are refined to avoid atmospheric absorption features within ETM+ bands. The biggest change occurs in OLI band 5 (0.845–0.885 μm) to exclude a water vapor absorption feature at 0.825 μm in the middle of the ETM+ near infrared band (band 4; 0.775–0.900 μm). The OLI panchromatic band, band 8, is also narrower relative to the ETM+ panchromatic band to create greater contrast between vegetated areas and surfaces without vegetation in panchromatic images. Additionally, two new bands are specified for the OLI; a blue band (band 1; 0.433–0.453 μm) principally for ocean color observations in coastal zones and a shortwave infrared band (band 9; 1.360–1.390 μm) that falls over a strong water vapor absorption feature and will allow the detection of cirrus clouds within OLI images (cirrus clouds will appear bright while most land surfaces

Table 1

OLI and ETM+ spectral bands.

OLI spectral bands			ETM+ spectral bands		
#	Band width (μm)	GSD (m)	#	Band width (μm)	GSD (m)
1	0.433–0.453	30	1	0.450–0.515	30
2	0.450–0.515	30	2	0.525–0.605	30
3	0.525–0.600	30	3	0.630–0.690	30
4	0.630–0.680	30	4	0.775–0.900	30
5	0.845–0.885	30	5	1.550–1.750	30
6	1.560–1.660	30	7	2.090–2.350	30
7	2.100–2.300	30	8	0.520–0.900	30
8	0.500–0.680	15			
9	1.360–1.390	30			

will appear dark through cloud-free atmospheres containing water vapor). Note that the refined near-infrared band (band 5) and the new shortwave infrared band (band 9) both closely match spectral bands collected by the MODerate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites. Note also that the OLI band widths are required to remain within plus-or-minus 3% of the specified band widths across the field-of-view.

NASA placed stringent radiometric performance requirements on the OLI. The OLI is required to produce data calibrated to an uncertainty of less than 5% in terms of absolute, at-aperture spectral radiance and to an uncertainty of less than 3% in terms of top-of-atmosphere spectral reflectance for each of the spectral bands in Table 1. These values are comparable to the uncertainties achieved by ETM+ calibration. The OLI signal-to-noise ratio (SNR) specifications, however, were set higher than ETM+ performance based on results from the ALI. Table 2 lists the OLI specifications next to ETM+ performance (Markham et al., 2003) for ratios at specified levels of typical, L_{typ} , and high, L_{high} , spectral radiance for each spectral band. Commensurate with the higher ratios, OLI will quantize data to 12 bits as compared to the eight-bit data produced by the TM and ETM+ sensors.

4.1.2. OLI design

The OLI is a push broom sensor employing a focal plane with long arrays of photosensitive detectors (Irons & Dwyer, 2010). A four-mirror anastigmatic telescope focuses incident radiation onto the focal plane while providing a 15-degree field-of-view covering a 185 km across-track ground swath from the nominal LDCM observatory altitude (Fig. 1). Periodic sampling of the across-track detectors as the observatory flies forward along a ground track forms the multispectral digital images. The detectors are divided into 14 modules arranged in an alternating pattern along the centerline of the focal plane (Fig. 2). Data are acquired from nearly 7000 across-track detectors for each spectral band with the exception of the 15 m panchromatic band that requires over 13,000 detectors. The spectral differentiation is achieved by interference filters arranged in a “butcher-block” pattern over the detector arrays in each module. Silicon PIN (SiPIN) detectors collect

Table 2

Specified OLI signal-to-noise ratios (SNR) compared to ETM+ performance.

OLI band	L_{typical} SNR		L_{high} SNR	
	ETM+ performance	OLI requirements	ETM+ performance	OLI requirements
1	N/A	130	N/A	290
2	40	130	140	360
3	41	100	186	390
4	28	90	140	340
5	35	90	244	460
6	36	100	183	540
7	29	100	137	510
8	16	80	90	230
9	N/A	50	N/A	N/A

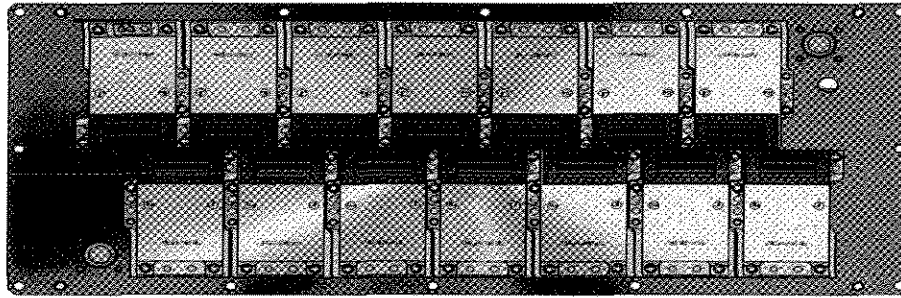


Fig. 2. Drawing of the OLI focal plane (Courtesy of Ball Aerospace & Technologies Corporation).

the data for the visible and near-infrared spectral bands (Bands 1 to 4 and 8) while Mercury–Cadmium–Telluride (MgCdTe) detectors are used for the shortwave infrared bands (Bands 6, 7, and 9).

The OLI telescope will view the Earth through a baffle extending beyond the aperture stop. A shutter wheel assembly sits between the baffle and the aperture stop. A hole in the shutter wheel will allow light to enter the telescope during nominal observations and the wheel will rotate when commanded to a closed position and act as a shutter preventing light from entering the instrument. A second baffle, for solar views, intersects the Earth-view baffle at a 90° angle and a three-position diffuser wheel assembly dissects the angle. A hole in the diffuser wheel allows light to enter the telescope for nominal Earth observations. Each of the other two wheel positions introduces one of two solar diffuser panels to block the optical path through the Earth-view baffle. When the wheel is in either of these two positions, the solar-view baffle will be pointed at the sun and a diffuser panel will reflect solar illumination into the telescope. One position will hold a “working” panel that will be exposed regularly to sunlight while the other position will hold a “pristine” panel that will be exposed infrequently and used to detect changes in the “working” panel spectral reflectance due to solar exposure. Additionally, two stimulation lamp assemblies will be located just inside the telescope on the aperture stop. The two assemblies will each hold six small lamps inside an integrating hemisphere and will be capable of illuminating the full OLI focal plane through the telescope with the shutter closed. These assemblies, the shutter wheel, diffuser wheel, and stimulation lamp assemblies, constitute the OLI calibration sub-system and their use for calibration is discussed further below.

4.1.3. Pre-launch OLI performance

BATC has conducted robust testing of OLI performance in accordance with their proposal and contract. These prelaunch tests

indicate that OLI performance meets specification with requirements exceeded in most cases. Figs. 3 and 4, for example, show SNRs derived from data collected by the OLI while illuminated by known spectral radiance from an integrating sphere traceable to National Institute of Standards and Technology sources. The OLI was operating within a thermal-vacuum chamber in a space-like environment when the data were collected. The observed SNRs are substantially greater than the required SNRs for all spectral bands at both typical, L_{typ} , and high, L_{high} , levels of spectral radiance.

As another example, Fig. 5 shows relative spectral response curves for OLI band 5, the near-infrared band, for each of the focal plane modules. The test data were collected with the OLI in the thermal-vacuum chamber and illuminated by narrow-band radiation from a double-monochromator. The plot indicates that the OLI meets band 5 specifications for band width, band center, spectral flatness, and spectral uniformity across the focal plane. Test data show that these specifications were met for all of the spectral bands.

4.2. The Thermal Infrared Sensor (TIRS)

Thermal imaging was initially excluded from the LDCM requirements in a departure from the data continuity mandate. Several earlier Landsat satellites collected data for a thermal spectral band in addition to data for shortwave spectral bands. The MSS on Landsat 3 collected data for a single thermal band with a 240 m spatial resolution (these data were not extensively used due to performance problems), the TM sensors on Landsat 4 and Landsat 5 collected a single band of thermal data with a 120 m resolution, and the ETM+ on Landsat 7 continues to collect thermal data for a single band with a 60 m resolution.

The benefits of thermal images were not deemed worth the cost of the capability in the early LDCM formulation efforts. Potential private sector partners did not see a sufficient return on investment during

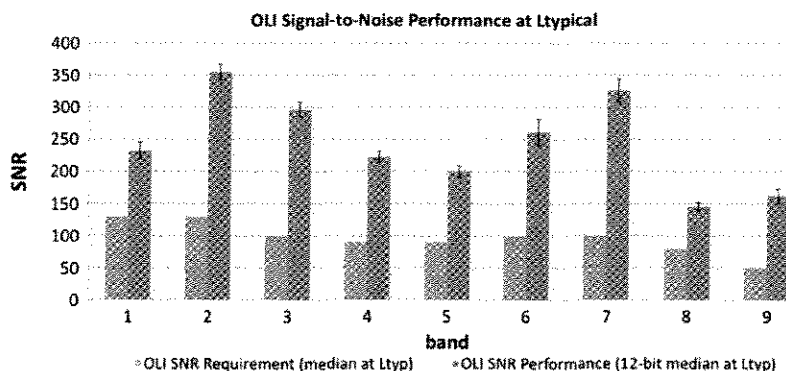


Fig. 3. OLI prelaunch signal-to-noise ratio (SNR) performance at L_{typ} . Red bars show measured SNR, blue bars show required SNR.

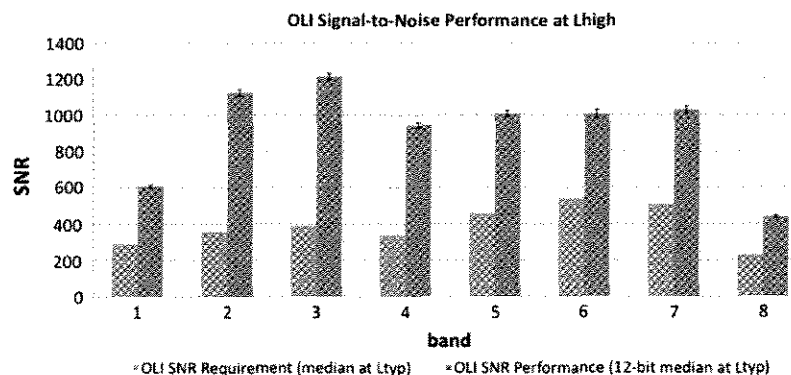


Fig. 4. OLI prelaunch signal-to-noise ratio (SNR) performance at L_{high} . Red bars show measured SNR, blue bars show required SNR.

the attempt to form a public–private LDCM partnership. This perspective persisted during the effort to incorporate Landsat sensors on NPOESS platforms and the NPOESS platform manifest left inadequate space for a separate thermal sensor. Applications of Landsat 5 TM and Landsat 7 ETM+ thermal data, however, began to blossom during this period due to the increased attention to rigorous calibration and to the systematic, reliable collection of data. The application of Landsat data to measuring water consumption over irrigated agricultural fields, in particular, began to emerge as a viable tool for water resources management in the semi-arid western U.S. (Allen et al., 2005). When NASA received direction to implement LDCM as a free-flyer satellite, western state water management agencies led by the Western States Water Council began to advocate for the restoration of thermal imaging to LDCM requirements (Western States Water Council, 2010).

NASA reacted by first procuring a satellite with sufficient space, mass, and power to accommodate the addition of a thermal sensor in a payload with an OLI. Next, NASA Headquarters directed GSFC to conduct instrument concept studies with the goal of defining a thermal sensor that could be built in time to prevent any delay in the December 2012 launch data set for an LDCM satellite carrying only an OLI. GSFC designed the Thermal Infrared Sensor (TIRS) and laid out an accelerated schedule for its development. NASA Headquarters gave approval in December 2009 for GSFC to build TIRS in house and add the sensor to the LDCM payload while holding to the 2012 launch date. The LDCM project offices at both GSFC and EROS are currently meeting the challenge of this late addition with a rapid instrument development effort, spacecraft accommodations for this second sensor, and the ground system modifications necessary to capture, archive, and process TIRS data in conjunction with OLI data.

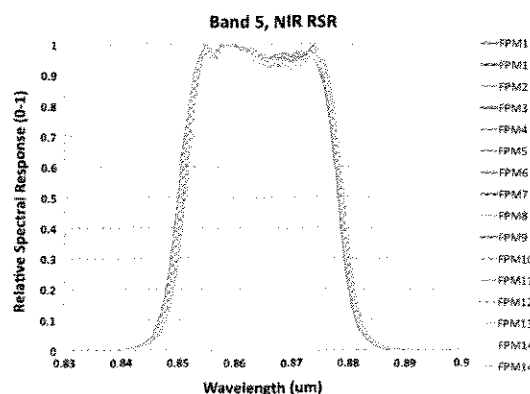


Fig. 5. Relative spectral response curves for each OLI Band 5 focal plane module (FPM).

4.2.1. TIRS requirements

TIRS requirements are specified in a manner similar to the OLI requirements. The specifications require TIRS to collect image data for two thermal infrared spectral bands with a spatial resolution of 120 m across a 185 km swath from the nominal 705 km Landsat altitude (Table 3). The two bands were selected to enable atmospheric correction of the thermal data using a split-window algorithm (Caselles et al., 1998) and represent an advancement over the single-band thermal data collected by previous Landsat satellites (the ETM+ and TM sensors collect data for a 10.0–12.5 μm thermal band). The 120 m spatial resolution is a step back from the 60 m ETM+ thermal band resolution and was specified as a compromise to the necessity of a rapid sensor development. The 120 m resolution is deemed sufficient for water consumption measurements over fields irrigated by center pivot systems (note that the instrument design exceeds requirements with a 100 m spatial resolution). These fields dot the U.S. Great Plains and many other areas across the world as circles 400 m to 800 m in diameter.

Like OLI, the TIRS requirements also specify cross-track spectral uniformity; radiometric performance including absolute calibration uncertainty, polarization sensitivity, and stability; ground sample distances and edge response; image geometry and geolocation including spectral band co-registration. The TIRS noise limits are specified in terms of noise-equivalent-change-in-temperature (NE Δ T) rather than the signal-to-noise ratios used for OLI specifications (Table 4). The radiometric calibration uncertainty is specified to be less than 2% in terms of absolute, at-aperture spectral radiance for targets between 260 K and 330 K (less than 4% for targets between 240 K and 260 K and for targets between 330 K and 360 K).

A major difference between OLI and TIRS specifications is that TIRS requires only a three-year design life. This relaxation was specified to help expedite the TIRS development. The designers were able to save schedule through more selective redundancy in subsystem components rather than the more robust redundancy required for a five-year design life.

4.2.2. TIRS design

Like OLI, TIRS is also a push broom sensor employing a focal plane with long arrays of photosensitive detectors (Fig. 6). A four-element refractive telescope focuses an f/1.64 beam of thermal radiation

Table 3
TIRS spectral bands and spatial resolution (as built).

Band #	Center wavelength (μm)	Minimum lower band edge (μm)	Maximum upper band edge (μm)	Spatial resolution (m)
10	10.9	10.6	11.2	100
11	12.0	11.5	12.5	100

Table 4
TIRS saturation radiance and noise-equivalent-change-in-temperature (NEAT) specifications.

Band #	Saturation temperature	Saturation radiance	NEAT at 240 K	NEAT at 300 K	NEAT at 360 K
10	360 K	20.5 W/m ² sr μ m	0.80 K	0.4 K	0.27 K
11	360 K	17.8 W/m ² sr μ m	0.71 K	0.4 K	0.29 K

onto a cryogenically cooled focal plane while providing a 15-degree field-of-view matching the 185 km across-track swath of the OLI. The focal plane holds three modules with quantum-well-infrared-photodetector (QWIP) arrays arranged in an alternating pattern along the focal plane centerline (Fig. 7). Each module is covered by spectral filters that transmit the two specified band widths. Each QWIP array is 640 detectors long cross-track allowing for overlap between the arrays to produce an effective linear array of 1850 pixels spanning the 185 km ground swath with a 100 m spatial resolution. TIRS will be the first spaceflight instrument to use QWIP arrays. A mirror controlled by a scene select mechanism will flip the field-of-view between nadir (Earth), an internal blackbody, and a deep space view for on-orbit radiometric calibration without changing the nominal earth-viewing attitude of the LDCM spacecraft (Irons & Dwyer, 2010; Montanaro et al., 2011).

A mechanical, two-stage cryocooler (Fig. 8) will cool the focal plane to permit the QWIP detectors to function at a required temperature of 43 K. BATC was selected to build the cryocooler through a competitive proposal process and BATC delivered the cryocooler to GSFC for instrument integration in April 2011. The cryocooler has the same three-year design life as the rest of the instrument. Two radiators will be mounted to the side of the instrument structure, one to dissipate heat from the cryocooler and the other to passively maintain a constant TIRS telescope temperature of 185 K.

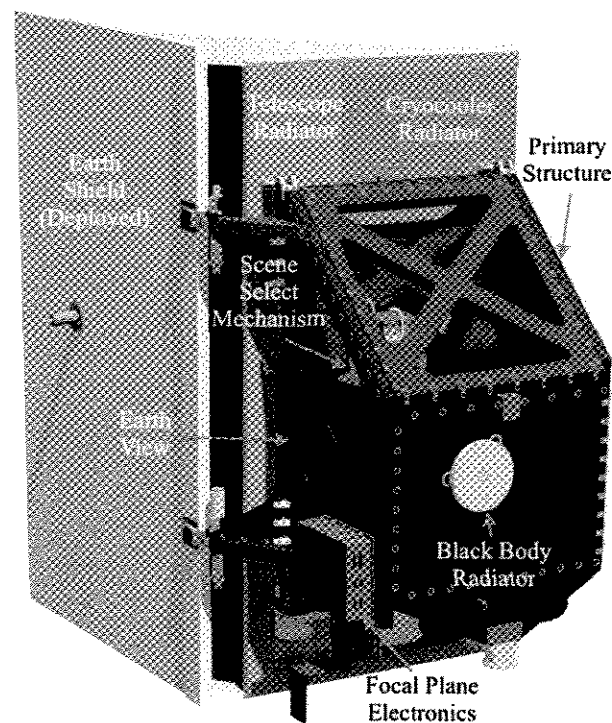


Fig. 6. Drawing of the Thermal Infrared Sensor (TIRS).

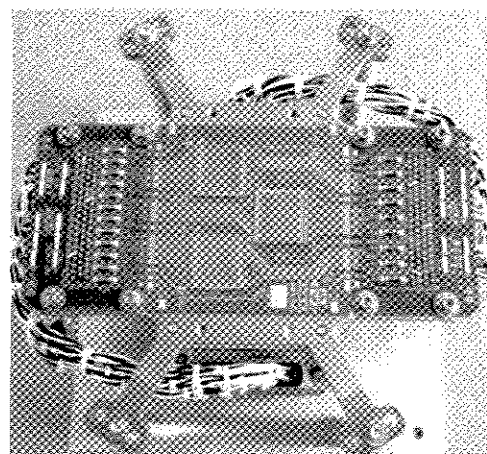


Fig. 7. Photograph of the TIRS focal plane showing the three QWIP detector arrays.

4.2.3. TIRS status

All of the TIRS subsystems have successfully completed environmental testing as of June 2011 and have been delivered to GSFC for integration and test at the assembled instrument level. These subsystems include: the cryocooler; the scene select mechanism; the integrated telescope, focal plane, and focal plane electronics; the main electronics box; harnessing to electrically connect the subsystems; thermal hardware to monitor and maintain instrument temperatures; and the structure that will hold it all together on the spacecraft. The next steps are to integrate these subsystems into the assembled instrument, perform pre-launch calibration and performance characterization, and conduct environmental testing. TIRS is scheduled to ship from GSFC for integration onto the spacecraft in December 2011.

4.3. On-orbit sensor calibration

The LDCM will perform rigorous on-orbit sensor calibrations to monitor the in-flight performance of OLI and TIRS and to develop the requisite radiometric and geometric correction and calibration coefficients for generating the LDCM science data products. Instrument calibration through the operational life of the mission involves observation of the on-board calibration sources augmented by ground-based measurements. The major observations for in-flight calibration data collection are summarized in Table 5.

The calibration observations will be made at different frequencies. The OLI shutter will be closed before the first scheduled Earth imaging interval in an orbit and then again just after the last imaging interval to provide the dark bias in the radiometric responses across the OLI detectors. The OLI stimulation lamps will be turned on once per week with the shutter closed to monitor stability of the OLI radiometric responses to the lamp illumination. Similarly, the TIRS scene select mirror will point the TIRS field of view at deep space once before and once after the Earth imaging portion of each orbit to determine the dark bias in the radiometric responses across the TIRS focal plane. The select mirror will also point the field of view at the TIRS black body after each deep space view to monitor the radiometric response to the radiance emitted from the black body at a known and controlled temperature.

The OLI "working" diffuser panel will be observed once per week and will serve as the primary source for a reflectance-based radiometric calibration of the OLI. The observation will require an LDCM spacecraft maneuver to point the solar-view baffle directly at the sun when the spacecraft is in the vicinity of the northern solar terminus. The solar diffuser wheel will rotate the panel into position to diffusely

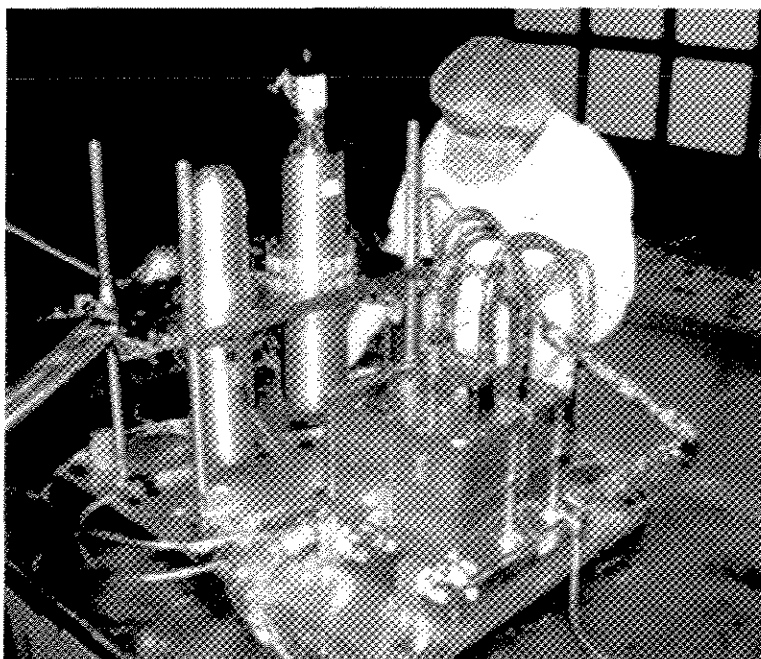


Fig. 8. Photograph of the TIRS cryocooler (courtesy of Ball Aerospace & Technologies Corporation).

reflect the illumination entering the baffle into the telescope. The spectral reflectance of the working and pristine panels will be measured pre-launch and the pristine panel will be observed infrequently to monitor changes to the working panel reflectance.

The LDCM spacecraft will also maneuver once per month to provide the OLI a view of the moon near its full phase during the dark portion of the LDCM orbit. The lunar surface reflectance properties are stable and a number of Earth observing satellites have used the moon as a calibration source. For example, the EO-1 satellite pointed the ALI at the moon for calibration (Kieffer et al., 2003). The USGS Robotic Lunar Observatory in Flagstaff, Arizona provides a model that will be used to predict the lunar brightness for the view and illumination geometries at the times of OLI observations (Kieffer et al., 2003). The OLI lunar data will be used to validate the OLI radiometric calibration.

OLI and TIRS will additionally collect data over a variety of Earth surface calibration sites at irregular intervals. The calibration sites include relatively homogenous sites such as the dry lake playa, Railroad Valley, near Ely, Nevada. Field measurements will be made of surface reflectance and atmospheric conditions as the LDCM passes over such sites to predict the spectral radiance received by the OLI. The predicted radiance will be used to validate OLI radiometric calibration, an approach referred to as vicarious calibration. Likewise, data will be collected over lakes where instrumented buoys measure the surface temperature of the water for the validation of TIRS radiometric

calibration. A comprehensive set of geometric "super" sites will provide a number of ground control points with highly accurate locations and elevations. Images collected over these sites will be used to characterize geometric performance and calibrate the OLI and TIRS lines-of-sight. The sensors on the earlier Landsat satellites and many other Earth observing sensors have collected similar surface observations for calibration.

5. The LDCM spacecraft

NASA awarded a contract for the LDCM spacecraft to General Dynamics Advanced Information Systems (GDAIS) in April 2008. Orbital Science Corporation (Orbital) subsequently acquired the spacecraft manufacturing division of GDAIS in April 2010. Orbital has thus assumed responsibility for the design and fabrication of the LDCM spacecraft bus, integration of the two sensors onto the bus, satellite-level testing, on-orbit satellite check-out, and continuing on-orbit engineering support under GSFC contract management (Irons & Dwyer, 2010). The specified design life is five years with an additional requirement to carry sufficient fuel to maintain the LDCM orbit for 10 years; the hope is that the operational lives of the sensors and spacecraft will exceed the design lives and fuel will not limit extended operations. The spacecraft design calls for a three-axis stabilized vehicle built primarily of aluminum honeycomb structure with a hexagonal cross-section. It is being built in Orbital's spacecraft manufacturing facility in Gilbert, Arizona.

5.1. Spacecraft Design

The spacecraft will supply power, orbit and attitude control, communications, and data storage for OLI and TIRS. The spacecraft consists of the mechanical subsystem (primary structure and deployable mechanisms), command and data handling subsystem, attitude control subsystem, electrical power subsystem, radio frequency (RF) communications subsystem, the hydrazine propulsion subsystem and thermal control subsystem. All the components, except for the propulsion module, will be mounted on the exterior of

Table 5
LDCM on-orbit calibration observations.

Type of calibration observation	Frequency of calibration data collection
Closed OLI shutter	Twice every Earth imaging orbit (approximately every 40 min)
TIRS black body	Twice every Earth imaging orbit
TIRS deep space	Twice every Earth imaging orbit
OLI stimulation lamps	Once per day
OLI solar diffuser panel	Once per week
Lunar	Once per month
Earth surface calibration sites	Variable

the primary structure. A 9×0.4 m deployable solar array will generate power that will charge the spacecraft's 125 amp-hour nickel–hydrogen (Ni–H₂) battery. A 3.14-terabit solid-state data recorder will provide data storage aboard the spacecraft and an earth-coverage X-band antenna will transmit OLI and TIRS data either in real time or played back from the data recorder. The OLI and TIRS will be mounted on an optical bench at the forward end of the spacecraft (Fig. 9).

A successful spacecraft critical design review was held in October 2009. When fully assembled, the spacecraft without the instruments will be approximately 3 m high and 2.4×2.4 m across with a mass of 2071 kg fully loaded with fuel. The spacecraft with its two integrated sensors will be referred to as the LDCM observatory. The observatory is scheduled to ship from the manufacturing facility to the launch site at Vandenberg Air Force Base, California in September 2012.

5.2. On-board data collection and transmission

The LDCM observatory will daily receive a load of software commands transmitted from the ground. These command loads will tell the observatory when to capture, store, and transmit image data from the OLI and TIRS. The daily command load will cover the subsequent 72 h of operations with the commands for the overlapping 48 h overwritten each day. This precaution will be taken to ensure that sensor and spacecraft operations continue in the event of a one or two day failure to successfully transmit or receive commands.

The observatory's Payload Interface Electronics (PIE) will ensure that image intervals are captured in accordance with the daily command loads. The OLI and TIRS will be powered on continuously during nominal operations to maintain the thermal balance of the two instruments. The two sensors' detectors will thus continuously produce signals that are digitized and sent to the PIE at an average rate of 265 megabits per second (Mbps) for the OLI and 26.2 Mbps for TIRS. Ancillary data such as sensor and select spacecraft housekeeping telemetry, calibration data, and other data necessary for image processing will also be sent to the PIE. The PIE will receive the OLI, TIRS, and ancillary data, merge these data into a mission data stream, identify the mission data intervals scheduled for collection, perform a lossless compression of the OLI data (TIRS data will not be compressed) using the Rice algorithm (Rice et al., 1993), and then send the compressed OLI data and the uncompressed TIRS data to the 3.14 terabit solid-state recorder (SSR). The PIE will also identify those image intervals scheduled for real time transmission and will send those data directly to the observatory's X-band transmitter. The International Cooperator receiving stations will only receive real time transmissions and the PIE will also send a copy of these data to the on-board SSR for playback and transmission to the LDCM Ground Network Element (GNE) receiving stations (USGS will capture all of the data transmitted to International Cooperators). Recall that OLI and TIRS will collect data coincidentally and therefore the mission data streams from the PIE will contain both OLI and TIRS data as well as ancillary data.

The observatory will broadcast mission data files from its X-band, earth-coverage antenna. The transmitter will be able to send data to the antenna on multiple virtual channels providing for a total data rate of 384 Mbps. The observatory will transmit real time data, SSR playback data, or both real-time data and SSR data depending on the time of day and the ground stations within view of the satellite. Transmissions from the earth coverage antenna allow a ground station to receive mission data as long as the observatory is within view of the station antenna.

6. The LDCM launch vehicle

The LDCM observatory will launch from Space Launch Complex-3E at Vandenberg Air Force Base aboard an Atlas V 401 launch vehicle built by the United Launch Alliance (ULA). This rocket is an evolved expendable launch vehicle capable of placing a 9370 kg satellite in low-Earth orbit. This capability offers ample mass margin for the LDCM observatory. A 4 m-diameter extended payload fairing will encapsulate the observatory atop the rocket through launch. The NASA Kennedy Space Center selected the Atlas V 401 for LDCM in December 2009.

7. The LDCM ground system

The LDCM ground system will perform two main functions. The first will be to command and control the LDCM observatory in orbit. The second will be to manage the data transmitted from the observatory. The daily software command loads that control the observatory will originate within the LDCM Mission Operations Center (MOC) at GSFC and will be transmitted to the observatory from the antenna of the LDCM Ground Network Element (GNE). The data transmitted by the observatory will be received by the GNE and then sent to the Data Processing and Archive System (DPAS) at EROS. The DPAS will archive the data and produce the LDCM data products distributed for science and applications. USGS manages ground system development and USGS successfully conducted a Ground System critical design review in March 2010.

7.1. The LDCM Mission Operations Center (MOC)

A flight operations team (FOT) will operate two computer systems within the MOC, the Collection Activity Planning Element (CAPE) and the Mission Operations Element (MOE). The CAPE will plan science data collection by building activity requests for the LDCM imaging sensors each day. The MOE will translate the activity requests into software command loads transmitted to the observatory.

The CAPE collection activity requests will include the following: requests supporting the LDCM Long-Term Acquisition Plan-8 (LTAP-8); International Cooperator requests; requests for observations of calibration sites; and special requests. Within the CAPE, LTAP-8 will address the mission objective of providing global coverage of the

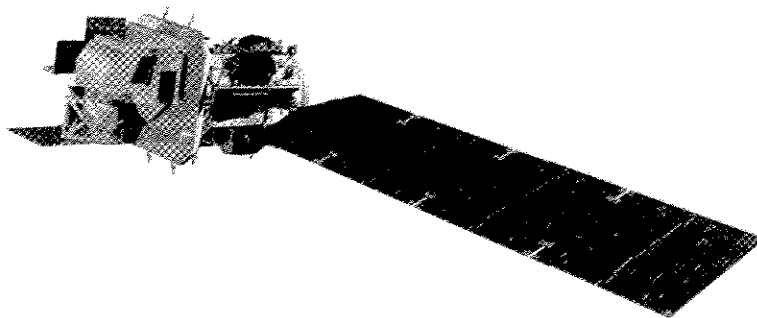


Fig. 9. Drawing of the LDCM Observatory (Courtesy of Orbital Sciences Corporation).

landmass on a seasonal basis. Each day the LTAP-8 will identify the WRS-2 scenes within view of the observatory during the next 72 h. For each of those three days, it will place scenes in a priority order for science data collection. The process will repeat every day with priorities reset for the overlapping 48 h. To set priorities, the LTAP-8 will use historical cloud fraction climatology and daily cloud cover predictions to minimize cloud contamination, will analyze historical records of vegetation indices to identify seasonal windows within which to capture vegetation dynamics, will account for data collection during previous observatory overpasses, and will constrain imaging in high latitude areas to periods of sufficient solar illumination. The LTAP-8 will thus be a daily instantiation of the long-term mission objective.

Special image requests, such as images of natural disasters or images supporting unique science research campaigns, will be forwarded to an LDCM Data Acquisition Manager (DAM) responsible for coordinating and approving special requests. The DAM will designate special requests requiring urgent data distribution (e.g., images supporting emergency response) as priority requests. The DAM will flag priority requests for expedited distribution through the entire image collection and production process.

The CAPE will daily accept the priority list of scenes from the LTAP, factor in special requests and the other requests listed above, incorporate observatory scheduling constraints provided by the MOE, and then generate a scene-based list of images for collection by the imaging sensors over the next 72 h with an average of 400 scenes requested per day. The CAPE will assign a unique identifier (WRS-2 path, row, and date) to each scene or imaging sensor activity in the request. The CAPE will share the identifiers with the MOE and the DPAS so that every individual scene request can be tracked throughout the entire planning, data collection, and data production process.

The CAPE will pass its daily list of scene requests to the MOE where observatory and ground system activities will be planned, coordinated, and scheduled. The MOE will convert requested scenes to imaging intervals; that is, periods of time over which imaging sensor data are collected and stored on the solid state recorder (SSR). Imaging intervals will be assigned a unique identifier and the MOE will maintain a scene to interval mapping table. The MOE will put the imaging interval requests together with health and safety maintenance requirements to generate a daily schedule of observatory activities with health and safety always taking precedence. The MOE will convert the activities schedule to a daily command load transmitted to the observatory through S-band communications from the LDCM GNE. The GNE will consist of three transmission and data receiving stations: one at USGS EROS in Sioux Falls, South Dakota; one at Gilmore Creek, Alaska; and one at Svalbard, Norway.

Initial versions of the CAPE and the MOE have been installed in the MOC. USGS EROS is developing the CAPE. NASA awarded a contract to The Hammers Company, Incorporated in September 2008 to build the MOE. The MOC is currently engaged in a sequence of tests leading to launch readiness. Upgrades and revisions to the CAPE and the MOE will be delivered through the testing process until the full command-and-control capability is in place and proven ready for mission operations. USGS will assume responsibility for MOC operations following the launch and in-orbit check out of the LDCM observatory.

7.2. The LDCM Data Processing and Archive System (DPAS)

The USGS is also developing the DPAS to manage the mission data transmitted from the LDCM observatory. The DPAS will be operated at EROS along with the rest of its Landsat data archive and it will consist of several subsystems: Storage and Archive (SA), Ingest System (IS), Subsetter System (SS), Image Assessment System (IAS), Level 1 Product Generation System (LPGS), and User Portal (UP). These subsystems will work together to ingest, store, and archive LDCM data and will also generate LDCM data products for distribution.

The GNE will send LDCM mission data to EROS over the internet. The Storage and Archive (SA) subsystem will first receive, store, and archive the data in the file-based format received from the GNE. These data will be archived offline with an additional backup copy archived off site. The SA will also perform all archive and storage functions in support of the other DPAS subsystem functions.

The SA will pass data from the GNE to the Ingest System (IS). The IS will process the OLI and TIRS file-based mission data into an interval-based format for the on-line archive and will create the associated inventory metadata. In the process the IS will decompress the OLI data, analyze the data for impulse noise and saturated pixels, fill dropped data, eliminate duplicate data, correct ancillary data, generate metadata, and collect processing metrics. The data in this format will be called Level-0 Reformatted archive (LORa) data. The DPAS will use Hierarchical Data Format 5 (HDF5) for the LORa data with the data grouped in multiple HDF5 files (Folk & Choi, 2004), one file per OLI or TIRS spectral band plus an ancillary data file, metadata file, and checksum file. Each raw 12-bit datum from OLI or TIRS will be stored across two eight-bit bytes. The IS will send the Level 0Ra data files to the SA for online storage. The LORa data will be the format archived for long-term storage and this archive will be part of the USGS National Satellite Land Remote Sensing Data Archive (NSLRSDA).

The Subsetter System (SS) will retrieve LORa data from the SA and subset the OLI and TIRS LORa data into Landsat WRS-2 scenes for distribution or for the generation of Level-1 products and their associated metadata. These scene-based data sets will be called Level-0 Reformatted product (LORp) data and will be stored in the same HDF5 format as LORa data. No data processing will be performed up to this point with the exception of reformatting and filling in dropped data; LORa and LORp data files will contain raw OLI and TIRS data. With the use of 2 B for 12-bit data each uncompressed LDCM LORp data product will consist of 1384 MB for a full WRS-2 scene. In comparison, LDCM ETM+ data products, with 8-bit data stored on single bytes, consist of less than 500 MB per scene. The DPAS will therefore store a daily average of 540 GB of LORp data given an average reception of 400 LDCM scenes per day.

LORp data files will be sent back to the SA for on-line storage and the Level-1 Product Generation System (LPGS) will retrieve each LORp scene to radiometrically and geometrically correct the image data. The radiometric correction will transform raw OLI data to digital counts linearly scaled to top-of-the-atmosphere spectral reflectance and will transform raw TIRS data to digital counts linearly scaled to at-aperture spectral radiance. In both cases the LPGS will scale the raw 12-bit data to 16-bit integers for the Level 1 products.

The geometric correction will use digital elevation models and ground control points to resample the radiometrically corrected data using cubic convolution and create orthorectified images of Earth's surface registered to the Universal Transverse Mercator (UTM) cartographic projection or, in the case of polar scenes, registered to the Polar Stereographic projection. The OLI pixels will be resampled to a 30 m ground sample distance for each spectral band with the exception of the panchromatic band resampled to a 15 m ground sample distance. The TIRS data will be over-sampled from the 100 m sensor resolution to a 30 m ground sample distance for alignment to the OLI data in the final product. The co-registered and terrain corrected OLI and TIRS data will be merged to create a single integrated Level-1 data product.

The LPGS will also generate a full-resolution browse image and a quality assurance band that identifies filled-in pixels, identifies pixels obscured by terrain, and provides a cloud cover mask generated by an automated cloud cover assessment algorithm. The corrected digital images along with metadata and the quality assurance band will be referred to as Level-1T (L1T) data. The L1T data product will consist of a set of uncompressed GeoTiff files for each of the OLI and TIRS spectral bands, a file containing the scene-based metadata, and a file

for the quality assessment band. LPGS will routinely generate a L1T product and a browse image for each of the 400 scenes collected per day.

The Image Assessment System (IAS) will perform OLI and TIRS data characterization, analysis, and trending over the operational life of the mission to monitor LDCM observatory performance and to create the calibration parameters required by the LPGS for Level-1 product generation. Calibration coefficients will initially be derived from pre-launch OLI, TIRS, and integrated observatory testing. The IAS will update coefficients during mission life using on-orbit OLI and TIRS observations of observatory calibration sources, surface calibration sites, and the moon. The IAS will make the calibration coefficients available to accompany requests for LORp data as well as to International Cooperators to help them remain current and consistent with products distributed by the LDCM ground system. The IAS will also manage and update the auxiliary data sets used by the LPGS to create L1T products. These auxiliary data sets include a ground control point library and digital elevation models.

The LORp and L1T WRS-2 scenes will constitute the standard LDCM science data products. The general public will be able to search, browse, and order LORp and L1T scenes from the User Portal (UP) on the internet. The UP will electronically transmit ordered scenes over the internet to LDCM data users at no cost to the users. Access through the UP will be nondiscriminatory and no restrictions will be placed on the use and redistribution of the data.

These subsystems of the DPAS will together orchestrate LDCM data archiving, processing, and distribution to meet key requirements. L1T data product quality requirements include a geolocation uncertainty of less than 12 m circular error, a band-to-band co-registration uncertainty of less than 4.5 m for the OLI spectral bands, a co-registration uncertainty of less than 24 m for the two TIRS spectral bands, and a co-registration uncertainty of less than 30 m between the OLI and TIRS spectral bands where all of these uncertainties are at a 90% confidence level. Ground system performance requirements include the processing of 85% of the LDCM scenes to L1T products within 48 h of data collection by the observatory, the processing of 400 scenes per day to L1T, and distributing 3500 scenes per day by the third year of the mission. Current best estimates indicate that the ground system will be capable of substantially exceeding these performance requirements with a predicted data processing latency of 12 h for 85% of the data, the capacity to process 890 scenes per day, and the ability to distribute 4700 scenes per day.

8. Conclusion

The end result of the LDCM satellite system development and operation will be the archiving and distribution of image data that meet the Landsat data continuity mandate. LDCM data will be comparable to data from the earlier Landsat satellites in terms of spatial resolution, swath width, global geographic coverage, and spectral coverage and this compatibility will allow comparisons to earlier data for land cover change detection and characterization over time. The Landsat satellite system will also offer advancements with respect to refined spectral band widths, two new shortwave spectral bands, two thermal spectral bands rather than one, improved radiometric performance, and a ground system with greater capacities for capturing, archiving, processing, and distributing data. The Landsat data archive managed by USGS provides the longest record of land cover change as viewed from space with almost 40 years of observations. The LDCM will extend that record with well-calibrated data providing global coverage each season of the year.

The LDCM will be the first Landsat satellite launched during an era of free Landsat data distribution by the USGS. The relatively recent deci-

sion to provide data at no cost has fostered rapid advancements in the ability to process and analyze large numbers of Landsat images for long-term and large-scale assessments of change over time. Previously, the high cost of data hindered the development and applications of methodologies for handling such large volumes of Landsat data collected over multiple dates by the different sensors on the Landsat satellite series. Now, the true value of the Landsat program and its data archive is being revealed as researchers and managers begin to put the entire archive to work. A full return on investment in the LDCM requires a continuation of the current data policy so that its data may be added to the analyses and assessments without restriction.

The LDCM development is on schedule for a December 2012 launch. The launch cannot occur too soon. The two Landsat satellites currently remaining in operation, Landsat 5 and Landsat 7, are both well beyond their design lives; Landsat 5 was launched in 1984 with a three-year design life and Landsat 7 was launched in 1999 with a five-year design life. The operations of both are impaired by subsystem degradations and failures due to age. Additionally, land cover and land use are changing at accelerating rates due to population growth and advances in technology. These changes have profound consequences for society with respect to food and fiber production, water resource management, ecosystem services, air and water quality, health, and climate change. Landsat data are critical to characterizing, understanding, trending, and predicting global land cover change and a Landsat data gap would disrupt the time series of observations and impede the ability to monitor the global land surface. A successful LDCM will prevent a data gap and hopefully lead to an operational strategy for the Landsat program with the launch of a follow-on mission coinciding approximately with the end of the LDCM design life.

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