NASA Report to Congress

regarding

Landsat Data Continuity Mission (LDCM) Data Continuity

July 2008

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I. Introduction

The following direction for NASA is included in the Explanatory Statement accompanying the FY 2008 Omnibus Appropriations Act (P.L. 110-161):

> ***"NASA is directed to provide a plan on all continuity of data for the Landsat Data Continuity Mission not later than 120 days after the enactment of this act."***

In response to this direction, this report provides background information on the Landsat series of satellites and addresses the technical and programmatic steps that are in process in order to ensure sufficient continuity of data via the Landsat Data Continuity Mission (LDCM).

For over 35 years, Landsat satellites have been observing the global land surface from space at a scale that enables human land use to be discerned and differentiated from seasonal and climatic changes to land cover. When launched in July 1972, Landsat-1 (initially called the Earth Resources Technology Satellite) was the first and only civilian satellite designed specifically for land observations. A sequence of six more Landsat satellites was subsequently launched, resulting in the uninterrupted collection of land observations from at least one on-orbit Landsat satellite at all times since 1972 (Fig. 1). Data from these satellites are archived by the Department of Interior United States Geological Survey (DOI/USGS) Earth Resources Observation and Science (EROS) Center providing an unparalleled record of global land surface change over three decades. The most recent launch occurred in April 1999, when Landsat 7 was placed in orbit. Both Landsat 5 (launched in 1984 with a three-year design life) and Landsat 7 remain in operation today, despite reduced capabilities resulting from the effects of aging. The major purpose of the LDCM is to extend this land surface record by collecting data that can be compared with the data from the previous Landsat satellites for the detection and characterization of global and regional land cover change.

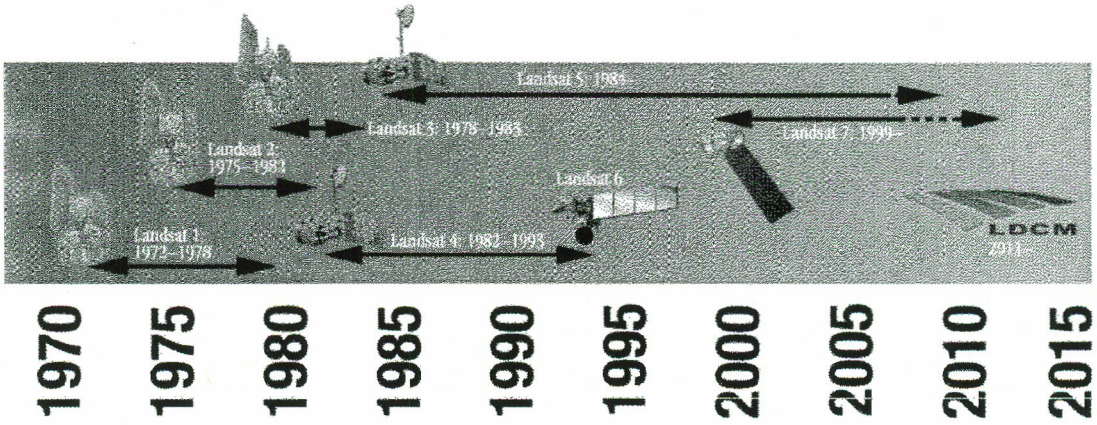


FIGURE-1

II. Historical Background of Landsat Measurements

II A. Strategic Importance

About four billion people subsisted on the Earth's land surface when Landsat 1 was launched in 1972. The population has since grown to 6.6 billion, with a forecast of 9 billion in 2050. As a result, land cover and land use are changing globally at rates unprecedented in human history, with profound consequences for weather and climate change, ecosystem function and services, carbon cycling and sequestration, resource management, the national and global economy, human health, and other societal concerns. Approximately 80 percent of 150 million square-kilometer global land area has been directly disturbed by human use. Landsat is the only U.S. or international satellite system designed and operated to observe the global land surface repeatedly at a moderate scale. Further, Landsat is the only national or international program committed to preserving a consistent, long-term record of the Earth's land surface at this scale. The Director of the Office of Science and Technology Policy expressed the strategic importance of the Landsat program in his August 13, 2004 memorandum on "Landsat Data Continuity Strategy:"

> "*Landsat is a national asset and its data have made – and continue to make – important contributions to U.S. economic, environmental, and national security interests. Specifically, Landsat images are the principal source of global, medium resolution, spectral data used by Federal, state, and local government agencies, academia, and the private sector in land use/land cover change research, economic forecasting, disaster recovery and relief, and the scientific study of human impacts on the global environment. Additionally, Landsat data are utilized by over 70 countries and are an important part of a global, integrated Earth observation system.*

The Congress has further reflected the importance of Landsat in U.S. law and government policy, most notably within the Land Remote Sensing Policy Act of 1992, (P.L. 102-555), which directs the Federal agencies responsible for Landsat management to: "...serve the civilian, national security, commercial, and foreign policy interests of the United States..." and ensure that "...the Landsat system is responsive to the broad interests of the civilian, national security, commercial, and foreign users of the Landsat system..." Furthermore, the Congress declared the following within this law:

> "*The continuous collection and utilization of land remote sensing data from Space are of major benefit in studying and understanding human impacts on the global environment, in managing the Earth's natural resources, in carrying out national security functions, and in planning and conducting many other activities of scientific, economic, and social importance.*"

The importance of preserving and extending this record is further captured in the strategic plans of numerous national and international Earth observation programs,

including the *Science Plan For NASA's Science Mission Directorate 2007 – 2016* and *A Plan for a U.S. National Land Imaging Program*. Other examples include the *Strategic Plan for the U.S. Climate Change Science Program* and the *Strategic Plan for the U.S. Integrated Earth Observation System*. These programs, and many others, have documented the scientific and operational requirements for continuing Landsat observations.

II B. Landsat Sensors and Data

All of the Landsat satellites have carried sensors that collect wide field-of-view images of the Earth's surface. Each of the first three Landsat satellites carried a Remote Beam Vidicon (RBV) camera and an experimental (at that time) instrument called a Multispectral Scanner Subsystem (MSS). The RBV cameras were essentially color television cameras. While these cameras proved unreliable and were little used, the MSS sensors provide unprecedented views of the land surface that found extensive utility over a wide scope of scientific inquiry and land management applications.

The MSS sensors were a type of instrument called an optical-mechanical scanner. These sensors used an oscillating mirror to scan the instrument field-of-view across a 185-kilometer (km) swath along the ground track of the orbiting satellite. The MSS sensors collected image data that resemble the images from today's digital cameras. Digital cameras collect data for three colors--blue, green, and red--that create color pictures when combined. The MSS sensors collected data for four "colors," called spectral bands, where two of the spectral bands encompass longer wavelengths of light that are not visible to the human eye. These wavelengths are called near-infrared and short-wave infrared light. The sun illuminates the Earth at these invisible, longer wavelengths, and images from near-infrared and shortwave-infrared bands reveal features that are not discernable to the naked eye. Healthy vegetation, for example, is highly reflective of near-infrared wavelengths and MSS images proved useful for discriminating between healthy and stressed vegetation.

Both Landsat 4 and Landsat 5, launched in 1982 and 1984, respectively, carried two sensors: an MSS and a more advanced optical-mechanical scanner called a Thematic Mapper (TM). The TM sensors collected data for seven spectral bands, as compared with the four MSS bands. Additionally, the TM sensors provided an improved spatial resolution relative to the MSS instruments. Each picture element (also known as a pixel) in an MSS image represents an 80-by-80 meter (m) surface area, as compared with a TM pixel that represents a 30-by-30 m area. An analogy can be made to the more recent digital cameras on the market that provide more pixels than the earlier models.

Analysts found that TM data significantly improved capabilities for recognizing and mapping land cover types and for detecting land cover change relative to MSS data. Part of the improvement was attributed to better spatial resolution, part was attributed to a more informed selection of spectral bands, and part was due to improved sensor performance resulting from technical advancements. The better spatial resolution and additional spectral bands also significantly increased the volume of digital image data,

and this volume was considered daunting in the 1980's. Many Landsat data users initially preferred to continue using MSS data due to the lower data volumes. These concerns dissipated as computer technology advanced and the TM sensors eventually emerged as the preferred source of land images from Landsat 4 and Landsat 5. Today, the multispectral digital image data from a 185-by-180 km TM scene fits on a single compact disk (CD) and the images can be displayed and analyzed on a desktop computer using commercial-off-the-shelf software.

One of the technical advancements provided by the TM sensors was the collection of image data for a thermal spectral band at a spatial resolution of 120 m. All of the other spectral bands provided by the TM and MSS sensors measure the intensity of solar radiation reflected from the land surface at wavelengths less than 3000 nanometers (nm). The sun illuminates the Earth with light having wavelengths between about 300 nm and 3000 nm (a nanometer is one-billionth of a meter) and the human eye is sensitive to wavelengths between 400 nm and 700 nm. The cooler Earth emits radiation at longer wavelengths beginning beyond 3000 nm. The TM thermal channel is sensitive to wavelengths between 10,000 nm and 12,500 nm and the amount of radiation emitted in this range depends on surface temperature. Images from the TM thermal can therefore be used to map the variation of surface temperature across the landscape. None of the other MSS and TM spectral bands were sensitive to surface temperature.

With the emerging preference for TM data, the next two Landsat satellites, Landsat 6 and Landsat 7, were built to carry single sensors that were close derivatives of the TM design. The Landsat 6 sensor was called the Enhanced Thematic Mapper (ETM). ETM was enhanced by the addition of a panchromatic band sensitive to a broad wavelength range of 520 to 900 nm with 15-m spatial resolution. Data from this band were intended principally for combination with data from the other 30 m spectral bands to make images sharper. The Landsat 7 sensor was called the Enhanced Thematic Mapper – Plus (ETM+). The "plus" refers to an improvement in the ground resolution of the thermal band to 60 m. Landsat 6 failed to achieve orbit when launched in July 1993 (the only Landsat launch failure). Landsat 7 was successfully launched in April, 1999.

All of the Landsat satellites have been launched into orbits that circle the Earth from the North Pole to the South Pole, referred to as circular (constant altitude) polar orbits. Landsat 1, 2, and 3 operated at a 920 km altitude, while Landsat 4, 5, and 7 are at a 705 km altitude. All of the satellites flew from the north to south over the daylight portion of the Earth, and then continued to fly from south to north over the dark side of the Earth on each orbit. This approach brought almost the entire surface of the Earth within view of the sensors during the sunlit portion of the orbit over a period of days (18 days in the case of Landsat 1, 2, and 3; 16 days in the case of Landsat 4, 5, and 7). Further, the orbits have been maintained to trace a consistent, repeated path along the ground during each multiple day period. The ground tracks were designated as numbered "paths," and each Landsat image is centered along a particular path. Consequently, every 18 or 16 days, a Landsat image could be acquired along a particular path allowing for consistent geographic coverage over time.

The numbered orbital paths have been divided into 180 km segments, referred to as "rows." The rows are numbered from north to south and the center of each row is specified by a latitude/longitude coordinate. As Landsat image data are collected along a path and transmitted to a ground receiving station, the data are broken up into 180-km along track segments corresponding to the rows. Consequently, the 185 km cross-track by 180 km along-track image segments constitutes the standard unit of Landsat image data referred to as a "scene." The set of path/row number pairs forms a coordinate system used to catalogue Landsat scenes in data archives. Each Landsat scene is centered on the latitude/longitude coordinate corresponding to the center of a specific row along a particular path.

Landsat 1, 2, and 3, in 920 km orbits, were operated to fly along the same set of ground tracks. The resulting path/row coordinate system is called the World-wide Reference System – One (WRS-1). Landsat 4 flew along a different set of ground tracks due to the change to a 705 km orbital altitude. These new set of paths formed a second path/row coordinate system called the World-wide Reference System – Two (WRS-2), and Landsat 5 and 7 are operated to fly along the paths established by Landsat 4. MSS scenes from Landsat 1, 2, and 3 are therefore catalogued using the WRS-1 path/row coordinates. MSS and TM scenes from Landsat 4 and 5 and ETM+ scenes from Landsat 7 are catalogued using WRS-2 path/row coordinates.

The USGS EROS Center in Sioux Falls, South Dakota, holds the U.S. archive of Landsat data. The archive contains data from all six of the successfully launched Landsat satellites that provide intra-annual and inter-annual coverage of the global land surface over a period of more than three decades. The general public is able to search the archive and order Landsat scenes. EROS distributes ordered scenes in digital formats, either through the internet or on digital media such as CD's and DVD's. The EROS archive continues to grow with data collected from Landsat 5 and 7. EROS placed its two-millionth Landsat scene into the archive in February 2007.

Additionally, the Landsat satellites have directly transmitted data to a network of international ground receiving stations, with the number of stations varying over the years. Ten to fifteen stations have typically been in operation at any one time. The stations are usually operated by, or associated with, foreign governments, referred to as international cooperators. The international cooperators currently receive data under the auspices of bilateral memoranda of understanding (MOU's) with the U.S. Government. International cooperators hold their own archives of Landsat data with data distribution policies varying amongst the cooperators. These archives are limited to scenes covering the area within the receiving circles of the ground station antenna. EROS holds the only Landsat data archive providing global land surface coverage, and the United States is the only nation committed to preserving a global record of multi-decadal land observations at the scale provided by the Landsat sensors.

In summary, Landsat sensors have provided multispectral images of the global land surface since 1972. The images are digital in nature, similar to the data collected by today's hand-held digital cameras. The Landsat sensors have collected images not only

for visible colors but also for wavelengths of reflected solar energy not visible to the eye and, in the past two decades, for a thermal spectral band sensitive to emitted long-wave radiation indicative of surface temperature. The Landsat images are stored as scenes that each covers a 185-by-180 km surface area designated by a path/row coordinate system. The images are used principally to map land cover type and characteristics and to detect changes over the landscape with time. This capability is invaluable given the current pace of land cover change, and particularly since human land use and disturbance can be detected and differentiated from natural changes at the scale and resolution of Landsat images. The capability results in a broad and diverse community of Landsat data users that have non-discriminatory access to the U.S. Landsat data archive at EROS.

II C. History of Landsat Satellite Operations

Management of Landsat satellite operations has been inconsistent over the 35 years of the program. Landsat 1, 2, and 3 were launched and operated as research missions by NASA. The MSS data from these first three Landsat satellites proved so useful that the Carter Administration transferred responsibility for Landsat 2 and 3 satellite operations to the Federal agency that operates operational weather satellites, the National Oceanic and Atmospheric Administration (NOAA), in 1979 (Landsat 1 was decommissioned in 1978). The Carter Administration further recommended the gradual transition of Landsat satellite operations to the private sector.

As NASA was building Landsat 4 and 5, the U.S. Government accelerated the transition to private sector operations during the Reagan Administration. The Land Remote-Sensing Commercialization Act of 1984 (P.L. 98-365), repealed by the Land Remote Sensing Policy Act of 1992 (P.L. 102-555), directed that NOAA contract with private industry for Landsat satellite operations. After NASA launched Landsat 4 and 5 in 1982 and 1984, respectively, NOAA conducted a competitive procurement process and selected a consortium of private companies called the Earth Observation Satellite Company (EOSAT) to operate Landsat 4 and 5. The contract allowed EOSAT to sell Landsat data commercially and to charge international cooperators fees for the transmission of Landsat data to ground stations. The contract also required that EOSAT build and launch the next two Landsat satellites, Landsat 6 and Landsat 7, with U.S. Government subsidization of the cost.

The attempt to commercialize satellite operations proved detrimental to the Landsat program. The price for Landsat data rose to $4500 per scene, substantially limiting the number of scientists and resource managers who could afford Landsat data. Calibration of the sensors was not maintained, and collection of data was diminished to the point where global coverage was not achieved even annually. Most detrimental was the loss of Landsat 6 when it was launched on October 5, 1993. Landsat 6 was the only Landsat satellite that was not built and launched under NASA management.

The Land Remote Sensing Policy Act of 1992 (P.L. 102-255) superseded much of the Commercial Remote Sensing Act of 1984. The 1992 Act directed that Landsat

Program Management, a partnership of U.S. Government Federal agencies, build and operate Landsat 7. Landsat Program Management evolved into a partnership between NASA and DOI/USGS when an Amendment to Presidential Decision Directive/NSTC-3, dated October 16, 2000, directed that NASA build and launch Landsat and that USGS assume on-orbit satellite operations and data management. Landsat 7 was successfully launched on April 15, 1999. Additionally, Space Imaging, a private company that bought EOSAT in 1996, voluntarily relinquished management of Landsat 4 and Landsat 5 to the U.S. Government in 2001 (Landsat 4 ceased the transmission of sensor data in 1993 and was maintained in orbit until decommissioning in 2001). USGS took over Landsat 4 and 5 operations and accepted the full complement of Space Imaging/EOSAT Landsat data holdings into the EROS archive. USGS continues to operate Landsat 5 and Landsat 7 today.

Landsat 7 operations and performance under U.S. Government management established a benchmark for the Landsat program in several respects. First, NASA and USGS instituted a systematic data collection strategy to provide coverage of the global land area on a seasonal basis. This strategy ensures that a record of important land surface trends and changes will be captured into the data archive. Second, NASA and USGS have rigorously maintained and updated sensor calibration. This rigor is necessary to detect change and to compare ETM+ data with images from past Landsat sensors, with images from future Landsat sensors, and with other Earth observation data. Finally, USGS dramatically reduced the cost of Landsat data and removed commercial restrictions to data sharing. The price of a Landsat scene was dropped to $600, consistent with U.S. Government policy to distribute government-collected data at a price not to exceed the incremental cost of satisfying a user request. Once Landsat data are purchased from the USGS, no restrictions are placed on the free and open sharing of the data, greatly facilitating scientific collaboration. The USGS is now moving toward a policy of distributing Landsat data at no cost via the internet. EROS has developed a prototype system that offers no-cost access to a limited selection of Landsat 7 ETM+ data. Full implementation of a no-cost data distribution policy would dramatically increase the exploitation of the Landsat data record.

II D. Land Remote Sensing Policy Act of 1992 and Data Continuity

As described earlier, the Congress found that there was compelling benefit to land remote sensing and enacted those findings in the Land Remote Sensing Policy Act of 1992 (P.L. 102-555). Section 5641 specifically addresses continuity of Landsat data by directing that Landsat Program Management study options for a successor mission to Landsat 7, as follows:

> *"... **(1)** encourage the development, launch, and operation of a land remote sensing system that adequately serves the civilian, national security, commercial, and foreign policy interests of the United States;*
>
> ***(2)** encourage the development, launch, and operation of a land remote sensing system that **maintains data continuity with the Landsat system**..."*

The Act defines "continuity" as:

> *"...the continued acquisition and availability of unenhanced data which are, from the point of view of the user --*
>
> *(A)* ***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; and*
>
> *(B) compatible with such data and with methods used to receive and process such data."*

These salient characteristics of the law have been the foundation of the current formulation of LDCM.

III. Landsat Data Continuity

Although technically straightforward, ensuring "Landsat data continuity" has often proven difficult due to disparate stakeholder interests influencing the course of development of the system. One primary contributor to the system instability has been changes in programmatic management responsibilities. As described earlier, Landsat 1-5 were managed and launched by NASA. Landsat 6 management was transferred to NOAA and, unfortunately, the satellite did not achieve orbit. The U.S. Air Force started to build Landsat 7 in 1990, but subsequently transferred their contracts to NASA in 1994 (per a May 10, 1994, Presidential Decision Directive), and NASA successfully launched Landsat 7 in 1999.

Continuity of data has been the subject of debate for several years, and almost inevitably centers on the definition outlined in the Land Remote Sensing Act of 1992 that specifies that data be "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." The following sections define that consistency for the LDCM.

III A. Acquisition Geometry

The LDCM satellite will be launched into the same 705 km orbit flown by Landsat 4, 5, and 7. In orbit, the satellite will precisely follow the ground tracks defined by the WRS-2 path/row coordinate system. The LDCM sensor, the Operational Land Imager (OLI), will collect image data across a 185 km swath identical to the swath width viewed by TM and ETM+ sensors aboard Landsat 4, 5, and 7. The OLI will provide 30 m spatial resolution for all spectral bands, with the exception of a 15 m panchromatic band. This resolution is equivalent to the resolution of the data acquired by the TM and

ETM + and, thus, the OLI will collect image data with geometry consistent with TM and ETM+ multispectral images.

III B. Coverage Characteristics

The Landsat 7 ETM+ collects approximately 400 scenes of image data per day with 250 of those scenes captured by EROS for the U.S. archive. The remainder of the 400 scenes is transmitted to international ground stations. The Landsat 7 mission operations center sends an ETM+ data collection schedule up to the satellite once per day. The schedule is based on the orbital paths that will be flown that day, the location of landmasses along those paths, cloud cover forecasts, and an algorithm for selecting the cloud-free land scenes that will be within view of the ETM+. The algorithm implements a strategy for imaging the global land surface once per season and it takes into account climatology and the record of cloud-free scenes collected during previous 16-day periods. Evaluation of the ETM+ scenes archived by EROS since the launch of Landsat 7 indicates that the strategy has successfully met its objective.

The LDCM OLI is also being built to collect 400 scenes per day with all 400 scenes transmitted back to EROS. A data collections strategy similar to that employed for Landsat ETM+ operations will be used to schedule OLI collections daily. The objective will again be to archive scenes covering the global land surface at least once per season. With the additional 150 scenes transmitted to EROS, the LDCM OLI will easily exceed the coverage provided by the Landsat 7 ETM+ and will thus be sufficiently consistent with ETM+ coverage to ensure global and regional change detection.

III C. Spectral Characteristics

Table 1 lists the wavelength ranges of the spectral bands sensed by the Landsat 7 ETM+ and the spectral bands specified for the LDCM OLI. The list shows that the OLI will collect data for spectral bands consistent with the ETM+ spectral bands with the exception of the thermal spectral band (ETM+ Band 6). Otherwise, the OLI multispectral bands are comparable and include small changes to avoid atmospheric absorption features within the ETM+ bands. The largest change occurs for the near-infrared band, where the OLI Band 5 excludes a strong water vapor absorption band that has attenuated the signal in the ETM+ Band 4 data. The OLI panchromatic band (Band 8) is also narrower in frequency than the ETM+ panchromatic band (Band 8). This change will increase the contrast between vegetation and bare surfaces in panchromatic images. All of the OLI spectral band refinements will improve the ability to detect and map land cover change.

Table 1. Landsat 7 ETM+ and LDCM OLI Spectral Bands

L7 ETM+ Bands	L7 ETM + Bands (Wavelength in μm)	LDCM OLI Band Specifications (Wavelength in μm)	LDCM OLI Bands
		30 m Coastal/Aerosol **0.433 - 0.453**	Band 1
Band 1	30 m Blue **0.450 - 0.515**	30 m Blue **0.450 - 0.515**	Band 2
Band 2	30 m Green **0.525 - 0.605**	30 m Green **0.525 - 0.600**	Band 3
Band 3	30 m Red **0.630 - 0.690**	30 m Red **0.630 - 0.680**	Band 4
Band 4	30 m Near-IR **0.775 - 0.90**	30 m Near-IR **0.845 - 0.885**	Band 5
Band 5	30 m SWIR-1 **1.550 - 1.750**	30 m SWIR-1 **1.560 - 1.660**	Band 6
Band 6	60 m LWIR **10.00 - 12.50**	N/A	
Band 7	30 m SWIR-2 **2.090 - 2.35**	30 m SWIR-2 **2.100 - 2.300**	Band 7
Band 8	15 m Pan **0.520 - 0.900**	15 m Pan **0.500 - 0.680**	Band 8
		30 m Cirrus **1.360 - 1.390**	Band 9

The OLI spectral band complement also contains two new spectral bands. OLI Band 1 was specified principally to aid sensing of chlorophyll and phytoplankton concentrations in coastal waters. Ocean sensors on other satellite systems, such as SeaWiFS on the SeaStar satellite and the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra and Aqua satellites, collect data for this spectral band at much coarser spatial resolutions. Chlorophyll and phytoplankton concentrations vary at a much finer scale in coastal areas than in the open ocean. The 30 m spatial resolution specified for OLI Band 1 will help characterize and monitor coastal region water conditions. Data from this band may also contribute to the atmospheric correction of data from the other spectral bands as this band will be the most sensitive to atmospheric aerosol concentration.

OLI Band 9 was specified to detect the presence of cirrus clouds in OLI scenes. Cirrus clouds attenuate the radiation transmitted through the atmosphere in the other spectral bands and this attenuation is not always obvious. The ETM+ and TM sensors had no capabilities for detecting the presence of thin cirrus clouds. Cirrus clouds will be much more apparent in OLI Band 9 images and will provide information to analysts as to the impact of cirrus clouds on the data in the other spectral bands.

III D. Thermal Infrared

In keeping with the Landsat programmatic goals stated in the Land Remote Sensing Policy Act of 1992 (P.L. 102-555), the National Space Policy of 1996, and the Commercial Space Act of 1998 (P.L. 105-303), in FY 2000, NASA, in cooperation with the DOI/USGS, began formulation of the LDCM as a commercial data buy. Within the context of the data buy strategy, the Government acquisition strategy of "partnering" with industry was characterized by having both "partners" (in this case the Government and a contractor) provide consideration and receive benefit from the asset once data was captured. During the data buy formulation, NASA awarded two study contracts to develop preliminary designs for a system that would provide both continuity and enable the consideration for each partner. Both study contractors convinced the Government that the return on investment for thermal data, due to the limited number of users, was far too low for consideration. Based on this assessment by the potential commercial partners in the data buy, the thermal capability was removed from the LDCM requirements baseline in 2002.

Following the delivery of the preliminary designs by the data buy study contractors, the Government requested proposals for implementation of the system and completion of the data-buy partnership. After the proposal evaluation process was completed, the selection official determined that acceptance of a proposal was not in the best interest of the Government due to lack of competition and decided not to complete the data buy procurement.

Following the non-award of the commercial data buy in 2003, the Office of Science and Technology Policy chartered an Interagency Working Group (IWG), chaired by the National Security Council and NASA, to study an implementation strategy for the Landsat Program. After a nine-month study, the IWG recommended that land data (a Landsat capability) be obtained by developing instruments for flight aboard National Polar-orbiting Operational Environmental Satellite System (NPOESS) satellites. Once the initial technical evaluation of this instrument concept was complete, the thermal capability was found to be technically unachievable on the NPOESS platform, and the analysis for land imaging instruments on the NPOESS platform went forward without the thermal capability.

Subsequent technical evaluation determined that Landsat capability was not compatible with the NPOESS satellite configuration, and further consideration of Landsat on NPOESS was discontinued in December 2005. NASA was directed to pursue a free-flyer mission approach for Landsat. In early CY 2006, NASA began re-formulation of the LDCM as a free-flyer and industry was notified of NASA's intention to openly compete the mission development. Following an extensive reformulation of the mission during CY 2006 and early CY 2007, open competitions were initiated for the separate elements of the LDCM.

While the implementation strategy for Landsat data continuity was being worked out, assumption of Landsat 5 and Landsat 7 operations by the U.S. Government led to

more reliable and systematic imaging of the land surface. In particular, the Landsat 5 TM and Landsat 7 ETM+ sensors provided well-calibrated thermal images along with the data from the other spectral bands. Previously, a relatively small group of Landsat data users developed useful applications of thermal data (examples include the early detection of water stress in crops and tracking of sediment and chemical transport in lakes and coastal waters), but these applications were not considered sufficiently significant by NASA to justify the cost of continued thermal imaging.

Throughout CY 2006 and CY 2007, the thermal data user community interest increased due to the increased reliance on thermal data in applications of water management. Precipitated by the advent of more frequent, reliable coverage, methods to estimate water consumption at the scale of an irrigated farm field using the thermal images were becoming heavily relied upon in many arid regions. Western state and local governments had begun to adopt these methods to better manage over-subscribed water resources. As a result of this interest, NASA initiated detailed technical and programmatic studies of a thermal capability development in early CY 2007.

In mid-2007, NASA's analyses indicated that the schedule for development of a thermal instrument would drive the overall LDCM mission schedule and delay the launch date. At that time, analysis indicated the development time for a thermal imaging instrument could delay the LDCM launch significantly and increase the potential Landsat data gap.

Due to the timing of the re-designation of LDCM as a free flyer in December 2005, the FY 2006 budget as enacted still reflected LDCM as an NPOESS-manifested capability. It was not until the FY 2007 budget that the new LDCM satellite mission was addressed, but due to the expected high cost and low priority of the thermal capability relative to the other Landsat instrument spectral requirements, it was not included in the FY 2007 budget request. In sum, since the development of the FY 2002 budget, neither NASA's budget requests nor its annual appropriations have included funding for a thermal capability for LDCM. However, as a result of the technical analyses performed in 2007, NASA decided to provide for accommodation of a potential thermal sensor, albeit unfunded, as part of the LDCM spacecraft design.

IV. Landsat Data Continuity Mission

Today, LDCM development is progressing rapidly to minimize the data gap, and the partnership of NASA and the DOI is proceeding with the most reliable approach to completing the mission while minimizing the data gap. The LDCM mission objective, consistent with policy and legislation, is to extend the ability to detect and quantitatively characterize changes on the global land surface at a scale where natural and man-made causes of change can be detected and differentiated. The scope of the LDCM includes development and launch of a land imaging observatory and all ground segment capabilities to operate the observatory including operations, data handling, archive and distribution.

IV A. Schedule Urgency

Development of the LDCM is of the highest priority to the United States due to the high probability of a data gap between the demise of Landsat 7 and receipt of on-orbit data from LDCM. Both Landsat 7 and Landsat 5 are presently experiencing technical problems and are expected to run out of fuel in late 2010. Combine this fact with the most expedient development for LDCM and the outcome is that a Landsat data gap is inevitable. Although the Office of Science and Technology Policy recognized this issue and chartered a study group to find mitigation strategies, the outcome of the study was clear: there is no replacement for Landsat available and the only data sources available will only partially mitigate the data gap.

The LDCM mission is currently in the initial phase of development, but is moving quickly to achieve its earliest possible launch date. The implementation plan defined in the FY 2009 budget request targeted a launch no earlier than July 2011. The LDCM content, cost and schedule are under review as part of ongoing Preliminary Design Review and Confirmation Review activities, and a revised baseline with a later launch readiness date is considered to be likely. Following NASA standard mission development policies, in the summer of 2008, NASA will conduct this formulation phase review, including a review of the overall programmatic approach, along with the mission development risk posture. At the conclusion of this review, a development schedule to launch will be estimated that correlates with a 70 percent confidence level for achieving the launch date as the project enters the final formulation phase (B). The final phase of formulation will end by mid-CY 2009 with entry into the implementation phase and will provide a formal NASA commitment for cost and schedule at the 70 percent confidence level.

IV B. LDCM Acquisition Strategy and Status

NASA's acquisition strategy for the LDCM was ratified in close coordination with stakeholders and the DOI/USGS, and leverages the agencies' strengths to achieve a successful LDCM. In general, the responsibilities for the LDCM implementation are divided by mission segment areas. NASA is responsible for the development of the Space Segment, Launch Segment, and for developing the Mission Operations Element (MOE) on behalf of the DOI/USGS; USGS is responsible for the development of the Ground System (comprising the Flight Operations and Data Processing and Archive Segments), excluding procurement of the MOE. After the completion of the on-orbit checkout period, NASA will transfer ownership of the LDCM satellite to the DOI/USGS, which will then be responsible for LDCM mission operations.

NASA has developed an effective and efficient acquisition strategy for the LDCM space segment and has held open competitions for the separate developmental elements of the mission. NASA has held open competitions for the instrument (a multispectral imaging instrument known as the Operational Land Imager, or "OLI") and the launch

vehicle, and is in the process of completing the procurements for the spacecraft and the MOE.

In July 2007, NASA awarded the OLI instrument contract to Ball Aerospace and Technologies Corporation (BATC). Work on the OLI was immediately initiated by Ball and, in early March 2008, a successful Preliminary Design Review was conducted that marked the completion of the OLI preliminary design. During the time period of the preliminary phase of the OLI design, the LDCM Project office began procurement of the LDCM launch vehicle through the NASA Kennedy Space Center's Launch Services Program and a contract was awarded to the United Launch Alliance (ULA), in October 2007, for an Atlas – V 401 launch vehicle. Shortly following the launch vehicle procurement, NASA initiated procurements for a spacecraft through the NASA Rapid Spacecraft Development Office, and the MOE. General Dynamics Advanced Information Systems was selected as the spacecraft provider. NASA and DOI/USGS are nearing completion of the MOE procurement process.

V. Conclusion

Landsat's 35-year history of providing scientifically accurate and internationally renowned global land surface data is unprecedented. No other spaceflight program has matched the breadth of use, historical record and significant societal contributions. The Landsat series of land observing satellites has consistently provided multi-spectral data using sensors that have been developed with increasingly complex technologies in order to increase data resolution and quality. Correspondingly, the scientific and research communities have leveraged the Landsat data capabilities to provide a broad and diverse range of insight into the Earth's land cover change and land use. The first 20 years of Landsat data resulted in such a compelling case for societal benefit that, in 1992, the Congress enacted the Land Remote Sensing Policy Act (P.L. 102-555) to ensure that continuous Landsat data would be provided. It is under P.L. 102-555 that Landsat-7 and the current LDCM developments were mandated. Also within this law, Landsat data continuity is defined as:

> *"...the continued acquisition and availability of unenhanced data which are, from the point of view of the user --*
>
> *(A)* ***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; and*
>
> *(B) compatible with such data and with methods used to receive and process such data."*

These salient elements of the law have been the foundation of the current formulation of LDCM with data capabilities that are sufficiently consistent in terms of acquisition geometry, coverage characteristics, and spectral characteristics. It is only thermal data continuity that is currently not accommodated by the LDCM instrument complement due

to the programmatic history, evolution of thermal data demand, and resulting current funding of the LDCM.

Early in the formulation of LDCM, NASA attempted commercialization of the Landsat development and discovered that, not only was Landsat data commercialization unviable, but that thermal data had very little commercial market. Additionally, during further formulation effort, NASA found that thermal applications were not sufficiently significant to justify the cost of continued thermal imaging. As formulation continued with LDCM, thermal research and utility advanced, but the thermal capability development remained unfunded due to low priority and high development cost. Funding for development of a thermal capability on LDCM has not been included in annual budget requests since FY 2002. The user community has commented upon these facts and has urged the U.S. Government to seek solutions for a thermal data capability. Appendix A provides a synoptic analysis of options for thermal capability, and Appendix B provides descriptions of current/future missions that have thermal imaging capabilities.

Appendix A. Options for a Thermal Capability

I. Background

This appendix discusses the characteristics of thermal infrared data, consistent with previous Landsat data; the availability of current or planned missions in the near term that could provide such data; and potential bridge alternatives for providing thermal data.

I.A. Current Landsat Thermal Imaging Data Characteristics

The capability to provide thermal sensor infrared data for the Landsat series of missions was initiated with the launch of the Landsat 4 mission in 1982, and has been provided to the present with subsequent successful Landsat 5 launched in 1984, and Landsat 7 mission, launched in April 1999. Both the Landsat 5 and Landsat 7 missions are currently in extended lifetime operations providing thermal infrared data to users through the USGS EROS Center.

Thermal infrared data are acquired simultaneously with the non-thermal Landsat moderate resolution multi-spectral data. Like all Landsat data, thermal data are collected on all global land surfaces at least once per season to create a long term land cover data archive for land change, land cover research and applications. A summary table of the current Landsat thermal imaging capabilities is provided in Table 1.

Mission	*Sensor*	*Launch*	*# IR bands*	*IR wavelength*	*GSD*	*NEDT*	*Swath*	*Revisit time*	*MLT*
L5	*TM*	*1984*	*1*	*10.4-12.8μm*	*120m*	*0.22K*	*185km*	*16 days*	*9:45 am*
L7	*ETM+*	*1999*	*1*	*10.4-12.8μm*	*60m*	*0.22K*	*185km*	*16 days*	*10:00 am*

Table 1 – Current Landsat Mission thermal infrared capabilities (GSD=Ground Sample Distance, NEDT =Noise Equivalent Delta Temperature and MLT = Mean Local Time)

A thermal capability that would provide data consistent with the current Landsat thermal infrared data would require at least one thermal infrared band (between 10μm to 12μm) that captures all images of all land surfaces of the globe at least once per season. This implies that the sensor must have a moderate swath (~100km) and moderate revisit time (~20days) over the same ground target in order to image all global land masses. Additionally, the thermal imaging sensor must have a ground sampling resolution no coarser than 120m and the ability to detect temperature changes (NEDT) that are less than 0.5 (with a 0.2 goal) degrees Centigrade. For research and scientific applications,

the sensor must remain accurate (<2% or 0.2 degree C) over a mission lifetime of five years.

I.B. Current and Planned Earth remote sensing thermal imaging systems

A review of current or planned missions over the next decade (see Appendix B for details) indicates that there are no missions that will provide reliable thermal infrared data consistent with the current Landsat 5 and Landsat 7 capabilities until the latter part of the next decade. Current and planned missions are either are too coarse in resolution (ground sampling distance) or provide insufficient collections and coverage to meet the Landsat science and management needs for imaging the entire global land masses at least once per season.

The recommended NRC Earth Science Decadal Survey mission HyspIRI, proposed for launch in the later part of the next decade, is currently conceived to enable thermal imaging capabilities consistent with, or better than, the current Landsat series of missions. Additionally, the China-Brazil Earth Remote Sensing Satellite-4, planned for launch in 2011, is planned to include a thermal channel with capabilities consistent with the previous Landsat satellites; however, data calibration, global coverage capability and data distribution policy are uncertain.

II. Potential Landsat Thermal Infrared imaging continuity options

Over the last decade, a number of potential options have been assessed for providing continuity of Landsat thermal data.

II.A. LDCM

The history of Landsat thermal imaging and the consideration of adding a thermal imaging capability to LDCM are described in section III of this report.

As noted in Section III, a decision was made in FY 2007 to provide for accommodation, in the LDCM spacecraft design, of a potential thermal sensor. However, as of this date, no funding has been requested, authorized, or appropriated for further pursuit of this option, and any future decision to go forward with this option potentially could delay the launch of LDCM and exacerbate the anticipated gap for Landsat multispectral data.

IRD-1650 The compatible mounting interfaces of the TIRS instrument shall be either the -X, +X, -Y, or -Z face of the instrument as represented in Figure 3-10.

TIRS images in +Z (nadir).

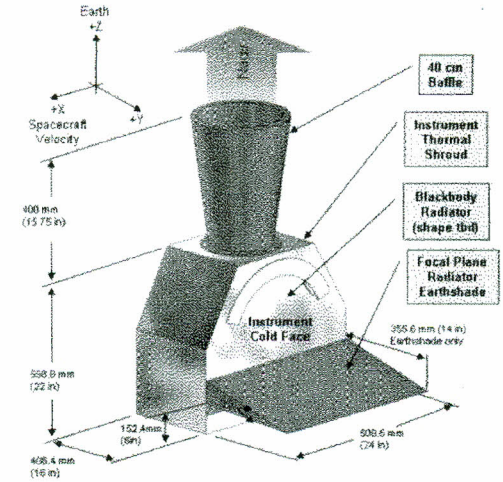


Figure A1. Potential thermal infrared sensor accommodation on the LDCM Spacecraft bus

II.B. Free-Flyer dedicated to Thermal imaging (lower risk)

A dedicated thermal imaging free-flyer mission could be launched no earlier than mid calendar year 2013, assuming significant funding was made available beginning in FY 2009. A thermal imaging sensor, consistent with Landsat, competitively acquired through industry would need to be contracted by early FY 2010. The specific ground sampling resolution of the thermal sensor (between 60m and 120m) could be scaled per budget availability, with the decision made prior to moving into preliminary design phase. The mission would be designed for five years operation and could be potentially launched on a medium size launch vehicle (e.g., Taurus). The cost of a dedicated free-flyer mission fitting within these requirements was estimated to range between $400-$500 million.

As of this date, no funds have been requested, authorized, or appropriated for further development of this option by NASA or other U.S. government departments or agencies.

II.C. Free Flyer dedicated to thermal imaging (higher risk)

A higher risk approach, but one that could bring thermal sensor data sooner, is the approach used for acquiring the New Millennium Earth Observing-1 Mission, launched in 2001. Under this scenario, a government lab (FFRDC or NASA Center) would be directed to develop a dedicated thermal imaging sensor that meets the minimum Landsat

thermal imaging requirements under strict schedule and cost constraints and with high-risk design criteria (less than 3-year design life). A potential SmallSat or low cost commercial spacecraft bus would be procured or built in-house. An alternate, but potentially higher risk launch vehicle (Minotaur, Falcon 1), providing low-cost space access would be procured to further reduce overall mission cost. Essentially, a schedule from start of development to launch in less than 48 months could provide thermal data for a design life of approximately three years following launch beginning in late 2012, assuming significant funding were provided beginning in FY 2009 for expedited acquisition of the thermal infrared sensor. The cost of a dedicated free-flyer mission fitting within these requirements was estimated to range between $250-$350 million.

Overall, risks would be greater for the spacecraft and instrument development because this mission would have a higher risk acquisition approach. Also, the availability to NASA of a low-cost launch vehicle is uncertain. This mission would have a higher risk of a failure or degradation since parts quality and reliability requirements would need to be relaxed to achieve the expedited schedule.

As of this date, no funds have been requested, authorized, or appropriated for any further development of this option in the NASA or other U.S. government departments or agencies.

II.D. Missions of Opportunity

Missions of Opportunity (MOOs) are potential missions launched by the U.S. government or international partners that have additional capacity (mass, power, volume, data) that can be used to fly additional sensors. However, the usual ground rules for contributing partner sensors are that they must be compatible and can be de-manifested if delivery schedule is not met. The contributing instrument may not interfere with the operation of the prime mission. The following MOOs were considered for manifesting a thermal infrared sensor consistent with current Landsat thermal data requirements.

II.D.1. International Space Station (ISS)

An option for incorporating a thermal sensor on the ISS was assessed; however, the lower inclination (~51.6 degrees) orbit of the ISS does not enable a thermal infrared sensor to view higher latitude landmass areas of the globe. This essentially eliminates the ability of a thermal sensor to view and image globally all land masses seasonally and does not meet the Landsat data consistency requirements.

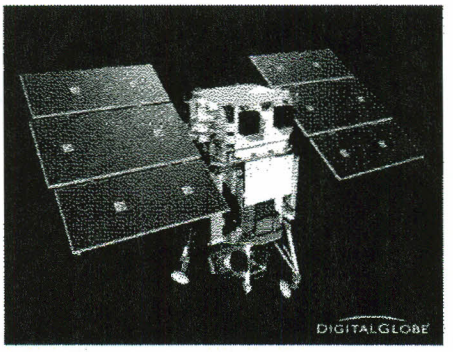
Although significant ISS truss accommodation areas exist for nadir (Earth view) sensors, significant issues exist with respect to stability of the imager and optical contamination sources. The higher data rate of a thermal sensor and fairly high power demands would be competing for resources on the ISS. Additionally, the ability to transport and install a thermal sensor following retirement of the Space Shuttle in 2010 is a significant challenge.

For these reasons, especially ensuring consistency with acquiring thermal over all global landmasses, the ISS option was not considered as viable in meeting Landsat thermal data consistency requirements.

II.D.2. Commercial Mission of Opportunity

A survey of the NOAA/NESDIS commercial remote sensing program indicated that there are currently no potential U.S. commercial remote sensing missions that have applied for, or have been granted remote sensing licenses that indicate they have provision for spacecraft resources to accommodate a thermal infrared sensor nor are there any commercial companies that are licensed to provide thermal infrared data.

However, two commercial missions providing data to NGA do provide opportunities for potentially manifesting a thermal sensor; specifically, the Digital Globe's Worldview-2 and GeoEye's GEOEYE-1 satellites missions, which provide orbital characteristics similar to Landsat. However, these missions have near-term launches in 2008 or 2009, and have both completed fabrication and integration, thus there would be a low probability of pragmatically manifesting an additional thermal sensor on either mission.



Additionally, a study was conducted in 2004 that analyzed the potential manifest of a thermal imaging sensor on a next-generation NextView-sponsored high-resolution imaging spacecraft. The results of this study indicated that accommodating a thermal imager on a high-resolution imaging spacecraft platform would likely be highly complex due to the requirement of maintaining the pointing of the thermal sensor directly nadir (towards Earth) while the spacecraft pointed to specific areas to collect high-resolution images.

Several factors make this option unviable. First, the U.S. Government would likely have to bear the full cost and risk of both the sensor development and the more complex accommodation costs. Second, NGA and the commercial provider would have to agree to the initiative. Third, the accommodation would have to be technically feasible (orbit, mass, power, volume and data capacity would have to be within requirements for

B) on a SARAL spacecraft bus with launch on an Indian launch vehicle in the 2012 timeframe; however, discussion has not formally begun and potential collaboration is uncertain.

There are no plans for an international contribution of a thermal capability development on either the current LDCM mission or other near-term NASA missions, and there no funding has been requested, authorized, or appropriated to provide in-kind contributions of a thermal sensor to an international mission.

III. Assessment and Summary

Table A2 provides an overall comparison of the options considered. Although potential moderate-cost, bridge mission opportunities exist for developing and manifesting a thermal infrared sensor, the following key issues exist with respect to further pursuing missions with thermal imaging capability consistent with Landsat data performance:

1. For all viable (i.e. excluding ISS option) thermal bridge mission options, there is currently no funding requested, authorized, appropriated or planned within the NASA budget to further develop or accommodate a thermal infrared sensor.

2. Operational missions currently planned for the near term cannot provide thermal infrared data consistent with Landsat, as their resolution is either too coarse, image collection capability is too sparse or the data are not available to the U.S. science teams.

    a. The only long-term mission planned with potential thermal capabilities consistent with Landsat is the NRC Decadal Survey mission HyspIRI recommended to be launched in 2013-2016.

3. Currently there is no international partner that is planning on providing a thermal sensor for the current LDCM mission or any future near-term NASA missions.

4. Currently, there is no thermal mission bridge option identified that could result in a less-than two-year gap in thermal data consistent with the current Landsat missions (assuming loss of the current Landsat capability at the end of calendar year 2010.)

5. Developing and manifesting a thermal sensor on the current LDCM mission potentially could delay the launch of LDCM and exacerbate the anticipated gap for Landsat multispectral data.

Table A2. Comparison of mission options, with estimated costs that are unfunded and international partnerships that have not had high-level discussions.

Option #	Mission Description	Earliest Possible Launch Date	Coverage	Accomodation Issues	Technical Risk Evaluation	Schedule Risk Evaluation (Ability to deliver on-time)	Total Cost Range	Viability?
II.A	LDCM	1Q/2013	Meets	Meets	Meets	Meets	Moderate ($140M - $200M)	Viable but significant delay to current LDCM mission
II.B	Free Flyer	4Q/2013	Meets	Meets	Meets	Meets	High ($400-$500M)	Viable but High cost
II.C	High Risk Gap Filler	1Q/2013	Meest	Meets	Marginally meets	Moderate risk	Moderate to high cost (250-350M)	Viable, but high cost and greater mission failure risk
II.D.1	ISS	2Q/2012	Does not meet	Does not meet	Does not meet	Dependent on Instrument Schedule	Not evaluated	[illegible]
II.D.2	Commercial	No missions planned	N/A	N/A	N/A	N/A	N/A	[illegible]
II.D.3	NSS	No specific plans	N/A	N/A	N/A	N/A	N/A	[illegible]
II.D.4	International Partnership	1Q/2013	Meets	Meets	Meets	Meets	Moderate to high $150-$250M if cost split evenly	Viable, Moderate risk overall,
	HyperSI	NET 2015	Exceeds	Meets	Meets or exceeds	Instrument delivery in 42 mths	Moderate to High ($350 - $500M)	Viable, Low risk but significant thermal data gap (5 years or more)

Appendix B. Near-Term and Long-Term Missions with Thermal Imaging Capabilities

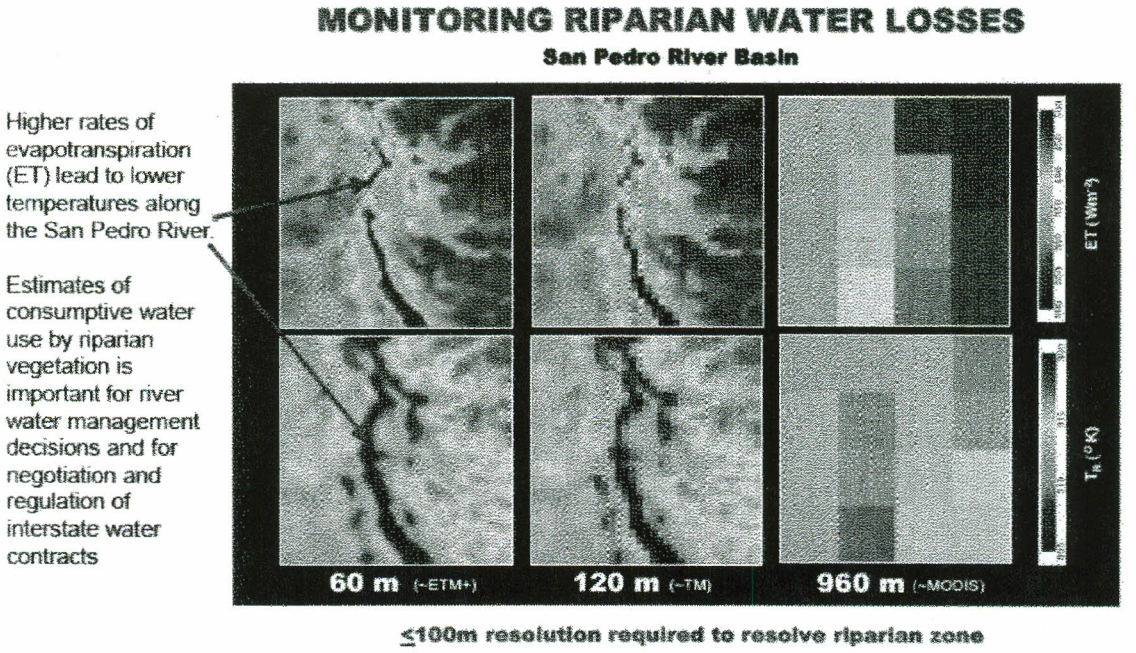
I. Current and Near-Term Missions with Thermal Imaging Capabilities

In addition to the Landsat 5 and 7, the following other operational and near-term (2009-2012) Earth remote sensing spacecraft have thermal infrared imaging capabilities (table B1.)

Table B1. Thermal infrared imaging capabilities

Sensor	Built by / Study by	Mission	Year of Launch/Study	# of IR Bands	IR Bands	Design Life	GSD	MLT	NEDT	Accuracy	Swath	Revisit every	Sensor Technology
MODIS	Raytheon / SBRS	Terra/Aqua	2000	6	10.8-11.2 and 11.8-12.3	5	1000 m	10:00 a.m / 1:30 pm	0.05K	<2%	2330km	Daily	Scanned cooled TBD detectors
IASI	Sodern	METOP	2006	N/A	10.3 - 12.5um	5	1000 m	10:30AM	1K	<2%	TBS	Daily	Fourier Transform, Uncooled uBol
ASTER	JAXA	Terra	2000	5	1@10.25um-10.95um, 1@10.95um-11.65um	5	90m	10:00 a.m	<0.3K	<2%	60km	Scheduled daily	Scanned cooled TBD detectors
IIR	NASA / CNES	CALIPSO	2006	3	10um, 12.0um, 8.5um	3	1km	1:30 p.m	0.5K	<1K	64km	Daily	Pushbroom, ubolometer
IRMSS	China/Brazil	CBER-02	2003	1	10.4-12.5um	TBD	156m	morning	10:30 a.m.	Not available	120km	26 days	tbd
VIIRS	Raytheon / SBRS	NPP / NPOESS	2010/2013	4	1@10.763um 1@12.01um	5	750m	1:30 p.m	0.05K		3000km	Daily	Scanned cooled TBD detectors

Key differences in current systems are the ground sampling distance for all of the missions. For the current operational IASI, IIR, MODIS sensors, although the thermal bands are consistent with Landsat, the minimum ground sampling distance is over eight times coarser than the coarsest Landsat resolution (1km vs. 120km). For ASTER, the ground sampling distance is consistent with Landsat, but the instrument coverage is significantly reduced (60 km swath width vs. Landsat 185km) and the ASTER image data collection duty cycle is low due to on-board recorder capacity on the Terra spacecraft. These factors significantly limit the collection of ASTER thermal imaging data and are insufficient to fulfill Landsat data consistency needs. Additionally, the Terra spacecraft and ASTER instrument are currently operating well beyond their original design lifetimes (9 years in orbit vs. 5-year design lifetime).



The near-term, planned NPP and NPOESS missions all provide thermal data global coverage (daily revisit of all Earth land and water areas), through the common VIIRS instrument and provide similar thermal bands as Landsat 5 and 7. However, the VIIRS instrument provides only 750m x 750m ground sample resolution for its thermal bands, again too coarse to be considered useful for Landsat data thermal consistency purposes. Likewise, future METOP satellites through its IASI imager will provide a similar coarse (1km x 1km) thermal imaging capability.

Only the CBER's series of missions may carry comparable thermal bands and swaths compared to Landsat series. However, data from this joint Chinese and Brazilian mission is not available as part of an open data policy to United States researchers and data collection is currently focused on mainland China and Brazil only.

II. Long Term Earth Science Decadal Survey HyspIRI Mission

The 2007 NRC Earth Decadal Survey (reference *Earth Science and Applications from Space – National Imperatives for the Next Decade and Beyond*) includes, among other recommendations, the development of the HyspIRI mission. The HyspIRI mission is part of the second set of missions to be launched in the later part of the next decade. As part of the HyspIRI mission the NRC recommends…

> *"The HyspIRI mission uses imaging spectroscopy (optical hyperspectral imaging at 400-2500 nm and multispectral IR at 8-12 m) of the global land and coastal surface. The mission would obtain global coverage from LEO with a repeat*

frequency of 30 days at 45-m spatial resolution. A pointing capability is required for frequent and high-resolution imaging of critical events, such as volcanoes, wildfires, and droughts."

The payload consists of a hyperspectral imager with a thermal multispectral scanner, both on the same platform and both pointable. Given recent advances in detectors, optics, and electronics, it is now feasible to acquire pushbroom images with 620 pixels cross-track and 210 spectral bands in the 400- to 2,500-nm region. If three spectrometers are used with the same telescope, a 90-km swath results when Earth's multispectral imager similar to ASTER is required in the thermal IR region.

For the proposed HyspIRI mission thermal channels (five bands in the 8- to 12-μm region), the requirements for volcano-eruption prediction are high thermal sensitivity of about 0.1 K and a pixel size of less than 90 m. An opto-mechanical scanner, as opposed to a pushbroom scanner, would provide a wide swath of as much as 400 km at the required sensitivity and pixel size. These capabilities would be consistent and, in many cases (spectrally, coverage, and sensitivity), exceed Landsat thermal imaging requirements.

The HyspIRI mission has its heritage in the imaging spectrometer Hyperion on EO-1 launched in 2000 and in ASTER, the Japanese multispectral SWIR and thermal IR instrument flown on Terra. The hyperspectral imager's design is the same as the design used by JPL for the Moon Mineralogy Mapper (M3). The Indian Space Research Organization (ISRO) has proposed joint NASA-ISRO discussions regarding the flight of HyspIRI on a SARAL spacecraft bus with launch on an Indian launch vehicle possible in the 2012 timeframe.