Remote Sensing of Environment 122 (2012) 22–29

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Landsat: Building a strong future

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ARTICLE INFO

Article history:
Received 3 May 2011
Received in revised form 13 September 2011
Accepted 16 September 2011
Available online 15 February 2012

Keywords:
Landsat
Remote sensing
Earth observation
Land imaging future
Climate data records

ABSTRACT

Conceived in the 1960s, the Landsat program has experienced six successful missions that have contributed to an unprecedented 39-year record of Earth Observations that capture global land conditions and dynamics. Incremental improvements in imaging capabilities continue to improve the quality of Landsat science data, while ensuring continuity over the full instrument record. Landsats 5 and 7 are still collecting imagery. The planned launch of the Landsat Data Continuity Mission in December 2012 potentially extends the Landsat record to nearly 50 years. The U.S. Geological Survey (USGS) Landsat archive contains nearly three million Landsat images. All USGS Landsat data are available at no cost via the Internet. The USGS is committed to improving the content of the historical Landsat archive though the consolidation of Landsat data held in international archives. In addition, the USGS is working on a strategy to develop higher-level Landsat geo- and biophysical datasets. Finally, Federal efforts are underway to transition Landsat into a sustained operational program within the Department of the Interior and to authorize the development of the next two satellites — Landsats 9 and 10.

1. Introduction

The history of Landsat and the characteristics of specific missions have been chronicled in several previous articles (see Lauer et al., 1997; Goward & Williams, 1997; Goward et al., 2001; Sheffner, 1994; and Williams et al., 2006). Clearly, the concept for Landsat was visionary and in spite of the fact that Landsat has essentially been an *ad hoc* program (recognizing that the science objectives have remained consistent over time), the legacy is remarkable. With imagery covering all but the highest polar latitudes going back to July 1972, the six successfully launched Landsats have contributed to the longest and most geographically comprehensive record of the Earth's land surface ever assembled.

The credit for this record belongs to many visionary scientists and engineers, but Dr. William Pecora, former U.S. Geological Survey (USGS) Director and Assistant Secretary for Water and Science in the Department of the Interior (DOI), and Interior Secretary Stewart Udall provided the scientific leadership and political savvy that led to the Landsat program. The vision for a civilian Earth observation capability originated with William Pecora when he was director of the USGS. In the mid-1960s, Pecora proposed a remote sensing satellite program to gather facts about the Earth's natural resources (Lauer et al., 1997). He was influenced by the early reports on the value of classified imagery for defense and intelligence purposes as well as the multi-spectral imagery experiments underway in NASA.

In 1966, Secretary Udall announced "Project EROS" (Earth Resources Observation Satellite) by stating "…the time is now right and urgent to apply space technology towards the solution of many pressing natural resource problems being compounded by population and industrial growth" (Department of the Interior, 1966). Udall acknowledged that Project EROS was possible "…because of the vision and support of NASA." While there were some initial programmatic challenges, in 1970 NASA initiated building the Earth Resources Technology Satellite (ERTS — later renamed Landsat 1), which, when launched in July 1972, ushered in the era of civilian remote sensing of land from space. Since then, there has been remarkable mission-to-mission consistency in spite of the lack of a formal government commitment to an operational Landsat program.

Even though the Landsat concept originated through the DOI and the USGS, and became a reality through the efforts of NASA, neither agency was ever assigned the responsibility to make Landsat operational. In fact, across over four decades, based on directives from Congress and various Administrations, responsibilities for Landsat mission acquisition have moved from NASA to NOAA, nearly to the private sector, and back to NASA with brief involvement of the Department of Defense. Mission operations also changed hands several times starting with NASA but then transferring to NOAA and its intended commercial successor, the Earth Observation Satellite Company (EOSAT), and finally to the USGS (since October 2000). For the entire 39-year period that Landsats have been in orbit, science data archive operations have been handled by the USGS through the Earth Resources Observation Systems (EROS) Data Center (now named the Earth Resources Observation and Science (EROS) Center — including the 1983 to 1998 period when NOAA exercised programmatic responsibility for Landsat data.

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0034-4257/$ – see front matter. Published by Elsevier Inc.
doi:10.1016/j.rse.2011.09.022

In spite of the lack of operational mission status and the variability in Federal leadership and technical responsibilities, Landsat has successfully and continuously provided global Earth observations. The longstanding Landsat program goal has been to acquire, archive, and distribute repetitive global multi-spectral imagery of the Earth's land surfaces at a scale where natural and human-induced changes can be detected, characterized, and monitored over time (Goward & Williams, 1997). Landsat's mission is to contribute to understanding the extent and consequences of a changing Earth, as well as the operational management and monitoring of resources for ensuring economic and environmental quality, public health and human well-being, and national security. Whether the application is scientific, commercial, or operational, the needs are the same — a global perspective, a long-term record of observation, and well-calibrated high-resolution multispectral data. Since July, 1972, that is what six successful Landsat missions have provided.

The Earth observation capabilities offered by the six past and current Landsat missions have ensured consistency and continuity of measurements but with periodic incremental improvements that increased the utility of the data for science and applications. The Multi-spectral Scanner System (MSS) flew on Landsats 1–5 with four spectral bands (the Landsat 3 MSS added a short-lived thermal channel) and 80 m spatial resolution based on a 57 m by 79 m ground sampling distance. Global MSS coverage spans 1972 to 1992. Landsat 4 and 5 introduced the Thematic Mapper (TM) with seven spectral bands, including middle- and thermal-infrared, and improved spatial resolution — 30 m for the visible through middle infrared channels and 120 m for the thermal band. Global TM coverage exists since 1982 and continues to be collected due to the remarkable performance of Landsat 5. Since 1999, the Enhanced Thematic Mapper Plus (ETM+), launched on Landsat 7, has provided multispectral coverage similar to TM (six visible through middle infrared bands at 30 m) but with a 60 m thermal band and a new 15 m panchromatic band. Table 1 provides a summary of mission life spans and instrument payloads for the Landsat missions, Table 2 summarizes general instrument capabilities, and Fig. 1 presents Landsat images over the Columbia River region from each of the six missions.

2. Current Landsat status

Two Landsats (5 and 7) are still acquiring data, and the USGS EROS Center archive holds nearly three million Landsat images. Following launch in December 2012, the LDCM, renamed to Landsat 8, will begin adding image data to the archive. The following section describes the status of the Landsat 5 and 7 missions, Landsat image data processing capabilities, image data archive status, and the web-enabling of the complete Landsat archive.

2.1. Landsat 5 status

The Landsat 5 satellite was launched March 1, 1984 and continues to operate to this day. The satellite carried two instruments: the MSS, which had been flown on the previous four missions; and the TM instrument that was introduced on Landsat 4. The MSS instrument was decommissioned in August 1995. The mission had a minimum design life of 3 years and the original mission operations concept allowed for the satellite's orbit to be lowered approximately 320 km for retrieval by the Space Shuttle for refurbishment and return to orbit. This required the spacecraft to carry a very large fuel supply. Although this operational concept was never realized, the large fuel volume has proven to be fortuitous.

Like Landsat 4, Landsat 5 does not carry an on-board data recorder. Instead, a Ku-band antenna was flown to transmit global science (image) and telemetry data over the horizon through the NASA Tracking and Data Relay Satellite System (TDRSS). A U.S. station received the data from TDRSS and sent it onto the USGS data archive for processing and distribution. The Landsat 5 satellite also includes an X-band antenna for the real-time downlink of data to ground receiving stations with direct lines of site to the satellite. International Cooperators (IC's) operate an extended network of X-band receiving stations under U.S. Government agreements that allow the IC's to receive and distribute Landsat 5 data in accordance with the operating agencies' data policies. When the Landsat 5 Ku-band transmission system failed in 1992, data transmission became limited to the direct, real-time X-band transmissions and that limited U.S. reception to data collected while the satellite was within a U.S. station line-of-site. The number and geographic distribution of ground stations has varied through the lifetime of the mission; therefore the global geographic and temporal coverage of imagery varies, with a significant amount of data residing in IC archives.

As Landsat 5 continued to operate well beyond its 3-year design life, it gradually began to experience failures of components in the attitude control system, propulsion and power modules, the solar array drives, and the traveling wave tube amplifier (TWTA) in the wide-band communication module. Fortunately these major systems were built with redundant capabilities, and the flight operations team has been able to implement a series of engineering and procedural solutions to sustain collection and transmission of image data to ground stations. Nonetheless, there remains little redundancy in key spacecraft systems. As of this writing, the spacecraft operations are primarily constrained by power and communications concerns. The spacecraft is pitched twice each orbit to point the array at the sun to keep the batteries charged, now that the solar array drive is no longer able to rotate the array. Usage patterns of the TWTA for X-band transmission of the science data are constantly monitored and tweaked, as currents approach end-of-life limits. These factors have combined to induce constraints on data collection by essentially restricting the amount of worldwide continuous imaging. On average, around 260 Landsat 5 scenes are collected each day and downlinked daily to the U.S. and IC ground stations.

Despite the operational degradation of Landsat 5 capabilities, the TM data that are being collected, along with data in the USGS archives, have been well characterized and calibrated for radiometric and geometric accuracy. The Landsat 5 MSS data serve as the

Table 1
Landsat mission summary.

Mission	Instruments	Repeat cycle	Equatorial crossing	Launch	End of imaging
Landsat 1	MSS, RBV[1]	18 days	9:30 a.m. ± 15 min	July 23, 1972	January 6, 1978
Landsat 2	MSS, RBV	18 days	9:30 a.m. ± 15 min	January 22, 1975	February 25, 1982
Landsat 3	MSS, RBV	18 days	9:30 a.m. ± 15 min	March 5, 1978	March 31, 1983
Landsat 4	TM, MSS	16 days	9:45 a.m. ± 15 min	July 16, 1982	December 14,1993
Landsat 5	TM, MSS[2]	16 days	9:45 a.m. ± 15 min[3]	March 1, 1984	Ongoing
Landsat 6	ETM	16 days	10:00 a.m. ± 15 min	October 5, 1993	Failed to reach orbit
Landsat 7	ETM+[4]	16 days	10:00 a.m. ± 15 min	April 15, 1999	Ongoing
LDCM (Landsat 8)	OLI, TIRS	16 days	10:00 a.m. ± 15 min	December 2012 (tentative)	TBD

Notes: [1] RBV – Return Beam Vidicon; [2] MSS operation ended in August 1995 but routine acquisitions were discontinued in 1992 for the U.S., and in 1993 for International Cooperators; [3] adjusted to 10:00 to match Landsat 7 when USGS assumed operation in 2001; [4] scan-line corrector failure on May 31, 2003.

Table 2
Landsat payloads.

Instrument	Mission	Spectral bands	Ground sampling
Return Beam Vidicon (RBV)[1]	Landsats 1, 2, and 3	Visible blue-green (475–575 nm) Visible orange-red (580–680 nm) Visible red to near-infrared (690–830 nm)	80 m
Multispectral Scanner (MSS)	Landsats 1, 2, 3, 4, and 5	Visible green (0.5–0.6 μm) Visible red (0.6–0.7 μm) Near-infrared (0.7–0.8 μm) Near-infrared (0.8–1.1 μm) Thermal (10.4–12.6 μm)[2]	57 m × 79 m
Thematic Mapper (TM)	Landsats 4 and 5	Visible blue (0.45–0.52 μm) Visible green (0.52–0.60 μm) Visible red (0.63–0.69 μm) Near-infrared (0.76–0.90 μm) Mid-infrared (1.55–1.75 μm) Thermal (10.40–12.50 μm) Mid-infrared (2.08–2.35 μm)	30 m for VIS, NIR, MIR 120 m for Thermal
Enhanced Thematic Mapper Plus (ETM+)	Landsat 7	Visible blue (0.45–0.52 μm) Visible green (0.52–0.60 μm) Visible red (0.63–0.69 μm) Near-infrared (0.77–0.90 μm) Mid-infrared (1.55–1.75 μm) Thermal (10.40–12.50 μm) Mid-infrared (2.08–2.35 μm) Panchromatic (0.52–0.90 μm)	30 m for VIS, NIR, MIR 60 m for Thermal 15 m for Panchromatic
Operational Land Imager (OLI)	LDCM (Landsat 8)	Visible "ultra" blue (0.43–0.45 μm) Visible blue (0.45–0.52 μm) Visible green (0.53–0.60 μm) Visible red (0.63–0.68 μm) Near-infrared (0.85–0.89 μm) Mid-infrared (1.56–1.66 μm) Mid-infrared (2.10–2.30 μm) Mid-infrared "cirrus" (1.36–1.39 μm) Panchromatic (0.50–0.68 μm)	30 m for VIS, NIR, MIR 15 m for Panchromatic
Thermal Infrared Sensor (TIRS)	LDCM (Landsat 8)	Thermal (10.3–11.3 μm) Thermal (11.5–12.5 μm)	100 m nominal

Notes: [1] Landsat 3 RBV was changed to two panchromatic bands with 40 m ground resolution; [2] A thermal channel was added to the Landsat 3 MSS.

reference to which all previously acquired MSS data are calibrated. Likewise, Landsat 5 TM data serve as the reference to which Landsat 4 TM data are calibrated, and to which the TM data record has been cross-calibrated with the Landsat 7 ETM+ instrument data. The Landsat 5 TM and MSS sensors provide a bridge to the absolute calibration of MSS data.

2.2. Landsat 7 status

The Landsat 7 satellite was launched April 15, 1999 carrying the ETM+ instrument with a 5-year mission design life and improved capabilities over the previous TM instruments: a 15-meter resolution panchromatic band, high- and low-gain settings on a per-band basis, and a 60-meter thermal infrared band that was brought down in both a high- and low-gain mode to optimize the emissive measurements of the Earth's surface. Several new operations concepts were also introduced with the Landsat 7 mission: a long-term acquisition plan (LTAP) that defined the systematic collection of data on a global basis; development of an image assessment system (IAS) that would enable routine in-flight performance monitoring of the ETM+ instrument; and an under-fly with Landsat 5 during ascent to orbit to enable coincident imaging of selected geographic areas.

The LTAP was developed to optimize data collection based on the seasonal phenology of natural vegetation and agricultural practices; during scheduling, priorities based on this seasonality were modified using a region's predicted cloud cover relative to its historical cloud climatology and using acquisition history (Arvidson et al., 2001). The IAS was designed to monitor the in-flight performance of the ETM+ and to maintain calibration parameters for product generation. The under-fly activity afforded the opportunity for scientists to execute ground-based studies to collect in situ measurements of surface spectral properties and atmospheric conditions at the time of the coincident Landsat 5 TM and Landsat 7 ETM+ image acquisitions. These vicarious field campaigns and acquisitions over pseudo-invariant calibration sites have continued throughout the mission and have proven critical to our ability to maintain inter-calibration of Landsat 5 TM and Landsat 7 ETM+ data and will contribute to the rapid absolute calibration of data from the Landsat Data Continuity Mission (LDCM) once it becomes active.

Landsat 7 exceeded its design life in May 2004 and has experienced failures of some of its subsystems and components, but like Landsat 5, it was built with redundant capabilities. After irregular performance was observed, the USGS turned off one of three gyros in the attitude control system, leaving two for normal operations. A few memory boards within the solid-state recorder have been shut down, a few solar array circuits have also been shut down, and fuel line thermostats in the reaction control system have failed, but in all cases there is sufficient redundancy to maintain nominal spacecraft operations. The failure of the ETM+ scan line corrector (SLC) on May 31, 2003, which compensates for the forward motion of the spacecraft to align the forward and reverse scans of the ETM+, has resulted in scan line gaps resulting in a 22% data loss per scene. The radiometric and geometric performance of the ETM+ instrument, however, remains stable and the science quality of the data remains intact. Although a number of the ICs have ceased to receive direct downlink of ETM+ data, the solid-state recorder continues to enable global data collection and transmission to the network of ground stations maintained by the U.S.

2.3. Landsat archive status

The Landsat archive managed by the USGS includes nearly three million scenes covering the globe and dating back to 1972, and

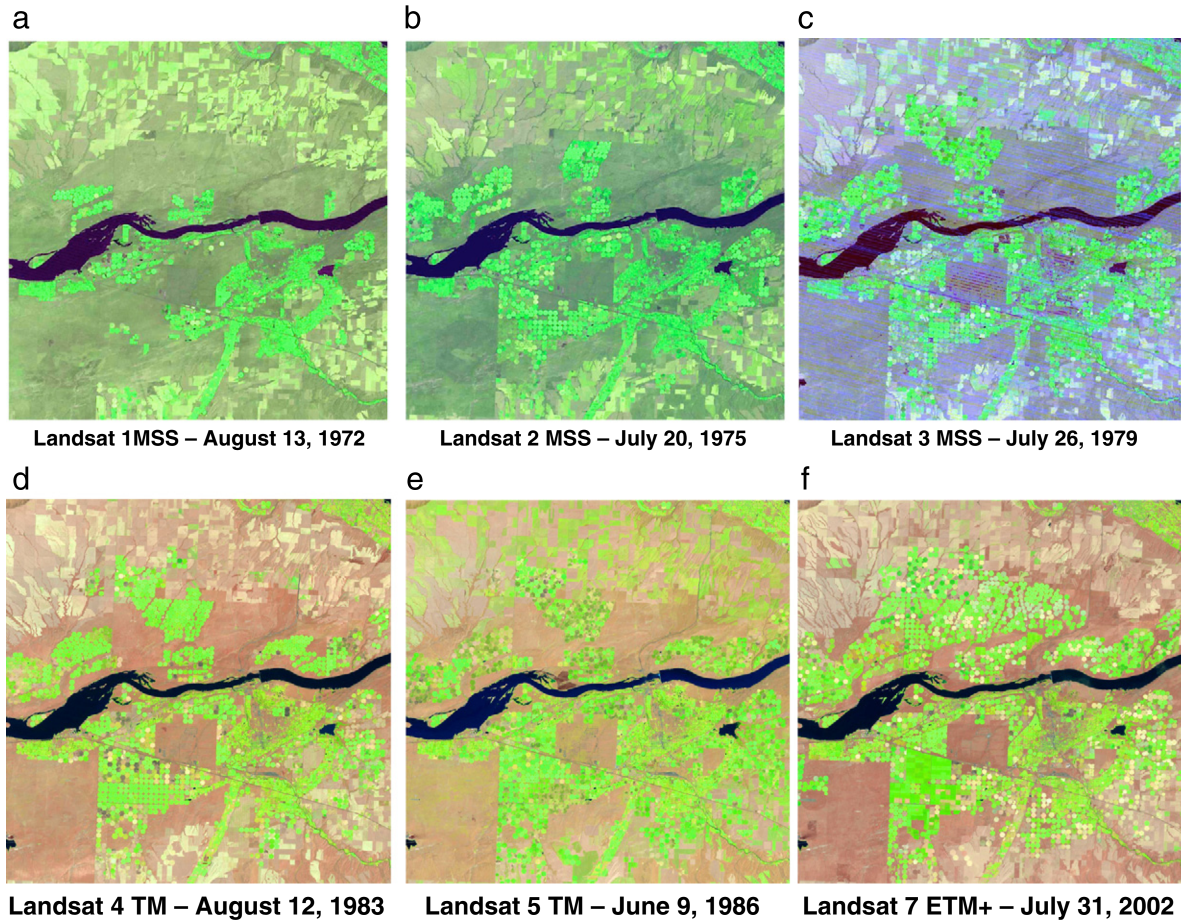

Fig. 1. Landsat 1–3 MSS, Landsat 4–5 TM, and Landsat 7 ETM+ images display irrigation expansion along the Columbia River (OR and WA) from 1972 to 2002.

approximately 440 new Landsat TM and ETM+ scenes are added to the archive every day (Table 3). Some concepts from the Landsat 7 LTAP have recently been incorporated into a new scheduling system for Landsat 5 to optimize data collection within the spacecraft's operating constraints as described earlier. Between 225–250 Landsat 5 images are acquired each day — depending on amount of sun lit land for a given day, including land within the IC ground station acquisition circles and all images of the contiguous United States. Of these, approximately 140 are added to USGS archives; Landsat 7 collects an average of 340 scenes per day, of which 300 are added to USGS archives. These missions comprise a unique, long-term, systematic collection of moderate resolution imagery (10–100 m spatial resolution) of the global land masses, resulting in an extensive global Landsat archive and the longest satellite remote sensing observations record of the earth's land surface.

All USGS-held Landsat data are archived on tapes and a digital copy of every image is also stored off-site. The Landsat holdings are periodically migrated to new storage media for preservation purposes. In order to decrease product generation latency, the USGS is in the process of moving all Level 0R (raw, unformatted) data to online storage in order to increase processing throughput for product generation.

Table 3
U.S. Landsat archive holdings as of April 15, 2011.

	MSS	TM	ETM+	Total
Number of available scenes	613,828	1,097,240	1,136,437	2,847,505
Data volume (terrabytes)	18	550	1055	1550
Number of scenes added daily	0	140	300	440

2.4. Web-enabled Landsat data

In late 2008, following changes to the USGS-NASA Landsat data policy, the U.S. Department of the Interior announced that all Landsat data would be "web-enabled", meaning that a standard Landsat product would be made available from the USGS archives via electronic distribution at no cost to the end user. Implicit in this announcement was sustainment of the longstanding policy of non-discriminatory access to the archive. Achieving this revolutionary change in Landsat data policy required a transformation in the product generation and distribution systems. Up to this point customers were able to order data products and specify the parameters for product generation (projection, pixel size, resampling method) and media options for distribution, but only Federal customers were allowed to order terrain-corrected orthorectified scenes. The cost for such products could range up to $600 per scene, and distribution peaked in 2003 with approximately 23,000 products, much of which was ETM+ data. In order to provide open access to products from the archive, a "standard web-enabled product" was prescribed—an orthorectified Level-1T (L1T). The L1T specifications are found in Table 4.

Now, with Landsat data available at no cost to users, as of this writing an average of 7600 scenes are being downloaded on a daily basis and another 2600 scenes are requested for on-demand processing each day. During the first year that web-enabled products were available (October 2008 through September 2009) over 1.14 million Landsat products were distributed. In the second year, more than 2.4 million products were distributed, and half-way through the third year 1.6 million products were distributed. In August of 2011, cumulative distribution of "web-enabled" Landsat products exceeded 6 million. Of notable significance is that the demand for data from the

Table 4
Description of the standard Level-1T (L1T) Landsat product.

Product type	Systematic or precision terrain correction pending availability of ground control points
Pixel size	30 m (TM, ETM+), 60 m (MSS)
Map projection	Universal transverse mercator
Datum	WGS84
Orientation	North-up
Resampling method	Cubic convolution
Output format	GeoTIFF
Geometric accuracy	~30 m RMSE (U.S.), ~50 m RMSE (Global)

historical archive increased significantly in addition to the demand for data from recent years. The new data policy truly revolutionized the use of Landsat data for education, research, and applications.

2.5. Expanding the historical global Landsat archive

The USGS Landsat holdings represent only a portion of the Landsat scenes acquired since the launch of Landsat 1. In addition to acquisitions obtained by the USGS through direct downlink, data relay, or other means, Landsat scenes are acquired and independently archived by the Landsat ICs. Recent analysis suggests that approximately 5 million Landsat scenes are held in international archives maintained by the ICs, and perhaps as many as 3 million of these scenes are unique and not duplicated in the USGS Landsat archive. The international ground stations hold significant amounts of historical Landsat data and the long-term viability of those data could, in some cases, be in jeopardy. In addition, the IC archives represent an invaluable collection to which uncomplicated access is needed by the science and applications user community (Loveland & Irons, 2007).

At the recommendation of the USGS–NASA Landsat Science Team, the USGS is working toward repatriating as much of these historical holdings as possible through the Landsat Global Archive Consolidation (LGAC) initiative (Loveland & Irons, 2007; Loveland & Irons, 2010). The benefits of doubling the size of the global Landsat archive and providing centralized access to all Landsat data will benefit all Landsat users. However, determining the exact extent of the international holdings is challenged by the fact that some ground stations have been inactive for many years and access to the data may not be possible. Some of the early coverage is in danger of being permanently lost due to loss of accessibility and archive media degradation. In addition, the U.S. did not retain the rights to data from Landsat 1–5 so cooperation in the archive consolidation initiative is voluntary. Most ICs recognize the value of the USGS Landsat Global Archive Consolidation initiative. The most important LGAC partner is the European Space Agency with an estimated 2.09 million scenes, or 42% of the internationally held Landsat data. Table 5 summarizes the current analysis of expected scene availability.

The LGAC initiative has benefitted from improved Internet technology in the IC countries that enables many ground stations to send current Landsat data to EROS as they are collected. Updates to the Landsat 5 scheduler will take advantage of the availability of cloud-cover assessments from the IC acquisitions.

At this point, the USGS is working with willing ICs to begin gathering and transferring historical Landsat images to the USGS archive. The implementation plan prioritizes repatriation opportunities based on science needs (e.g., data most endangered, areas where the USGS Landsat holdings are limited or deficient, and areas with special significance such as the humid tropics and Arctic regions). Progress is already being made and as of today, more than 300,000 Landsat scenes have been added to the USGS archive. These scenes have come from Canada, Australia, Argentina, and Indonesia. The repatriated scenes are accessible using the standard Landsat query and selection tools. All IC-contributed data are being processed consistently to the L1T standard, regardless of data origin.

Table 5
Estimated Landsat holdings in International Cooperator archives.

Station location and code	Number of scenes in 1000s	Percent of international holdings
Europe (ESA)	2,090	42%
Australia (GA-NEO)	629	13%
Canada (CCRS)	532	11%
China (CEODE)	449	9%
Japan (RESTEC)	275	6%
Brazil (INPE)	234	5%
Argentina (CONAE)	195	4%
South Africa (CSIR-SAC)	154	3%
Thailand (GISTDA)	90	2%
Germany (DLR) @ESA	87	2%
Saudi Arabia (KACST MAW)	69	1%
India (NRSA)	51	1%
US (U of Puerto Rico)	42	1%
Ecuador (CLIRSEN)	40	1%
Pakistan (SUPARCO)	24	<1%
Japan (HIT)	21	<1%
Indonesia (LAPAN)	8	<1%
Total estimated international scenes	4990	100%

Other additions to the USGS archive are the “MSS orphans.” These are Landsat 1–3 MSS scenes that could not be processed due to missing ephemeris (e.g., scene center latitude and longitude, spacecraft attitude, sun elevation/azimuth, and sensor gain). USGS engineers and technicians located ephemeris data from old 9-track tapes and were able to recover over 170,000 scenes, of which 106,335 are new unique additions to the USGS Landsat archive. It is anticipated that much of the IC MSS data will fall into this category.

2.6. Landsat product generation system

The Landsat product generation system (LPGS) is based on a modular and scalable architecture to which additional storage and processing nodes can be easily added to increase capacity and performance. As Landsat 5 and 7 data are received and archived at the USGS EROS Center, an automated cloud cover assessment algorithm computes the percentage of cloud cover for each scene as an attribute for the inventory metadata. Scenes that are acquired with less than 60% cloud cover are immediately processed to generate L1T products. The Earth Explorer (http://edcsns17.cr.usgs.gov/NewEarthExplorer/) and Global Visualization Viewer (http://glovis.usgs.gov/) tools can be used to search and query the archive. These tools enable the viewing of browse images and determining whether standard products are available for immediate download. In cases where the desired data are not immediately available for download, an on-demand processing request can be submitted, which includes the ability to order and process any of the nearly three million archived Landsat images. Once the data have been processed, an email is sent to the requestor with a universal resource locator (URL) from which to retrieve the data via FTP. The current processing capacity of LPGS is 3500 scenes per day, although a record 9,000 scenes were recently processed in a single day. L1T products are held in an online cache for FTP retrieval for 90–100 days.

Current enhancements to LPGS emphasize improved geometric accuracy, absolute radiometric calibration for all sensors, fewer source images that fail to process, and improved access to data to facilitate the automatic analysis of long dense time series. Both IAS and LPGS populate an extensive trending database of geometric and radiometric parameters that are used for the continual improvement of the Landsat products. The LPGS system is increasingly robust and can process data with minimal control. Much of the data from ICs will benefit from these LPGS enhancements and the lessons learned.

A new capability was recently added to the LPGS to generate a 3-band full spatial resolution “browse” image from L1T products that are created both routinely and on-demand. The “LandsatLook” products use bands 5, 4, and 3 of TM and ETM+ data, and bands 2, 4, 1 for MSS data. These images have been processed to top of atmosphere reflectance to normalize solar illumination and viewing geometry, as well as earth–sun distance to adjust for seasonal variation of the solar irradiance. The data are scaled to 8-bits per band and provided in JPEG format. LandsatLook products were developed to enable geospatial applications that do not have the need or capability to perform quantitative multispectral image analysis. The LandsatLook products are available as options when downloading the L1T data through the Earth Explorer and Glovis client interfaces. LandsatLook images may be downloaded simply as JPEG images or with geographic reference information for import into a geographic information system or image processing software packages.

3. The future of Landsat

The next few years are quite possibly going to be Landsat's "golden years" and could be the time in which the Landsat program achieves its full potential. There are several activities underway that are the foundation of a new Landsat era. These include the impacts of the Landsat free data policy, efforts to expand the historical global Landsat archive, the steps underway to produce Landsat science products, and the establishment of an operational Landsat program.

3.1. The Landsat free data era benefits

In the short time since the USGS made their entire Landsat archive available to anyone at no cost via the Internet, significant benefits are already being realized within the Landsat data user community. For the first time, Landsat data users can now access the data they *need* for their research or applications, rather than the data they could *afford*. Free data benefits include the following:

Free data is key to LGAC. The ability to process new and historical IC data to a high quality calibrated product results in a cost savings to the ICs and provides them access to data that they cannot currently process efficiently, if at all.

Significant resource savings for projects. This is an obvious but significant benefit. Funds normally reserved for Landsat data purchases can now be used to improve analysis results or other aspects of the project. For example, the cost savings can be used to improve reference data (e.g., field data collection or very large scale imagery acquisitions), expand study scope or objectives, or accelerate project schedules.

Enables investigations that were previously not feasible. This is especially the case for studies that span larger geographic areas, address land change over longer periods of time, or are conducted in persistently cloudy areas (e.g., humid tropics, high latitudes). In Broich et al.'s (2011) study of Indonesian forest change, they concluded that consistent and timely forest cover loss updates from regional to biome scales were now possible due to the elimination of Landsat data costs. In another example, the United Nations Food and Agriculture Organization is now able to use Landsat to conduct remote sensing survey of global forest cover in 2010 (Potapov et al., 2011).

Improved accuracy of derived products. The advantages of multi-temporal analysis as a means to improve the accuracy of characterizations of land surface conditions is well known (Kennedy et al., 2010). With Landsat, multi-temporal analysis was problematic due to the high cost of individual Landsat scenes. Studies were typically restricted to using a small number of near-cloud free scenes for budgetary reasons. Now, users can use all scenes, even those with significant amounts of cloud cover.

Innovations in data handling and processing. New algorithms for analysis of dense time series (e.g., Kennedy et al., 2010) are emerging due to Landsat data affordability. Roy et al. (2010) have developed an innovative Landsat 7 data handling strategy in which over 6500 Landsat scenes per year are being used to produce temporally composited mosaics of the conterminous U.S. and Alaska. These datasets include seamless monthly, seasonal, and annual composites. Roy et al.'s strategy also provides evidence that the impacts of the Landsat 7 ETM+ scan-line corrector data gaps can be mitigated using every available cloud-free pixel.

These emerging capabilities indicate that we are entering a period of unprecedented innovation in Landsat science and applications. The unlimited access to Landsat data will stimulate academic, government, and commercial research in new Landsat analysis strategies and applications. The exposure of Landsat to broader audiences will increase the awareness of the value of Landsat and contributes to improving the understanding of the changing Earth.

3.2. Landsat science products

With the support of the Landsat Science Team, the USGS is developing plans to produce and distribute science-quality, applications-ready, time series of key terrestrial variables that are consistent over the full 39-year record and suited to detecting and monitoring changes in land surface conditions. In today's information-driven geospatial world, an increased understanding of the complexity of many of today's most challenging problems coupled with ubiquitous geographic information systems and significant advances in computational modeling has created an almost insatiable demand for timely, accurate, and relevant datasets. While Landsat data are an extraordinary source for many environmental variables, in fact, the process of transforming Landsat spectral measures into useful geospatial datasets is complex and exceeds the capabilities and resources of many users.

The terrestrial variables will follow the guidelines established through the Global Climate Observing System (GCOS) and include Fundamental Climate Data Records (FCDRs) of calibrated radiances for each of the instrument data records, Thematic Climate Data Records (TCDRs) that consist of geophysical parameters retrieved from Landsat data (e.g., surface reflectance and surface temperature), and Essential Climate Variables (ECVs) that represent specific geo-and biophysical land properties (World Meteorological Organization, 2010).

The Landsat Science Team is providing technical input regarding CDR and ECV priorities and processing algorithms. The Team has recommended that the FCDRs have the following characteristics to serve as the building blocks for TCDRs: (a) calibration across the Landsat instrument record, (b) orthorectification, (c) cloud and shadow masking. The FCDR's must be further processed to remove or reduce the effects of all scattering and absorbing constituents. In addition, because of data gaps caused by clouds, shadows, and instrument anomalies, temporal compositing and mosaicking will likely be necessary.

The USGS plans to produce prototype on-demand surface reflectance products in 2011 using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) atmospheric correction approach (Masek et al., 2008; Vermote & Saleous, 2007). The EROS Science Processing Architecture (ESPA) framework was developed for processing Landsat science products. ESPA provides a modular design with science computing capabilities and scalable capacity. The LEDAPS software has been integrated into ESPA. Following an evaluation period, an operational surface reflectance processing capability is planned for 2012. Procedures for surface temperature processing are being developed and plans are to produce prototypes in 2012.

In addition to the surface reflectance and temperature plans, the USGS also is committed to developing and distributing terrestrial ECVs. The highest priority is the establishment of a global 30 m land cover mapping and monitoring capability (DOI, 2010). Preliminary plans call for the development of land cover continuous fields on an annual basis, and land cover types every five years. The second priority is a global leaf area index (LAI) dataset. In the case of LAI, USGS plans are to initially distribute data produced by researchers at the NASA Ames Research Center, with the goal of transitioning this processing capability to the USGS EROS Center.

3.3. Landsat data continuity mission

The next Landsat mission, LDCM, is a collaboration between NASA and the USGS. LDCM, which will be renamed Landsat 8 following launch in December 2012, has a five year design life and 10 years of consumables. LDCM can potentially extend the Landsat record to 50 years. The LDCM payload consists of two science instruments. The Operational Land Imager (OLI) provides visible, near-infrared, and middle-infrared observations at 30 m spatial resolution (see Table 2), and a panchromatic band at 15 m spatial resolution. OLI includes two new spectral bands — an "ultra" blue visible channel designed for water resources and coastal zone investigations, and a middle-infrared band for use in detecting cirrus clouds. OLI is a pushbroom imaging system and is being built by Ball Aerospace and Technology in Boulder, CO. The Thermal InfraRed Sensor (TIRS) has two thermal channels at 100 m spatial resolution. TIRS is being built by NASA Goddard Space Flight Center and the instrument is based on quantum well infrared photodetector (QWIP) technology. Both TIRS and OLI will collect 12 bit data and even though OLI and TIRS are separate instruments, scene-based products will be integrated and available as L1T orthorectified image data sets.

Like past Landsats, LDCM will orbit at 705 km, image a 185-km-cross-track-by-180-km-along-track swath, and repeat coverage every 16 days. Like Landsat 7, LDCM will use the LTAP to acquire global seasonal coverage each year. LDCM will have a higher imaging capacity than previous Landsats. LDCM is required to return 400 scenes per day to the USGS data archive (150 more than Landsat 7 design specifications), increasing the probability of capturing cloud-free scenes. Irons et al. (2012, in this issue) provide a comprehensive discussion of the LDCM mission.

4. An operational national land imaging program?

William Pecora and Stewart Udall might be pleased with the scientific and operational impacts that have been achieved through the six successful Landsat missions, and they would surely be quite enthusiastic about the upcoming Landsat Data Continuity Mission. However, they would be disappointed that, in spite of the many successes, Landsat has yet to achieve operational status. That situation may be changing.

In 2007, the Future of Land Imaging Interagency Working Group (2007) sponsored by the White House Office of Science and Technology Policy (OSTP) issued a set of policy recommendations to achieve a sustainable Landsat-class imaging capability, and to ensure continued US scientific, technical, and policy leadership in civil land imaging. Specific recommendations called for the formation of a National Land Imaging Program in the DOI, and making Landsat an operational program. While the recommendations were not carried out prior to the change in administrations, the current administration has adopted the essence of the 2007 report.

As part of the President's National Space Policy released in June 2010 (Office of the President, 2010), NASA and the DOI were directed to work with the OSTP and the Office of Management and Budget (OMB) to define an approach for establishing an operational land imaging program that would include a sustained a commitment to the development and operation of future Landsat missions. It was agreed that the DOI would have the programmatic lead, including budget and requirements responsibilities, NASA would retain responsibility for the flight systems development, and DOI through the USGS would continue to be responsible for the ground systems development, mission operations, and data archiving, processing and distribution. In late 2010, this approach to managing an operational Landsat program was agreed to by NASA, DOI, OSTP, and OMB.

On February 14, 2011, President Obama submitted his fiscal year 2012 budget to Congress. The budget includes language designating DOI as the leader of a new National Land Imaging Program, and includes a request for funds to initiate Landsats 9 and 10. Should funding be approved by the Congress, the USGS and NASA will work toward a goal for a late-2018 Landsat 9 launch, followed by a 2023 Landsat 10 launch. The USGS will assume management of the program, but NASA will continue to play a primary role and will develop the space segment for future Landsat missions. Because avoidance of a Landsat data gap is a high priority, and because the development-to-launch cycle for Landsat-class satellites is typically five years, Landsat 9 will likely use technologies based on LDCM. However, the USGS will conduct a rigorous requirements review before finalizing Landsat 9 and 10 capabilities.

Considering all of these developments, Landsat may have come full circle. From the early promotion of the Landsat concept by Pecora and Udall to the recent recommendation to assign Landsat leadership to the DOI, the long-term fate of Landsat may finally become stable. With its historical performance consistency, continuous global coverage, and very high quality of data, Landsat has become a vital tool worldwide for understanding scientific issues related to land use and natural resources. International applications of Landsat data have become widespread for use in agriculture, forestry, mapping, land and water assessments and climate change study. The major challenge facing Landsat users has been the tenuous nature of Landsat missions and funding. Perhaps that challenge will be lifted soon.

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