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Landsat 8: The plans, the reality, and the legacy

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ABSTRACT

Landsat 8, originally known as the Landsat Data Continuity Mission (LDCM), is a National Aeronautics and Space Administration (NASA)-U.S. Geological Survey (USGS) partnership that continues the legacy of continuous moderate resolution observations started in 1972. The conception of LDCM to the reality of Landsat 8 followed an arduous path extending over nearly 13 years, but the successful launch on February 11, 2013 ensures the continuity of the unparalleled Landsat record. The USGS took over mission operations on May 30, 2013 and renamed LCDM to Landsat 8. Access to Landsat 8 data was opened to users worldwide. Three years following launch we evaluate the science and applications impact of Landsat 8. With a mission objective to enable the detection and characterization of global land changes at a scale where differentiation between natural and human-induced causes of change is possible, LDCM promised incremental technical improvements in capabilities needed for Landsat scientific and applications investigations. Results show that with Landsat 8, we are acquiring more data than ever before, the radiometric and geometric quality of data are generally technically superior to data acquired by past Landsat missions, and the new measurements, e.g., the coastal aerosol and cirrus bands, are opening new opportunities. Collectively, these improvements are sparking the growth of science and applications opportunities. Equally important, with Landsat 7 still operational, we have returned to global imaging on an 8-day cycle, a capability that ended when Landsat 5 ceased operational Earth imaging in November 2011. As a result, the Landsat program is on secure footings and planning is underway to extend the record for another 20 or more years.

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1. Introduction

The NASA-USGS Landsat Data Continuity Mission (LDCM) was successfully launched on February 11, 2013 ensuring the continuity of the unparalleled Landsat record. Following 3 months of on-orbit verification of LDCM's capabilities by NASA and LCDM partners, the USGS took over mission operations on May 30, 2013, renamed LCDM to Landsat 8, and opened access to Landsat 8 data to users worldwide.

True to the continuity name, LDCM was to add to the longest, continuous, and unprecedented space-based global land survey (NASA, 2013). "The LDCM is the successor mission to Landsat 7. Landsat satellites have continuously acquired multispectral images of the global land surface since the launch of Landsat 1 in 1972. The Landsat data archive constitutes the longest continuous moderate-resolution record of the global land surface as viewed from space. The LDCM mission objective is to extend the ability to detect and quantitatively characterize changes on the global land surface at a scale where natural and human-induced causes of change can be detected and differentiated."

The conception of LDCM to the reality of Landsat 8 followed a winding path extending over nearly 13 years. Initially, LCDM was to be a Federal data purchase activity involving a privately-owned and commercially operated system. This system was to provide 250 scenes daily that were consistent with previous Landsat collections but would include two new bands, blue and cirrus, and would not have a thermal imaging capability (Irons et al., 2003). That plan gave way to a new approach to include Landsat imaging capabilities on the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) with an instrument named the Operational Land Imager (OLI) that would be launched in 2009 (Irons and Ochs, 2004). Finally, in 2005, when a third strategy was defined for a free-flying satellite (Fig. 1), the development of what became Landsat 8 started in earnest (Irons and Masek, 2006). Irons et al. (2012) provide a detailed summary of the free-flying LDCM requirements and capabilities, including the plans for OLI and the addition of the Thermal Infrared Sensor (TIRS). The LDCM development was a partnership between NASA and the USGS, with NASA responsible for the space segment including instruments, spacecraft, and launch, and the USGS responsible for the ground system development and operational activities following launch.

Now 3 years past the successful launch, with this special issue, we present the science and applications lessons learned so far. We

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Fig. 1. Artist's depiction of the Landsat 8 in orbit.

summarize major Landsat 8 characteristics, lessons learned, and we review whether the expectations for the mission are being met.

2. LDCM/Landsat 8 mission requirements

As the follow-on to Landsat 7, the LDCM mission objective was to "extend the ability to detect and quantitatively characterize changes on the global land surface at a scale where natural and human-induced causes of change can be detected and differentiated" (NASA, 2013). The major mission objectives were to:

- *Collect and archive moderate-resolution, reflective multispectral image data affording seasonal coverage of the global landmass for a period of no less than 5 years.* This objective led to inclusion of the OLI instrument.
- *Collect and archive moderate-resolution, thermal multispectral image data affording seasonal coverage of the global landmass for a period of no less than 3 years.* This objective led to the inclusion of the TIRS instrument.
- *Ensure that LDCM data are sufficiently consistent with data from the earlier Landsat missions, in terms of acquisition geometry, calibration, coverage characteristics, spectral and spatial characteristics, output product quality, and data availability to permit studies of land cover and land use change over multi-decadal periods.* This resulted in the continued use of the World Reference System-2 that allows a 16-day repeat cycle using a 185-km-wide swath consistent with Landsat 4–7 as well as OLI and TIRS spectral bands covering the range afforded by the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors.
- *Distribute standard LDCM data products to users on a nondiscriminatory basis and at no cost to the users.*

Consistent with the Landsat legacy, LDCM promised significant evolutionary technical improvements in capabilities needed for Landsat scientific and applications investigations. Major improvements included:

- Collecting 11 bands of multispectral imagery with OLI and TIRS with 30 m and 100 m spatial resolution respectively (see Table 1).
- Changing instrument technology that provided improved (1) onboard radiometric calibration, (2) significant improvements in each band's signal to noise ratio (SNR), and (3) the quantization of observations at 12-bit radiometric resolution. Geolocation capabilities were also improved.
- Improving the daily acquisition capacity. The Landsat 8 requirement was 400 images per day as compared to the Landsat 7 requirement to collect 250 images per day.
- Improving the ground network so that all data imaged each day are relayed to the USGS EROS for immediate processing and distribution to Landsat users.

Table 1
Spectral bands of the Operational Land Imager (bands 1–9) and Thermal Infrared Sensor (bands 11–12). Observations are quantized over a 12-bit dynamic range and provided to users as 16-bit numbers. Note that the 100 m thermal bands are resampled to 30 m in the Landsat 8 data product.

Bands	Wavelength (micrometers)	Spatial resolution (meters)
Band 1 – coastal aerosol	0.43–0.45	30
Band 2 - blue	0.45–0.51	30
Band 3 - green	0.53–0.59	30
Band 4 - red	0.64–0.67	30
Band 5 - near infrared (NIR)	0.85–0.88	30
Band 6 - SWIR 1	1.57–1.65	30
Band 7 - SWIR 2	2.11–2.29	30
Band 8 - panchromatic	0.50–0.68	15
Band 9 - cirrus	1.36–1.38	30
Band 10 - Thermal Infrared 1	10.60–11.19	100
Band 11 - Thermal Infrared 2	11.50–12.51	100

- Standardizing the primary Landsat 8 WRS-2 scene-based Level 1 products, in both terrain-corrected orthorectified formats (L1T) or systematically corrected (L1G) – see Irons et al. (2012) for specifications.

Detailed discussions of the requirements, specifications, design considerations, and pre- and post-launch instrument performance of LDCM/Landsat 8 have been summarized in many publications. For example, prior to the February 2013 LCDM launch, Irons et al. (2012) published an overall mission description, and Markham et al. (2012) and Reuter et al. (2010) published details on OLI and TIRS technologies and capabilities respectively. Following launch, Markham et al. (2014) organized a special issue of *Remote Sensing* on "Landsat-8 Sensor Characterization and Calibration" that provided design, pre-launch, and on-orbit spectral and geometric characterizations of the OLI and TIRS instruments.

In the special issue collection, Knight and Kvaran (2014) provided a detailed description of OLI design and performance. Markham et al. (2014) summarized both pre-launch and on-orbit OLI radiometric calibration and stability and reported, except for the coastal aerosol band, OLI stability has been better than 0.3%. Morfitt et al. (2015) concluded that OLI radiometric performance met or exceeded expectations due to pre-launch calibration efforts, and that since launch, calibration updates have improved image quality even more. Finally, Storey et al. (2014) summarize on-orbit geometric performance and concluded that all geometry requirements are being met or exceeded.

In more recent journal publications, Pahlevan et al. (2014) provided an on-orbit radiometric assessment of OLI and concluded that that for aquatic applications, the absolute radiometric performance of visible and near-infrared channels (except for the new 443-nm coastal aerosol band - band 1) over water agrees with top-of-atmosphere (TOA) radiances estimated by ocean color satellites. In addition, Czapla-Myers et al. (2015) conducted OLI TOA spectral reflectance and radiance comparisons with ground-based measurement and conclude that except for band 7 (shortwave), reflectance is within $\pm 3\%$ and radiance is within $\pm 5\%$ of the OLI design specifications. They also report that Landsat 7 ETM+ and OLI TOA radiance and reflectance obtained during the March 2013 tandem acquisitions are within $\pm 2\%$ and 4% respectively.

Regarding TIRS performance, in the *Remote Sensing* special issue, Reuter et al. (2015) provide an overview of the TIRS instrument design, pre-launch calibration, and initial on-orbit performance. More details on TIRS performance was provided by Barsi et al. (2014), including their comparison of TIRS observations with buoy in situ measurements that showed that TIRS data in both thermal bands resulted in TOA brightness temperatures that were too warm (+2.1 K for band 10 and +4.4 K at 300 K for band 11) when compared to buoy-measured surface water temperatures propagated through model atmospheres. Even following a ground system calibration update, the variability was still larger than desired for both band 10 and band 11 (0.87 and 1.67 K, respectively, at 300 K). Barsi's team concluded that the source of the calibration error was out-of-field stray light. Montanaro et al. (2014a, 2014b) provided additional details on on-board radiometric performance and they conclude that band 10 has generally adequate uniformity performance but because of the stray light issues, band 11 should not be used. Because of the band 11 problems, the USGS advises against the use of band 11 and split window techniques for atmospheric corrections leading to surface temperature retrievals. Meanwhile, stray light correction methods are being developed.

TIRS has suffered an anomaly that has resulted in an alternate mode of operations to collect thermal imagery. An increase in the current flowing to an encoder for the TIRS scene select mirror (SSM) was found in late 2014. The SSM transitions the TIRS view from the Earth to an on-board black body and to deep space for calibration. The encoder precisely records the SSM position to facilitate geolocation of the thermal data for registration to OLI data and to the cartographic projection used for Level 1 products. Alternate modes of operating TIRS without sending power to the encoder were tested and then operations were switched to a redundant set of TIRS electronics, known as Side B, and the nominal mode of operation was resumed in early 2015. The symptoms of high encoder current reappeared on Side B in late 2015 and a decision was made to operate on Side B in an alternate mode, known as Mode 0, beginning in early 2016. In Mode 0 the SSM will be moved to view the black body and deep space on a less frequent basis than in the nominal mode; approximately once every 2 weeks compared to before and after each orbit. The TIRS detectors have been stable and no degradation in radiometric calibration accuracy is anticipated.

Only a few days of TIRS data collection have been lost through the anomaly investigations and changes to operations. Processing of thermal data, however, has been delayed. In Mode 0 no current is applied to the SSM encoder when TIRS views the Earth and encoder data are no longer available to precisely locate the mirror position. Instead, the mirror position has to be determined from ground control and this has up to now required procedures not yet automated. TIRS data collected during the last quarter of 2015, for example, were not processed until early 2016. Reprocessing has since been performed to provide the products with valid thermal data and routine provision of Level 1 products with thermal data has resumed. As with radiometric calibration, there is little or no degradation to the geolocation of TIRS data. Mode 0 operations pose no known threat to the TIRS operational lifetime and thermal data collection is expected to continue long past the 3-year TIRS design life.

Comprehensive information on Landsat 8 systems, algorithms, and other relevant technical documentation are found in the on-line Landsat 8 Data Users Handbook (http://landsat.usgs.gov/l8handbook.php). In the remainder of this paper, we summarize the current status of Landsat 8 and the scientific and technical advances achieved thus far.

3. Landsat 8 mid-term evaluation

Landsat 8 continues the legacy of continuous observations since mid-1972, meeting the continuity objective and there are high expectations that Landsat 8 will extend the Landsat record to 45–50 years, or more. In addition, in tandem with Landsat 7, we have returned to global imaging on an 8-day cycle, a capability that ended when Landsat 5 ceased operational imaging in November 2011.

To date, the evidence shows that with Landsat 8, we are acquiring more data than ever before, those data are generally technically superior to data acquired by past Landsat missions, and the new measurements, e.g., the coastal aerosol and cirrus bands, are opening new opportunities. Collectively, these improvements are sparking the growth of science and applications opportunities.

3.1. More data

With Landsat 8′s significantly improved imaging capacity, approximately 725 images per day are now being acquired and the newly acquired images are available to users in less than 8 h after acquisition. This exceeds the design requirement by 55%. In addition, Landsat 8′s capabilities have led to improvements in Landsat 7′s acquisition plans and rates, and the result is an unprecedented addition of nearly 1200 Landsat 7 and 8 images to the Landsat archive each day. Wulder et al. (2016) trace the dramatic increase in daily acquisitions and the scientific and operational benefits now and in the future. The expanded acquisitions are benefiting all applications, especially international studies.

The ability to image more frequently in persistently cloudy areas (e.g., humid tropics, high latitudes) is improving studies in areas of critical importance for understanding climate and land use change. Fahnestock et al. (2016-in this issue) conclude that the higher acquisitions rate will significantly benefit snow and ice investigations because cloud-free pixel coverage in mountain terrain and polar regions can be acquired over shorter periods of time. Sheng et al. (2016-in this issue) found improvements in mapping lake extent in Oceania. Hansen et al. (2016-in this issue) noted consistent results in mapping tree cover and tree height attributes in Sub-Saharan Africa using Landsat 7 and 8 but noted that Landsat 8′s advantage is an increased number of observations. Dong et al. (2016-in this issue) concluded that increased daily acquisitions and return to 8-day imaging improved large-area paddy rice mapping in northeastern Asia.

3.2. Better data

Landsat 8 data are radiometrically and geometrically superior as compared with data from previous Landsat missions. Landsat 8 radiometry has improved significantly due to the improved signal-to-noise ratios (SNR), wider dynamic ranges, onboard radiometric calibration devices on both OLI and TIRS, and the change from 8- to 12-bit measurements. Regarding calibration, Mishra et al. (2016-in this issue) conclude that Landsat 8′s radiometry is more consistent than previous missions, and this is due to better on-board and vicarious calibration capabilities.

The advantages of improved SNR are cited in several articles. For example, Schott et al. (2016-in this issue) concluded that the improved SNR benefits almost all tested applications and that performance is strongly controlled by increased SNRs. Glenn et al. (2016-in this issue) found that the improved SNR and 12-bit radiometric resolution of OLI resulted in subtle but significant increases in the detection of dryland vegetation characteristics. Lymburner et al. (2016-in this issue) evaluated the impact of improved radiometry for studies of total dissolved solids in water and concluded that the improved SNR and increased quantization of OLI significantly reduced image noise and spectral heterogeneity, which should lead to more precise water quality retrievals than possible with Landsat 7.

In an investigation of the use of Landsat 8 data to quantify fine-scale albedo patterns, Wang et al. (2016-in this issue) cited improvements in OLI radiometry that eliminates saturation over snow, more stable geometry, and 30 m resolution, as reasons why Landsat 8 observations will become an important input to studies of early spring snow albedo dynamics. Schroeder et al. (2016-in this issue) concluded that OLI's radiometric improvements and 30 m spatial resolution will allow detection of active fires in significantly smaller areas than is possible with current operational satellite fire products, and this should lead to OLI-based active fire measurements becoming part of the international network for monitoring biomass burning.

Olmanson et al. (2016-in this issue) conclude that water clarity measurements using OLI observations are slightly improved over those from Landsat 7, indicating both measurement consistency and an incremental improvement over data from previous missions. Killic et al. (2016-in this issue) found that 12-bit quantization showed slightly improved evapotranspiration (ET) retrievals over 8-bit measurements, though the differences were low. They also demonstrated that data continuity and consistency objectives were met based on their comparison of ET calculated from March 2013 Landsat 7–8 underflight measurements.

Changes in bandwidth properties have improved OLI data's ability to meet requirements of specific applications but also have resulted in some technical challenges when comparing Landsat 8 data with those of previous Landsat missions. Holden and Woodcock (2016-in this issue) looked at the Landsat 7–8 underflight data from March 2013 and found that Landsat 8 blue, green, and red bands had consistently lower values than similar Landsat 7 bands and that adjustments would be needed if Landsat 8 data are integrated into Landsat 4–7 time series. Vogelmann et al. (2016-in this issue) concluded that while there are some differences between OLI, ETM + and TM surface reflectance data due to bandwidth differences, OLI data are generally comparable with ETM + and TM without major correction when monitoring vegetation condition in semi-arid settings. On the other hand, the Zhu et al. (2016-in this issue) urban greening trends study concluded that Landsat 8 data are not completely consistent with observations from previous Landsat missions and found that this leads to biases when using vegetation indices for looking at long-term vegetation condition trends. They suggest the use of the Enhanced Vegetation Index (EVI) will result in less bias than measures from the ubiquitous Normalized Difference Vegetation Index (NDVI).

Two additional studies address the differences and offer solutions that may be used in time series investigations spanning several Landsat missions. Roy et al. (2016-in this issue) found that the differences between OLI and ETM + TOA reflectance were greatest for NIR and SWIR bands due to dissimilarities in spectral response functions but the differences are reduced when atmospheric corrections are applied. While this leads to higher OLI NDVI versus ETM + NDVI for vegetated surfaces, correction coefficients can be used to normalize Landsat 8 data with observations from previous Landsat missions. Huntington et al. (2016-in this issue) noted the impact of different NIR bandwidths between OLI and ETM + but determined that linear regression can be used to adjust for the differences without impacting time series analyses.

Landsat 8′s geometric and geodetic accuracy is significantly better than previous Landsat missions (~11.4 m when referenced to ground control points, and ~37 m in absolute geodetic accuracy). In fact, in many cases, Landsat 8 accuracy exceeds the accuracy of current ground control. Development is underway to use Landsat 8 images to update ground control, and the new control should significantly improve the geometric stability of the entire Landsat archive. The improved geometry has significant benefits in studies of ice movement. Fahnestock et al. (2016-in this issue) showed that the combination of the improved geometry of the 15 m pan band (band 8) and the elimination of bright target saturation enables tracking of ice sheet displacements with nearly 1 m precision. Sheng et al. (2016-in this issue) evaluated Landsat 8 data for lake extent mapping and monitoring and found that water body identification improved due to improved radiometric properties. SNR improvements in the green and NIR bands and the 12-bit quantization were key reasons for the improvements. They also noted that improved geodetic performance benefits multi-temporal monitoring of water body extent.

3.3. New observations – enabling new measurements

Perhaps the most anticipated new Landsat 8 capabilities include the three additional spectral bands, band 1, coastal aerosol blue band (0.433–0.453 μm), band 9, cirrus band (1.360–1.390 μm), and thermal was split into two bands (bands 10 and 11) with the intent of enabling split window correction. Of these, the cirrus band has had a significant impact on a wide range of research studies and operational applications. Holden and Woodcock (2016-in this issue) found that the cirrus band allowed detection of subtle contamination from cirrus clouds. Senay et al. (2016-in this issue) found that the cirrus band enabled better cloud masking, and by removing contaminated pixels, ET estimates over large areas improved. Vermote et al. (2016-in this issue) took it a step further and concluded that atmospheric corrections and surface reflectance conversions benefit from both the coastal aerosol and cirrus bands. The coastal aerosol band aided retrieval of aerosol properties and the cirrus band also enhanced cloud and shadow masking.

Concha and Schott (2016-in this issue) concluded that the addition of the coastal aerosol band (band 1) and the improved SNR and 12-bit quantization enables calculation of water constituents comparable to performance from current ocean color satellites as long as an atmospheric correction is applied. Because Landsat 8′s spatial resolution is superior, Landsat can now be used to calculate water quality parameters over medium to small water bodies.

3.4. Multi-mission synergy

Landsat 8′s long-term impact expands when used in concert with other Earth observations. Whether Landsat 8 data are integrated with those from past Landsats or with data from current or upcoming missions, synergy will be increasingly important. For example, Semmens et al. (2016-in this issue) showed that Landsat 8 can be fused with MODIS and GOES thermal observations to provide daily ET measurements with relative errors in the 12–16% range. Both Hansen et al. and Glenn et al. (2016-in this issue) demonstrated the value of coupling OLI and laser altimetry. Glenn and colleagues demonstrated the use of airborne altimetry (a surrogate for data expected from the upcoming ICESat-2 mission) for quantifying changes in above-ground carbon, and Hansen et al. integrated ICESat GLAS measurements with Landsat 8 to estimate Sub-Saharan tree height.

Landsat's rich science and applications heritage dates back to 1972 and this has resulted in Landsat being a de facto centerpiece in the constellation of civilian Earth imaging satellites (Wulder et al., 2012). With the successful launch of Sentinel-2, we now have a small but very capable constellation of moderate resolution satellites that provide high quality global observations at a scale that can be used in studies requiring high temporal frequency measurements.

4. Conclusions

The contents of this special issue address Landsat 8 science and applications lessons. Collectively, the papers demonstrate that Landsat 8 is the most capable of the seven operational Landsat missions. There is solid evidence that the performance and new capabilities are enabling better research results, contributing to important operational applications, and leading to new opportunities.

Earlier, four broad mission objectives were presented. The question is this – are those objectives being met?

- Collect and archive moderate-resolution, reflective multispectral image data affording seasonal coverage of the global land mass for a period of no less than 5 years.

With the Landsat 8 mission just over 3 years old, it is too soon to conclude whether OLI meets the 5-year multispectral target. There is ample evidence that data quality is meeting the consistency and quality targets (see previous comments).

- Collect and archive moderate-resolution, thermal multispectral image data affording seasonal coverage of the global land mass for a period of no less than 3 years.

TIRS has met the 3-year mission objective though use of TIRS band 11 is currently compromised due to stray light artifacts (see Montanaro et al., 2014a, 2014b).

- Ensure that LDCM data are sufficiently consistent with data from the earlier Landsat missions, in terms of acquisition geometry, calibration, coverage characteristics, spectral and spatial characteristics, output product quality, and data availability to permit studies of land cover and land use change over multi-decadal periods.

There is significant evidence that Landsat 8 data are consistent with data from earlier missions and superior in many ways. Better radiometry and geometry, more robust acquisitions, and additional spectral bands are improving the detection of land change. Research results published here shows that Landsat 8 data can be used effectively with measurements from previous Landsat instruments but some corrections may be needed.

- Distribute standard LDCM data products to users on a nondiscriminatory basis and at no cost to the users.

Wulder et al. (2016) shows that Landsat 8 data are being distributed without charge to users worldwide at an unprecedented rate and are made available to anyone within hours of acquisition.

The Landsat archive continues to grow thanks to expanded acquisitions by both Landsat 7 and 8, and also because of the successful repatriation of historical Landsat data through the Landsat Global Archive Consolidation initiative. The amount of high quality, no cost Landsat data now available to the world-wide Landsat user community is fueling new innovations with substantial societal impact.

The major requirements are being met 3 years into the Landsat 8 mission. Landsat 8 should extend the long Landsat record to at least 45–50 years. The strong programmatic and congressional support for Landsat demonstrated through the establishment of the NASA-Department of the Interior/U.S. Geological Survey Sustaining Land Imaging program now has the Landsat program in an extraordinary situation. Planning is underway to lay out the strategy for the next 25 years of land imaging. The current plan to build and launch Landsat 9 using the basic specifications of Landsat 8 by 2021 will extend the investments that current Landsat data users are making as they incorporate Landsat 8 data into their ongoing research or applications. The plans to explore Landsat 10 options that increase measurement capabilities while preserving continuity and constraining costs could infuse incremental or perhaps even revolutionary improvements that extends Landsat's capabilities into new areas.

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