SEMI-CENTENNIAL OF LANDSAT OBSERVATIONS & PENDING LANDSAT 9 LAUNCH

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The first Landsat was placed in orbit on 23 July 1972, followed by a series of missions that have provided nearly continuous, two-satellite 8-day repeat image coverage of the Earth's land areas for the last half-century. These observations have substantially enhanced our understanding of the Earth's terrestrial dynamics, both as a major element of the Earth's physical system, the primary home of humans, and the major source of resources that support them. The history of Landsat is complex, reflective of the human systems that sustain it. Despite the conflicted perspectives surrounding the continuation of the program, Landsat has survived based on worldwide recognition of its critical contributions to understanding land dynamics, management of natural resources and Earth system science. Launch of Landsat 9 is anticipated in Fall 2021, and current planning for the next generation, Landsat Next is well underway. The community of Landsat data users is looking forward to another 50 years of the Landsat program.

Introduction

Many technological advances emerged from the World War II, including rockets, electronic computing, and non-photographic sensors. By the mid-1950s these technologies set the stage for satellite monitoring of the Earth. First employed for intelligence gathering, some researchers also saw great potential for civilian applications, which until that time had primarily been serviced by aerial photography. Experimentation with airborne multispectral sensors suggested great potential to monitor land resources from space (Figure 1). Initial funding from US military agencies supported university and federal investigators in exploring applications in agriculture, forestry, hydrology, geology, and geography. University of Michigan, University of California, Berkley, and Purdue University were early leaders.

In the mid-1960s as NASA looked beyond the Apollo program, they became increasingly interested in Earth observation missions that would exploit technologies developed for Apollo. However, researchers from US Geological Survey (USGS), US Department of Agriculture (USDA), and the Army Corp of Engineers became more interested in free-flying land-monitoring missions. Early disagreements between NASA and USGS led Stewart Udall, the then Department of the Interior (DOI) Secretary—with the encouragement of USGS Director William Pecora, to announce in 1966 that DOI would develop and launch an Earth Resources Observation Satellite (EROS). After considerable Washington discussions, NASA was given the task to develop this satellite, called the Earth Resources Technology Satellite (ERTS) and later renamed Landsat.

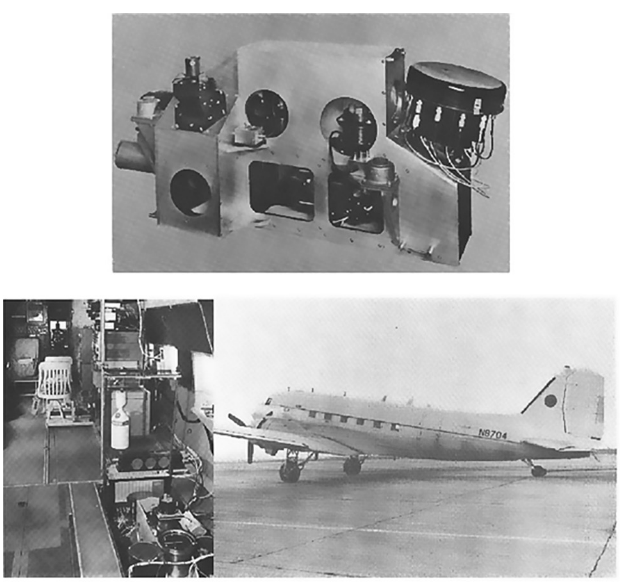

Figure 1. The M7 multispectral scanner (top; inspection plates removed) was mounted into the fuselage (bottom left) and flown aboard the ERIM C-47 aircraft (bottom right). Note the old operator chairs (bottom left). Multispectral images taken by the M7 were explored by researchers at the University of Michigan and Purdue University as an advanced means to monitor Earth resources. The M7 was a key inspiration for the MSS instruments flown on early Landsat satellites. (Photo credits: ERIM).

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The primary source for this narrative is *Landsat's Enduring Legacy* published by the American Society for Photogrammetry and Remote Sensing (Goward *et al.*, 2017). Updates for Landsat 8 and the Landsat Archive can be found in the special issue of *Remote Sensing of Environment* (Loveland & Irons, 2016). Recent activities that have explored the future of the Landsat program have been detailed in the recent Congressional Research Service report ***Landsat 9 and the Future of the Sustainable Land Imaging Program*** (Normand, 2020) and RSE journal articles (Masek *et al.,* 2020).

Early Landsat (L1-L3) and Agriculture

By 1967, NASA Goddard Space Flight Center (GSFC) had initiated the ERTS program with the goal of launching the first satellite by July 1972 (Figure 2). Potential users' first preference was to fly film-based camera systems that replicated aerial photography. However, the US intelligence community, already flying such systems, blocked their use for civilian applications. This left television technologies, such as the Return Beam Vidicon (RBV), used to find Apollo moon landing sites, or more novel multispectral scanners. Ultimately, NASA selected to fly both an RBV, developed by Radio Corporation of America (RCA), as the primary imaging instrument and the Multispectral Scanner System (MSS), developed by Hughes Aircraft, as a technical experiment. ERTS-1 was successfully launched on 23 July 1972. The remarkable quality of data returned from the digital MSS instrument astonished many. When an electrical short in the RBV nearly ended the mission shortly after launch, NASA made the decision to retire the RBV and make the MSS the primary imaging system (Figure 3).

Over the next three years, NASA funded an ERTS principal investigator (PI) program, the first such NASA program for the Earth science community. Over 300 PIs were selected to participate in this program. Meanwhile, the USGS initiated an ERTS archival system in Sioux Falls, South Dakota, the Earth Resources Observation System (EROS). In 1975, the ERTS program was renamed Landsat; Landsat 2 was launched, and NASA began studies to develop an advanced multispectral scanner system—the Thematic Mapper (TM). In 1978, Landsat 3 was placed into orbit.

The same year that Landsat 1 launched, the Union of Soviet Socialist Republics (USSR) concealed their major wheat crop failure and managed to purchase large portions of the US surplus wheat at low cost. When Congress heard of this intelligence lapse, they directed the USDA and NASA to engage the Landsat capabilities to monitor global wheat production; this became the multiagency Large Area Crop Inventory Experiment (LACIE) program. For the next decade, agriculture was the primary operational focus for the Landsat program.

Thematic Mapper and Commercial Era (L4 & L5)

Landsat 4 launched on 16 July 1982 carrying a four-band MSS and a second-generation sensor, the Thematic Mapper (TM) (Figure 4). A sensor similar to the TM had been considered for Landsat 1, but nearly a decade of technological advances was needed to realize a flight-ready version. The TM had a 30m spatial resolution and seven spectral bands that expanded into blue, shortwave infrared, and thermal infrared wavelengths.

Communication and power issues plagued Landsat 4, which limited TM collection for the life of the mission. The identified issues were rectified before the Landsat 5 launch. These fixes, plus a large fuel tank installed for an unrealized Space Shuttle capture-and-repair capability, enabled Landsat 5 to collect data for 28.8 years, carrying the mission well past the 1993 Landsat 6 loss (Figure 5).

Figure 2. Artistic rendition of Landsats 1 (ERTS), 2 and 3. The early Landsats used the same satellite bus developed for the NASA Nimbus weather satellites, adapted for the new Landsat instruments. Only two years after the initial meetings with the selected Landsat contractors, Landsat 1 was ready for launch. (Image credit: NASA)

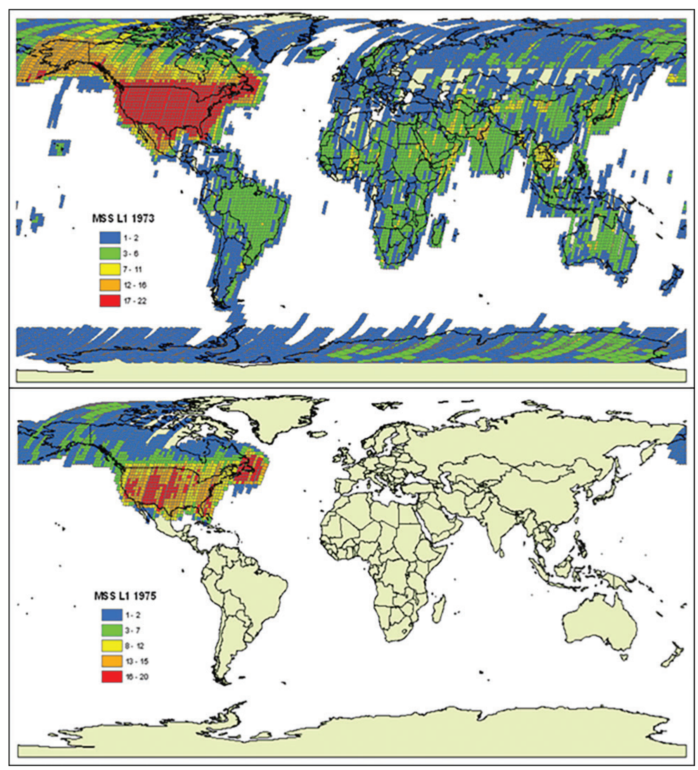

Figure 3. Landsat 1 (ERTS) coverage for 1973 (top) and 1975 (bottom). Onboard wide-band videotape recorders recorded image observations but generally failed after about 2.5 years. After this, only direct line-of-sight transmission to ground stations was possible, leading to only North American coverage via direct downlink in later years of the missions. (Image credit: USGS)

Figure 4. Artistic rendition of Landsats 4 and 5. The satellites had no onboard recorders; the large antenna on top of the satellite transmitted data from Landsat to TDRSS for global downlink. The first TDRS was placed over the Atlantic in 1983. The second TDRS was lost in the 1986 Challenger launch, so there was no ability for full global coverage via TDRSS until 1989. Additionally, Landsat's commercialization and the higher priority of Space Shuttle operations substantially reduced global coverage via TDRSS. Fortunately, Landsat data captured by International Ground Stations during this time have now been added to the US Landsat archive. (Image credit: NASA)

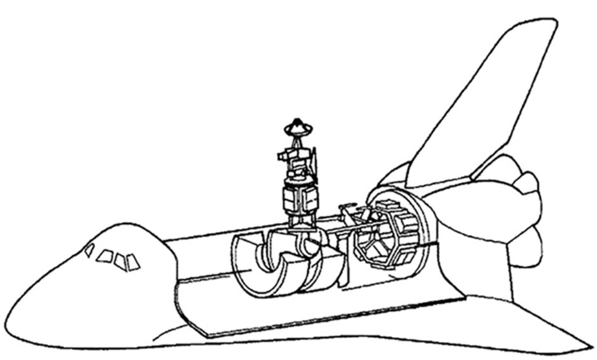

Figure 5. The proposed Shuttle Landsat retrieval system. To accomplish this feat, the Landsat satellite would need to be de-orbited to a possible Shuttle altitude and thus Landsats 4 and 5 were fitted with large fuel tanks. After the Challenger loss and the cancelation of Vandenberg Shuttle launch facilities, this retrieval was never attempted. However, the expanded fuel tank did permit Landsat 5 to continue operations for nearly 30 years, filling the gap in coverage that would likely have occurred after the loss of Landsat 6 during launch in 1993. (Image credit: NASA/Hughes SBRC)

Unlike weather satellites that were managed by the Federal government as a public good, Landsat followed the path of communication satellites to be spun-off to private industry for commercialization. The National Oceanographic and Atmospheric Administration (NOAA) had the unpopular task of recovering all Landsat operational costs via data sales and finding a commercial operator. EOSAT—the sole remaining bidder in a deeply flawed commercialization gambit—took control of the Landsat satellites in 1985. Despite lowering NOAA-set data prices, sales never took off. With no on-board recorders, Landsats 4 and 5 international acquisitions were dependent on either direct downlink to International Ground Stations or high-cost NASA tracking and data relay satellite system (TDRSS) transmissions, to the detriment of a global archive (Figure 6).

Despite the then-groundbreaking 30m resolution, data costs caused all but the best-funded scientists to migrate to NOAA's no-cost Advanced Very High Resolution Radiometer (AVHRR) data with more frequent observation repeat cycles but much coarser spatial resolution. With these AVHRR data, researchers refocused their collective energy on the development of robust methodologies for global vegetation analyses.

Fortunately, the concept of the MSS Basic Data Set during this period cemented the idea of long-term Landsat data preservation and, when coupled with a growing awareness of global change ramifications and satellites' monitoring role, helped propel Landsat data from a commodity back towards a public good.

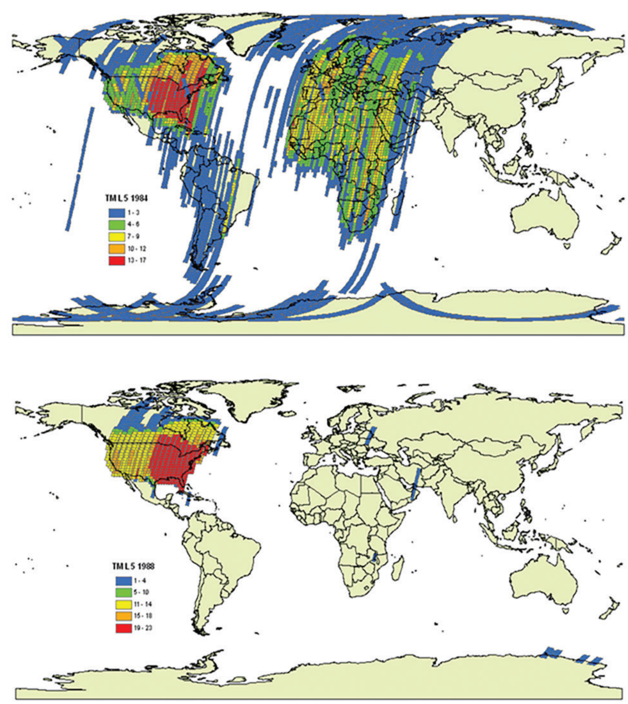

Figure 6. US Landsat 5 coverage for 1984 and 1988. Half global coverage was the result of losing the western TDRSS satellite during Challenger launch. By 1988 the satellite's primary link to the TDRSS had failed and most acquisitions were being made by Landsat 4. EOSAT continued acquisitions over the US via ground-based antenna at NASA Goddard and exchange agreement with western Canadian station. (Image credit: USGS)

Studying Global Change with Landsats 5 & 7

NASA's response to the 1990 Global Change Research Act was to focus its Earth Sciences division on the Mission to Planet Earth (MTPE) program and the development of the Earth Observation System (EOS). Landsat was integrated into MTPE as an EOS observatory. As such, MTPE supported The Landsat-based Pathfinder tropical deforestation and land cover change studies, investigation of follow-on Landsat technologies, and the USGS EROS rescue of deteriorating Landsat archive media. Later MTPE and USGS supported reprocessing and geodetic updating of global 1975, 1990, and 2000 Landsat-based EarthSat GeoCover data sets as well as adding 2005 and 2010 data. all of which were made freely available to users. With the at-launch loss Landsat 6 satellite in 1993, a primary goal of the MTPE Landsat program was to quickly develop and launch Landsat 7, no later than 1998 (Figure 7). The L7 design included several satellite advances including a spacious solid-state recorder, the Enhanced Thematic Mapper Plus (ETM+) sensor with multiple calibration options, and increased downlink capacity. In addition, ground system included a high-speed large-capacity data processing, a dedicated Image Assessment System, and the Long-Term Acquisition Plan (LTAP) that implemented systematic global acquisition of data (Figure 8). Further, In 1996 MTPE funded formation of the first-ever Landsat Science Team (LST) in recognition of Landsat's new EOS role. The LST aided refinement of L7 operations as well as exploring specific PI-driven science goals. Unfortunately, the LST was abandoned in 2001 in anticipation of a second attempt to commercialize Landsat with Landsat 8. Throughout the operational life of Landsat 7 (1999-present), improvements have been made in acquisition rates (250 scenes/day to near 500), data accuracy, the routine provision of higher-level data products, and, no cost data access in December 2008. After return of Landsat 5 to government management in 2001, it was incorporated into the LTAP, thus maximizing the archive contents.

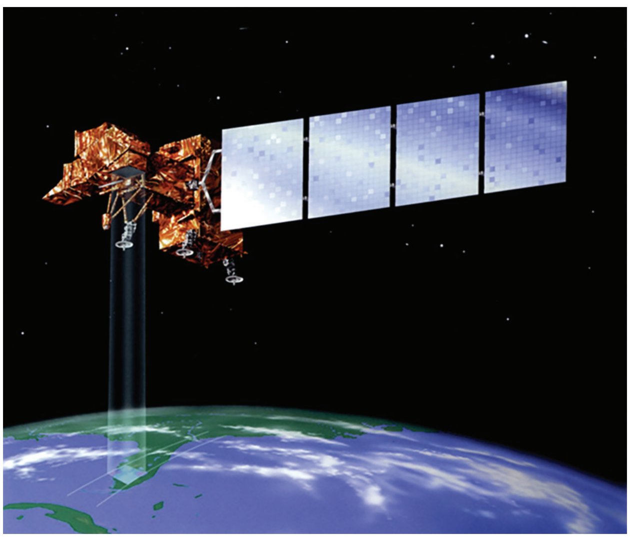

Figure 7. Artistic rendition of Landsat 7 imaging Florida. The three X-band antennae on the bottom of the satellite enabled transmission of image data to multiple ground stations at the same time. An onboard solid-state recorder enabled data collected outside of US ground station acquisition circles to be stored for later downlink and processing into the US archive. An automated Long-Term Acquisition Plan ensured global acquisition coverage priorities. (Image credit: NASA/USGS)

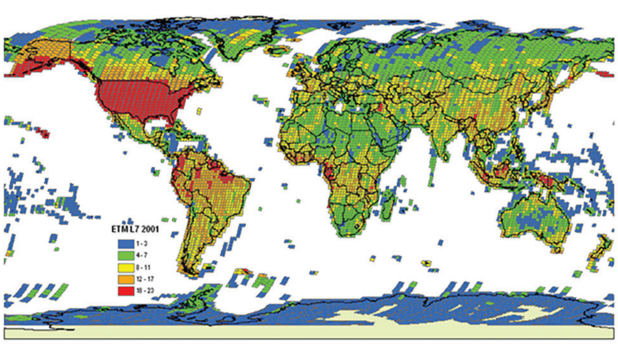

Figure 8. 2001 Landsat 7 global coverage. Landsat 7 was the first of the series to truly approach global coverage, including islands and reefs as well as the polar regions. This was thanks to technology improvements onboard and in the processing chain, as well as scheduling guidance from the Long-Term Acquisition Plan (LTAP). (Image credit: USGS)

Earth System Science with Landsats 8 & 9

The Landsat 8 era began with uncertainty and evolved towards a stable, sustainable strategy for follow-on Landsat missions (Figure 9). Following the launch of Landsat 7, NASA sequentially initiated and abandoned two implementation strategies for a follow-on mission before receiving direction to build a free-flyer satellite that was successfully launched as the Landsat Data Continuity Mission (LDCM) on 11 February 2013. The 1992 Land Remote Sensing Policy Act expressed a preference for a private sector follow-on to Landsat 7. In accordance with that preference, NASA first attempted to implement the follow-on mission as a data buy from a privately-owned and operated satellite and called the initiative the LDCM. NASA issued a Request for Proposals (RFP) and then declined to accept any of the tendered proposals in late 2003, deeming the proposed levels of public risk too high. The Office of Science and Technology Policy (OSTP) then in 2004 directed NASA to incorporate a Landsat

Figure 9. Artistic rendition of Landsat 8 in orbit over SE United States. Landsats 8 and 9 use the same satellite bus—a fourth-generation Landsat bus design. Improvements in communication bandwidth, science instrument design, and solid-state recorder capacity, and an updated LTAP produce coverage that substantially exceeds Landsat 7 coverage. The collection of nearly all possible images for much of the globe greatly enhances the ability to stitch together a less cloudy data base of imagery. (Image credit: NASA/USGS)

sensor into the ill-fated National Polar-Orbiting Operational Environmental Satellite System (NPOESS). With NPOESS encountering difficulties, OSTP revised its guidance in December 2005 and directed NASA to build a free-flyer follow-on to Landsat 7.

NASA retained the LDCM moniker and managed the development and launch of a satellite observatory consisting of a spacecraft bus procured from Orbital Sciences Corporation to carry a two-instrument payload, the Operational Land Imager (OLI) procured from Ball Aerospace and the Thermal InfraRed Sensor (TIRS) built by NASA Goddard. These two sensors were the first pushbroom imaging radiometers flown by a Landsat mission and offered improved radiometric performance relative to the whiskbroom sensors flown aboard prior Landsat satellites. LDCM was turned over to USGS for operation after in-orbit check out and USGS renamed the observatory Landsat 8.

Landsat 8 operates in a rapidly advancing Earth observation infrastructure. Where Landsat satellites were once the only civilian space assets designed for land observations, Landsat 8 now shares low Earth orbit with a proliferation of international and commercial satellites observing all components of the Earth system — the atmosphere, oceans, cryosphere, and continents. These global observations propel forward Earth system science where the Earth is studied as an integrated system of processes that encompass all the components.

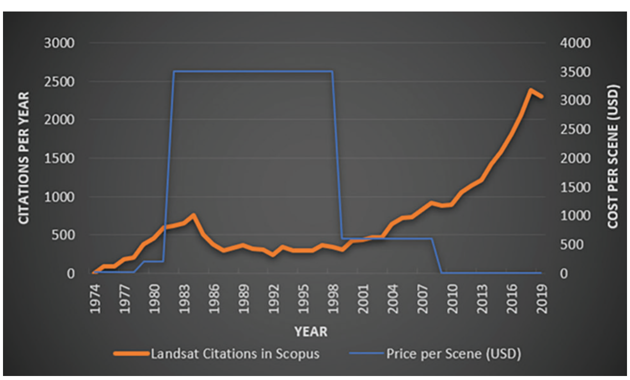

Figure 10. Number of Landsat-related citations since 1974. Citations greatly increased after the open data policy decision in December 2008. As if December 2020 over 100 million Landsat scenes have been downloaded from archive. For more details see Landsat Project Statistics (usgs.gov) (Image credit: USGS

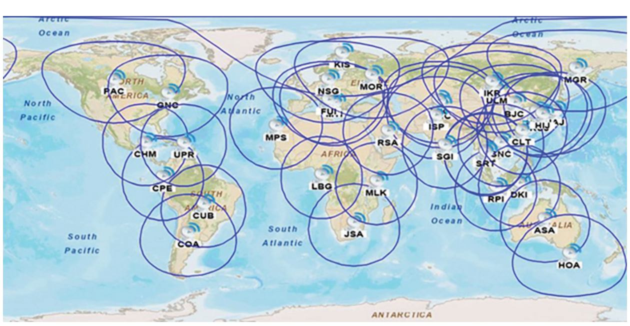

Figure 11. Locations of Landsat international ground stations from 1972 to current. The number of ground stations active at any given time was quite variable. For details concerning specific ground stations see https://landsat.usgs.gov/historical-international-ground-stations (Image credit USGS)

The long delay between the Landsat 7 and Landsat 8 launches led NASA and USGS to conceive a Sustainable Land Imaging (SLI) program to define and plan for future missions. The first SLI mission architecture study resulted in a decision to build Landsat 9 as a near-identical copy of the Landsat 8 observatory with a launch planned for Fall 2021. Landsat 9 will contribute to Earth system science by continuing to build upon the now five-decade-long record of Landsat observations.

Advancing the Landsat Archive

Two decisions, made in the early days of the LDCM development, had major impacts on the use of Landsat. First, the USGS and NASA ratified a change to the Landsat Data Policy that resulted in the provision of non-discriminatory access to free orthorectified Landsat data. Second, USGS and NASA reconvened a Landsat Science Team (LST) in 2006 and every 5 years since that time.

The 2008 opening of the archive transformed Landsat data use (Figure 10). Landsat time series analyses for monitoring landscape change are now commonplace. With LDCM largely defined and underway, the LST tackled the role of community needs and defining science-based input that improve uses of the Landsat archive.

The LST focused on ideas to expand the historical Landsat archive, resulting in the Landsat Global Archive Consolidation initiative that started repatriation of all Landsat 1–7 data held by International Ground Stations (IGs) (Figure 11). With full cooperation from the IGs, over 5.41 million additional, unique historical scenes are now available to Landsat users worldwide (Figure 12).

Landsat 7 and 8 acquisition strategies pushed the technical capabilities of both missions doubling the daily growth of the archive. Landsat 7 now collects over 500 scenes per day and Landsat 8 collects up to 740 scenes per day. In addition, the SLI long-term commitment that includes the planned 2021 launch of Landsat 9 will expand the aggressive global acquisition strategy.

The USGS, with LST input, also focused on ideas for improving the usability of the archive. Community R&D led to major improvements in the geometric correction and geo-location of all Landsat data. Instrument cross calibration and measurement uncertainties were defined and applied to improve radiometric consistency and comparability for all 9 million Landsat 1-8 archive scenes. The USGS implemented and applied these advances using a collection management strategy that standardized and controlled the characteristics of Level 1 products and added derived Level 2 geophysical products and pixel-based metadata. The Landsat program is moving toward providing “analysis-ready” virtual data cubes that will further improve the efficiency and consistency of time series studies. The entire archive has recently been moved to a cloud environment that will ensure more timely reprocessing and more robust access to the archive.

Landsat Next

Recognizing that Landsat observations continue to provide unique and critical information for science, the US Government has made a long-term commitment to continue

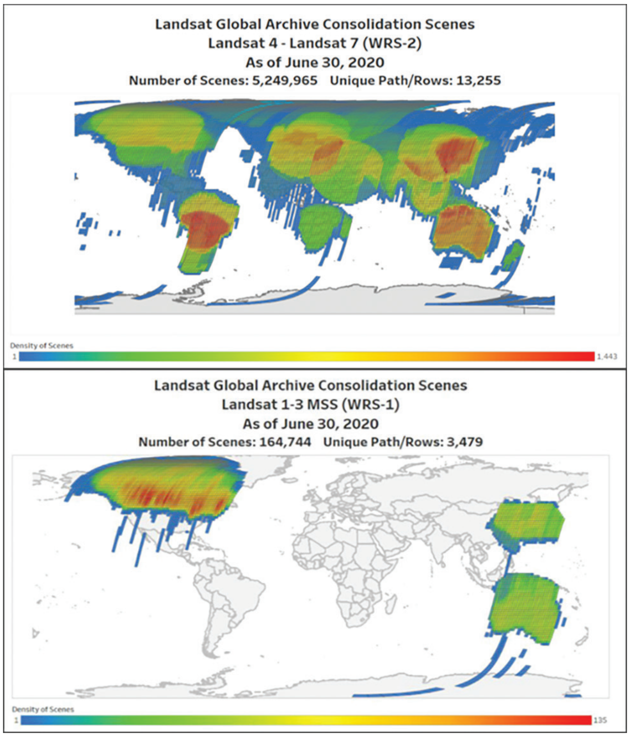

Figure 12. International station contributions to global archive consolidation. As of June 2020, the newly incorporated international scenes were nearly double the number of the previous holdings from Landsat 1–7. The unique path-rows are locations that had not been previously imaged for the US archive. As of September 2020, the LGAC scenes more than doubled the previous Landsat 1-7 holdings. (Image credit: USGS)

these measurements through the Sustainable Land Imaging program. Not surprisingly, both technology and user expectations have evolved since the Landsat 8/9 systems were scoped in the early 2000s. User surveys by USGS have revealed a strong preference for improved spatial resolution, more frequent observations, and additional spectral channels to support new applications such as water quality and cryospheric studies. In part, these findings reflect the influence of the operational European Sentinel-2 satellite series, which has acquired Landsat-like images with finer spatial resolution and greater frequency than the current Landsat program. At the same time, reports from the National Research Council and USGS Landsat Advisory Group have urged NASA and USGS to pursue more innovative ways of implementing Landsat missions, including exploration of commercial and international partnerships.

NASA and USGS have recently advanced the Landsat Next concept centered on collection of a "superspectral" data set encompassing some 25 spectral bands, with a spatial resolution of 10-20m (for the reflective bands) or 60m (for the thermal infrared). This mission, to be launched as early as the late-2020s, would significantly advance Landsat observational capabilities and provide a robust complement both to other international imaging systems, as well as to upcoming hyperspectral missions such as the NASA Surface Biology and Geology (SBG) mission. While the exact architecture of the Landsat Next mission will not be finalized until late 2021, non-traditional approaches, including acquiring the data set via a constellation of smaller satellites, are being explored.

Summary

The Landsat program over the last half-century has created an unparalleled observation record of the state and dynamics of Earth's land conditions. The major signals captured in these measurements document how life-sustaining biological activity varies in space and time. We have learned how to separate atmospheric and land surface signals to provide highly accurate estimates of this activity, which provides important insights into Earth system processes and humans' role in modulating and managing this activity. The US has preserved this critical historical record of land processes that has already produced major new insights into how Earth sustains life on this planet. Continuation of this record into the future and enhancement of these measures is of vital importance today and for future generations.

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