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The global Landsat archive: Status, consolidation, and direction

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ABSTRACT

New and previously unimaginable Landsat applications have been fostered by a policy change in 2008 that made analysis-ready Landsat data free and open access. Since 1972, Landsat has been collecting images of the Earth, with the early years of the program constrained by onboard satellite and ground systems, as well as limitations across the range of required computing, networking, and storage capabilities. Rather than robust on-satellite storage for transmission via high bandwidth downlink to a centralized storage and distribution facility as with Landsat-8, a network of receiving stations, one operated by the U.S. government, the other operated by a community of International Cooperators (ICs), were utilized. ICs paid a fee for the right to receive and distribute Landsat data and over time, more Landsat data was held outside the archive of the United State Geological Survey (USGS) than was held inside, much of it unique. Recognizing the critical value of these data, the USGS began a Landsat Global Archive Consolidation (LGAC) initiative in 2010 to bring these data into a single, universally accessible, centralized global archive, housed at the Earth Resources Observation and Science (EROS) Center in Sioux Falls, South Dakota. The primary LGAC goals are to inventory the data held by ICs, acquire the data, and ingest and apply standard ground station processing to generate an L1T analysis-ready product. As of January 1, 2015 there were 5,532,454 images in the USGS archive. LGAC has contributed approximately 3.2 million of those images, more than doubling the original USGS archive holdings. Moreover, an additional 2.3 million images have been identified to date through the LGAC initiative and are in the process of being added to the archive. The impact of LGAC is significant and, in terms of images in the collection, analogous to that of having had *two* additional Landsat-5 missions. As a result of LGAC, there are regions of the globe that now have markedly improved Landsat data coverage, resulting in an enhanced capacity for mapping, monitoring change, and capturing historic conditions. Although future missions can be planned and implemented, the past cannot be revisited, underscoring the value and enhanced significance of historical Landsat data and the LGAC initiative. The aim of this paper is to report the current status of the global USGS Landsat archive, document the existing and anticipated contributions of LGAC to the archive, and characterize the current acquisitions of Landsat-7 and Landsat-8. Landsat-8 is adding data to the archive at an unprecedented rate as nearly all terrestrial images are now collected. We also offer key lessons learned so far from the LGAC initiative, plus insights regarding other critical elements of the Landsat program looking forward, such as acquisition, continuity, temporal revisit, and the importance of continuing to operationalize the Landsat program.

1. Introduction

Following the opening of the Landsat archive in 2008 (Woodcock et al., 2008), interest around and use of Landsat imagery has increased dramatically (Roy et al., 2014; Wulder, Masek, Cohen, Loveland, & Woodcock, 2012). Users need to know what is in the archive, how the archive was and continues to be populated, and what applications are possible when users are no longer restricted by data access or processing limitations. Moreover, knowledge of the archive is required to determine the science and applications options that are possible for a given location or extent (i.e., regional to global). The required information on image availability is both geographic and temporal: given cloud cover, shadows, and related causes of view obscurity and past acquisition

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strategies, are there enough images to make a map for a given time period? (Geographic completeness); are there enough images to do change detection or time series analysis? (Temporal coverage); are there enough images to undertake time series analysis over a large area? (Geographic and temporal). Questions such as these are further complicated by considerations such as the level of processing of images in the archive (e.g., L1T verses L1G), acquisition date, and sensor, with the eventual image yield less than the total number of images present.

The most recent Landsat satellite—Landsat-8—benefits from the inclusion of modern technology in sensor and satellite components (Irons, Dwyer, & Barsi, 2012). Onboard recording capacity and X-band downlink and receiving capacity are sufficiently high that nearly all terrestrial collection opportunities are made. By comparison, Landsats-1 to -3 had very limited onboard data recording capacity, while Landsats-4 and -5 had *no* onboard recording capacity and also suffered technical problems with data relay capabilities (Markham, Storey, Williams, & Irons, 2004). The Landsat-5 TM relay capability failed in 1992. The primary Ku-band link failed in July 1988 and the redundant link in July 1992. Following this failure, data transmission became limited to direct, real-time X-band transmission and only Landsat 5 TM data sensed within a U.S. ground station line-of sight were copied to the USGS archive (Chander, Helder, Malla, Micijevic, & Mettler, 2007). These limitations led to a reliance on the network of International Ground Stations (IGS), operated by International Cooperator (IC) nations. These ICs partnered with the Landsat program and paid an annual fee for reception and data distribution rights (Draeger, Holm, Lauer, & Thompson, 1997). Although there was never any systematic process implemented to enable the transfer of data acquired by ICs to the USGS Landsat data archive housed at the Earth Resources Observation and Science (EROS) Center in Sioux Falls, South Dakota, the ICs were obligated, through formal Memoranda of Understanding (MOU), to periodically forward image metadata to the USGS. Goward et al. (2006) noted that the metadata transfers were rarely enforced, leading to a general lack of knowledge concerning the extent or quality of the data held by the ICs. The status quo was that while the USGS maintained its Landsat data archive at EROS, ICs were simultaneously building and maintaining their own regional archives, and had the freedom to process and distribute the data according to their own policies and mechanisms (Draeger et al., 1997).

As reported in 2006, it became increasingly apparent that the volume of Landsat data holdings held by ICs far exceeded what was held by the USGS Landsat archive (Goward et al., 2006). As of March 2006, the USGS archive held an estimated 1.9 million images, while it was estimated that ICs held an additional 4 million images. Recognizing the value of these data and wanting to safeguard the considerable investment that had been made in the Landsat Program and realize its full benefit, the USGS-NASA Landsat Science Team recommended in early 2007 that the USGS build upon the information reported by Goward et al. (2006) and initiate the consolidation of the data from the ICs into the USGS Landsat data archive. Only then would there exist a truly global archive processed in a consistent manner that would improve the utility of the data for all users (Loveland & Dwyer, 2012). The Landsat Global Archive Consolidation (LGAC) initiative was commenced in early 2008 and continues today. As a result of LGAC and technological improvements in data storage and transmission realized onboard Landsat-8, the current Landsat archive is geographically broader and temporally deeper than at any other time. This depth and breadth, combined with free and open access, has fundamentally changed the way Landsat data are being used (Kennedy et al., 2014; Roy et al., 2014; Wulder et al., 2012). Applications using all available images for a given location are increasingly the norm (Brooks, Wynne, Thomas, Blinn, & Coulston, 2014; Zhu & Woodcock, 2014) and mapping land resources on global scales is now possible (Gong et al., 2013; Hansen et al., 2013). As suggested by Bolden (2015), the world does indeed rely on Landsat data and, moreover, guided by plans articulated in the 2016 U.S. Presidential budget (Foust, 2015), is poised to do so for decades to come.

In this paper, we describe the current status of the archive and the inception and evolution of the LGAC initiative. For context, we provide a brief synopsis of the Landsat program and document the status of the USGS Landsat data archive holdings as of January 1, 2015. We likewise document current acquisition status and strategies associated with the operation of Landsats-7 and -8, and look forward to acquisition capacity in the future and avail upon lessons learned to inform proposed operational land imaging activities. Our primary objective is to quantify the current and expected future contributions of LGAC to the USGS Landsat archive and in so doing, make a case for the important role that LGAC has played in both securing the historical legacy of the Landsat program and ensuring the continuity of the Landsat program into the future.

2. Background and current archive status

The first of the Landsat series, then known as the Earth Resources Technology Satellite (ERTS), was launched on July 23, 1972. The Earth observation program William Pecora envisioned in the 1960s (Pecora, 1966) has now evolved to the point that data from Landsat are now indispensable for science and natural resource management (Roy et al., 2014). Landsat data are in constant use for agricultural management, yield forecasting and insurance, for land use and cover change, for forestry, water resource management, study of ecosystem services and functioning, for climate science and climate change studies, for studying snow and ice, coastal areas, deserts, geology, soils, urban change and transport among many other applications. The data are used in science programs, they are used by educators in schools and universities worldwide, they help decision makers develop, implement, evaluate and refine policies on scales from local to global; they form a basis for international environmental agreements, for legal use, for agribusiness, humanitarian aid and homeland security (Miller, Richardson, Koontz, Loomis, & Koontz, 2013).

Landsat is only one of 73 satellite-based global land observing programs operated by 34 different sovereign states (Belward & Skøien, 2015), but Landsat occupies a truly unique place in this pantheon, as illustrated by the following:

- Landsat-1 was the first near polar orbiting satellite capable of observing the Earth's landmass at human scales (Townshend & Justice, 1988);
- The Landsat Program was the first to employ a global image acquisition strategy;
- Landsat is the longest running uninterrupted Earth observation program, and
  - o At 28 years and 10 months of operation, Landsat-5 the longest-lived individual satellite, operating for almost twice as long as *any* other Earth observing satellite (and there have been more than 200);
- The Landsat archive was the first to offer global imagery at 30 m resolution without restriction in a free and open manner (Woodcock et al., 2008);
- Landsat is the only program offering a cross-calibrated Earth observation record spanning more than four decades (Markham & Helder, 2012);
- Landsat data are more widely used than any other for ecological applications (Cohen & Goward, 2004), are the basis for more than twice as many refereed papers dealing with land cover than any other system (Belward & Skøien, 2015) and are preeminent for the study of forested environments (Wulder et al., 2012). William Pecora's vision from almost 50 years ago was prescient—Landsat is indeed Earth's resource satellite program.

While the vision of the 1960s may have been on target, mission management has varied substantially over the Program's forty-three year lifespan, shifting from public to commercial responsibility and back again (Loveland & Dwyer, 2012). Among many consequences, such as fluctuating costs of acquiring Landsat data (Wulder et al., 2008), these