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Landsat 9 and the Future of the Sustainable Land Imaging Program

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Landsat 9 and the Future of the Sustainable Land Imaging Program

SUMMARY

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The National Aeronautics and Space Administration (NASA) launched Landsat 9, a remote sensing satellite NASA developed in partnership with the U.S. Geological Survey (USGS), on September 27, 2021. Landsat satellites have collected remotely sensed imagery of the Earth's surface at moderate spatial resolution since the launch of Landsat 1 on July 23, 1972. Currently, Landsat 7 and Landsat 8 are in orbit and supplying images and data. Stakeholders use Landsat data in a variety of applications, including land use planning, agriculture, forestry, natural resources management, public safety, homeland security, climate research, and natural disaster management. Landsat data support government, commercial, industrial, civilian, military, and educational users throughout the United States and worldwide. Landsat 9 development was initiated in March 2015, with a design that is essentially a rebuild of Landsat 8. Once Landsat 9 is operational (estimated to be about 100 days after launch), it and Landsat 8 will acquire roughly 1,500 high-quality images of the Earth per day, with a repeat visit every eight days, on average, and Landsat 7 is to be decommissioned.

Various entities have led the Landsat program over the past five decades. It was initiated in the late 1960s as a research program under NASA. In the 1980s, the executive branch proposed and Congress approved policies to privatize Landsat under the leadership of the National Oceanic and Atmospheric Administration (NOAA) and a commercial entity, the Earth Observation Satellite Company (EOSAT). The attempted privatization ended with the passage of the Land Remote Sensing Policy Act of 1992 (P.L. 102-555), which returned responsibility for management of the Landsat program to the federal government. In 2016, NASA and the Department of the Interior (DOI, the department overseeing the USGS) entered into an interagency agreement, redefining their long-term collaboration on Landsat through the Sustainable Land Imaging Program and outlining responsibilities for Landsat 9. Under the Sustainable Land Imaging Program, the agencies are to develop a multi-decade, spaceborne system that will provide high-quality, global, land-imaging measurements that are compatible with the existing Landsat record. In this partnership, NASA develops the satellite and the instruments, launches the spacecraft, and checks its performance. Then, the USGS takes over satellite operations and manages and distributes the data from the Earth Resources Observation and Science (EROS) Center in Sioux Falls, SD. NASA Landsat activities are funded under the Earth Science Division of the Science Mission Directorate, and USGS Landsat activities are funded under the National Land Imaging Program in the Land Resources Mission Area. As of FY2021, NASA has spent $699 million on its responsibilities for developing and launching Landsat 9 and the USGS has spent over $120 million on its ground system development.

Under a policy initiated in 2008, all Landsat data in USGS archives are available for download free and without restrictions. Every year, the USGS distributes millions of Landsat images to thousands of users. On March 11, 2020, a Landsat 8 image of New Zealand's North Island became the 100 millionth download from the USGS's user interface tools. Landsat data also are used for commercial applications and in derived products, such as Google Earth, which themselves have millions of users. Researchers estimate that Landsat imagery provided domestic and international users $3.45 billion in benefits in 2017 ($4.18 billion when including cloud vendors), with U.S. users accounting for $2.06 billion of those benefits. Because of Landsat's length of record, availability of data, global coverage, and calibration standards, it serves as the central reference comparison point for many other moderate- and high-resolution optical satellite systems operated by governments and commercial entities. Landsat also has influenced the development of other Earth remote sensing satellites by governments (e.g., the European Space Agency's Copernicus Program Sentinel-2 satellite constellation) and the private sector.

With the launch of Landsat 9, Congress may consider the future of the Sustainable Land Imaging Program. A future moderate-resolution mission could differ from previous Landsat satellites by adopting a smaller satellite design, increasing image resolution, increasing the number of images captured per day, reducing the time between images of a given location, sensing a wider variety of optical and infrared frequencies, or making other design changes. Alternative arrangements could include obtaining images from other sources, such as through public-private partnerships or by procuring data from other satellites. Reports from stakeholders such as the Landsat Advisory Group and the National Academies of Sciences, Engineering, and Medicine have discussed such options and their tradeoffs. A joint NASA-USGS Sustainable Land Imaging Architecture Study has developed options for the follow-on to Landsat 9, known as Landsat Next, and the agencies anticipate sharing information about Landsat Next in 2022. Whether Congress supports the agencies' plans for Landsat Next or prefers some alternative, it may consider shaping the Sustainable Land Imaging Program and Landsat Next development through oversight activities, authorizing legislation (such as amendments to the Land Remote Sensing Policy Act of 1992), and appropriations bills and report language.

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Introduction

The National Aeronautics and Space Administration (NASA) launched Landsat 9, a remote sensing satellite NASA developed in partnership with the U.S. Geological Survey (USGS), on September 27, 2021.[1] Landsat 9 is the latest in a series of Earth-observing satellites that began on July 23, 1972, with the launch of Earth Resources Technology Satellite 1, now known as Landsat 1.[2] Stakeholders use Landsat data in a variety of applications, including land use planning, agriculture, forestry, natural resources management, public safety, homeland security, climate research, and natural disaster management.[3] Landsat data support government, commercial, industrial, civilian, military, and educational users throughout the United States and worldwide. Once Landsat 9 is operational (estimated to be about 100 days after launch), it and Landsat 8 will acquire approximately 1,500 high-quality images of the Earth per day, with a repeat visit every eight days, on average.[4]

For almost 50 years, Landsat satellites have collected remotely sensed imagery of the Earth's surface at moderate spatial resolution, which refers to the amount of detail shown in the image or the size of a pixel on the ground.[5] At present, two satellites—Landsat 7 and Landsat 8—are in orbit and supplying images and data.[6] Landsat 7, however, is expected to consume its remaining fuel in 2021 and will be decommissioned once Landsat 9 is operational.

In 2016, NASA and the Department of the Interior (DOI), which oversees the USGS, entered into an interagency agreement, redefining their long-term collaboration through the Sustainable Land Imaging Program and outlining responsibilities for Landsat 9.[7] Under the Sustainable Land Imaging Program, the agencies are to develop a multi-decade, spaceborne system that will provide high-quality global land-imaging measurements that are compatible with the existing Landsat record. Landsat 9 has a design very similar to Landsat 8, in order to shorten the development time and reduce the risk of a Landsat data gap when Landsat 7 ceases to operate. In the NASA-USGS partnership, NASA develops Landsat satellites and instruments, launches spacecrafts, and checks the performance of Landsat missions. Then, the USGS takes over satellite

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[1] National Aeronautics and Space Administration (NASA), Earth Observatory, "NASA and USGS Launch Landsat 9," at https://earthobservatory.nasa.gov/images/148888/nasa-and-usgs-launch-landsat-9.

[2] U.S. Geological Survey (USGS), Landsat Missions, "Landsat Satellite Missions," at https://www.usgs.gov/land-resources/nli/landsat/landsat-satellite-missions.

[3] Zhuoting Wu et al., "User Needs for Future Landsat Missions," *Remote Sensing of Environment*, vol. 231 (September 15, 2019), p. 111214, at https://doi.org/10.1016/j.rse.2019.111214. Hereinafter Wu et al., "User Needs."

[4] USGS, Landsat Missions, "Landsat 9," at https://www.usgs.gov/land-resources/nli/landsat/landsat-9.

[5] Moderate-resolution land imaging satellites have a spatial resolution between 5 meters and 120 meters. Landsats 7, 8, and 9 have spatial resolution in the optical range of 30 x 30 meters (about the size of a baseball diamond) and in the thermal infrared range of 100 meters. The 100 x 100 meter thermal infrared observations are resampled to 30 meters during product generation. For a complete history of the Landsat program, see Sam N. Goward et al., *Landsat's Enduring Legacy: Pioneering Global Land Observations from Space* (Bethesda, MD: American Society for Photogrammetry and Remote Sensing, 2017). Hereinafter Goward et al., *Landsat's Enduring Legacy*.

[6] The Landsat Data Continuity Mission (LDCM, now called Landsat 8) initially was planned for launch in July 2011 and would have filled the data gap in Landsat coverage after the USGS stopped collecting data from Landsat 5. Due to schedule delays, the LDCM was not placed in orbit until February 2013, when it was renamed Landsat 8. On May 30, 2013, data from Landsat 8 became available. USGS, Landsat Missions, "Landsat Data Continuity Mission History," at https://www.usgs.gov/land-resources/nli/landsat/landsat-data-continuity-mission-history.

[7] USGS, "MOU - Sustainable Land Imaging Research, Development, and Operations," September 27, 2016, at https://www.usgs.gov/media/files/mou-sustainable-land-imaging-research-development-and-operations.

operations and manages and distributes the data from the Earth Resources Observation and Science (EROS) Center in Sioux Falls, SD.[8]

Beginning in 2008, the USGS began the process of making all Landsat data held in USGS archives available for download at no charge and without restrictions.[9] Every year, the USGS distributes millions of these remotely sensed Landsat images to thousands of users. On March 11, 2020, a Landsat 8 image of New Zealand's North Island became the 100 millionth download from the USGS's user interface tools.[10] USGS researchers estimate that Landsat imagery provided domestic and international users $3.45 billion in benefits in 2017, with U.S. users accounting for $2.06 billion of those benefits.[11] The Landsat program's policies and technologies also have inspired international governmental satellites, such as the European Space Agency's (ESA's) Copernicus Program Sentinel-2 satellite constellation and a new generation of commercial satellites with Landsat-like characteristics.[12]

With the launch of Landsat 9, Congress may wish to consider the future of the Sustainable Land Imaging Program. After completing a Sustainable Land Imaging Architecture Study initiated in 2018, NASA and the USGS are developing details and options for the follow-on to Landsat 9, known as Landsat Next. They anticipate sharing information about Landsat Next in 2022.[13]

This report describes the Sustainable Land Imaging Program, Landsat satellite instrumentation, uses of Landsat data, and aspects of Landsat's history. The report also discusses potential alternatives to the current Landsat satellite system and Sustainable Land Imaging Program, as well as possible tradeoffs among those alternatives.

Landsat and the Sustainable Land Imaging Program

Over the more than 50 years of Landsat planning and operations, various entities have led Landsat mission acquisition (i.e., planning, financing, building, prelaunch activity) and operations (i.e., management and data activities).[14] After initiating Landsat as a research program under NASA, the Carter and Reagan Administrations proposed and Congress approved policies in the 1980s to privatize Landsat under the leadership of the National Oceanic and Atmospheric Administration

[8] For more information on the USGS Earth Resources Observation and Science (EROS) Center, see USGS, "Earth Resources Observation and Science (EROS) Center," at https://www.usgs.gov/centers/eros.

[9] USGS, Landsat Missions, "Imagery for Everyone, Timeline Set to Release Entire USGS Landsat Archive at No Charge," April 2008, at https://www.usgs.gov/land-resources/nli/landsat/imagery-everyone.

[10] USGS, "A Landsat Milestone: One Hundred Million Downloads," at https://www.usgs.gov/center-news/a-landsat-milestone-one-hundred-million-downloads.

[11] Christa L. Straub, Stephen R. Koontz, and John B. Loomis, *Economic Valuation of Landsat Imagery*, U.S. Geological Survey Open-File Report 2019–1112, 2019, at https://doi.org/10.3133/ofr20191112. Hereinafter USGS, *Economic Valuation of Landsat Imagery*.

[12] For an overview of government and commercial land remote sensing satellites, see Jon B. Christopherson, Shankar N. Ramaseri Chandra, and Joel Q. Quanbeck, *2019 Joint Agency Commercial Imagery Evaluation—Land Remote Sensing Satellite Compendium*, USGS Circular 1455, 2019, at https://doi.org/10.3133/cir1455. National Geospatial Advisory Committee (NGAC), Landsat Advisory Group (LAG), *Recommendations for Possible Future U.S. Global Land Data Collection Missions Beyond Landsat 9*, April 2018, at https://www.fgdc.gov/ngac/meetings/april-2018/ngac-landsat-future-missions-recommendations-paper.pdf. Hereinafter LAG, *Recommendations Beyond Landsat 9*.

[13] Congressional briefing from NASA and the USGS on September 14, 2021. The NASA FY2022 Budget Request also states, "the Administration will make key strategic decisions for Landsat Next as part of the FY 2023 budget process." NASA, *FY2022 Budget Congressional Justification NASA Budget Request*, 2021, at https://www.nasa.gov/news/budget/index.html.

[14] Goward et al., *Landsat's Enduring Legacy*.

(NOAA) and a commercial entity, the Earth Observation Satellite Company (EOSAT).[15] The attempt at privatizing the Landsat system ended with the passage of the Land Remote Sensing Policy Act of 1992 (P.L. 102-555), which returned responsibility for management of the Landsat program to the federal government.[16] (For more background on the history of Landsat privatization, see **Appendix A**.) Thereafter, agency management of Landsat changed frequently from 1992 through 1998, with responsibility moving from a NASA-U.S. Air Force-USGS partnership to a NASA-NOAA-USGS partnership to the present NASA-USGS arrangement.[17]

In 2016, DOI and NASA signed a memorandum of understanding (MOU) to establish the Sustainable Land Imaging Program, intended to enable the development of a multi-decade space system to provide users worldwide with high-quality global land imaging measurements compatible with the previous 44-year record.[18] Under the agreement, NASA maintains responsibility for developing, launching, and testing space systems and DOI, through the USGS, is responsible for developing and maintaining associated ground systems (including satellite operation and mission data systems); operating the on-orbit spacecraft; and collecting, archiving, processing, and distributing data to users. The NASA Associate Administrator for Science and the DOI Assistant Secretary for Water and Science chair the Sustainable Land Imaging Joint Steering Group and meet periodically to coordinate and integrate efforts and to enable overall program strategy. The Sustainable Land Imaging Program MOU also calls for sensor and system studies, business model studies, and other user-need and technology investigations to reduce cost and risk for future missions.[19]

In accordance with guidance from the explanatory statement of the Consolidated and Further Continuing Appropriations Act, 2015 (P.L. 113-235),[20] NASA and DOI entered into an annex agreement of the Sustainable Land Imaging Program MOU to build and launch Landsat 9, generally a remake of Landsat 8, by 2020.[21] Landsat 9 launched on September 27, 2021, which experts expect to provide continuity of coverage, as NASA projects Landsat 7 has fuel through 2021.

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[15] Goward et al., *Landsat's Enduring Legacy*.

[16] Goward et al., *Landsat's Enduring Legacy*.

[17] National Research Council, *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*, 2011, at https://doi.org/10.17226/13042.

[18] USGS, "MOU - Sustainable Land Imaging Research, Development, and Operations," September 27, 2016, at https://www.usgs.gov/media/files/mou-sustainable-land-imaging-research-development-and-operations.

[19] Michael A. Wulder et al., "Current Status of Landsat Program, Science, and Applications," *Remote Sensing of Environment*, vol. 225 (May 2019), pp. 127-147, at https://doi.org/10.1016/j.rse.2019.02.015. Hereinafter Wulder et al., "Current Status of Landsat."

[20] Explanatory statement of the Consolidated and Further Continuing Appropriations Act, 2015 (P.L. 113-235), available at "Explanatory Statement," Proceedings and Debates of the 113th Congress, Second Session, *Congressional Record*, vol. 160, part 2 (December 11, 2014), p. H9349, at https://www.govinfo.gov/content/pkg/CREC-2014-12-11/pdf/CREC-2014-12-11-house-bk2.pdf. The explanatory statement called for Landsat 9 to cost substantially less than Landsat 8; to provide the same data quality as Landsat 8, so as to not require an overhaul of associated ground systems; and to provide no degradation or gap in data, including the eight-day continuous coverage. The explanatory statement did not endorse efforts to develop alternative approaches that would increase risk of a coverage gap and not meet the needs of the Landsat user community.

[21] USGS, "MOU - Collaborate on the Landsat 9 Project," September 14, 2016, at https://www.usgs.gov/media/files/mou-collaborate-landsat-9-project.

Agency Responsibilities and Budgets

The following describes the respective agency responsibilities of NASA and the USGS for the Sustainable Land Imaging Program and funding activities for Landsat 8, Landsat 9, and Landsat Next development.

NASA

Under the Sustainable Land Imaging Program, NASA is responsible for, among other things,[22]

- leading and managing the overall system architecture design and development;
- developing and executing agreements with potential international partners;
- developing and executing agreements for flight hardware development with potential external partners;
- supporting ground system development and leading and managing mission operational readiness;
- developing, integrating, and testing spacecraft, instruments, and launch vehicle services for the program;
- launching the mission, performing on-orbit checkout and commissioning, and transitioning Landsat to DOI for operations; and
- supporting the calibration, validation, and characterization of the instruments throughout the remaining mission life cycle.

NASA Landsat activities are funded under the Earth Science Division in the Science Mission Directorate.[23] NASA spent $857 million on Landsat 8.[24] As of the end of FY2021, NASA has spent $699 million on its responsibilities for launching Landsat 9, out of an overall life-cycle cost commitment of $885 million.[25] The President's budget request for NASA in FY2022 includes $2.8 million for Landsat 9 operations and transition to the USGS, and $56 million for the Sustainable Land Imaging Program and planning for Landsat Next.[26] Congress has provided funding each year for the Sustainable Land Imaging Program to support technology development activities for future land imaging sensors, as well as funding for the Landsat Next mission, which began pre-formulation activities in FY2020.[27]

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[22] USGS, "MOU - Sustainable Land Imaging Research, Development, and Operations," September 27, 2016, at https://www.usgs.gov/media/files/mou-sustainable-land-imaging-research-development-and-operations.

[23] NASA, *FY2022 Budget Congressional Justification NASA Budget Request*, 2021, at https://www.nasa.gov/news/budget/index.html.

[24] Personal correspondence between CRS and NASA on July 8, 2020.

[25] An overall life-cycle cost commitment is the not-to-exceed amount NASA committed to when formulating the mission. Personal correspondence between CRS and NASA on July 8, 2020, September 9, 2020, and October 21, 2021.

[26] Personal correspondence between CRS and NASA on July 8, 2020 and October 21, 2021. NASA, *FY2022 Budget Congressional Justification NASA Budget Request*, 2021, at https://www.nasa.gov/news/budget/index.html.

[27] Personal correspondence between CRS and NASA on July 8, 2020.

U.S. Geological Survey

Under the Sustainable Land Imaging Program, DOI, through the USGS, is responsible for, among other things,[28]

- defining the needs of national and international users for a land imaging system and providing technical, managerial, and scientific support to NASA related to those needs throughout the space system development life cycle;
- supporting, under NASA leadership, the overall land imaging system architecture design and development;
- leading and managing ground system development, including all pre- and postlaunch activities related to development of the ground-based component of the land imaging system;
- leading and managing the calibration, validation, and characterization of the instruments after reaching orbit;
- operating Landsat, as well as the downlink, archiving, processing, and distributing Landsat data;
- establishing cooperation in land imaging system data acquisition, data sharing, product development, and distribution with potential external partners;
- defining and representing to NASA the needs and desires of user communities, as well as providing unique expertise and guidance in the design of spacecraft and data operations, processing, and distribution methodologies and management approaches;
- developing a common set of land imaging data products and data dissemination; and
- maintaining the national archive of land imaging system data.

In addition, the USGS supports a Landsat Science Team consisting of USGS and NASA scientists and engineers, external scientists, engineers, and application specialists, representing industry and university research initiatives.[29] Landsat Science Teams (e.g., the 2018-2023 Landsat Science Team) consider technological design issues and evolution, changes to algorithms for data processing and distribution, and the design of standard data products to enable easier use of the data, among other objectives.

USGS Landsat activities are funded under the National Land Imaging Program in the Core Science Systems Mission Area.[30] The National Land Imaging Program, funded at $106.9 million in FY2021, has three main budget areas: Satellite Operations; Science, Research, and

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[28] USGS, "MOU - Sustainable Land Imaging Research, Development, and Operations," September 27, 2016, at https://www.usgs.gov/media/files/mou-sustainable-land-imaging-research-development-and-operations.

[29] USGS, Landsat Missions, "Landsat Science Teams," at https://www.usgs.gov/land-resources/nli/landsat/landsat-science-teams.

[30] USGS, "National Land Imaging Program," at https://www.usgs.gov/core-science-systems/national-land-imaging-program. Congress transferred the National Land Imaging Program to the Core Science Mission Area and eliminated the Land Resources Mission Area as requested by the Trump Administration in the USGS FY2021 budget request. Explanatory Statement accompanying Division G of P.L. 116-260, at https://www.congress.gov/117/cprt/HPRT43750/CPRT-117HPRT43750.pdf. USGS, *FY2021 USGS Budget Justification (Greenbook)*, 2020, at https://www.usgs.gov/about/organization/science-support/budget/usgs-fy2021-budget.

Investigations; and Land Cover Monitoring and Assessments.[31] Satellite Operations, funded at $84.3 million in FY2021, supports Landsat 9 ground system development, satellite operations activities other than the Landsat 9 ground system development, and continues to develop sustainable land imaging with Landsat Next.[32]

The USGS spent $180 million through FY2013 on its responsibilities for Landsat 8.[33] Through FY2020, the USGS has spent over $120 million on Landsat 9 for ground system development to operate the spacecraft in orbit; to collect the data and return it to the EROS ground station; and to calibrate, validate, archive, process, and distribute the data at EROS.[34] The request for $84.8 million for Satellite Operations in the President's FY2022 budget request would support Landsat 7, 8, and 9 and would continue to develop sustainable land imaging with Landsat Next.[35]

Landsat Satellites and Instruments[36]

Landsat sensors record reflected and emitted energy from Earth in various wavelengths of the electromagnetic spectrum. The electromagnetic spectrum includes all forms of radiated energy, from high frequency, short wavelength gamma rays and x-rays to low frequency, long wavelength radio waves. The human eye is sensitive to the visible wavelengths of this spectrum; humans can see color ranging from violet to red. Landsat instruments sense and record blue, green, and red light in the visible spectrum as well as near-infrared, shortwave-infrared, and thermal-infrared light that human eyes cannot perceive (although humans can feel the thermal-infrared light as heat). Landsat records this information digitally and transmits it to ground stations, where it is processed and stored in a data archive.

Since 1972, Landsat satellites have continuously gathered land imagery from space using several instruments mounted on the satellite. The instruments generally have improved in capability with the launch of each successive mission; the satellites, detectors, communications, downlink capacity, and ground system technology likewise have advanced and changed over time.[37] For a timeline of Landsat satellites, see **Figure 1**.

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[31] Science, Research, and Investigations funding supports classified data activity operations, non-satellite archive operations and data distribution, product development and improvement, remote sensing technology investigations, and education and outreach grants. In FY2021, the funding for Science, Research, and Investigations totaled $14.6 million; the FY2022 budget request is $14.6 million. According to the USGS, Land Cover Monitoring and Assessments creates a suite of annual land cover and change products for the United States based on time series data from the Landsat record. In FY2021, funding for Land Cover Monitoring and Assessments totaled $8.0 million; the FY2022 budget request is $17.5 million. USGS, *FY2022 USGS Budget Justification (Greenbook)*, 2021, at https://www.usgs.gov/about/organization/science-support/office-budget-planning-and-integration-bpi/usgs-fy2022-budget. P.L. 116-260.

[32] Satellite Operations funds the USGS to (1) keep pace with NASA's build and launch of the satellite, sensors, and launch vehicle; (2) support the flight and ground system operations and maintenance of Landsats; (3) continue the EROS national satellite archive operations and maintenance and data distribution; and (4) continue Landsat product development and improvement. Personal correspondence between CRS and the USGS on July 10, 2020, and October 7, 2021.

[33] Personal correspondence between CRS and the USGS on July 10, 2020.

[34] Personal correspondence between CRS and the USGS on July 10, 2020.

[35] Personal correspondence between CRS and the USGS on July 10, 2020, and October 7, 2021. USGS, *FY2022 USGS Budget Justification (Greenbook)*, 2021, at https://www.usgs.gov/about/organization/science-support/office-budget-planning-and-integration-bpi/usgs-fy2022-budget.

[36] Parts of this description are excerpted from NASA, Landsat Science, "Data: The Numbers Behind Landsat," at http://landsat.gsfc.nasa.gov/data/.

[37] The Landsat program has met with some failures in its history. For example, Landsat 6 failed to achieve orbit and an instrument aboard Landsat 7 stopped functioning properly—the scan line corrector, which compensates for the forward

Figure 1. Timeline of Landsat Satellites

Source: U.S. Geological Survey (USGS), "Landsat Missions Timeline," at https://www.usgs.gov/media/images/landsat-missions-timeline.

Note: Landsat 6 failed to achieve orbit.

Currently, Landsat 7 and 8 orbit the Earth at an altitude of 438 miles and complete 14 full orbits each day.[38] Each satellite crosses every point on Earth once every 16 days. With Landsat 7 and 8 both operating, each point on Earth gets complete coverage every eight days, although clouds can obscure the imagery over parts of the Earth at any given time. Landsat 8 captures approximately 750 images a day, an increase from the roughly 450 images a day captured by Landsat 7. Spatial resolution for each satellite is 30 x 30 meters for most observations, about the size of a baseball diamond.

Landsat 8 carries two instruments: an operational land imager (OLI), which observes many of the same bands of radiation as Landsat 7 but with improvements (see example OLI images in **Figure 2**), and a thermal infrared sensor (TIRS) that can measure land surface temperature in two different thermal infrared bands.[39] The thermal infrared bands on Landsat 8 provide improved temperature estimates and estimates of soil moisture compared with earlier Landsat instruments.[40]

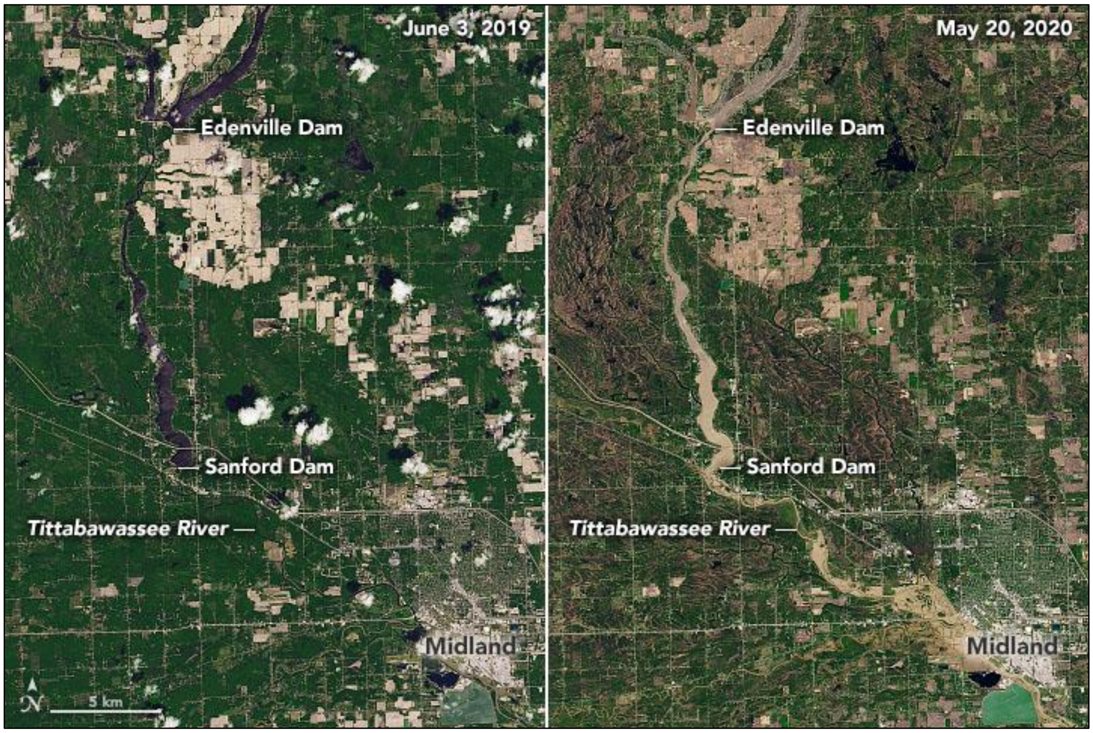
motion of the satellite to align forward and reverse scans necessary to create an image. Goward et al., *Landsat's Enduring Legacy*.

[38] USGS, "What Are the Acquisition Schedules for the Landsat Satellites?," at https://www.usgs.gov/faqs/what-are-acquisition-schedules-landsat-satellites.

[39] Early in the Landsat 8 mission, the thermal infrared sensor (TIRS) experienced stray light problems, and operators performed technical adjustments to stabilize its measurement performance in orbit. NASA, Landsat Science, Landsat 8, "Mission Details," at https://landsat.gsfc.nasa.gov/landsat-8/mission-details/.

[40] USGS, "What Are the Best Landsat Spectral Bands for Use in My Research?," at https://www.usgs.gov/faqs/what-are-best-landsat-spectral-bands-use-my-research.

Figure 2. Landsat 8 Images Showing the Effects of Flooding from Dam Failures



Source: National Aeronautics and Space Administration (NASA) Earth Observatory, "Muddy Flooding in Michigan," at https://earthobservatory.nasa.gov/images/146752/muddy-flooding-in-michigan.

Note: The pair of natural color images shows flooding across Midland County, MI, in 2020 (image on the right) following two dam failures on the Tittabawassee River as observed by the operational land imager on Landsat 8. The 2020 image shows the impacts of flooding, with light brown colors indicating increased sediment in flood waters and deposition of sediment downstream of the dams.

Initiated in March 2015, Landsat 9 (see **Figure 3**) has a design very similar to that of Landsat 8, in order to shorten the development time and reduce the risk of a Landsat data gap when Landsat 7 ceases to operate.[41] The instruments on board Landsat 9 are similar to but are improvements over those currently collecting data on board Landsat 8; Landsat 9's instruments include the Operational Land Imager–2 (OLI–2), built by Ball Aerospace & Technologies Corporation, and the Thermal Infrared Sensor–2 (TIRS–2), built at the NASA Goddard Space Flight Center.[42] Northrop Grumman Innovation Systems built the spacecraft, and General Dynamics built the mission operations element.[43] The Landsat ground system at USGS EROS has undergone improvements to support both Landsat 8 and Landsat 9 operations and to increase the computational efficiency of data processing, archiving, management, and distribution.[44]

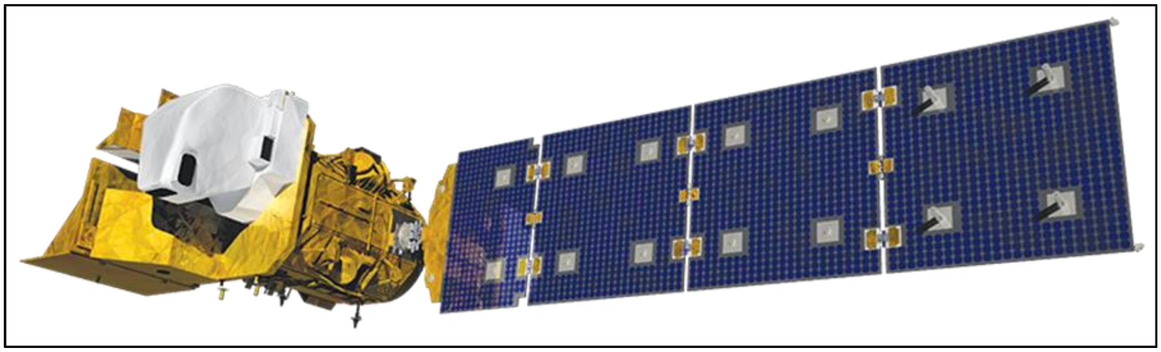
[41] NASA, Landsat Science, "Landsat 9," https://landsat.gsfc.nasa.gov/landsat-9/. Statement of NASA Administrator Charles F. Bolden Jr., in U.S. Congress, House Committee on Science, Space, and Technology, Subcommittee on Space, *An Overview of the Budget Proposal for the National Aeronautics and Space Administration for Fiscal Year 2017*, 114th Cong., 2nd sess., March 17, 2016, HRG-2016-TEC-0020.

[42] The original Landsat 8 TIRS had an optical design problem that degraded the radiometric accuracy of the instrument, and the encoder for the TIRS image select mirror stopped operating early in the mission. The revised TIRS-2 design addressed these problems. Wulder et al., "Current Status of Landsat."

[43] Earth Observation Portal, "Landsat-9," at https://directory.eoportal.org/web/eoportal/satellite-missions/l/landsat-9.

[44] Wulder et al., "Current Status of Landsat."

Figure 3. Rendering of the Landsat 9 Design



Source: NASA, Landsat Science, Landsat 9, "Landsat 9 Overview," at https://landsat.gsfc.nasa.gov/landsat-9/landsat-9-overview/.

Landsat 9 launched on September 27, 2021, from Vandenberg Air Force Base, CA, on board a United Launch Alliance Atlas V 401 rocket.[45] NASA is now positioning Landsat 9 into the current orbit of Landsat 7, which NASA is expected to decommission when Landsat 9 becomes fully operational. Landsat 9 is to image the Earth every 16 days in an 8-day offset with Landsat 8.[46] Landsat 9 is to collect as many as 750 images per day; with Landsat 8, the two satellites are to add nearly 1,500 new images a day to the USGS Landsat archive. Both instruments on Landsat 9 have a 5-year mission design life, and the spacecraft has more than 10 years of fuel. Data acquired by Landsat 9 are intended to be consistent with archived data and therefore should allow for long-term comparisons of changes in the Earth's land features.

Use of Landsat Data

In response to congressional direction in the NASA Authorization Act of 2010 (P.L. 111-267), the White House led an assessment of national programs for civil Earth observations in 2014, which named Landsat one of the most critical U.S. systems, third only to the satellite-based Global Positioning System and the National Weather Service satellites.[47] Satellite remote sensing data provide a relatively low-cost alternative to aerial surveys, offering the potential to survey large areas, albeit with possibly lower resolution.[48] Data from Landsat are used widely in the United States and worldwide to support operational decisionmaking and research in areas such as agriculture, forestry and range resources, land use and mapping, geology, hydrology, coastal resources, environmental monitoring, disaster response, and national security (see **Figure 4**).[49] Landsat data also are used for commercial applications and in derived products, such as Google

[45] USGS, Landsat Missions, "Landsat 9," at https://www.usgs.gov/land-resources/nli/landsat/landsat-9.

[46] Because of cloud cover, the period between clear observations for an application may be longer than the revisit time. To get seasonal observations, the satellite must acquire several images during the season to increase the likelihood that the area will be cloud free during at least one overpass per season.

[47] Office of Science and Technology Policy (OSTP), *National Plan for Civil Earth Observations*, July 2014, at https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/NSTC/2014_national_plan_for_civil_earth_observations.pdf. Hereinafter OSTP, *National Plan for Civil Earth Observations*.

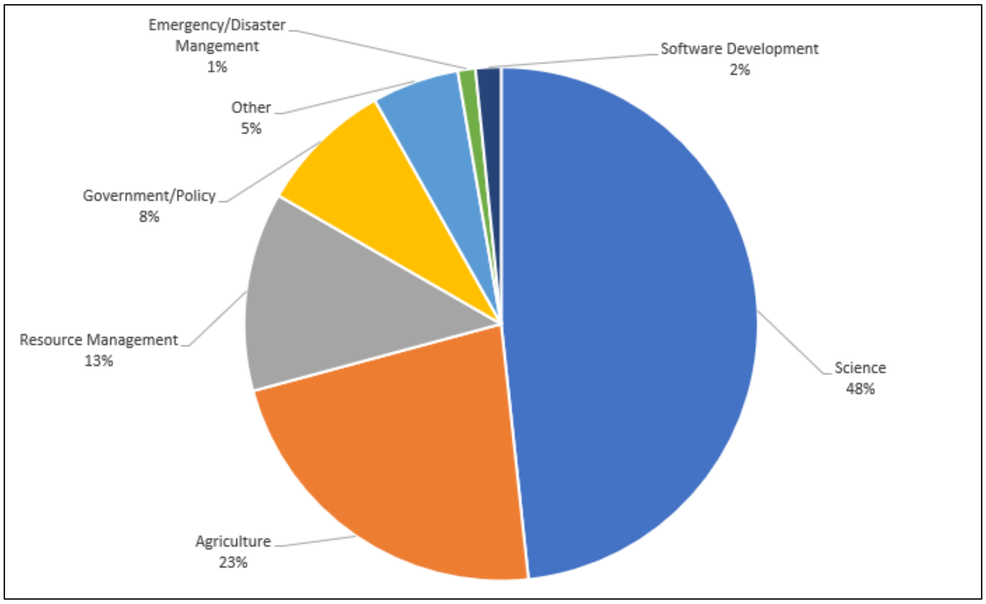
[48] Ginger Butcher, Linda Owen, and Christopher Barnes, "Landsat: the Cornerstone of Global Land Imaging," *GIM International*, February 2, 2019, at https://www.gim-international.com/content/article/landsat-the-cornerstone-of-global-land-imaging. Hereinafter Butcher et al., "Landsat the Cornerstone."

[49] USGS, *Economic Valuation of Landsat Imagery*; National Research Council (NRC), *Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program*, 2013, at https://doi.org/10.17226/18420. Hereinafter NRC, *Landsat and Beyond*.

Earth, which themselves have millions of users.[50] Studies have noted that users of Landsat data are overwhelmingly government agencies, academic institutions, and nongovernmental organizations, with commercial entities constituting a small fraction of users.[51] USGS researchers estimate that Landsat imagery provided U.S. users with $2.06 billion in benefits in 2017, with an additional $1.39 billion in benefits for international users.[52] When those researchers incorporated the number of images downloaded from EROS by cloud vendors, the benefits to domestic and international users were estimated at $4.18 billion in 2017.

Figure 4. Primary Uses of Landsat Data

(October 1, 2021-September 30, 2021)



Source: USGS, Landsat Missions, "Landsat Project Statistics," accessed on November 3, 2021, at https://www.usgs.gov/land-resources/nli/landsat/landsat-project-statistics.

Notes: Top uses of Landsat data, as indicated by Earth Resources Observation and Science (EROS) registration system user profile demographics.

[50] USGS, *Economic Valuation of Landsat Imagery*.

[51] NRC, *Landsat and Beyond*.

[52] USGS, *Economic Valuation of Landsat Imagery*.

Use of Landsat by the Federal Government

The federal government is a prominent user of Landsat data, in part due to its land management responsibilities. More than 30 federal agencies and departments use Landsat data. The federal government owns roughly 640 million acres of land in the United States, which constitutes 28% of the 2.27 billion acres of land in the country. In addition, the Department of Defense (DOD) owns, leases, or otherwise possesses 26.9 million acres of land worldwide (in the United States and other countries). Landsat data are used operationally by virtually every U.S. land management agency to define broad land-cover categories and to monitor changes (e.g., fire impacts). The following are some examples of long-term use of Landsat data by the federal government:

- In the U.S. Department of Agriculture (USDA), the Foreign Agricultural Service uses Landsat data to monitor global crop supplies and stocks to forecast shortfalls or gluts of various crops on the market. The USDA also uses Landsat to assess and quantify flood damage to crops to determine crop-insurance payments to farmers.
- Within DOD, the U.S. Army Corps of Engineers uses Landsat data mostly for civilian water resource purposes, such as responding to flood events, whereas other DOD agencies use the data for cartography, topographic mapping, and other strategic ends. The U.S. military routinely generates up-to-date image base maps and three-dimensional visualizations of landscapes using Landsat for overseas deployments.
- The United States Global Change Research Program, authorized by the Global Change Research Act of 1990 (P.L. 101-606) and representing 13 federal agencies, identified Landsat as a critical observatory for climate and environmental change research due to the unbroken length of the Landsat record and its ability to monitor remote regions with surface features, such as glaciers, rainforests, permafrost, and coral reefs.

For more examples of Landsat use by federal agencies, see NASA, Landsat Science, "How Landsat Helps: Case Studies," at https://landsat.gsfc.nasa.gov/how_landsat_helps/case-studies-2/.

Sources: National Academies of Sciences, Engineering, and Medicine, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, 2018, at https://doi.org/10.17226/24938; CRS Report R42346, *Federal Land Ownership: Overview and Data*; Sam N. Goward et al., *Landsat's Enduring Legacy: Pioneering Global Land Observations from Space* (American Society for Photogrammetry and Remote Sensing: Bethesda, MD, 2017).

Some stakeholders have referred to Landsat as a *gold standard* for its length of record, availability of data, global coverage, and calibration standards.[53] Landsat serves as the central reference comparison point for many moderate- and high-resolution optical satellite systems operated by governments or commercial entities.[54] The Landsat program's policies and technologies also have influenced programs of foreign governments (e.g., the ESA's Copernicus Program Sentinel-2 satellite constellation; see **Appendix B**) and a new generation of commercial satellites.[55]

Increased Data Availability and Use Under Changing Policies

In early Landsat missions, the USGS relied on a network of international ground stations, operated by cooperating nations, to downlink and store Landsat images.[56] In 2006, the USGS recognized that the volume of Landsat data holdings held by international cooperators (an estimated 4 million images) far exceeded the holdings in the USGS Landsat archive at EROS (an

[53] NGAC, LAG, *Landsat Data: Community Standard for Data Calibration, October 2020*, at https://www.fgdc.gov/ngac/meetings/october-2020/ngac-paper-landsat-data-community-standard-for.pdf.

[54] NGAC, LAG, *Evaluation of a Range of Landsat Data Cost Sharing Models*, June 2019, at https://www.fgdc.gov/ngac/meetings/june-2019/ngac-paper-evaluation-of-a-range-of-landsat-data.pdf. Hereinafter LAG, *Evaluation of Landsat Data Cost Sharing Models*.

[55] LAG, *Recommendations Beyond Landsat 9*.

[56] Michael Wulder et al., "The Global Landsat Archive: Status, Consolidation, and Direction," *Remote Sensing of Environment*, vol. 185 (November 2016), pp. 271-283, at https://www.sciencedirect.com/science/article/pii/S0034425715302194. Hereinafter Wulder et al., "Global Landsat Archive."

estimated 1.9 million images).[57] In 2010, the USGS started the U.S. Landsat Global Archive Consolidation program to repatriate unique Landsat data.[58] The initiative had acquired and reprocessed more than 5 million images by December 2019, increasing the Landsat archive's coverage equivalent to the launch of an additional Landsat mission and expanding its historical spatial coverage (for more information, see **Appendix B**).[59]

In 2008, the USGS announced no-charge electronic access to any Landsat image held in the USGS-managed national archive.[60] This decision removed financial barriers for potential users, resulting in new and expanded Landsat applications.[61] The price for a single Landsat image varied from $20 to $200 from 1972 to 1982, increased to between $3,000 and $4,000 from 1983 to 1998, and then decreased to approximately $600 from 1999 to 2008.[62] Over these years, no more than 3,000 Landsat images were sold in a given month.[63] In 2009, the first full year of free and open access, users downloaded nearly 1 million images.[64]

Since 2008, the use of Landsat data has increased significantly, especially in global time-series applications, such as the World Resources Institute Global Forest Watch web application, which monitors global forests in near real time.[65] **Figure 5** shows the cumulative number of Landsat images downloaded from the USGS servers since full implementation of the free-access policy (in the figure, increments are labeled for every 10 million image downloads following the first million in 2009).[66] USGS statistics do not include data accessed from secondary platforms, such as Google Earth Engine or Amazon Web Services, which started hosting Landsat data after 2008; as a result, the actual increases are likely greater than those illustrated in **Figure 5**.[67] For example, a 2018 report stated that Google Earth delivers approximately 1 billion Landsat images to users per month.[68]

[57] Wulder et al., "Global Landsat Archive."

[58] Wulder et al., "Global Landsat Archive."

[59] USGS, Landsat Missions, "Landsat Global Archive Consolidation," at https://www.usgs.gov/land-resources/nli/landsat/landsat-global-archive-consolidation; Wulder et al., "Global Landsat Archive."

[60] USGS, Landsat Missions, "Imagery for Everyone, Timeline Set to Release Entire USGS Landsat Archive at No Charge," April 2008, at https://www.usgs.gov/land-resources/nli/landsat/imagery-everyone.

[61] USGS, "A Landsat Milestone: One Hundred Million Downloads," at https://www.usgs.gov/center-news/a-landsat-milestone-one-hundred-million-downloads.

[62] Zhe Zhu et al., "Benefits of the Free and Open Landsat Data Policy," *Remote Sensing of Environment*, vol. 224 (April 2019), pp. 382-385, at https://doi.org/10.1016/j.rse.2019.02.016. Hereinafter Zhu et al., "Benefits of Landsat Data Policy."

[63] Zhu et al., "Benefits of Landsat Data Policy."

[64] Zhu et al., "Benefits of Landsat Data Policy."

[65] Butcher et al., "Landsat the Cornerstone."

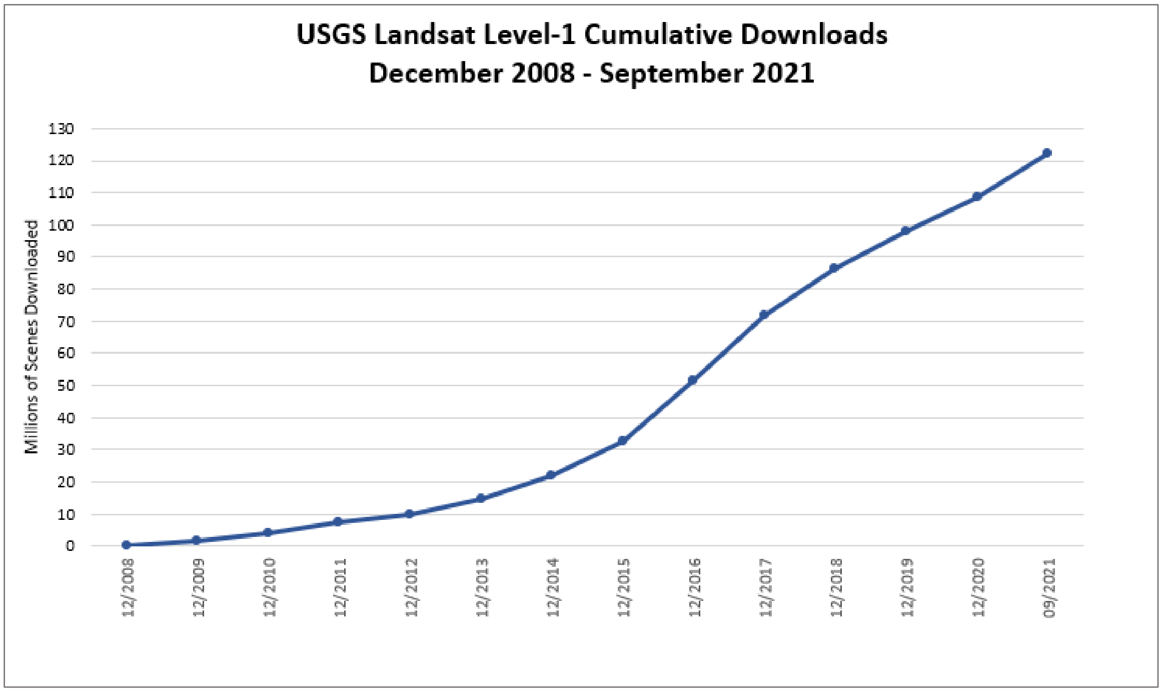
[66] USGS, Landsat Missions, "Landsat Project Statistics," at https://www.usgs.gov/land-resources/nli/landsat/landsat-project-statistics.

[67] Zhu et al., "Benefits of Landsat Data Policy."

[68] National Academies of Sciences, Engineering, and Medicine (NASEM), *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, 2018, at https://doi.org/10.17226/24938. Hereinafter NASEM, *Decadal Strategy for Earth Observation from Space*.

Figure 5. Cumulative Landsat Image Downloads from USGS Inventory Since the 2008 Data Policy for No-Charge Access to Landsat Images

(December 2008-September 2021)



Source: U.S. Geological Survey (USGS), provided to CRS on October 7, 2021.

Notes: Number of Landsat images downloaded since the entire USGS Landsat archive was made available at no charge to all users.

Anecdotal observations suggest Landsat users have gravitated toward commercial cloud computing vendors to download and process Landsat in the cloud.[69] Working under the 2018 Federal Cloud Computing Strategy, in 2020, the USGS placed a copy of its consolidated Landsat global data inventory into a commercial cloud.[70] Landsat's cloud architecture uses a hybrid approach that includes the USGS cloud hosting solutions program and existing EROS center private cloud capabilities. The USGS suggests the commercial cloud may be more convenient and cost-effective than traditional downloading for some users to reprocess Landsat data. The agency estimates that users following the traditional workflow may spend up to 80% of their Landsat work time downloading and processing files.[71] With cloud computing, users can run algorithms against the entire archive without having to download and locally store and process data. Cloud computing also allows users to access spatial or temporary subsets of data without having to download the entire image and subset the data locally.[72] In addition to this cloud architecture, the

[69] USGS, *Economic Valuation of Landsat Imagery*. For an explanation of cloud computing, see CRS Report R46119, *Cloud Computing: Background, Status of Adoption by Federal Agencies, and Congressional Action*, by Patricia Moloney Figliola.

[70] USGS, "Landsat Data Moving to Public Cloud in Early 2020," at https://www.usgs.gov/news/landsat-data-moving-public-cloud-early-2020.

[71] USGS, "Landsat Data in the Cloud," at https://www.usgs.gov/media/videos/landsat-data-cloud.

[72] Zhu et al., "Benefits of Landsat Data Policy"; USGS, "Landsat Data in the Cloud," at https://www.usgs.gov/media/videos/landsat-data-cloud.

USGS will continue to manage the original Landsat global data inventory at EROS, and the inventory will be available from traditional websites on a long-term basis.[73]

Documenting Landsat data use is important for identifying the needs of users for future missions and products. The current metric for data usage is *image downloads*. This metric may underestimate the use of Landsat images, as other websites host Landsat data. Moving forward, Congress may want to direct the USGS to consider new ways to document Landsat data use, as the metric of image downloads is less relevant when numerous users take advantage of in-the-cloud processing without actually downloading images.

Landsat After Landsat 9

With the launch of Landsat 9, Congress may wish to consider the future of the Sustainable Land Imaging Program. More specifically, Congress may want to consider whether to support the development of another moderate-resolution land imaging satellite after Landsat 9, and it may want to investigate potential alternatives.

A future moderate-resolution mission could differ from previous Landsat satellites in several ways. For example, such a mission could adopt a smaller satellite design, increase image resolution or the number of images captured per day, reduce the time between images of a given location, sense a wider variety of optical and infrared frequencies, or make other design changes.

There may be ways to acquire data similar to that provided by Landsat without building another fully federally funded satellite, like Landsat 8 or Landsat 9. Such arrangements could include developing alternative models for generating sources of multispectral and thermal imaging, such as a public-private partnerships, or procuring data from non-U.S. moderate-resolution satellite systems. These issues are discussed below in the context of the Sustainable Land Imaging Architecture Study, guidance from the Obama and Trump Administrations for the nation's Earth observation program, and reports and studies from advising bodies and stakeholders.

Sustainable Land Imaging Architecture Study

Under the Sustainable Land Imaging Program, NASA and the USGS work on planning activities, including requirements and technology development, in an effort to reduce cost and risk in future missions. The USGS partners with federal agencies and others to document the uses of and requirements for land imaging data.[74] For example, the USGS recently released a user-needs study documenting the needs of federal government civil subject matter experts who rely on moderate-resolution land imaging data across a diverse range of scientific research and application domains.[75] Based on the survey results, federal government civil users seek improvement to 10-meter spatial resolution, at least weekly cloud-free observation frequency, and the addition of spectral bands not currently measured.

Whereas the USGS leads the focus on the uses and requirements for land imaging data, NASA leads instrument studies, business model studies, and other technology investigations to reduce the cost and risk of satellite missions. For example, NASA called for proposals for sustainable

[73] USGS, "Landsat Data Moving to Public Cloud in Early 2020," at https://www.usgs.gov/news/landsat-data-moving-public-cloud-early-2020.

[74] USGS, "Requirements Capabilities & Analysis for Earth Observations," at https://www.usgs.gov/land-resources/nli/rca-eo.

[75] Wu et al., "User Needs."

land imaging technology development in 2015 to identify and develop key enabling technologies.[76] Ball Aerospace—one of six companies selected by NASA to receive study funding—developed, built, and flight tested a multispectral airborne imager with a much smaller volume and a lower cost than Landsat 8.[77]

The Sustainable Land Imaging Architecture Study Team, initiated in 2018 and consisting of scientists from NASA and the USGS, was created to advance measurement capability for the next mission after Landsat 9, while preserving continuity and constraining program costs.[78] The study team was to consider all options, including new, compact imaging technologies; international partnerships; and commercial-sector involvement. In late 2018, the study team requested public comments on draft sustainable land imaging science requirements for use by the study team.[79] The draft requirements were presented at a threshold level (the minimally acceptable performance level) and at a goal level (the desired level). For example, one of the draft requirements was that the Sustainable Land Imaging Program shall be capable of collecting imagery at the same location on Earth every eight days as the threshold level and every three days as the goal level.

In early 2020, the study team delivered the report to NASA and the USGS; as of October 2021, the report is not publicly available.[80] The study was supposed to suggest as many as three viable architecture concepts and capabilities for deciding future acquisition strategies and approaches based on the sustainable land imaging requirements. The agencies are further developing details and options. In September 2020, then-USGS Director James Reilly shared that the agencies looked at options other than a single large satellite bus, including acquiring Earth imagery from a number of different platforms that could be brought together as a system of systems.[81] A 2020 request for information (RFI) from NASA described the Landsat Next concept as centered on a "superspectral" dataset featuring both richer spectral information and higher spatial resolution compared to Landsat 8 and 9.[82] The RFI stated that NASA and the USGS would aim to begin Landsat Next operations in the late 2020s and that Landsat Next may either be a single satellite observatory or a small satellite constellation (approximately three to five satellites) performing coordinated imaging observations. The agencies anticipate sharing information about the mission, currently termed Landsat Next, in 2022.[83]

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[76] NASA called for additional proposals in 2019, with selection expected in 2020. NASA, "Sustainable Land Imaging Technology," at https://esto.nasa.gov/slit/.

[77] NASA, "2015 SLI-T Projects Awarded," at https://esto.nasa.gov/2015-sli-t-projects-awarded/; Dennis Nicks et al., "Continuation of the Landsat Mission with Sustained Land Imaging (SLI) and the Reduced Envelope Multispectral Imager (REMI)," Proceedings of SPIE Volume 11127, *Earth Observing Systems XXIV*, 111270X (September 2019), at https://doi.org/10.1117/12.2529570.

[78] USGS, "Architecture Study Team Narrowing Options for Landsat Next," at https://www.usgs.gov/center-news/architecture-study-team-narrowing-options-landsat-next.

[79] The draft requirements were derived from assessments of current Landsat and Sentinel-2 continuity and performance, USGS user needs, input from the Landsat Science Team, and subject matter expertise. Beta.sam.gov, "Sustainable Land Imaging (SLI) Program Beyond Landsat 9 Architecture Study," at https://beta.sam.gov/opp/ba6bec027510abc30e1f6fdafa74228c/view?keywords=%22%20NASA-SLI-Beyond-L9.%22&sort=-relevance&index=&is_active=true&page=1.

[80] USGS, "Landsat, Collections Forum Updates Missions, Products, and Future Possibilities," at https://www.usgs.gov/center-news/landsat-collections-forum-updates-missions-products-and-future-possibilities.

[81] Debra Werner, "Landsat Next likely to bear little resemblance to its predecessors," *SpaceNews*, September 28, 2020, at https://spacenews.com/landsat-next-likely-to-bear-little-resemblance-to-its-predecessors/.

[82] NASA, "Landsat Next," request for information, October 13, 2020, at https://sam.gov/opp/09a18f980f67449fa10608ecb0924883/view.

[83] Congressional briefing from NASA and the USGS on September 14, 2021. The NASA FY2022 Budget Request also states: "the Administration will make key strategic decisions for Landsat Next as part of the FY 2023 budget process."

The White House National Plan for Civil Earth Observations

The *National Plan for Civil Earth Observations* is intended "to provide strategic guidance for a balanced portfolio of Earth observations and observing systems."[84] The first plan was published in 2014, following direction in Section 702 of the NASA Authorization Act of 2010, which tasked the Office of Science and Technology Policy (OSTP) with developing a mechanism to ensure greater coordination of research, operations, and activities for civilian Earth observations, including development of a strategic implementation plan.[85] The statute requires OSTP to update the strategic implementation plan every three years.

In December 2019, the Trump Administration published an updated plan.[86] The plan stated that the Administration continues to support Landsat 9 via the Sustainable Land Imaging Program to continue the (then) 47-year Landsat record of global land imaging measurements. The report also reiterated that federal Earth observation data are public goods and that access to these data significantly enhances their value. The plan encouraged agencies to explore how best to leverage the growth in commercial Earth observation capabilities, including determining whether a commercial solution is available that might be more appropriate than creation of a new federal observing asset, while sustaining the data infrastructure needed by both commercial and government sectors. The plan recommended federal agency initiatives take advantage of technological advancements, such as cloud-based storage, computing, and distribution (the USGS is following that guidance by launching its cloud-based data services) and encouraged greater use of modeling and data assimilation, algorithm development, artificial intelligence, and high-performance and cloud computing. The report also reiterated prior support for enhancing international cooperation to enable more robust Earth observation architectures and to increase access to data from non-U.S. sources by working through international frameworks. (See **Appendix B**.)

Reports by the National Academies of Sciences, Engineering, and Medicine

The National Academies of Sciences, Engineering, and Medicine (NASEM) has produced several reports on Earth observation from space. A 2013 report on Landsat recommended that "a systematic and deliberate program, aimed at continuing to collect vital data within lower, well-defined, manageable budgets, replace the historical pattern of chaotic programmatic support and ad hoc design and implementation of spacecraft and sensors in the Landsat series."[87] Following that report, NASA and the USGS established the Sustainable Land Imaging Program, which mirrored many of the report's recommendations. The 2013 report also recommended that the program consider a combination of the following to increase capabilities while reducing costs for land imaging beyond Landsat 8

- pursue block buys and fixed-price contracting;
- collaborate with commercial and international partners;

NASA, *FY2022 Budget Congressional Justification NASA Budget Request*, 2021, at https://www.nasa.gov/news/budget/index.html.

[84] OSTP, *National Plan for Civil Earth Observations*.

[85] OSTP, *National Plan for Civil Earth Observations*.

[86] National Science and Technology Council, *2019 National Plan for Civil Earth Observations*, 2019, at https://usgeo.gov/uploads/Natl-Plan-for-Civil-Earth-Obs.pdf.

[87] NRC, *Landsat and Beyond*.

- streamline the design, construction, and launch process by using a single organizational unit approach consisting of both government employees and contractors working together as a fully integrated team;
- identify foreign sources of land imaging data complementary to land imaging requirements and seek formal data-sharing agreements with them;
- consider technological innovations, such as increasing the width of each scan and employing constellations of small satellites;
- incrementally incorporate new technologies that leverage industry, international, and other technology development activities but do not compromise core operational capabilities;
- accommodate candidates for improved or new instruments on a small satellite for the purpose of demonstrating new technologies; and
- take advantage of opportunities to fly as an additional mission on a launch vehicle that is launching other missions.

At Congress's direction, NASA and the USGS designed Landsat 9 essentially as a copy of Landsat 8; therefore, the government did not incorporate many of these recommendations (e.g., incorporating new technologies, launching as a secondary payload, or employing constellations of smaller satellites). Congress may consider revisiting the 2013 report's findings for future Landsat missions beyond Landsat 9.

NASEM also produces decadal strategies for Earth observations from space; the most recent decadal report was published in 2018.[88] That report noted that the Sustainable Land Imaging Program "transformed the Landsat program" by operating Landsat with consistency, connecting user communities and the developers of new measurement technologies, and archiving and distributing data products. The report also highlighted the success of extending Landsat's capability through cross-calibration and data sharing with ESA's Sentinel-2 (see **Appendix B**). The report recommended that NASA constrain cost growth in the development portion of the Sustainable Land Imaging Program and ideally reduce cost from one generation to the next. It also recommended that the USGS ensure budget growth is minimal to avoid strain on the overall USGS budget. In addition, the report recommended sustaining and expanding partnerships and user communities associated with the Sustainable Land Imaging Program.

National Geospatial Advisory Committee's Landsat Advisory Group

Each year, the USGS requests that the Landsat Advisory Group (LAG), a subcommittee of the National Geospatial Advisory Committee (authorized under the Geospatial Data Act of 2018, P.L. 115-254), provide specific advice on the Landsat program's requirements, objectives, and actions.[89] LAG membership includes representation from federal and nonfederal government, industry, academia, and the nonprofit sector. In recent years, the LAG has provided reports on its recommendations for future missions following Landsat 9, analysis of nonfederal Landsat user requirements, and evaluation of Landsat data cost-sharing models, among other topics.

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[88] NASEM, *Decadal Strategy for Earth Observation from Space*.

[89] For more information on the National Geospatial Advisory Committee and the Geospatial Data Act of 2018, see CRS Report R45348, *The Geospatial Data Act of 2018*, by Peter Folger.

In April 2018, the LAG provided the USGS with recommendations for future missions following Landsat 9 to support the Sustainable Land Imaging Architecture Study.[90] The LAG recommended the Sustainable Land Imaging Program pursue enhanced capabilities for future Landsat missions while maintaining continuity and current Landsat capabilities by investigating the following

- the adoption of newer technologies, especially in sensors and overall spacecraft electronics, that would result in substantial size, weight, power, and cost savings;
- an approach (similar to the approach of ESA's Copernicus constellations) of building multiple satellite constellations at once and launching them over time to reduce development and acquisition costs per satellite (e.g., Sentinel-2 costs are estimated at $250-$300 million per satellite versus Landsat 8's $857 million cost);[91] and
- the benefits and costs of changing future Landsats' ground sample distance to 10 meters or smaller (to increase compatibility with Sentinel-2 sensors, increase the width of each scan, increase coverage, and reduce overlap with commercial providers) and improving Landsat spectral resolution.[92]

In the 2018 report, the LAG also recommended a market study to determine if sufficient demand existed to explore the creation of a public-private partnership where the private contractor would provide two or more tiers of data—one meeting Landsat technical requirements for open and free distribution and others that provide superior data that is sold to users—thereby creating a revenue stream sufficient to offset at least some of the system's building and operating costs. The LAG noted that any pursuit of a public-private partnership model must ensure an equitable balance of risk between the federal government and the private-sector partner.

In 2019, the LAG, charged by the USGS to consider a range of possible Landsat data cost-sharing approaches, further analyzed the public-private partnership and other models.[93] The report first recommended not charging any fees for Landsat data with the characteristics of Landsat 8 and 9. The LAG predicted that a fee for these data would generate little revenue, cost the USGS to sell the data, cost other federal agencies to buy the data, stifle remote-sensing and value-added industries, and require changes to current laws and regulations. The LAG recommended further investigation of three other approaches to further determine feasibility, cost, benefits, and risks:

- generating revenue by selling *enhanced* imagery products and tailored image-collection requests from sensors on board Landsat satellites, while keeping standard Landsat 8 and 9 imagery data free and openly available;
- moving EROS from the current government-owned, contractor-operated business model to a contractor-owned, contractor-operated business model that may more efficiently deliver Landsat data and data-management services at lower costs; and

[90] LAG, *Recommendations Beyond Landsat 9*.

[91] Sentinel-2 was designed as a four-satellite acquisition (e.g., a four-satellite buy with two satellites in orbit at any one time), thereby reducing development and acquisition costs per satellite.

[92] In the 2016 LAG study, nonfederal Landsat users identified improved spatial and temporal resolution as the most important improvements needed for Landsat 10. NAGC, LAG, *Analysis of Non-Federal Landsat User Requirements*, 2016, at https://www.fgdc.gov/ngac/meetings/april-2016/landsat-user-requirements-analysis-ngac-june-2016.pdf.

[93] LAG, *Evaluation of Landsat Data Cost Sharing Models*.

- creating public-private partnership(s) for the federal government to benefit from some of private industry's efficiencies, while maintaining Landsat continuity and preserving public availability of Landsat 8 and 9 quality data.[94]

The LAG report concluded that, considering the 2019 report's findings, a more impactful study on how to reduce public expenditures would analyze how the government could reduce the costs of building and launching Landsat sensors, as discussed in the 2018 report, rather than focusing on the cost sharing of operations.

In 2020, the USGS tasked the LAG to provide a modernized interpretation of the Land Remote Sensing Policy Act of 1992 that would inform future land remote sensing policy formulation and remain consistent with the spirit of the existing language.[95] The report's conclusions were not prescriptive; instead, the discussion outlined several questions for the agencies to consider on how to achieve the objectives of the law in a modern context.

- How should the Landsat program approach and accomplish data continuity?
- In the interest of meeting the act's broad goals, should the Landsat program expand its objectives beyond medium resolution land imaging to include the collection of water and atmospheric data?
- What role does Landsat play in global leadership as other nations expand their satellite programs, and how can or should the Landsat program leverage partnerships with programs like Copernicus?
- What principles for a new national land remote sensing policy would best serve to inform and maintain global leadership for the United States?

Congressional Deliberation

Since FY2015, Congress has supported the development of Landsat 9 by appropriating funding for what is essentially a rebuild of Landsat 8.[96] Congress has deliberated future missions and alternative options through hearings and legislation.[97] In 2015 and 2016, the Space Subcommittee of the House Committee on Science, Space, and Technology discussed alternatives for Landsat missions during hearings on commercial opportunities for Earth science and remote sensing.[98] The subcommittee discussed the possibility of smaller, less expensive satellites; satellites as a payload on another launch platform; alternative business models, including public-private partnerships; the possibility of leveraging the ESA's Sentinel-2 constellation while augmenting

[94] According to the LAG, this approach depends upon the ability of private industry to develop and implement a successful business model and upon any legal changes required, including amending the Land Remote Sensing Policy Act of 1992 (P.L. 102-555).

[95] NGAC, LAG, *Revisiting the Land Remote Sensing Policy Act of 1992*, April 2021, at https://www.fgdc.gov/ngac/meetings/april-2021/ngac-paper-revisiting-the-land-remote-sensing.pdf.

[96] Since FY2015, Congress has provided appropriations for Landsat 9 in Commerce, Justice, Science, and Related Agencies appropriations bills and in Interior, Environment, and Related Agencies appropriations bills.

[97] In the 115th Congress, the Senate passed and the House rejected the Space Frontier Act of 2019 (S. 3277), which included a provision providing technical changes to 51 U.S.C. §60147 relating to agency consultation for the Landsat program. In the 116th Congress, the Senate Committee on Commerce, Science, and Transportation reported the Space Frontier Act of 2019 (S. 919), which included the same provision.

[98] U.S. Congress, House Committee on Science, Space, and Technology, Subcommittee on Space, *Exploring Commercial Opportunities to Maximize Earth Science Investments*, 114th Cong., 1st sess., November 17, 2015; U.S. Congress, House Committee on Science, Space, and Technology, Subcommittee on Space, *Commercial Remote Sensing: Facilitating Innovation and Leadership*, 114th Cong., 2nd sess., September 7, 2016.

the data with a thermal infrared sensor; and reforms to the Land Remote Sensing Policy Act of 1992.

Congress may consider revisiting these discussions, in addition to examining the stakeholder reports discussed above. For example, many of these reports recommend further exploring technological improvements, cost savings opportunities, public-private partnerships, and international cooperation and data sharing. In addition, these reports underscore the importance of appraising users and uses of Landsat data so that the program can continue to meet user needs, including a wide range of required federal government activities. Congress also may reexamine, for example, the National Aeronautics and Space Administration Authorization Act of 2018 (H.R. 5503, 115th Congress). That bill would have limited the obligation of funds for Landsat 11 (the mission following Landsat Next) or any other subsequent Landsat system until NASA completes a study assessing which aspects of Landsat system observations and associated science requirements can be provided by purchasing data from the private sector or through public-private partnerships.[99]

In addition, development of new approaches to operating satellite missions may alter planning for future missions. For example, Congress directed NASA (in report language accompanying appropriations legislation in FY2019 and FY2020) to launch a robotic spacecraft to refuel Landsat-7 before its fuel supply runs out as a demonstration of satellite-servicing technologies.[100] Due to delays, the Restore-L mission is now working toward a launch readiness date of December 2023, years after Landsat-7 is projected to run out of fuel.[101] Nonetheless, the outcomes of the Restore-L mission may have implications for future Landsat and other government and commercial space missions.[102]

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[99] The House Committee on Science, Space, and Technology reported the National Aeronautics and Space Administration Authorization Act of 2018 (H.R. 5503, 115th Congress), but the House did not vote on the provision before the end of the 115th Congress.

[100] The Senate reports accompanying the Commerce, Justice, and Science appropriations bills for FY2019 (S.Rept. 115-275) and FY2020 (S.Rept. 116-127), which are incorporated in conference reports accompanying enacted appropriations, directed NASA to launch Restore-L before Landsat-7's fuel supply runs out. Section 607 of the National Aeronautics and Space Administration Authorization Act of 2020 (H.R. 5666) would direct the NASA Administrator to continue development of Restore-L technologies and capabilities for a planned on-orbit demonstration to refuel the Landsat 7 spacecraft and to produce an assessment of in-space assembly and servicing technologies, the potential uses of those technologies, and related issues.

[101] U.S. Government Accountability Office, *NASA, Assessments of Major Projects*, GAO-20-405, April 2020, pp. 43-44, at https://www.gao.gov/assets/710/706505.pdf.

[102] The FY2021 House Commerce, Justice, and Science appropriations report (H.Rept. 116-455) directs NASA to conduct an orbital refueling mission in 2022 but does not mention Landsat-7 as the target satellite to refuel. The report also encourages the development of satellite-servicing technologies to benefit not only NASA but also other government entities (e.g., the Department of Defense) and the private sector. For more information about this mission, see NASA, "NASA's Restore-L Mission to Refuel Landsat 7, Demonstrate Crosscutting Technologies," *Space Tech*, August 6, 2017, at https://www.nasa.gov/feature/nasa-s-restore-l-mission-to-refuel-landsat-7-demonstrate-crosscutting-technologies.

Appendix A. Privatizing Landsat: A Brief History

Almost since the beginning of satellite launches, including both land imaging and weather satellites, privatization of satellite systems has been discussed. Efforts to privatize Landsat began during the Carter Administration and accelerated during the Reagan Administration. The Carter Administration initiated the move toward privatization when it released Presidential Directive 54 in 1979, which recommended transfer of Landsat operations from a research land remote sensing system under the National Aeronautics and Space Administration (NASA) to an operational system under the National Oceanic and Atmospheric Administration (NOAA).[103] The Carter Administration asserted that Landsat was mature enough to move from a research system to an operational system and that the user base for Landsat data eventually would grow under NOAA management. The directive also recommended development of a plan for eventual transition of Landsat to private-sector operation. Private companies would assume responsibility for their own remote sensing systems and would provide data for government and private customers.[104]

In a policy shift to more rapid privatization of operational satellite systems, the Reagan Administration in March 1983 proposed to move both Landsat and NOAA weather satellite system operations, as well as future ocean-observing satellite systems, from the federal government to the private sector.[105] Congress raised concerns that the Reagan Administration was moving too quickly toward privatizing weather satellites without congressional involvement. The opposition from Congress and other stakeholders to privatizing NOAA weather satellites led to Congress enacting language prohibiting their sale in the FY1984 appropriations act funding the Department of Commerce (P.L. 98-166).[106] In deliberations leading up to that prohibition, the House Science and Technology Committee suggested that pursuing the sale of the weather satellites distracted from the more important issue—maintaining global leadership in land remote sensing (i.e., Landsat). In contrast to its opposition to the privatization of NOAA weather satellites, Congress did not oppose Reagan Administration efforts to transition Landsat to the private sector. In fact, the committee urged that the debate shift back to its original track—namely, how best to accomplish a transfer of land remote sensing capability to the U.S. private sector.[107]

[103] See out-of-print CRS Issue Brief IB92092, *U.S. Civil Earth Observation Programs: Landsat, Mission to Planet Earth, and the Weather Satellites*, by David P. Radzanowski, available from Anna Normand to congressional clients on request.

[104] Ray A. Williamson, "The Landsat Legacy: Remote Sensing Policy and the Development of Commercial Remote Sensing," *Photogrammetric Engineering and Remote Sensing*, vol. 63, no. 7 (July 1997), pp. 877-885. Hereinafter Williamson, "Landsat Legacy."

[105] U.S. Congress, House Committee on Science and Technology, Subcommittee on Space Science Applications, *Commercialization of Land and Weather Satellites*, committee print, prepared by the Congressional Research Service, 98th Cong., 1st sess., June 1983.

[106] "No funds made available by this act, or any other act, may be used ... by the National Oceanic and Atmospheric Administration to transfer the ownership of any meteorological satellite (METSAT) or associated ground system to any private entity." Departments of Commerce, Justice, and State, the Judiciary, and Related Agencies Appropriation Act, 1984 (P.L. 98-166).

[107] U.S. Congress, House Committee on Science and Technology, *Transfer of Civil Meteorological Satellites*, report to accompany H.Con.Res. 168, 98th Cong., 1st sess., November 8, 1983, Report No. 98-509.

Stakeholder Perspectives on Landsat Privatization in the 1980s

The larger context for the future of Landsat was, in part, a dispute over whether the satellite served primarily public or private interests. Landsat provided the government with data for scientific research, managing federal lands, and carrying out other responsibilities. It also provided data with direct economic value for managing private lands, or for exploration for oil, gas, and minerals. The argument over Landsat's future concerned which use was more important.

Some Landsat proponents supported the move to privatization, in part because of fears that the Reagan Administration would cancel the program altogether. Proponents also were concerned that uncertainty over the program's future would forestall investment in hardware and software necessary to process Landsat data. In addition, Landsat supporters argued that privatization would ensure continuity of the data—an important feature of time-series observational data from satellites generally, allowing data users to analyze changes over time. Supporters argued that privatization eventually would result in a lower price for Landsat data.

Sources: Ray A. Williamson, "The Landsat Legacy: Remote Sensing Policy and the Development of Commercial Remote Sensing," *Photogrammetric Engineering and Remote Sensing*, vol. 63, no. 7 (July 1997), pp. 877-885.

It was recognized at the time that the market for Landsat products was small and the customer base grew smaller each time the price of Landsat data rose. The price of a Landsat image rose 300% in 1981, when the Office of Management and Budget directed that operating costs would be recovered by data sales.[108] Sales shrank again when NOAA took over full responsibility for the program in 1983 and raised prices for Landsat data to cover its costs and to prepare customers for commercial prices.[109]

Despite these indicators that the commercial market for Landsat data was not robust, Congress gave its support to privatization by passing the Land Remote Sensing Commercialization Act of 1984 (P.L. 98-365). The law established broad policy and financial requirements for the transfer and authorized the Department of Commerce to license private remote sensing space systems that complied with provisions of the act.[110] The law required operators to make available unenhanced Landsat data to all users on a nondiscriminatory basis; no preference could be given to one class of data buyers over another.

The Land Remote Sensing Commercialization Act of 1984, which sought to privatize and recoup the costs of the national investment in Landsat, resulted in exponential cost increases for Landsat data, with images costing up to $4,400 each. Although computing power and the use of geographic information systems (GIS) were increasing, orders for Landsat imagery were decreasing—primarily due to the higher costs. These costs prompted some scientists to migrate to other, coarser-resolution datasets, such as NOAA's Advanced Very High Resolution Radiometer.

Because the market for remote sensing data was considered underdeveloped in 1984, the federal government decided to provide a $250 million subsidy to the Earth Observation Satellite Company (EOSAT), which NOAA selected to operate the Landsat system. EOSAT would use the subsidy, in addition to its capital, to develop two new spacecraft, Landsat 6 and Landsat 7, which would replace the then-operating Landsat 4 and Landsat 5. In addition to the $250 million subsidy, the federal government would pay launch costs for the two new satellites and would

108 Williamson, "Landsat Legacy."

109 Williamson, "Landsat Legacy."

110 See out-of-print CRS Issue Brief IB92092, *U.S. Civil Earth Observation Programs: Landsat, Mission to Planet Earth, and the Weather Satellites*, by David P. Radzanowski, available from Anna Normand to congressional clients on request.

continue to cover operational costs for the Landsat program through the expected lifetimes of Landsat 4 and Landsat 5.[111]

The Reagan Administration decided not to fulfill the original funding obligation to EOSAT, and several years of dispute ensued between the Administration and Congress over Landsat funding. Ultimately, the contract was revised to require the development of only Landsat 6, despite earlier agreement that two satellites would be needed to ensure data continuity.[112] The funding dispute led to further debates over the future of the Landsat program. Complicating the debate were different views about which launch vehicle should carry the next Landsats into orbit; EOSAT proposed that the satellite be designed for the space shuttle, but the Reagan Administration disagreed. NOAA instructed EOSAT to prepare the spacecraft for launch on an expendable rocket.

Outcome and Lessons Learned

The Land Remote Sensing Policy Act of 1992 (P.L. 102-555) ultimately resolved the issues of whether and how to privatize the Landsat system, which federal agency should be responsible for the system, and how public and private funding and operations should be combined. The act transferred Landsat program management from the Department of Commerce to NASA and the Department of the Interior (DOI), which effectively ended nearly a decade of debate over privatizing Landsat.

Although the Land Remote Sensing Policy Act of 1992 reversed the privatization track for Landsat and returned the satellite system to the federal government, the act also authorized the Secretary of Commerce to license operators of private remote sensing space systems.[113] It allowed the operators to use their data as they wish, including choosing their customers and offering their data at prices that vary by customer. Some analysts regard this licensing provision under Subtitle VI of the act as perhaps the most important provision for fostering commercial remote sensing prospects in the United States.[114] Further, the development of technology to download, store, and distribute remotely sensed data contributed to commercial interests' ability to add value to satellite data. The advent and rapid growth of GIS have spurred an explosion of interest in the use of geospatial information, which typically includes land remote sensing data from space (e.g., Google Earth).

Recognizing Landsat as a Public Good

Whereas weather satellites were quickly identified as a public good during the 1983 debate, Landsat proved more difficult to categorize. One distinction is that NOAA has long had a clear mandate to provide satellite data for weather services. In contrast, NOAA was selected to manage the Landsat program because of the agency's success with operating the weather satellites and as an interim step en route to privatizing Landsat. The relatively unclear mandate for collecting land surface remote sensing data at NOAA also may have eroded customer confidence in the Landsat

[111] See out-of-print CRS Issue Brief IB92092, *U.S. Civil Earth Observation Programs: Landsat, Mission to Planet Earth, and the Weather Satellites*, by David P. Radzanowski, available from Anna Normand to congressional clients on request.

[112] See out-of-print CRS Report 87-477, *Privatization of the Landsat Remote Sensing Satellite System: Current Issues*, by Marcia S. Smith, available from Anna Normand to congressional clients on request.

[113] P.L. 102-555, Subtitle VI.

[114] Williamson, "Landsat Legacy."

system and in NOAA's commitment to developing infrastructure, training personnel, and making other investments that would have bolstered the market for Landsat products.[115]

Differing views of the Landsat program's nature—namely, whether the satellites served public or private interests—shaped the outcome of the privatization effort.[116] Evolving views over the public or private nature of the program were influenced by factors other than funding. One observer identified four factors:[117]

1. Landsat data proved important in planning U.S. military operations in the 1992 Gulf War.
2. Other countries had launched similar land remote sensing satellites, and these spacecraft—particularly the French SPOT satellite—were perceived as possible challenges to the U.S. stake in the international market for remote sensing data.[118]
3. Growing interest in global climate change and its effects on the Earth's surface led scientists to increasingly value time-series data from a consistent platform in space for identifying environmental changes.
4. The difficulties of commercializing the Landsat system became clear, and federal agencies perceived that private companies might not be able to provide equivalent data at the scale the agencies required.

These and other factors led Congress to accept the idea of Landsat as a public good and to enact the Land Remote Sensing Policy Act of 1992. One other factor, for example, was the cost of Landsat images. The Land Remote Sensing Policy Act of 1992 found that "the cost of Landsat data has impeded the use of such data for scientific purposes, such as for global environmental change research, as well as for other public-sector applications." Consequently, the act established, with some restrictions, that unenhanced data from Landsat should be made available "at the cost of fulfilling user requests," or COFUR. The U.S. Geological Survey (USGS) extended the COFUR policy to all Landsat data products in its Landsat Data Distribution Policy, which also stated that pricing would not be based on the recovery of capital costs of satellites, ground systems, or other capital assets previously paid for by the U.S. government. The current USGS policy is to make all Landsat imagery and data available at no cost and without restriction.

[115] Williamson, "Landsat Legacy."

[116] Williamson, "Landsat Legacy."

[117] Williamson, "Landsat Legacy."

[118] However, images from SPOT also were deemed extremely important for coalition forces during the Gulf War.

Appendix B. International Collaboration

The Landsat program has catalyzed international collaboration in various forms. For example, international partners downlink and share Landsat data from their international ground stations, and NASA and the USGS find areas of compatibility between Landsat and other national and multinational observation programs (e.g., the European Space Agency's [ESA's] Copernicus Program Sentinel-2 constellation) that also provide collected data as free and open access.[119]

International Ground Stations

In early Landsat missions, the USGS relied on a network of international ground stations, operated by cooperator nations, to downlink and store Landsat images due to inadequate Landsat satellite onboard data storage and limited receiving capacity.[120] These international cooperators partnered with the Landsat program and paid an annual fee for reception and data distribution rights. While the USGS maintained its Landsat data archive at the Earth Resources Observation and Science (EROS) Center in Sioux Falls, SD, international cooperators simultaneously built their own regional archives, processing and distributing data according to their own policies.[121] Over time, more than 50 ground stations received Landsat data.[122] In 2006, the USGS recognized that the volume of Landsat data held by international cooperators (an estimated 4 million images) far exceeded that held by the USGS Landsat archive (an estimated 1.9 million images).[123] Much of the data held internationally are unique, relative to each station's area of coverage.

In 2010, the USGS started the U.S. Landsat Global Archive Consolidation program to repatriate Landsat data missing from the U.S. archive but stored at international cooperator ground stations.[124] Following repatriation to EROS, the USGS reprocesses the data to current collection standards and provides the processed images at no cost to the international ground stations and the global user community. The initiative had acquired and reprocessed more than 5 million images by November 2019, increasing the Landsat archive's coverage equivalent to the launch of an additional Landsat mission and expanding the historical spatial coverage (see **Figure B-1**).[125] The initiative continues, as the USGS works with foreign ground stations to retrieve datasets and develops tools and methods to adapt their often-archaic data formats into the archive at EROS.

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[119] Sam N. Goward et al., *Landsat's Enduring Legacy: Pioneering Global Land Observations from Space* (Bethesda, MD: American Society for Photogrammetry and Remote Sensing, 2017).

[120] Michael Wulder et al., "The Global Landsat Archive: Status, Consolidation, and Direction," *Remote Sensing of Environment*, vol. 185 (November 2016), pp. 271-283, at https://www.sciencedirect.com/science/article/pii/S0034425715302194. Hereinafter Wulder et al., "Global Landsat Archive."

[121] Wulder et al., "Global Landsat Archive."

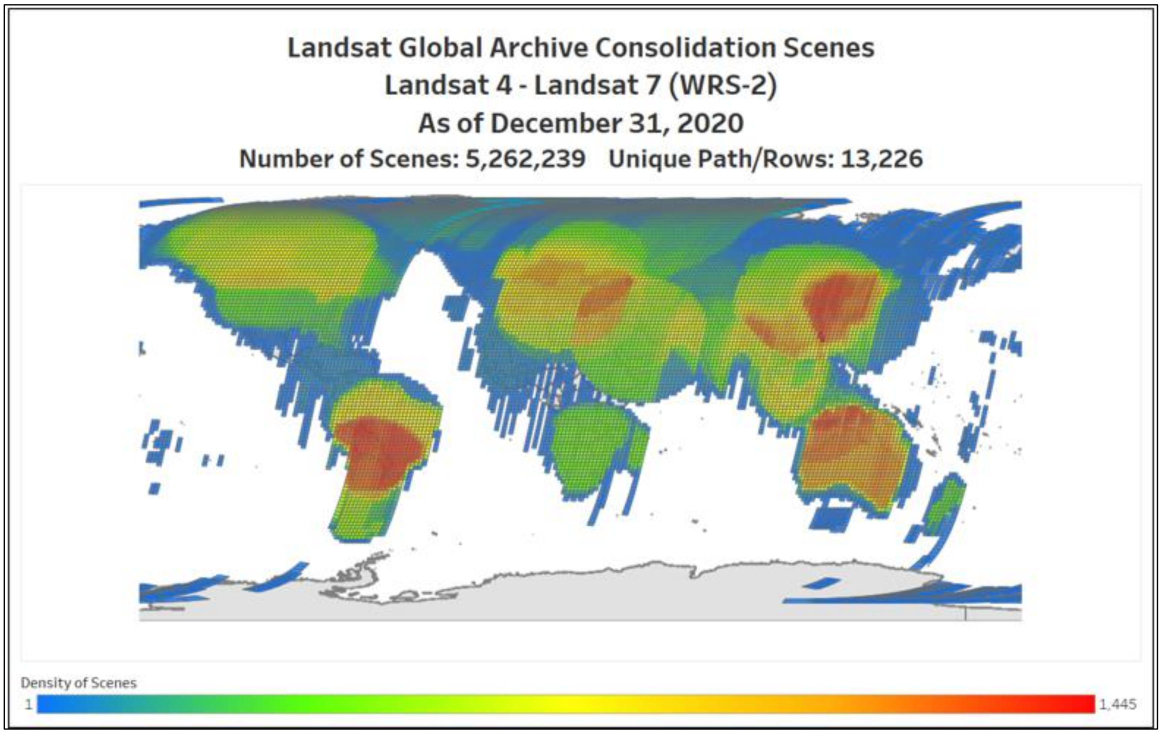
[122] Wulder et al., "Global Landsat Archive."

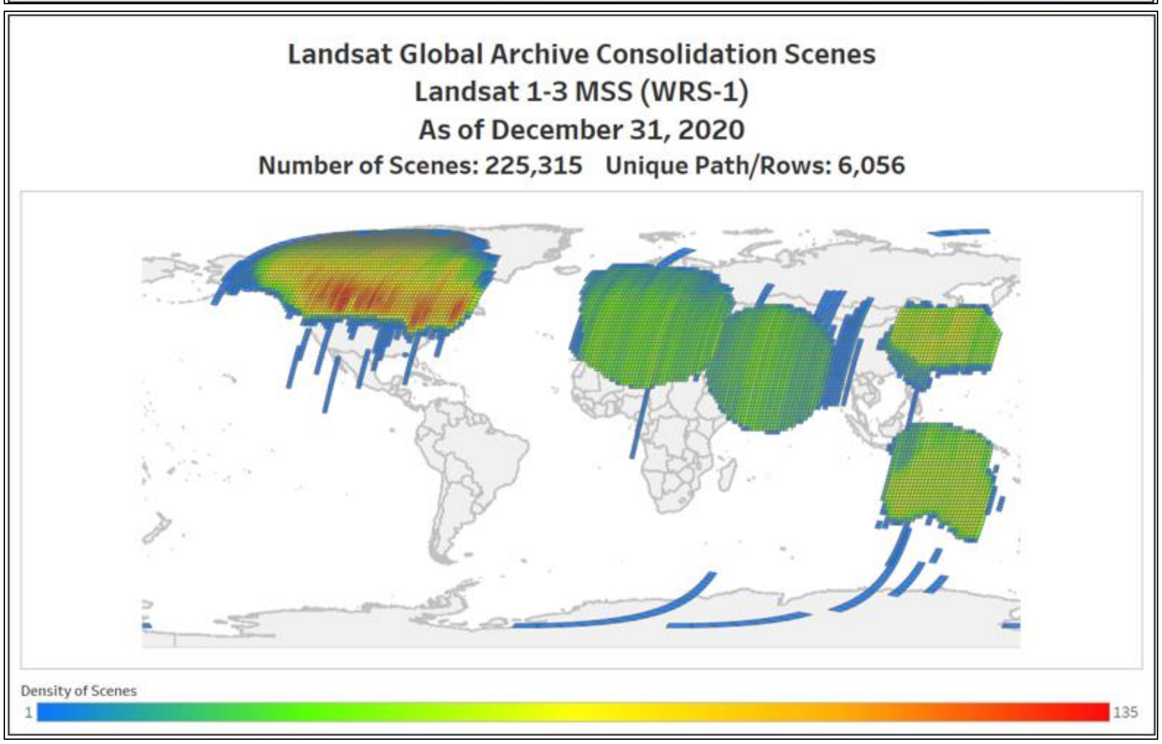
[123] Wulder et al., "Global Landsat Archive."

[124] Wulder et al., "Global Landsat Archive."

[125] USGS, Landsat Missions, "Landsat Global Archive Consolidation," at https://www.usgs.gov/land-resources/nli/landsat/landsat-global-archive-consolidation.

Figure B-1. Landsat Global Archive Consolidation Images





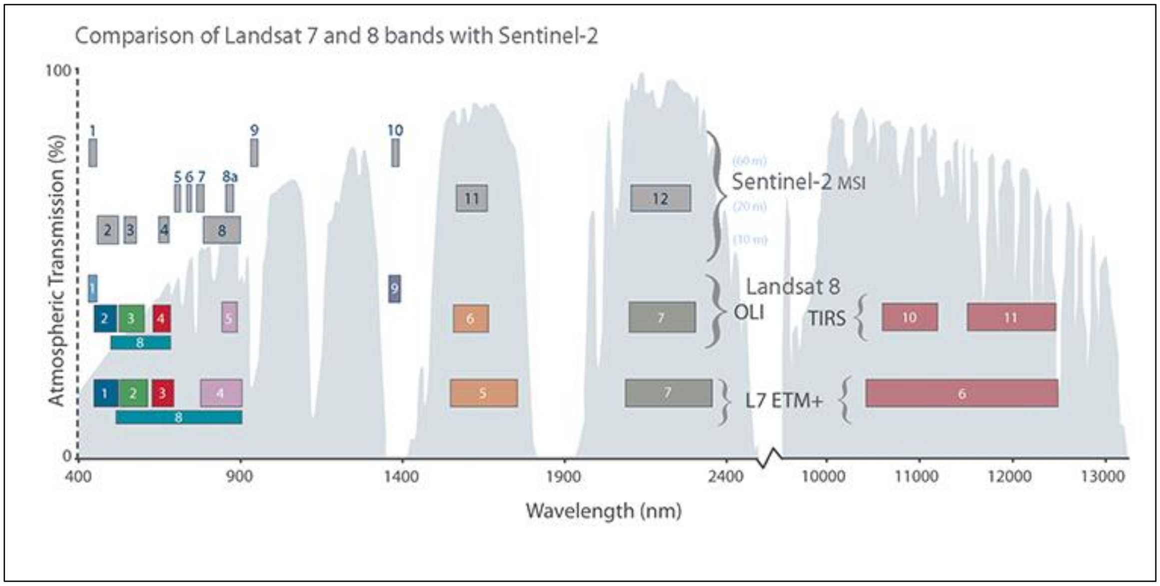
Source: U.S. Geological Survey (USGS), Landsat Missions, "Landsat Global Archive Consolidation," accessed on November 3, 2021, at https://www.usgs.gov/land-resources/nli/landsat/landsat-global-archive-consolidation.

Notes: The heat maps show how many images the USGS has repatriated into the Earth Resources Observation and Science (EROS) Center archives from international ground stations.

Sentinel-2 Constellation

ESA's Copernicus Earth Observation Program launched Sentinel-2A in 2015 and Sentinel-2B in 2017, which share many of the technical characteristics of Landsat 8.[126] The Sentinel-2 constellation has a wider swath (covering 290 kilometers) than Landsat 8 (covering 185 kilometers), thus providing a routine five-day revisit over Earth's land areas.[127] Unlike Landsat 8, Sentinel-2 satellites do not have thermal infrared capability. Sentinel-2 satellites provide features unique from Landsat: red-edge and water vapor spectral bands and higher spatial resolution visible to shortwave infrared bands (10-meter and 20-meter bands compared with Landsat's 30-meter bands).[128]

Figure B-2. Comparison of Landsat 7 and 8 Bands with Sentinel-2 Bands



Source: USGS, "Comparison of Landsat 7 and 8 Bands with Sentinel-2," 2015, at https://www.usgs.gov/media/images/comparison-landsat-7-and-8-bands-sentinel-2.

Notes: ETM+ = Enhanced Thematic Mapper Plus; MSI = Multispectral Instrument; m = meter; nm = nanometer; OLI = Operational Land Imager; TIRS = Thermal Infrared Sensor. The figure shows the specific placement of the Sentinel-2A bands, as compared with Landsat 7 and 8 bands. The main visible and near-infrared Sentinel-2A bands have a spatial resolution of 10 meters, and its red-edge (red and near-infrared bands) and two shortwave infrared bands have a 20-meter spatial resolution. The coastal/aerosol, water vapor, and cirrus bands have a spatial resolution of 60 meters.

NASA, the USGS, and ESA have collaborated to demonstrate areas of compatibility between Landsat 8 and Sentinel-2 measurements. The combined coverage of Landsat 8, Sentinel-2A, and Sentinel-2B provides a global median average revisit interval of 2.9 days.[129] This revisit

[126] The European Space Agency conducted a block buy of four Sentinel-2 imagers and has two imagers in reserve, ready to be launched when needed. USGS, "USGS EROS Archive - Sentinel-2," at https://www.usgs.gov/centers/eros/science/usgs-eros-archive-sentinel-2.

[127] Wulder et al., "Current Status of Landsat."

[128] USGS, "USGS EROS Archive - Sentinel-2," at https://www.usgs.gov/centers/eros/science/usgs-eros-archive-sentinel-2.

[129] Jian Li and David P. Roy, "Global Analysis of Sentinel-2A, Sentinel-2B and Landsat-8 Data Revisit Intervals and Implications for Terrestrial Monitoring," *Remote Sensing of the Environment*, vol. 9, no. 9 (2017), at https://doi.org/10.3390/rs9090902.

frequency improves mapping processes that are highly dynamic in time, including vegetation phenology, fire dynamics, and water quality. With the launch of Landsat 9, the combined Landsat and Sentinel-2 constellation will approach a two-day global median average revisit cycle.[130] This resulting virtual constellation of satellites is an example of a system of systems, called for in the recent decadal strategy for the Earth observation from space.[131] The free and open data-sharing policies of both programs facilitate such a virtual constellation; the Sustainable Land Imaging Program may consider similar collaboration with other international programs as other governments launch more satellites.

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[130] Wulder et al., "Current Status of Landsat."

[131] Zhe Zhu et al., "Benefits of the Free and Open Landsat Data Policy," *Remote Sensing of Environment*, vol. 224 (April 2019), pp. 382-385, at https://doi.org/10.1016/j.rse.2019.02.016; National Academies of Sciences, Engineering, and Medicine, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, 2018, at https://doi.org/10.17226/24938.