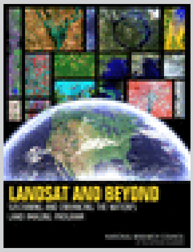


Landsat and Beyond: Sustaining and Enhancing the Nation's Land Imaging Program

ISBN
978-0-309-29001-2

73 pages
8 1/2 x 11
PAPERBACK (2013)

Committee on Implementation of a Sustained Land Imaging Program; Space Studies Board; Division on Engineering and Physical Sciences; National Research Council

LANDSAT AND BEYOND

SUSTAINING AND ENHANCING THE NATION'S LAND IMAGING PROGRAM

Committee on Implementation of a Sustained Land Imaging Program
Space Studies Board
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this project was provided by Cooperative Agreement Number G11AP20217 from the United States Geological Survey. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the USGS.

International Standard Book Number-13: 978-0-309-29001-2
International Standard Book Number-10: 0-309-29001-5

Cover: Design by Tim Warchocki; see page 63 for image credits.

Copies of this report are available free of charge from

Space Studies Board
National Research Council
The Keck Center of the National Academies
500 Fifth Street, NW
Washington, DC 20001

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. C. D. Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. C. D. Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

OTHER RECENT REPORTS OF THE SPACE STUDIES BOARD

Lessons Learned in Decadal Planning in Space Science: Summary of a Workshop (Space Studies Board [SSB], 2013)
Solar and Space Physics: A Science for a Technological Society (SSB, 2013)

Assessment of a Plan for U.S. Participation in Euclid (Board on Physics and Astronomy [BPA] with the SSB, 2012)
Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies (SSB, 2012)
Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey (SSB, 2012)
The Effects of Solar Variability on Earth's Climate: A Workshop Report (SSB, 2012)
NASA's Strategic Direction and the Need for a National Consensus (Division on Engineering and Physical Sciences, 2012)
Report of the Panel on Implementing Recommendations from the New Worlds, New Horizons Decadal Survey (BPA and SSB, 2012)
Technical Evaluation of the NASA Model for Cancer Risk to Astronauts Due to Space Radiation (SSB, 2012)

Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions (SSB, 2011)
Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics (BPA and SSB, 2011)
Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era (SSB, 2011)
Sharing the Adventure with the Public—The Value and Excitement of "Grand Questions" of Space Science and Exploration: Summary of a Workshop (SSB, 2011)
Vision and Voyages for Planetary Science in the Decade 2013-2022 (SSB, 2011)

Capabilities for the Future: An Assessment of NASA Laboratories for Basic Research (Laboratory Assessments Board with SSB and Aeronautics and Space Engineering Board [ASEB], 2010)
Controlling Cost Growth of NASA Earth and Space Science Missions (SSB, 2010)
Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies: Final Report (SSB with ASEB, 2010)
An Enabling Foundation for NASA's Space and Earth Science Missions (SSB, 2010)
Forging the Future of Space Science: The Next 50 Years (SSB, 2010)
Life and Physical Sciences Research for a New Era of Space Exploration: An Interim Report (SSB with ASEB, 2010)
New Worlds, New Horizons in Astronomy and Astrophysics (BPA and SSB, 2010)
Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce (SSB, 2010)

America's Future in Space: Aligning the Civil Space Program with National Needs (SSB with ASEB, 2009)
Approaches to Future Space Cooperation and Competition in a Globalizing World: Summary of a Workshop (SSB with ASEB, 2009)
Assessment of Planetary Protection Requirements for Mars Sample Return Missions (SSB, 2009)
Near-Earth Object Surveys and Hazard Mitigation Strategies: Interim Report (SSB with ASEB, 2009)
A Performance Assessment of NASA's Heliophysics Program (SSB, 2009)
Radioisotope Power Systems: An Imperative for Maintaining U.S. Leadership in Space Exploration (SSB with ASEB, 2009)

Limited copies of SSB reports are available free of charge from

Space Studies Board
National Research Council
The Keck Center of the National Academies
500 Fifth Street, NW, Washington, DC 20001
(202) 334-3477/ssb@nas.edu
www.nationalacademies.org/ssb/ssb.html

COMMITTEE ON IMPLEMENTATION OF A SUSTAINED LAND IMAGING PROGRAM

JEFF DOZIER, University of California, Santa Barbara, *Chair*
CARLOS E. DEL CASTILLO, NASA Goddard Space Flight Center
JACK D. FELLOWS, EnviroGen International Foundation and G2Groups, Inc.
KATHLEEN O. GREEN, Kass Green & Associates
JOHN R. JENSEN, University of South Carolina
DENNIS P. LETTENMAIER, University of Washington
BERRIEN MOORE III, University of Oklahoma
DIANE E. PATAKI, University of Utah
DAVID S. SCHIMEL, Jet Propulsion Laboratory
WALTER S. SCOTT, DigitalGlobe, Inc.
WILLIAM F. TOWNSEND, Independent Aerospace Consultant, Annapolis, Maryland
HOWARD A. ZEBKER, Stanford University
MARY LOU ZOBACK, Stanford University

Staff

ABIGAIL A. SHEFFER, Study Director
ARTHUR A. CHARO, Senior Program Officer
JOSEPH K. ALEXANDER, JR., Senior Program Officer
LINDA M. WALKER, Senior Program Assistant

MICHAEL H. MOLONEY, Director, Space Studies Board

SPACE STUDIES BOARD

CHARLES F. KENNEL, Scripps Institution of Oceanography, University of California, San Diego, *Chair*
JOHN KLINEBERG, Space Systems/Loral (retired), *Vice Chair*
MARK R. ABBOTT, Oregon State University
JAMES ANDERSON, Harvard University
JAMES BAGIAN, University of Michigan
YVONNE C. BRILL,[1] Aerospace Consultant
ELIZABETH R. CANTWELL, Lawrence Livermore National Laboratory
ANDREW B. CHRISTENSEN, Dixie State College of Utah
ALAN DRESSLER, The Observatories of the Carnegie Institution
THOMAS R. GAVIN, California Institute of Technology
HEIDI B. HAMMEL, AURA
FIONA A. HARRISON, California Institute of Technology
JOSEPH S. HEZIR, EOP Group, Inc.
ANTHONY C. JANETOS, University of Maryland
JOAN JOHNSON-FREESE, U.S. Naval War College
ROBERT P. LIN,[2] University of California, Berkeley
MOLLY K. MACAULEY, Resources for the Future, Inc.
JOHN F. MUSTARD, Brown University
ROBERT T. PAPPALARDO, Jet Propulsion Laboratory, California Institute of Technology
MARCIA J. RIEKE, University of Arizona
DAVID N. SPERGEL, Princeton University
MEENAKSHI WADHWA, Arizona State University
CLIFFORD M. WILL, Washington University
THOMAS H. ZURBUCHEN, University of Michigan

MICHAEL H. MOLONEY, Director
CARMELA J. CHAMBERLAIN, Administrative Coordinator
TANJA PILZAK, Manager, Program Operations
CELESTE A. NAYLOR, Information Management Associate
CHRISTINA O. SHIPMAN, Financial Officer
SANDRA WILSON, Financial Assistant

[1] Dr. Brill passed away on March 27, 2013.
[2] Dr. Lin passed away on November 17, 2012.

Preface

The nation's economy, security, and environmental vitality rely on routine observations of Earth's surface to understand changes to the landscape at local, regional, and global scales. The National Aeronautics and Space Administration (NASA) conceived and built the first Landsat satellites as a research activity. Over the years, Landsat missions have assumed an operational character, with a diverse set of users reliant on the continuing availability of Landsat imagery and derived data products. However, responsibility for funding, management, development, and operations of the Landsat series has changed hands numerous times, with responsibilities shifting among government agencies and private-sector entities. While the U.S. Department of the Interior's (DOI's) U.S. Geological Survey (USGS) has established and maintained management of land remote sensing data acquisition, archiving, and dissemination, no clearly defined and sustainable land imaging program has yet been created.

What may be viewed as the groundwork for such a program is seen in a 2007 report from the White House Office of Science and Technology Policy,[1] which provided a vision for space-based land imaging. Also the 2010 National Space Policy[2] directed the DOI, through the USGS, to take more responsibility for conducting research on natural and human-induced changes to Earth, for managing a global land surface data national archive, and for providing environmental and disaster-related data to other civil government agencies. It is against this backdrop that the USGS requested, in 2011, that the National Research Council (NRC) assess the needs and opportunities to develop a national space-based operational land imaging capability. The USGS request also has ties to the 2007 NRC decadal survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*.[3] Requested by NASA, the National Oceanic and Atmospheric Administration, and the USGS, that report recommends a systems approach to space-based and ancillary observations featuring 17 new research missions.

The statement of task[4] for the Committee on Implementation of a Sustained Land Imaging Program includes the request for recommendations to facilitate the transition of single-mission NASA research-based land imaging

---

[1] *A Plan for a U.S. National Land Imaging Program,* Office of Science and Technology Policy–National Science and Technology Council, Future of Land Imaging Interagency Working Group, August 2007. Available online at http://www.whitehouse.gov/sites/default/files/microsites/ostp/fli_iwg_report_print_ready_low_res.pdf.

[2] *National Space Policy of the United States of America,* June 28, 2010, http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.

[3] National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

[4] The complete text of the statement of task is included in Appendix A.

technology or missions to sustained USGS land imaging program technology or missions. However, it is also important to recognize the limits to this charge given continuing instability in national policy for space-based land remote sensing. Even as the committee was writing its report, agency responsibilities for the future of land imaging appeared to be shifting once again in the fiscal year 2014 budget request.[5] Consequently, in the present report, the committee does not make recommendations regarding particular agency responsibilities for land imaging, which in any event are properly in the purview of the executive and congressional branches of the government. The committee does comment on several overarching issues—for example, coordination among the relevant federal agencies, alignment of agency responsibilities with budgets, steps that might lead to lower-cost implementations of successors in the Landsat series, and the desired elements of a future national land imaging system.

This report is organized around Tasks 1-4 of the statement of task as follows:

- Chapter 1 addresses Task 1 of the statement of task by providing an introduction to the report, including an overview of the benefits of Landsat data to the nation and a review of the program's chaotic history.
- Chapters 2 and 3 focus on Task 2 by discussing elements of what the committee finds to be the critical core elements of any future land imaging system, based on continuity with earlier systems and technical characteristics their users employ.
- Chapter 3 expands the discussion in Chapter 2 to include the elements of a fully capable land imaging system, beyond Landsat itself. The chapter describes the committee's vision for a sustained and enhanced land imaging program and gives an overview of potential new observing capabilities. The role of commercial and international partners is also discussed.
- Chapter 4 focuses on Task 3—data systems. As discussed in the chapter, to achieve a sustained land imaging capability requires not only plans for data acquisition but also attention to the development of data products (including climate data records and essential climate variables) and their management, as well as considerations of data availability.
- Chapter 5 presents the committee's view on Task 4, discussing future opportunities and the path forward with particular attention to alternative, lower-cost acquisition strategies for future land imaging systems, along with ideas for sensor designs to meet users' requirements.

[5] "In 2014, USGS will work with NASA to analyze user requirements and develop a successor mission to Landsat 8, formerly known as the Landsat Data Continuity Mission. Funding to begin work on the successor mission is provided in the 2014 budget for NASA, which will be responsible for development of Landsat-class land imaging satellites going forward. The USGS will continue its operational role in managing the collection, archiving, and dissemination of Landsat data to users." From "Bureau Highlights," U.S. Geological Survey, p. BH-55 in Office of Management and Budget, *Fiscal 2014 Budget of the U.S. Government,* Executive Office of the President, Washington, D.C., available at http://www.whitehouse.gov/omb/ budget/Overview.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the Report Review Committee of the National Research Council (NRC). The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Mark Brender, GeoEye Foundation,
W. Peter Cherry, Independent Consultant, Ann Arbor, Michigan,
Nancy Colleton, Institute for Global Environmental Strategies,
Giles Foody, University of Nottingham, U.K.,
Joanne Gabrynowicz, University of Mississippi,
George Hilley, Stanford University,
Anthony C. Janetos, Boston University,
Christopher O. Justice, University of Maryland,
Thomas M. Lillesand, University of Wisconsin, Madison (professor emeritus),
Emilio F. Moran, Michigan State University,
John R. Schott, Rochester Institute of Technology, and
A. Thomas Young, Lockheed Martin Corporation (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Edwin P. Przybylowicz, Eastman Kodak Company. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Summary

Beginning with the 1972 NASA launch of the Earth Resources Technology Satellite (ERTS), later renamed Landsat 1, and continuing with the February 2013 launch of Landsat 8, the United States has amassed a sustained 40-year record of land remote sensing data acquired by satellites. Despite the transformational value of the data for diverse applications—including agriculture, forestry, hydrology, urbanization, homeland security, disaster mitigation, and climate change—the availability of these critical data for planning our nation's future is at risk.[1]

The Department of the Interior's (DOI's) U.S. Geological Survey (USGS) tasked the National Research Council's (NRC's) Committee on Implementation of a Sustained Land Imaging Program to assess the needs and opportunities to develop a national space-based operational land imaging capability. The committee was asked to identify stakeholders and their data needs, recommend characteristics and critical program support areas expected of a sustained land imaging program, suggest critical baseline products and services derived from land imaging, and provide recommendations to facilitate the transition from NASA's research-based series of satellites to a sustained USGS land imaging program.[2]

The committee met with stakeholders, including the DOI, NASA, the Office of Science and Technology Policy, the National Oceanic and Atmospheric Administration, the U.S Department of Agriculture, the U.S. Forest Service, commercial data providers, and multiple land imaging data users, and analyzed earlier reports on the uses and value of moderate-resolution multispectral data.

In this report, the committee recommends 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. The committee concurred with former NASA Administrator James Fletcher's perspective and provided recommendations for the robust land imaging program he envisioned, albeit nearly 40 years later:

> If I had to pick one spacecraft, one Space Age development to save the world I would pick ERTS and the satellites which I believe will be evolved from it later in this decade.
>
> James C. Fletcher, NASA Administrator, 1975

[1] Benefits of land imaging to the United States are discussed in Chapter 1 in the section "Benefits of Land Imaging for the Nation."
[2] See Appendix A for the complete statement of task.

IMPERATIVE FOR A SUSTAINED AND ENHANCED LAND IMAGING PROGRAM

Landsat 8, launched on February 11, 2013, has a 5-year design life, 10 years of fuel, and no assured successor. A successor mission has been under discussion in the U.S. executive and congressional branches, but their deliberations have not yet been made public. Moreover, the potential sharing of responsibilities with commercial and foreign contributors has not been articulated. The cost for Landsat 8 runs to approximately $1 billion. Although a budget to start planning the next Landsat mission has been provided to NASA in the fiscal year 2014 budget request, replacing Landsat 8 with a mission of similar scope will not be possible within the currently planned budget, unless it is a mission with a reduced set of requirements. Several of the Landsat satellites have been justified, planned, and executed separately, and the 40-year record owes more to the remarkable survival of Landsat 5 for two decades beyond its design life than to careful planning.[3] Given this history and uncertainties about the future of the Landsat series of satellites, the committee, as a result of its activities over the course of the study, arrived at the following findings:

- The United States pioneered global, synoptic, frequent-repeat global imaging. Other nations are now developing systems whose capability rivals or exceeds that of U.S. systems. National needs require the United States to reassert leadership and maintain and expand capabilities.
- Space-based land imaging is essential to U.S. national security as it is a critical resource for ensuring our food, energy, health, environmental, and economic interests.
- The economic and scientific benefits to the United States of Landsat imagery far exceed the investment in the system.
- To best serve the needs of the United States, the land imaging program of the future requires an overarching national strategy and long-term commitment, including clearly defined program requirements, management responsibilities, and funding.
- The continuity of Landsat imagery has never been ensured through the development of a sustained government program. Instead, responsibility has been shifted from one organization to another over Landsat's 40-year history, resulting in persistent uncertainty for the future of this important asset.
- NASA has demonstrated that it is the civil agency with the technical capacity and the congressional support to design and build civilian space missions.
- The USGS-operated data management and distribution systems function effectively and efficiently.
- Building a satellite sequence with new requirements and technologies for each individual instrument is an expensive way to acquire land imaging data and inhibits the addition of new capabilities.
- ***A sustained land imaging program will not be viable under the current mission development and management practices.***

The committee's primary recommendation is that the U.S. government should establish a Sustained and Enhanced Land Imaging Program with persistent funding to respond to current and future national needs. Such a program would

- **Develop a plan for a comprehensive, integrated program that capitalizes on the strengths of USGS and NASA, maintains current capability and the existing archive, and enhances the program as technology enables new imaging capabilities and data products;**
- **Ensure acquisition of land imaging data continuously from orbital platforms and, periodically, from airborne platforms, to respond to the needs of producers and consumers of derived data products along with users who analyze imagery;**
- **Establish partnerships with commercial firms and international land imaging programs to leverage enhanced capabilities;**
- **Coordinate land imaging data buys across the U.S. government; and**

[3] Discussion of the history of the Landsat series of satellites is included in Chapter 1 in the section "A Chaotic History."

• Include a research and development component to improve data products based on core measurements and to develop new measurement methods and consider evolving requirements.

For the Sustained and Enhanced Land Imaging Program to be successful, program responsibilities should be divided between USGS and NASA such that the agency responsible for balancing science requirements with mission complexity and cost is also provided with the necessary budget. Both agencies should participate in an iterative process to design missions that meet the needs of research and operational communities, but final decisions should be made by the agency that has been given the budget.

The committee recommends key elements of a successful Sustained and Enhanced Land Imaging Program (SELIP) no matter where the federal government decides it should reside.

TECHNICAL CHARACTERISTICS OF THE CORE PROGRAM

SELIP would provide a core set of capabilities and measurements that continue to support operations and scientific investigations and maintain and enhance continuity with the information available since 1972. Landsat has provided an unequaled record of moderate-resolution (30-100 m) multispectral measurements of Earth's surface, the long-term continuity of which is critical for quantifying ecological, environmental, and land-use change. Preserving program continuity requires a satellite system and launch schedule that provides a continuous stream of land images and data and at the same time implicitly requires strategies to contend with future instrument or launch failures. Risk mitigation strategies could range from instruments ready to launch to securing agreements with international partners for data access. A "hot spare" on orbit or available for quick launch—as weather satellites have been managed historically—is not required.

The core scientific and operational requirement for the SELIP is the capture and distribution of global, moderate-resolution, multispectral data calibrated sufficiently to allow the rigorous comparison of future image products with previous collections, easily accessible by all users, and free. Ensuring continuity of the ongoing data stream does not require continuing to fly the same sensor, nor does it require that all measurements be made from a single space platform. The section "Findings," in Chapter 2, presents a detailed list of user requirements. These include spatial resolution no coarser than 30 m, except in the thermal band; spectral coverage from the visible through the thermal infrared; and temporal coverage at 7- to 10-day frequency.

The top priorities for the Sustained and Enhanced Land Imaging Program (SELIP) should be to ensure that the core program provides for continuity of Landsat products and coverage on a secure and sustainable path.

The SELIP should take advantage of technological innovation in sensors, spacecraft, and data management and analysis to improve system performance, allow for new analyses that better exploit the data and meet future needs. Because future measurements will derive from both current and new technologies, new implementations of existing data products derived from a multispectral sensor should be cross-calibrateable with Landsat legacy products and be essentially interchangeable for scientific and operational purposes.

To better meet these primary goals, the committee recommends that the program should

• Systematically monitor users and uses of Landsat data so that the program can evolve with changing user requirements and

• Consider alternative implementations that continue to enable the collection of global, moderate-resolution data with the full range of spectral capabilities.

ENHANCING A SUSTAINED LAND IMAGING PROGRAM

Landsat has been the cornerstone of U.S. land imaging, but it has never comprised the totality of that effort. Although the core program of SELIP is a set of measurements and data products that preserve the continuity of the current record, the program can benefit from, and future users may require, the inclusion of data from other technologies. SELIP could benefit from defining land imaging more broadly, recognizing the increasing contributions from a diverse set of U.S. government, private-sector, and international airborne and spaceborne assets. The value added by increasing the synergistic use of these data is sufficient to consider broadening the scope of SELIP's data holding, while retaining the focus on Landsat-type measurements to continue the historical legacy. Some incorporation of other types of data requires only better coordination across the government by increased sharing of existing or planned data.

The committee recommends that the Sustained and Enhanced Land Imaging Program integrate measurements from commercial partners, spaceborne sensors recommended by the 2007 NRC report *Earth Science and Applications from Space*,[4] and a variety of airborne sensors and acquisitions to enable analyses not possible using only moderate-resolution multispectral data. These measurements should include, but not be restricted to, the following:

- **Airborne and spaceborne fine-resolution remote sensing data from public and commercial sources that can be used for detailed land use and land cover, urban infrastructure, transportation, hydrology, and disaster response;**
- **LiDAR data that can be used to extract precise digital surface and terrain models, building and vegetation height information, and vegetation canopy and its internal structure information;**
- **Synthetic aperture radar (SAR) and interferometric SAR (InSAR) images at resolutions suitable for studies of deformation, elevations, and surface cover; and**
- **Hyperspectral data collection and information extraction capabilities for hydrology, ecosystem health and biodiversity, and soil science and mineralogy.**

DATA SYSTEMS

The decision in 2008 to allow Landsat images to be downloaded free of charge greatly expanded the use of Landsat data and set a standard for international cooperation. There are now more downloads in 1 day than there were sales in an entire year when Landsat data were sold. USGS websites effectively provide access to imagery and derived products, with varying degrees of ease of use. Moreover, several commercial companies—for example, the Earth Sciences Resources Institute (ESRI), Google, Microsoft, and Yahoo—also provide high-resolution aerial and spaceborne images, Landsat imagery, and products based on imagery. Although these sites and services offer innovative ways to search for, display, and provide images and derivative products, they lack the comprehensive access to land imaging archives that are best offered to the public from an authoritative federal government source.

USGS, as part of the Sustained and Enhanced Land Imaging Program, should continue to deliver derived products from imagery without explicit cost to the end users.

USGS should

- **Improve search capabilities and transparency to users and**
- **Continue to interface with the private sector to improve access to public- and private-domain land imaging data products and services.**

The Sustained and Enhanced Land Imaging Program should develop a systematic process for identifying and prioritizing a wider suite of products, including essential climate variables, that can be derived from moderate-resolution land imagery, and for documenting and validating algorithms, including their modifications or replacements. In doing so, the program should

---

[4] National Research Council, *Earth Science and Applications from Space, National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C., 2007.

- **Define criteria that government-provided authoritative data sets should meet, among them such attributes as calibration, accuracy assessment, and validation, and including ground truth;**
- **Define criteria for which products should be provided by the government and which by the private sector;**
- **Implement procedures for development, cost estimation, peer review, and publication of algorithms that produce derived products; and**
- **Implement plans, procedures, and budgets for ongoing validation.**

OPPORTUNITIES ON THE PATH FORWARD

A sustained land imaging program will not be viable with current mission development and management practices. However, following the launch of Landsat 8 on February 11, 2013, there are several options for a sustainable land imaging program of core requirements that also allow for enhanced capabilities and data products. Important opportunities include ensuring stable funding, programmatic improvements, and less cumbersome contracting processes.

The Sustained and Enhanced Land Imaging Program should create an ambitious plan to incorporate opportunities to improve land imaging capabilities while at the same time increasing operational efficiency and reducing overall program cost.

The program should consider a combination of the following to increase capabilities while reducing the costs for land imaging beyond Landsat 8:

- **Shift the acquisition paradigm by means of block buys and fixed-price contracting and by collaborating with commercial and international partners;**
- **Streamline the process by which satellites and sensors are designed, built, and launched, using a single organizational unit approach (a collaborative team approach) consisting of both government employees and contractors working together as a fully integrated team;**
- **Identify foreign sources of land imaging data that complement the U.S. core land imaging requirements and seek formal data-sharing agreements with them;**
- **Consider technological innovations, such as increasing the swath width 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 a secondary payload or as a shared ride.**

Looking forward, a new, comprehensive, integrated operational approach is needed, one based on a federal commitment to an operational land imaging capability in parallel with the existing operational space-based observation programs for weather forecasting and for study of the atmosphere and oceans. This integrated approach, as recommended, will take into consideration the land-imaging needs of federal and state agencies, academia, and value-added providers and will determine which data are critical to national interests, including national security, food security, natural resource management, and natural hazard risk reduction. An optimized program will look to the future, ensuring readily interoperable data among spaceborne and airborne sensors, some with finer spatial resolution and some with more frequent coverage.

The capabilities of the program can also be enhanced by incorporating other types of data, some already available. Other aspects of an evolving program may be achieved through partnerships or arrangements with other countries and entities that pursue advanced remote sensing technologies.

1

Imperative for a Sustained and Enhanced Land Imaging Program

Over the coming decades the United States and the world face growing challenges related to an increasing population, rising demand for natural resources, concerns about food security, and a changing climate. According to the National Intelligence Council's *Global Trends 2030*[1] report, the demand globally for food and water represents one of the eight tectonic shifts that it foresees over the next decades. The report projects that "demand for food is expected to rise at least 35 percent by 2030, while demand for water is expected to rise by 40 percent. Nearly half the world's population will live in areas experiencing severe water stress. Fragile states in Africa and the Middle East are most at risk of experiencing food and water shortages, but China and India are also vulnerable."[2]

The global land surface covers 150 million km^2, about 29 percent of Earth's surface. Outside ice-covered regions, humans occupy or use more than 75 percent of that land area, with roughly 40 percent in either rangeland or cropland.[3] To meet these challenges over such broad regions, decision makers will require data on the spatial and temporal distribution of land surface characteristics and land use. To address this need, satellite-based land imaging provides synoptic, repetitive data on the physical, chemical, and biological characteristics of the land surface, which includes the rock and soil and the vegetation covering it, along with snow, ice, and inland waters.

BENEFITS OF LAND IMAGING FOR THE NATION

From 1972 to the present, moderate-resolution images from the Landsat series of satellites (Figure 1.1), along with information from aircraft, commercial satellites, and foreign missions, have recorded the human imprint on the land surface. The 40-year record of Earth's surface as seen from space has transformed the understanding of regional, national, and global-scale agriculture, forestry, urbanization, hydrology, homeland security, disaster mitigation, and other changes in land use and land cover. With populations growing from 7 billion today to 9 billion by 2050, effective land management will be essential to feed and protect people throughout the world.

[1] National Intelligence Council, *Global Trends 2030: Alternative Worlds,* NIC 2012-001, 2012, available at http://www.dni.gov/files/documents/GlobalTrends_2030.pdf.
[2] Ibid., p. v.
[3] E.C. Ellis and N. Ramankutty, Putting people in the map: Anthropogenic biomes of the world, *Frontiers in Ecology and the Environment* 6:439-447, 2008.

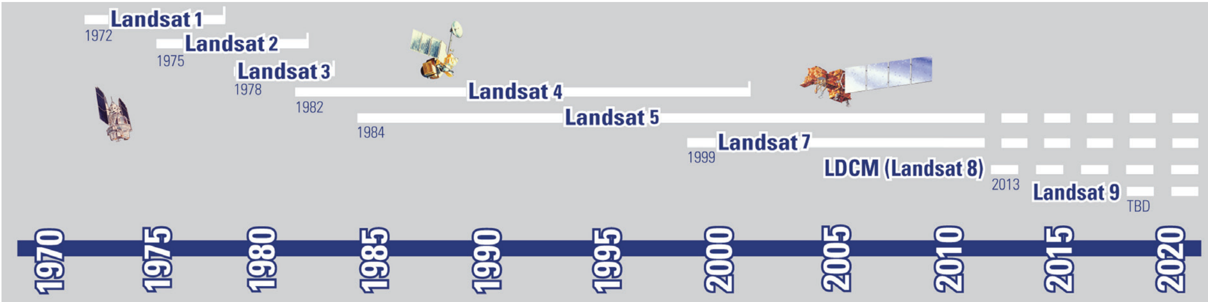


FIGURE 1.1 History of the Landsat suite of remote sensing satellites. When Landsat 6 failed on launch in 1993, a gap in data collection was avoided by the fortuitous survival of Landsat 5 far beyond its design life of 3 years. It was finally decommissioned in 2013. In 2003, Landsat 7 suffered the loss of the scan line corrector on the Enhanced Thematic Mapper Plus instrument, resulting in the loss of 25 percent of the data for any given scene. NOTE: LDCM, Landsat Data Continuity Mission, now Landsat 8. SOURCE: U.S. Geological Survey, "Landsat 1 History. July 23, 1972-January 6, 1978," available at http://landsat.usgs.gov/about_mission_history.php.

Land imaging data from the Landsat series of satellites forms the basis and model for civil remote sensing in the United States and has been used for applications ranging from wildfire management, to urban planning, to disaster mitigation and response. Figure 1.2, for example, shows urban growth in the Las Vegas, Nevada, area between 1990 and 2010. Landsat data are used operationally by virtually every U.S. land management agency to define broad land cover categories—through the U.S. Geological Survey (USGS) National Land Cover Database—and to monitor rapid changes, such as pre- and postburn forest conditions (Table 1.1). The federal government owns between 635 and 640 million acres of land, which constitutes 28 percent of the 2.27 billion acres of land in the United States. Four agencies administer 609 million acres of this land: the U.S. Forest Service (USFS) in the Department of Agriculture and the National Park Service, Bureau of Land Management, and the Fish and Wildlife Service in the Department of the Interior (DOI). Most of these lands are in the western states and Alaska. In addition, the Department of Defense (DOD) administers 19 million acres in military bases, training ranges, and more.[4]

Specific examples of benefits to the United States made possible by analysis of Landsat data include the following:

- *Agricultural forecasting and management*—The U.S. Department of Agriculture uses Landsat data to monitor global crop supplies and stocks to forecast shortfalls or gluts of various crops on the market. The multimillion-dollar U.S. agricultural commodities market relies on these crop predictions when conducting futures trading.[5] These important functions benefit U.S. food and economic security as well as national security.
- *Monitoring climate change impacts*—Landsat data facilitate the monitoring of the distribution and rates of impacts of climate change on remote regions, including glaciers, rainforests, and permafrost, and coral reefs—often early harbingers of climate and temperature change.[6] The U.S. Climate Change Science Program, representing 15 federal agencies, has identified Landsat as a critical observatory for climate and environmental change research due to the unbroken length of the Landsat record and its importance to identifying the root causes and impacts

[4] R.W. Gorte, C.H. Vincent, L.A. Hanson, and M.R. Rosenblum, *Federal Land Ownership: Overview and Data,* R42346, Congressional Research Service, available at http://www.fas.org/sgp/crs/misc/R42346.pdf, July 29, 2013.

[5] J.R. Irons, Landsat's Critical Role in Agriculture, NASA/USGS Fact Sheet, 2012, available at http://landsat.gsfc.nasa.gov/pdf_archive/Landsat_AG_fs_4web.pdf.

[6] For example, F. Paul, A. Kääb, and W. Haeberli, Recent glacier changes in the Alps observed by satellite: Consequences for future monitoring strategies, *Global and Planetary Change* 56:111-122, 2007; A.C. Baker, P.W. Glynn, and B. Riegl, Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook, *Estuarine, Coastal and Shelf Science* 80:435-447, 2008.

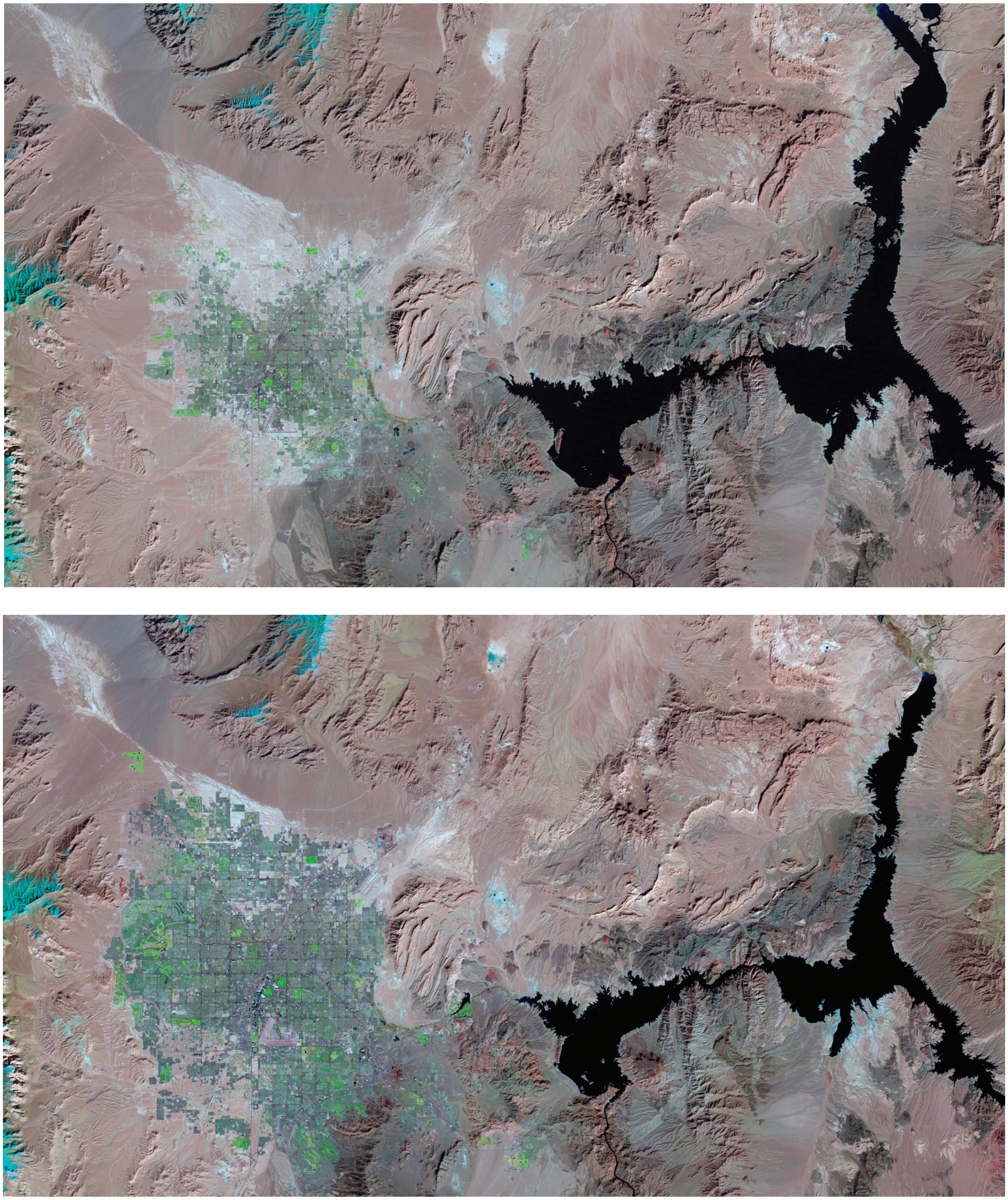


FIGURE 1.2 Global Land Survey Landsat images of Las Vegas, Nevada, and Lake Mead in 1990 (*top*) and 2010 (*bottom*). The images were acquired by Landsat 5 from the Thematic Mapper instrument. The urban areas have expanded into the surrounding desert, and Lake Mead has diminished because of below-average snow and rainfall in the Rocky Mountains. SOURCE: U.S. Geological Survey LandsatLook Viewer, available at http://landsatlook.usgs.gov.

TABLE 1.1 Operational Programs Currently Using Moderate-Resolution Land Imaging Data

Carbon cycle monitoring	Mineral exploration
Coastal change analysis	Monitoring grant performance
Crop estimates	Range management
Deforestation monitoring	Recreation planning
Design of defense systems	Snow and ice monitoring
Detecting and monitoring volcanic activity	Soil analysis and sediment redistribution
Ecosystem mapping	Space cartography
Emergency response	Support of Department of Defense operations
Forest management	Water resource planning and administration
Invasive species monitoring	Water rights monitoring
Inventorying toxic releases	Weather prediction
Irrigation management	Wetlands rehabilitation
Land use and land cover change	Wildland fire risk assessment
Mapping groundwater discharge zones	Wildlife reintroduction

SOURCE: Executive Office of the President, Future of Land Imaging Interagency Working Group, *A Plan for a U.S. National Land Imaging Program,* August 2007, available at http://www.landimaging.gov.

of climate change.[7] Such comprehensive monitoring helps anticipate the types and scales of adaptation strategies needed in the United States and throughout the world.

- *Monitoring natural defenses to natural disasters*—Coastal wetlands and mangrove swamps provide important protection against hurricane winds and storm surges. The National Oceanic and Atmospheric Administration's (NOAA's) Coastal Change Analysis Program[8] uses Landsat data as the most cost-effective way to track changes in these wetlands areas. The Landsat data are integrated with aerial photography and field data to identify those coastal regions most crucial for protecting vulnerable populations and infrastructure.
- *Wildfire risk management*—USFS and USGS utilize Landsat data to assess fire susceptibility, to estimate the percentage of vegetation and trees killed by fire, and to identify improvements in management strategies to reduce future fire risk.[9]

The science accomplishments from Landsat data are equally important and include the following:

- Landsat provided the basis for the quantitative estimation of deforestation and ended a decades-long debate over its magnitude,[10] thus providing a critical constraint on the global carbon cycle. Australia's National Carbon Accounting System, for example, utilizes a time series of Landsat mosaics to quantify land cover change and the associated changes in the terrestrial carbon stock in Australia (Figure 1.3).
- Landsat's coverage and longevity have allowed it to be used for long-term studies of ecological change at scales fine enough to detect effects of herbivores, disease, and other processes whose spatial signatures are too fine for instruments with daily temporal resolution but coarser spatial resolution, such as MODIS aboard the Terra and Aqua satellites and AVHRR aboard the NOAA polar-orbiting satellites. In the area of policy, Landsat data are used to evaluate worldwide deforestation and degradation, and this information is useful to the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries.[11]

---

[7] J.R. Irons, Landsat and Climate, NASA/USGS Fact Sheet, 2012, available at http://landsat.gsfc.nasa.gov/pdf_archive/landsat+climate_vf_4web.pdf.

[8] See http://www.csc.noaa.gov/digitalcoast/data/ccapregional/.

[9] J.R. Irons, Landsat's Critical Role in Managing Forest Fires, NASA/USGS Fact Sheet, 2012, available at http://landsat.gsfc.nasa.gov/pdf_archive/LandsatFireFactSheet.pdf.

[10] D.L. Skole, W.H. Chomentowski, W.A. Salas, and A.D. Nobre, Physical and human dimensions of deforestation in Amazonia, *BioScience* 44(5), 1994.

[11] K.G. Holly, B. Sandra, O.N. John, and A.F. Jonathan, Monitoring and estimating tropical forest carbon stocks: Making REDD a reality, *Environmental Research Letters* 2:045023, 2007.

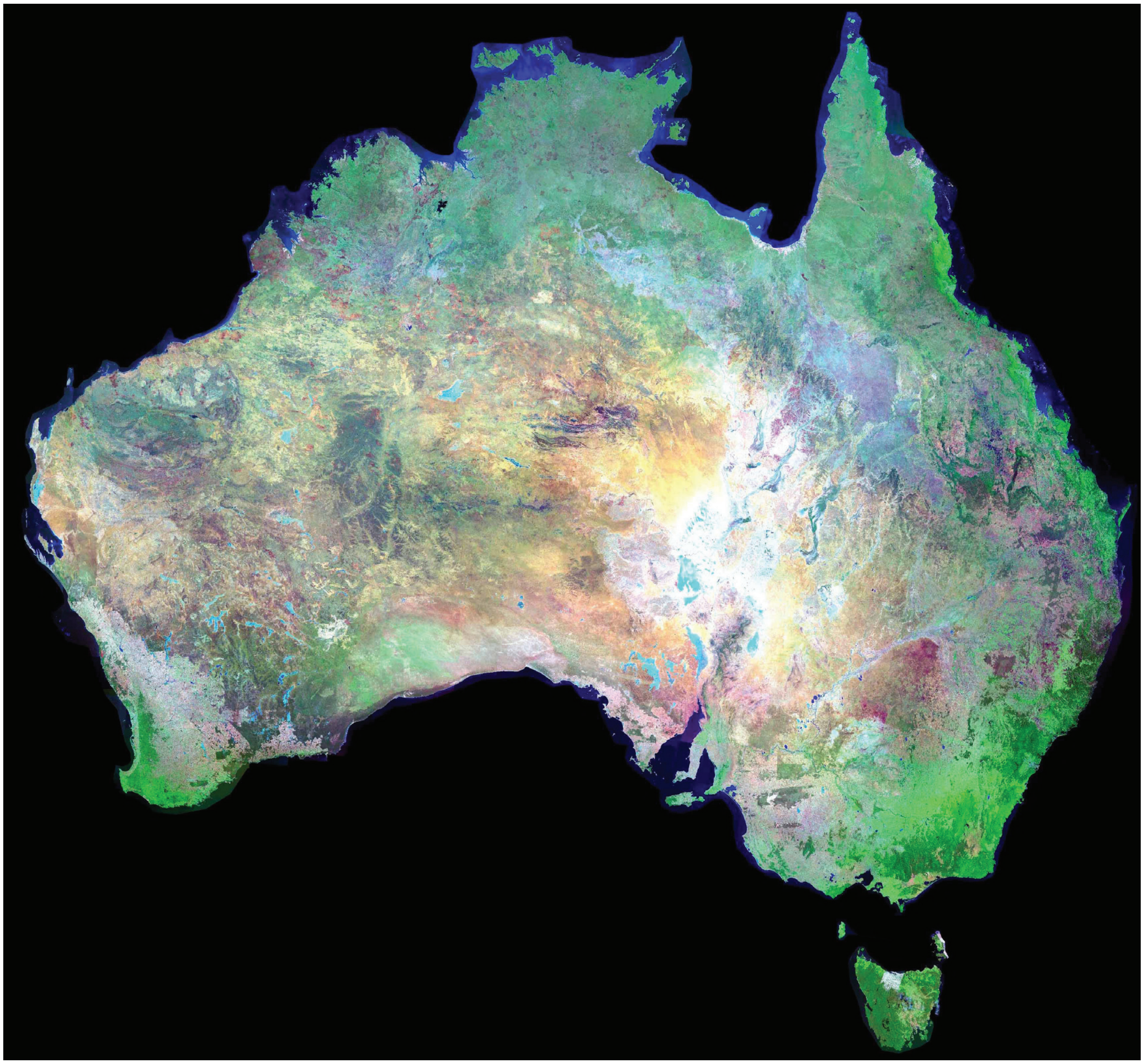


FIGURE 1.3 Mosaic of Australia from 369 Landsat 7 scenes acquired in 1999-2000. The color composite maps red, green, and blue to three different spectral bands (7, 4, and 2, respectively). Time series of such mosaics are used to map land cover change and associated changes in terrestrial carbon stocks. SOURCE: Australian Greenhouse Office, Landsat-7 Picture Mosaic Map of Australia, Scale: 1:5,000,000, © Commonwealth of Australia (Geoscience Australia) 2013. Available at https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS& catno=48410.

- The basis for monitoring vegetation from space requires differentiating the spectral responses of soil from those of healthy and moisture-stressed vegetation. In the 1970s, early Landsat data were used to derive the tasseled cap model of vegetation,[12] relevant for understanding vegetation stress, and thereby enabling forecasts of worldwide agricultural productivity.

[12] E.P. Crist and R.J. Kauth, The tasseled cap demystified, *Photogrammetric Engineering and Remote Sensing* 52:81-86, 1986.

- Analysis of seasonal and permanent snow and ice cover[13] provide data for hydrologic modeling and for estimating glacier velocities. These analyses were made possible by scientists who developed and tested algorithms with Landsats 4 and 5, which enabled snow-cloud discrimination (Figure 1.4).
- The combination of Landsat-like images—with 15- to 100-m spatial resolution and 8- to 16-day temporal resolution—with coarser-resolution daily imagery allows for useful synergy, whereby the data with daily temporal resolution identify changes to the dynamic surface, and the moderate-resolution imagery provides spatial detail. The correlations between sensor resolution and temporal repeat are shown in Table 1.2. For example, Landsat thermal infrared data help estimate evapotranspiration from agricultural lands at the scale of individual fields. These estimates are used to monitor agricultural water use and to model plausible scenarios resulting from climate change.

Continuing the long record of land imaging has both scientific and management benefits. As the record lengthens, the ability of Landsat-class data to observe environmental change continues to increase in value, recording effects of climate variability, invasive species, and land use that have no direct analog in past events. Long observation records are needed to differentiate between short-term climate variability (e.g., El Niño, North Atlantic Oscillation) and longer-term trends.

Landsat images make critical contributions to the U.S. economy, environment, and security. Specific economic analyses of some of the benefits derived from the Landsat series of satellites demonstrate its great value for the nation. Most of the analyses use imagery provided without charge by USGS, so their value is not set by market forces. However, analyses of just 10 selected applications—including consumptive water use, mapping of agriculture and flood mitigation, and change detection among them—show more than ***$1.7 billion in annual value*** for focused operational management in the United States.[14] This is compared to a cost (including design, launch, and data management) of about $1 billion amortized over 5 to 7 years of mission life.

Although the increase in scientific knowledge is more difficult to assess, approximately 1,700 scientific papers describing the use of Landsat data in a tremendous variety of scientific applications have been published in refereed journals every year.[15] Many of those papers document not only the ability to measure biological and geophysical variables from space, but also the use of such spatially extensive and temporally consistent measurements to reveal new knowledge about Earth.

A CHAOTIC HISTORY

The continuous collection of land remote sensing data from space has long been recognized as providing benefits of critical importance to the United States. In the Land Remote Sensing Policy Act of 1992,[16] Congress declared that

> The continuous collection and utilization of land remote sensing data from space are of major benefit in studying and understanding human impacts on the global environment, in managing the Earth's natural resources, in carrying out national security functions, and in planning and conducting many other activities of scientific, economic, and social importance. . . . The national interest of the United States lies in maintaining international leadership in satellite land remote sensing and in broadly promoting the beneficial use of remote sensing data.

[13] J. Dozier, Spectral signature of alpine snow cover from the Landsat Thematic Mapper, *Remote Sensing of Environment* 28:9-22, 1989.

[14] V. Adams and E. Pindilli, "Improving the Way Government Does Business. The Value of Landsat Moderate Resolution Imagery in Improving Decision-Making," 2012, available at http://calval.cr.usgs.gov/wordpress/wp-content/uploads/Pindilli_JACIE_Presentation_final.pdf.

[15] From ISI Web of Knowledge, Topic=landsat. From 2009 through February 2012, 6,752 papers have been published that reference Landsat.

[16] See 1992 National Space Policy Directive 5 (NSPD-5), "Landsat Remote Sensing Strategy," Public Law 102-555, "Land Remote Sensing Policy Act of 1992," 1994 Presidential Decision Directive NSTC-3, "Landsat Remote Sensing Strategy," U.S. National Space Policy of the United States of America 2006, 2007 White House Office of Science and Technology Policy Report, *A Plan for a U.S. National Land Imaging Program,* and 2007 National Research Council report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* The National Academies Press, Washington, D.C.

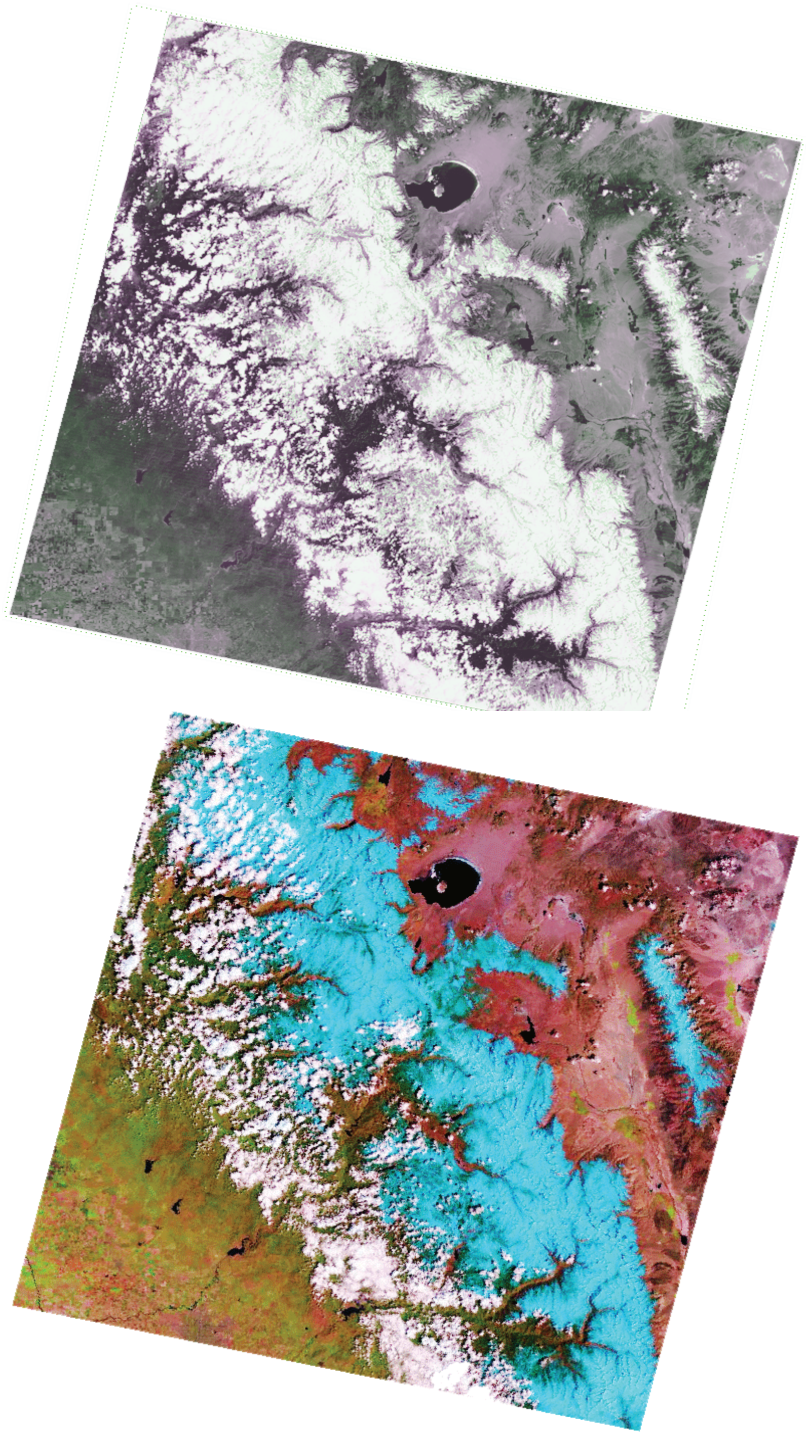


FIGURE 1.4 Snow-cloud discrimination in the Sierra Nevada (Mono Lake is near the top of the images) from the Landsat 4 Thematic Mapper. The top image maps the displayed color to true color, such that red-green-blue maps to bands 3, 2, and 1, and the clouds are difficult to distinguish from the snow cover. In the bottom image, the bands are 5, 4, and 2; snow is bright in band 2, less bright in band 4, and dark in band 5, whereas clouds are bright in all the bands. SOURCE: Courtesy of U.S. Geological Survey, processing by Jeff Dozier, University of California, Santa Barbara.

TABLE 1.2 Characteristics of Space-Based Land Imaging Satellites

Type of Sensor	Spatial Resolution (m)	Geographic Coverage Swath per Image (km)	Frequency of Repeat Coverage of Every Location[a]
High resolution	<5	10-15	Months to years
Moderate resolution	10-100	50-200	15-30 days
Low resolution	>100	500-2500	1-2 days

[a] With a pointable instrument, high-resolution sensors can achieve frequent coverage at some locations but not all.
NOTE: Sensors with high resolution cover a small area of Earth's surface with each image and take a longer time to return to view the same area again. Sensors with lower resolution cover a larger surface area, but this also allows for a faster return. Landsat-like sensors have moderate resolutions (10-100 m) and 15-30 day repeat frequencies.

However, the procurement of the series of Landsat satellites has been ad hoc and has had a chaotic history, characterized by frequent shifting of responsibilities among government agencies and the private sector.[17] ***Indeed, despite the documented record of achievements and the proven necessity for the data, the future of moderate-resolution U.S.-provided land remote sensing continues to be at risk.*** The Landsat series has never truly been a "program." The satellites have been justified, planned, and executed separately or at most in pairs (Landsat 1-2, Landsat 4-5), and the 40-year record owes more to the remarkable survival of Landsat 5 for two decades beyond its design life than to careful planning. Landsat 7 is currently operating in a degraded mode, and Landsat 8, launched on February 11, 2013, will soon begin returning data. Landsat 8 has only a 5-year design life,[18] and there is no assured successor. Landsat 9 is under discussion in the U.S. executive and congressional branches, but its configuration remains under debate. Prospects for missions beyond Landsat 9 are unclear, and the sharing of responsibilities with commercial and foreign contributors has not been articulated.

Following the initial Landsat launches in 1972 and 1975, NASA launched Landsat 3 in 1978. The major sensor on all three of those Landsats was the Multispectral Scanning System, with four spectral bands at 79-m spatial resolution plus a thermal band added to Landsat 3. The imaging capabilities expanded to the Thematic Mapper (TM) on Landsat 4 in 1982 and Landsat 5 in 1984, with six spectral bands at 30-m resolution and a thermal band at coarser (120-m) resolution, then to the Enhanced Thematic Mapper (ETM+) on Landsat 7 in 1999, which added a 15-m panchromatic band and refined the thermal band's resolution to 60 m. Although a 1987 failure in the downlink capability severely restricted collection of data worldwide, Landsat 5 operated for 27 years, until November 2011, more than 20 years beyond its design life. Landsat 6 failed on launch in 1993. Landsat 7 operated flawlessly until the scan line corrector failed in 2003, compromising about 22 percent of the data. Landsat 8, whose characteristics are described in Box 1.1, launched in February 2013. In Chapter 2, Tables 2.1 and 2.2 describe the spatial and spectral properties of the bands on all Landsat missions.

The Land Remote Sensing Commercialization Act of 1984[19] shifted responsibility for Landsat from the government agencies that had previously managed the satellites (NOAA, NASA, and the DOI) to NOAA, with the intent of then transferring satellite development and operations to the private sector. NOAA selected EOSAT, Inc., a private consortium, to run Landsat. NOAA retained responsibility for overall system operation. When sales fell short of those needed to make the EOSAT commercial venture profitable, the parent organizations were forced to incrementally raise the prices for Landsat images, eventually increasing them to as much as $4,400 per image.[20] With each price increase, sales fell further. Additionally, uncertainty regarding the commercial development of

[17] Since NASA's initial launch in 1972, the responsibility for the Landsat program has changed hands to NOAA, to NOAA/private industry, to DOD/NASA, to NASA/NOAA, to NASA/NOAA/USGS, and currently to NASA/USGS.
[18] The Thermal Infrared Sensor (TIRS) has a design life of 3 years. The 5-year requirement was relaxed to expedite instrument development. See http://ldcm.gsfc.nasa.gov/spacecraft_instruments/tirs_reqs.html.
[19] See http://thomas.loc.gov/cgi-bin/bdquery/z?d098:HR05155:|TOM:/bss/d098query.html.
[20] $4,000 for digital Landsat 4 scenes. See http://remotesensing.usgs.gov/landsat_fees.php.

BOX 1.1
About the Landsat Data Continuity Mission (LDCM), Renamed Landsat 8

The latest satellite in the Landsat series, Landsat 8, launched on February 11, 2013. Landsat 8 orbits at an altitude of 705 km and an inclination of 98.2 degrees; the orbit is Sun-synchronous, with a descending node over the equator at a mean local time of 10:11 a.m. (see Figure 1.1.1). Because the orbit is near polar, the spacecraft is able to image all but the Earth's polar regions above about 82 degrees latitude. The sensor swath width is 185 km, identical to that of Landsat 7; the swath is diagrammed in Figure 1.1.2. The spacecraft orbits the earth every 98 minutes, and repeats the same ground track every 16 days. The spacecraft has a design life of 5 years and fuel life of 10 years.[1,2]

Landsat 8 has two main instruments on board: the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). The OLI is a "push-broom" style sensor array, with over 7,000 detectors per spectral band. The OLI images in nine spectral bands: the seven heritage bands of Landsat 7, six of which have improved sensitivity; a deep blue visible band designed for water and coastal zone investigations (shown as Band 1 on Figure 1.1.3); and a shortwave infrared band designed for the detection of cirrus clouds (shown as Band 9 on Figure 1.1.3). TIRS was added to Landsat 8 to enable continued study of the Earth's thermal energy, as well as to support new applications such as mapping evapotranspiration for water resource management. Like OLI, TIRS is a push-broom style sensor, and has a 185-km field of view and spatial resolution of 100 m. TIRS was added to the Landsat 8 payload after mission design was under way, as the importance of the thermal data from previous Landsat missions became evident. One consequence of the belated development is that the design life of TIRS was set to only 3 years.[3,4]

---

[1] Landsat Data Continuity Mission Press Kit, NASA/USGS, February 2013.
[2] Landsat Data Continuity Mission, "Continuously Exploring Your World," NASA/USGS Mission Brochure, 2012.
[3] Landsat Data Continuity Mission, "Continuously Exploring Your World," 2012.
[4] USGS Landsat Missions, available at http://landsat.usgs.gov/index.php. Accessed May 15, 2013.

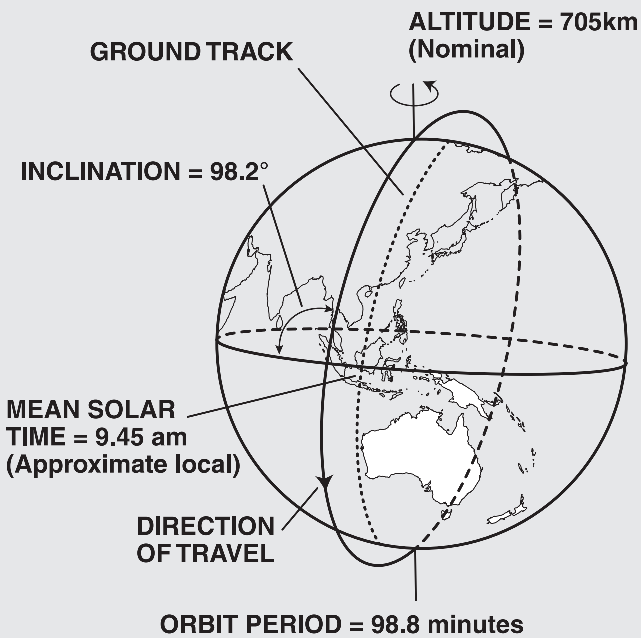


FIGURE 1.1.1 Orbit mechanics of the current Landsat missions. Note the mean solar time varies for each spacecraft.
SOURCE: NASA Landsat 7 Science Data Users Handbook.

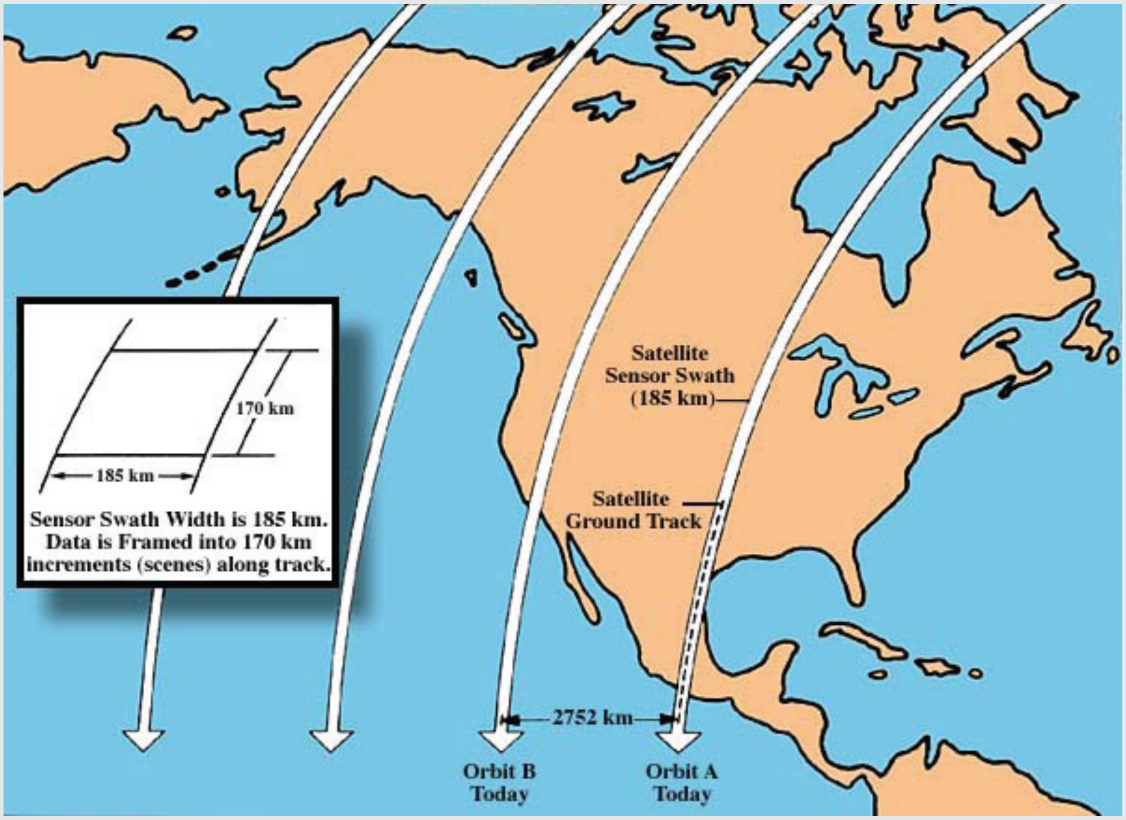


FIGURE 1.1.2 Sensor swath for both Landsat 7 and Landsat 8. SOURCE: NASA Landsat 7 Science Data Users Handbook.

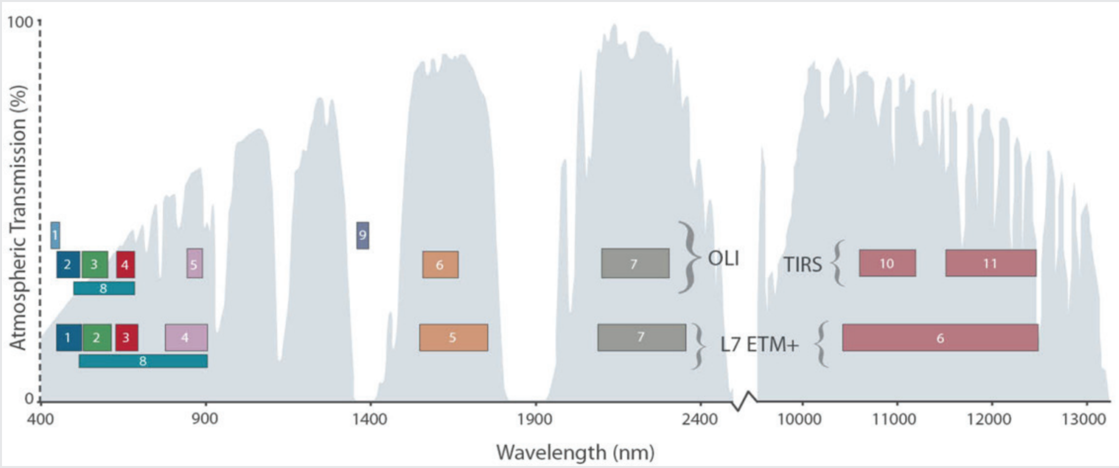


FIGURE 1.1.3 Comparison between the bands of Landsat 8 (*upper row*) and legacy missions (*lower row*). SOURCE: NASA Landsat Data Continuity Mission, available at http://landsat.gsfc.nasa.gov/about/ldcm.html, accessed May 15, 2013.

Landsat 7 left data continuity at risk.[21] Thus, the Land Remote Sensing Policy Act of 1992[22] repealed the 1984 act and shifted responsibility for Landsat 7 entirely back to the government (DOD and NASA). The death knell of this commercialization attempt was the failure of EOSAT's Landsat 6 to achieve orbit in 1993.

As Landsat 7 approached launch in 1999, in accordance with the Land Remote Sensing Policy Act of 1992 and responding to increased pressure from Congress, NASA started considering the possibility of implementing the next Landsat as a data purchase. The concept was known as the Landsat Data Continuity Mission (LDCM) and resulted in a competition between Boeing-backed Resource 21, a private-sector consortium, and DigitalGlobe. However, the original LDCM data purchase concept was cancelled in 2003 when no agreement could be reached, partially caused by the perception of a limited commercial market for moderate-resolution imagery.

In 2004, an attempt was made to fly a Landsat instrument on NPOESS, an ambitious weather satellite program originally involving DOD, NASA, and NOAA. However, accommodation of Landsat on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) proved to be costly, and other instruments on NPOESS were beginning to overrun substantially, so this effort was terminated in 2005. Thus, responsibility for implementation of the Landsat space segment was assigned, once again, to NASA. The resulting revised LDCM approach resulted in the launch of Landsat 8 on February 11, 2013.

In 2005, then Science Advisor and Office of Science and Technology Policy (OSTP) Director John Marburger, recognizing the value of Landsat's continuous monitoring of Earth's land surface as well as its chaotic and ad hoc administrative history, tasked an interagency working group to develop a long-term plan for future land imaging. He specifically requested options to achieve technical, financial, and managerial stability for operational land imaging ensuring future U.S. needs will be met. The findings and policy recommendations of the interagency working group were presented in the 2007 report *A Plan for a U.S. National Land Imaging Program.*[23] The principal recommendations of the report were the following:

> The U.S. must commit to continue the collection of moderate-resolution land imagery (p. 3).
>
> The United States should establish and maintain a core operational capability to collect moderate-resolution land imagery through the procurement and launch of a series of U.S.-owned satellites (p. 6).

The 2007 report also recommended that DOI would be the appropriate department to lead the proposed program. Since that report, an attempt has been made by the administration to follow its recommendations and shift the responsibility for Landsat to the USGS via the 2010 National Space Policy.[24] The USGS was to provide data requirements and funding, and NASA was to build the Landsat satellites for the USGS on a reimbursable basis, much as NOAA funds NASA to implement U.S. weather satellites.[25] The USGS responded in the 2012 President's budget request for DOI by requesting $48 million in fiscal year (FY) 2012 to establish a permanent program for Landsat 9, but Congress appropriated $2 million for program development only, expressing doubt as to whether USGS was the right home for Landsat.[26] In early 2012, at the request of the Office of Management and Budget/

[21] U.S. Congress, Office of Technology Assessment, Civilian Satellite Remote Sensing: A Strategic Approach, OTA-ISS-607, U.S. Government Printing Office, Washington, D.C., September 1994.

[22] See http://geo.arc.nasa.gov/sge/landsat/15USCch82.html.

[23] See http://www.landimaging.gov/fli_iwg_report_print_ready_low_res.pdf.

[24] National Space Policy of the United States of America, June 28, 2010, http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.

[25] Statement of Ken Salazar, Secretary of the Interior, before the Subcommittee on Interior, Environment, and Related Agencies, Senate Committee on Appropriations, on the 2012 President's budget request.

[26] "The conferees have not agreed to transfer budgetary authority for the launch of Landsat satellites 9 and 10 from [NASA] to the Survey [USGS]… There is little doubt that resources will not be available within the Interior Appropriations bill to support these very large increases without decimating all other Survey programs… [B]oth technological advances and a vastly different economic environment may point to other, less costly, options for obtaining Landsat data." See Military Construction and Veterans Affairs and Related Agencies Appropriations Act, 2012, Conference Report (To accompany H.R. 2055), p. 1059, available at http://www.gpo.gov/fdsys/pkg/CRPT-112hrpt331/pdf/CRPT-112hrpt331.pdf.

OSTP, and recognizing that the estimated $1 billion[27] or more required to implement Landsat 9 was unlikely to be forthcoming, USGS issued a request for information (RFI) on creative, innovative implementation approaches for a much lower cost mission. The results of this RFI have not been released to the public, but in the FY 2014 budget request, the intent to begin a sustained land imaging program in the USGS has been reversed, and budgetary responsibility for operating, building, and launching future Landsat satellites is once again to be assigned to NASA.

> In 2014, USGS will work with the National Aeronautics and Space Administration to analyze user requirements and develop a successor mission to Landsat 8, formerly known as the Landsat Data Continuity Mission. Funding to begin work on the successor mission is provided in the 2014 budget for NASA, which will be responsible for development of Landsat-class land imaging satellites going forward. The USGS will continue its operational role in managing the collection, archiving, and dissemination of Landsat data to users.[28]

Although funding to begin the next mission would be promising, the necessary budget appropriation has not yet been enacted. No sustained program has been established to ensure the future of land imaging, ***and it is clear that the continuation of the Landsat program is once again in jeopardy.*** Landsat 5 has stopped operating and was officially retired on January 6, 2013. Landsat 7 is operating in a degraded mode. Had the launch of Landsat 8 failed, the nation would soon be without its own source of moderate-resolution data.

CHARGE TO THE COMMITTEE

Against the backdrop of this chaotic history and uncertainties about the future of Landsat, USGS tasked the National Research Council (NRC) Committee on Implementation of a Sustained Land Imaging Program to assess the needs and opportunities to develop a national space-based operational land imaging capability. The tasks in that charge are the following (see Appendix A for the committee's statement of task):

> Task 1—Identify and/or validate primary organizations and segments of society and their fundamental historical, present-day, near-future, and long-term data, information, and service requirements that need to be supported by a sustained land imaging program.

Chapters 2 and 3 address the elements of what the committee finds to be the critical core elements of any future land imaging system, based on continuity with earlier systems and technical characteristics their users employ.

> Task 2—Identify and recommend characteristics and critical program support areas expected of a sustained land imaging program including, but not limited to, the continuous operation and refinement of U.S. government-owned, spaceborne land imaging capabilities (e.g., passive, as in optical land imaging; active, as in LiDAR or [synthetic aperture radar] SAR measurements).

Chapter 3 expands the discussion in Chapter 2 to include the elements of a fully capable land imaging system. The chapter describes the committee's vision for a Sustained and Enhanced Land Imaging Program (SELIP) and gives an overview of potential new observing capabilities. The role of commercial and international partners is also discussed.

> Task 3—Suggest critical baseline products and services derived from sustained land imaging capabilities, including higher-level information products such as climate data records [CDRs] and terrestrial essential climate variables [ECVs].

---

[27] As of the NASA FY 2013 Earth Science budget request, the total life-cycle cost of LDCM was $931.2 million, not including the cost of the USGS ground system. See http://www.nasa.gov/pdf/632679main_NASA_FY13_Budget_Science-Earth-Science-508.pdf.

[28] Quote from Bureau Highlights, U.S. Geological Survey, p. BH-55, in Office of Management and Budget, *Fiscal 2014 Budget of the U.S. Government,* Executive Office of the President, Washington, D.C., available at http://www.whitehouse.gov/omb/budget/Overview.

Chapter 4 focuses on data systems. As discussed in the chapter, to achieve a sustained land imaging capability requires not only plans for data acquisition, but also the development of data products (including CDRs and ECVs), their management, and considerations of data availability.

> Task 4—Considering the requirements for an operational land imaging capability, provide recommendations to facilitate the transition of single-mission NASA research-based land imaging technology or missions to sustained USGS land imaging program technology or missions, including the relationships between USGS, NASA, and NOAA in developing, maintaining, and effectively utilizing land imaging capabilities.

Chapter 5 includes detailed recommendations about program governance. Chapter 5 also discusses the committee's view regarding future opportunities and the path forward with particular attention to alternative sensor design strategies and lower-cost acquisition strategies for future land imaging systems.

Although Task 4 includes the request for recommendations to facilitate the transition of single-mission NASA research-based land imaging technology or missions to sustained USGS land imaging program technology or missions, the committee recognizes the limits to this charge given continuing instability in national policy for space-based land remote sensing.[29] In the committee's opinion recommending how the government should make this organizational decision would not be appropriate for a number of reasons. There are considerable challenges, for instance, in having the two agencies involved, NASA and the USGS, supporting such a program when their appropriations are under the authority of different congressional appropriations subcommittees. In addition, the assignment of land imaging activities to one agency or another involves issues that go beyond land imaging to the broader issue of the roles, responsibilities, and authority for observational space systems that provide sustained observations of key data. In addition, any chance that the establishment of SELIP in one location or the other might harm the operation of other necessary programs at either agency would have to be mitigated. Implementing the recommendations in this report may require that a sustained land imaging program be established at a level of government where there is sufficient authority to make organizational decisions, and that in turn might require executive or legislative actions that this committee was not tasked with recommending. What the committee has done is recommend key elements of a successful program no matter where the federal government decides it should reside.

FINDINGS

Based on a series of meetings with stakeholders, including DOI, NASA, OSTP, NOAA, USDA, USFS, commercial data providers, and multiple land imaging data users, as well as analysis of prior reports regarding the uses and value of Landsat and discussion among committee members, the committee offers the following findings:

- The United States pioneered global, synoptic, frequent-repeat global imaging. Other nations are now developing systems whose capability rivals or exceeds that of U.S. systems. National needs require the United States to reassert leadership and maintain and expand capabilities.
- Space-based land imaging is essential to U.S. national security as it is a critical resource for ensuring our food, energy, health, environmental, and economic interests.
- The economic and scientific benefits to the United States of Landsat imagery far exceed the investment in the system.
- To best serve the needs of the United States, the land imaging program of the future requires an overarching national strategy and long-term commitment, including clearly defined program requirements, management responsibilities, and funding.
- The continuity of Landsat imagery has never been ensured through the development of a sustained government program. Instead, responsibility has been shifted from one organization to another over Landsat's 40-year history, resulting in persistent uncertainty for the future of this important asset.

[29] See the section "A Chaotic History" for a detailed discussion of the chaotic political history of the Landsat series of satellites.

- NASA has demonstrated that it is the civil agency with the technical capacity and the congressional support to design and build civilian space missions.
- The USGS-operated data management and distribution systems function effectively and efficiently.
- NOAA uses Landsat data to monitor Earth's coastal regions, but NOAA's primary use of satellite data focuses on the ocean and the atmosphere.
- Building a satellite sequence with new requirements and technologies for each individual instrument is an expensive way to acquire land imaging data and inhibits the addition of new capabilities.
- ***A sustained land imaging program will not be viable under the current mission development and management practices.***

RECOMMENDATION

The committee's primary recommendation is that the U.S. government should establish a Sustained and Enhanced Land Imaging Program with persistent funding to respond to current and future national needs. Such a program would

- **Develop a plan for a comprehensive, integrated program that capitalizes on the strengths of USGS and NASA, maintains current capability and the existing archive, and enhances the program as technology enables new imaging capabilities and data products;**
- **Ensure acquisition of land imaging data continuously from orbital platforms and, periodically, from airborne platforms, to respond to the needs of producers and consumers of derived data products along with users who analyze imagery;**
- **Establish partnerships with commercial firms and international land imaging programs to leverage enhanced capabilities;**
- **Coordinate land imaging data buys across the U.S. government; and**
- **Include a research and development component to improve data products based on core measurements and to develop new measurement methods and consider evolving requirements.**

For the Sustained and Enhanced Land Imaging Program to be successful, program responsibilities should be divided between USGS and NASA such that the agency responsible for balancing science requirements with mission complexity and cost is also provided with the necessary budget. Both agencies should participate in an iterative process to design missions that meet the needs of research and operational communities, but final decisions should be made by the agency that has been given the budget.

The committee has not recommended where in the government the SELIP should reside. In the committee's opinion, recommending how the government should make this organizational decision would not be appropriate. A discussion of the committee's reasoning for this decision is included in the section "Charge to the Committee."

2

Technical Characteristics of the Core Program

The Landsat suite of satellite sensors has been the most successful remote sensing effort dedicated to Earth observations.[1] Born of civilian rather than military needs, the Landsat suite has provided 40 years of standardized, moderate-spatial-resolution, multispectral images of the world.[2] No other data sets allow assessment of the changing human condition so effectively. No other data sets can match Landsat's comprehensive record of Earth and its resources.

Consensus exists among government, commercial, and research users about the need for a sustained land imaging program. Sustainability can be achieved by developing an operational observing system whereby satellites will be designed and launched to provide a continuous stream of land images and data, similar to the policy articulated in the 2010 *National Space Policy.*[3] Compared to other spaceborne moderate-resolution sensors, long-term continuity has distinguished the Landsat sensor suite.

The committee's definition of an "operational" program preserves continuity as the main goal: design the satellite system and launch schedule to provide a continuous stream of land images and data, implicitly requiring strategies to contend with future instrument or launch failures. The committee's interpretation is that this goal does not require a "hot spare" that is already in orbit, but rather a commitment to adopt risk mitigation strategies that could range from instruments ready to launch to securing agreements with international partners for data access.

Surveys[4] generally show that users want, aside from continuity, frequent, moderate-resolution imagery, and that concerns about orbits, calibration, and shape of spectral bands are secondary. Long-term stability and the ability to integrate with other sensors enable detection and analysis of rates of change. Fine-resolution land data—less than 5-m spatial resolution—appear to have a commercial market. At the coarse end of the scale, imagery at 250- to 1,100-m spatial resolution with daily worldwide coverage is used for regional- to global-scale science and operational weather prediction, oceanography, and snow-cover mapping. Between these scales, history and

[1] J.R. Irons, J.L. Dwyer, and J.A. Barsi, The next Landsat satellite: The Landsat Data Continuity Mission, *Remote Sensing of Environment 122:11-21, 2012.*

[2] T.R. Loveland and J.W. Dwyer, Landsat: Building a strong future, *Remote Sensing of Environment* 122:22-29, 2012.

[3] National Space Policy of the United States of America, June 28, 2010, available at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.

[4] For example, K. Green, J. Plasker, G. Nelson, and D. Lauer, Report to the White House Office of Science and Technology Policy Future Land Imaging Working Group on the American Society for Photogrammetry and Remote Sensing survey on the future of land imaging, *Photogrammetric Engineering and Remote Sensing* 73:5-9, 2007.

TABLE 2.1 Landsat Satellite Characteristics

System	Sensors	Radiometric Resolution	Temporal Resolution	Orbit Altitude	Launch Date	Decommission or Expiration Date
Landsat 1 (ERTS-A)					July 23, 1972	January 6, 1978
Landsat 2 (ERTS-B)	RBV and MSS	6 bits	18 days	900 km	January 22, 1975	February 5, 1982
Landsat 3					March 5, 1978	March 31, 1983
Landsat 4					July 16, 1982	June 15, 2001
	MSS and TM	8 bits	16 days	705 km		
Landsat 5					March 1, 1984	TM: November 2011 MSS: January 6, 2013
Landsat 6	ETM	8 bits	16 days	705 km	Launch failed October 5, 1993	
Landsat 7	ETM+	8 bits	16 days	705 km	April 15, 1999	
Landsat 8 (LDCM)	OLI and TIRS	12 bits	16 days	705 km	February 11, 2013	

NOTE: ETM, Enhanced Thematic Mapper; MSS, Multispectral Scanning System; OLI, Operational Land Imager; RBV, Return Beam Vidicon; TIRS, Thermal Infrared Sensor; TM, Thematic Mapper.
SOURCE: NASA Goddard Space Flight Center, see http://landsat.gsfc.nasa.gov.

user surveys have shown that Landsat data at moderate resolutions (15 to 100 m, at 8- to 16-day frequency) have significant intrinsic value for a broad range of federal and nonfederal scientific and operational uses but little promise for commercialization.

CURRENT AND PAST LANDSAT TECHNOLOGIES

Spurred by photographs of Earth from the Apollo missions in the 1960s, the Department of the Interior and the U.S. Department of Agriculture (USDA) envisioned a program to provide unclassified remotely sensed data in support of resource studies and planning.[5] NASA launched the first Earth Resources Technology Satellite (ERTS) (subsequently renamed Landsat 1) in July 1972, and since then a total of seven successful missions have collected more than 2 million images of Earth spanning a 40-year period. While the technology used to capture Landsat data has evolved over its 40-year life span, each new Landsat system has been designed so that many of the imagery products are backward compatible. More important than each system's innovation and science is the Landsat suite's combined continuity of observations, which bring overwhelming value to each new Landsat system.

Tables 2.1 and 2.2 summarize the technical characteristics of the seven successful Landsat systems in the common categories of spectral, radiometric, spatial, and temporal resolutions. All systems have had the same swath width, 185 km. Over the span of the Landsat systems, spectral resolution has increased from 4 to 11 bands, with some changes in the shape of the spectral response functions, and the spatial resolution of those bands has narrowed from 80 to 15, 30, and 100 m.[6] Radiometric resolution has increased from 6 bits on Landsats 1 through 3, to 8 bits on Landsats 4 through 7, and to 12 bits on Landsat 8. Landsats 1 through 3 had an 18-day repeat cycle, which was shortened to 16 days on subsequent missions. Temporal resolution has sporadically increased from a 16-day revisit to an 8-day revisit only when and where two Landsat systems were operating simultaneously, which has, unfortunately, been rare over the past 20 years because of Landsat 5's inability to store data onboard and Landsat 7's scan line corrector failure in 2003.

While unique, Landsat is only one of many multispectral Earth observing sensing systems. Commercial providers such as DigitalGlobe, Inc.,[7] offer finer-spatial-resolution multispectral imagery for sale, but it is costly

[5] D.T. Lauer, S.A. Morain, and V.V. Salomanson, The Landsat program: Its origins, evolution, and impacts, *Photogrammetric Engineering and Remote Sensing* 63:821-838, 1997.

[6] Spatial resolution refers to the distance between distinguishable features in an image, whereas the pixel size in images delivered is often resampled. Note that the spatial resolution of the thermal band decreased from 120 to 60 m with Landsat 7, but reverted to 100 m on Landsat 8.

[7] DigitalGlobe acquired GeoEye in January 2013.

TABLE 2.2 Landsat Sensor Characteristics

Band Identifier	Spectral Range (μm)	Spatial Resolution (m)	Notes
RBV 1	0.475-0.575		
RBV 2	0.58-0.68	80	Landsats 1 and 2
RBV 3	0.69-0.83		
RBV pan	0.505-0.750	38	Landsat 3
MSS 4	0.5-0.6		
MSS 5	0.6-0.7		
MSS 6	0.7-0.8	68×83 resampled to 57×79	
MSS 7	0.8-1.1		
MSS 8	10.4-12.6		Landsat 3 only
TM 1	0.45-0.52		
TM 2	0.52-0.60		
TM 3	0.63-0.69	30	
TM 4	0.76-0.90		
TM 5	1.55-1.75		
TM 6	10.4-12.5	120	
TM 7	2.08-2.35	30	
ETM 1-7	same as TM		
ETM 8	0.52-0.90	15	
ETM+ 1-5	same as ETM		
ETM+ 6	10.4-12.5	60	ETM+ also has enhanced calibration
ETM+ 7-8	same as ETM		
OLI 1	0.433-0.453		
OLI 2	0.450-0.515		
OLI 3	0.525-0.600		
OLI 4	0.630-0.680	30	
OLI 5	0.845-0.885		With 12-bit quantization, dynamic range of the OLI does not saturate over clouds or snow
OLI 6	1.560-1.660		
OLI 7	2.100-2.300		
OLI 8	0.500-0.680	15	
OLI 9	1.360-1.390	30	
TIRS 10	10.6-11.2	100	
TIRS 11	11.5-12.5		

SOURCE: NASA Goddard Space Flight Center, see http://landsat.gsfc.nasa.gov and U.S. Geological Survey, see http://landsat.usgs.gov.

and license restricted, and the systems do not have the large synoptic geographic footprint of Landsat data. In the United States, the USDA National Agriculture Imagery Program subcontracts for suborbital aerial photography every 2-3 years and provides 1-m resolution imagery to the public domain at no cost. The images in Microsoft's Bing Map and Google Earth are acquired from Landsat, aircraft, and commercial satellites. Systems such as NASA's Moderate Resolution Imaging Spectroradiometer have daily temporal resolution and many more bands (36) but at a much coarser 250- to 1,000-m spatial resolution. Other governments and organizations outside the United States (e.g., France, China, India, and Korea) collect moderate-resolution multispectral imagery. However, none of these other systems have the unique combined characteristics of Landsat because their data are often difficult to access, and some providers charge for or restrict their coverage or the use of their products.

ANCILLARY MEASUREMENTS FROM COMMERCIAL AND FOREIGN REMOTE SENSING

A clear separation has developed between government and commercial sources of imagery, with the commercial sector providing the fine-resolution imagery (<5 m). While commercial products are mainly finer resolution than those provided by the Landsat system and are often not as comprehensive in coverage, they augment the operational capabilities available today and can enable focused studies that are impossible to undertake with Landsat-quality data. Formal agreements between the U.S. government and commercial remote sensing data providers would encourage the development and improvement of capabilities in the commercial remote sensing sector and likely increase the pool of experts in remote sensing.

Foreign data sources can supplement national imagery data sources and can function as data gap fillers if appropriate agreements are in place. Foreign imaging assets can be used for mitigation of risk—for example, if a U.S. satellite fails—but generally they are considered as complementary data sets. The history of obtaining remote sensing data from foreign agencies shows a few outstanding successes, like the European Space Agency's Envisat (until its failure in April 2012). This committee recognizes both potential benefits and risks of relying on foreign land image data sets, with the risks mainly relating to data availability and the matching of requirements to sensor characteristics.

USERS' CHARACTERISTICS AND REQUIREMENTS

The committee did not attempt any systematic analysis of Landsat users and their requirements because multiple studies and reviews have already been carried out. For example, in 2007, the American Society for Photogrammetry and Remote Sensing (ASPRS) conducted a survey of 1,295 Landsat users[8] and reported on their characteristics and their data requirements. In 2011, the U.S. Geological Survey (USGS) published a study on users, uses, and the value of Landsat and other moderate-resolution data,[9] and in 2012 the Landsat Advisory Group of the National Geospatial Advisory Committee[10] reviewed the cost savings accruing to 10 of the largest government operational uses of Landsat imagery. All of these studies comment on the broad range of uses of Landsat data, from agricultural monitoring, to water management, to forest pest detection, to national defense (Table 1.1). The studies also note that users of Landsat data are overwhelmingly government agencies, academic institutions, and nongovernmental organizations, with commercial entities constituting only a small fraction of users, about 18 percent.[11] Additionally, almost half of the users employ Landsat data to support operational decision making, with the remainder performing scientific research.[12]

The ASPRS study found that the characteristics of Landsat imagery most valued by users in order of priority are its low cost, SWIR bands, existence of the archive, the thermal band, and its moderate spatial resolution. During the public meetings held to obtain information for this report, the most common user request for technical improvements in Landsat was for more frequent temporal resolution, primarily to support agricultural monitoring and to increase the probability of coverage in the face of intermittent cloud cover.

---

[8] K. Green, J. Plasker, G. Nelson, and D. Lauer, Report to the White House Office of Science and Technology Policy Future Land Imaging Working Group on the American Society for Photogrammetry and Remote Sensing Survey on the Future of Land Imaging, *Photogrammetric Engineering and Remote Sensing* 73:5-10, 2007, available at http://www.asprs.org/a/publications/pers/2007journal/january/.

[9] H.M. Miller, N.R. Sexton, L. Koontz, J. Loomis, S.R. Koontz, and C. Hermans, *The Users, Uses, and Value of Landsat and Other Moderate-Resolution Satellite Imagery in the United States—Executive Report,* U.S. Geological Survey Open-File Report 2011-1031, 2011, available at http://pubs.usgs.gov/of/2011/1031/pdf/OF11-1031.pdf.

[10] See http://www.fgdc.gov/ngac/meetings/september-2012/ngac-landsat-economic-value-paper-FINAL.pdf.

[11] Miller et al., 2011.

[12] Green et al., 2007.

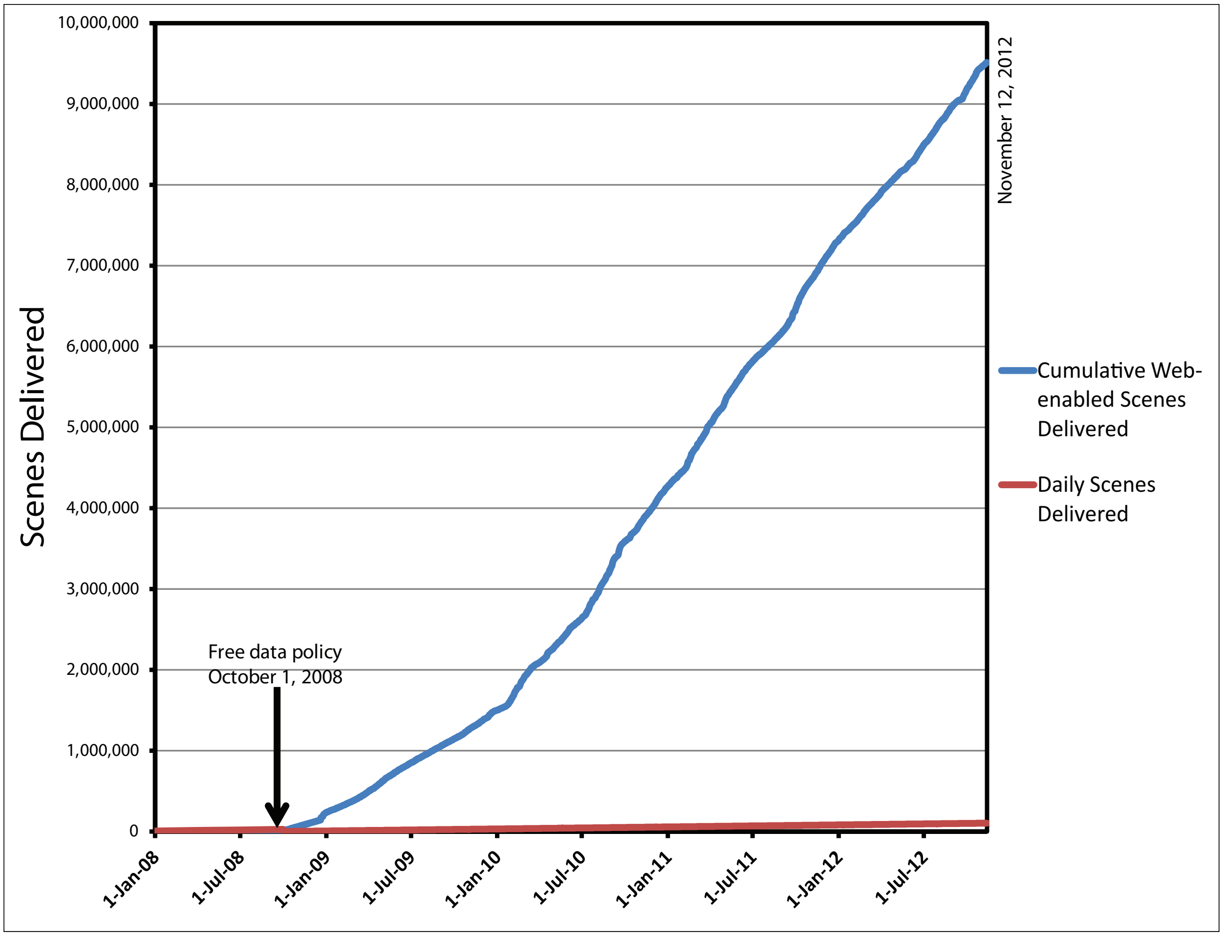


FIGURE 2.1 Increase in scenes delivered since USGS made Landsat imagery available on the Web in October 2008 at no cost. SOURCE: U.S. Geological Survey.

DATA MANAGEMENT AND DISTRIBUTION

Landsat data were originally available at low cost.[13] During the era of Landsat commercialization (see Chapter 1), Landsat imagery cost up to $4,400/scene. With the launch of Landsat 7, USGS lowered the cost to $600/scene, and in October 2008 made the entire Landsat imagery archive available on the Internet at no cost. Use of Landsat imagery increased rapidly (Figure 2.1). It has become ubiquitous as the moderate-resolution data set for both Google and Bing, is the foundation of Esri's ChangeMatters[14] website, and is employed in weather reporting by many television stations. Other examples of applications made possible by free and easy access to Landsat imagery include monitoring consumptive outdoor water usage, updating global land use or land cover maps, forest health monitoring, national agricultural commodities mapping, flood mitigation mapping, forest

[13] Approximately $15 for photographic prints and $200 per data set. See http://remotesensing.usgs.gov/landsat_fees.php and National Oceanic and Atmospheric Administration, 1983, Landsat data users notes: [Sioux Falls, S.D.], National Oceanic and Atmospheric Administration [variously paged].

[14] See http://www.esri.com/landsat-imagery/viewer.html, and K. Green, Change matters, *Photogrammetric Engineering and Remote Sensing* 77:305-309, 2011.

fragmentation detection, forest change detection, world agriculture supply and demand estimates, wildfire management, and coastal change analysis.

Recently, the Landsat Advisory Group of the National Geospatial Advisory Committee[15] was asked by the Department of the Interior to investigate the feasibility of once again charging for Landsat data. The Group strongly advised that Landsat data should continue to be distributed at no cost. It found that charging for Landsat data would

- Severely restrict data use;
- Violate existing Office of Management and Budget guidelines, federal law, Office of Science and Technology Policy, and U.S. National Space Policy,
- Require statutory changes;
- Cost more than the amount of revenue generated by the charges;
- Create a circular payment basis for public agencies;
- Stifle the innovation and business activity that create jobs;
- Inhibit data analysis in scientific and technical analyses;
- Negatively impact international relations with respect to national, homeland, and food security; and
- Negatively impact foreign policy and U.S. standing as the leader in space technology.

FINDINGS

To meet the requirements for continuity in the face of technological development and ongoing understanding of the land surface, the Sustained and Enhanced Land Imaging Program (SELIP) relies on well-defined users with clear scientific or operational requirements so that program goals are clearly articulated. Because users of land imaging data are widely spread across the government and private sector, current and future users groups will be diverse and broadly inclusive. Agreement on a set of core measurements simplifies the development of standardized sensors, data archiving, processing, and dissemination.

Although it will always be difficult to satisfy every user need, the committee found remarkable consistency in user requirements. The core scientific and operational requirement for the SELIP is the capture and distribution of global, moderate-resolution (30-100 m), multispectral data products, enhanced by a panchromatic band at finer resolution. The suite of applications for analyses of the data requires the full range of spectral capabilities—visible, near infrared, shortwave infrared, and thermal infrared—but there are no requirements to provide all measurements on the same platform, nor to continue to fly the same sensor, nor to restrict future systems to the current viewing angles and swath width. It is no coincidence that these requirements echo the present capability of the Landsat sensor suite, because assuring continuity of the ongoing data stream is the key aim for the future program.

The following requirements would satisfy a broad range of key federal and nonfederal users, both scientific and operational:

- *Spatial resolution*
  - — 30 m except in the thermal band, which would have coarser spatial resolution.
  - — Finer resolution (10-15 m), perhaps in a panchromatic band, was desired by some.
- *Spectral requirements*
  - — Visible and near-infrared region (VNIR, 0.4-1.1 μm).
  - — Shortwave infrared region (SWIR, 1.2-2.8 μm).
  - — Thermal infrared region (8-12 μm, with some interest in 3.5-4.0 μm).
  - — Calibration sufficient to allow backwards-compatible comparisons of future image products to earlier image collections.
  - — A larger dynamic range in the VNIR region to prevent saturation over snow and clouds; this requirement has been met in the Landsat 8 Operational Land Imager, with its 12-bit instead of 8-bit quantization.

[15] National Geospatial Advisory Committee-Landsat Advisory Group Statement on Landsat Data Use and Charges, September 18, 2012, available at http://www.fgdc.gov/ngac/meetings/september-2012/ngac-landsat-cost-recovery-paper-FINAL.pdf.

- *Coverage and repeat cycle*
  - — Ability to acquire and make available imagery anywhere on Earth, except perhaps for areas very near the poles, at approximately weekly frequency. (This frequency is desired not necessarily to acquire weekly data but rather to acquire cloud-free images.) The 705-km Landsat orbit, at 98 degrees inclination, provides 16-day frequency.
  - — Increased temporal frequency could be achieved with a slightly larger swath and consequently slightly larger off-nadir view angles at the edge (the users queried did not object to this).
- *Data management and distribution*
  - — A free data policy, as is currently in place, provides huge benefits to the nation as well as the international user community by supplying imagery to operational programs critical to U.S. needs as well as spurring innovation in the private sector.
  - — The USGS data distribution system is successful and effective but could continue to make technological advances and to streamline methods for managing Landsat imagery and derived products.

This set of requirements could be met by implementing the system as a series of satellite platforms, possibly with smaller satellites, whereby all capabilities may not reside on a single spacecraft. Many applications do not require precise simultaneity of all spectral bands, so that satellites flying in formation with nodes adjusted so that multiple spectral bands are acquired within hours could suffice.

RECOMMENDATIONS

The top priorities for the Sustained and Enhanced Land Imaging Program (SELIP) should be to ensure that the core program provides for continuity of Landsat products and coverage on a secure and sustainable path.

The SELIP should take advantage of technological innovation in sensors, spacecraft, and data management and analysis to improve system performance, allow for new analyses that better exploit the data and meet future needs. Because future measurements will derive from both current and new technologies, new implementations of existing data products derived from a multispectral sensor should be cross-calibrateable with Landsat legacy products and be essentially interchangeable for scientific and operational purposes.

To better meet these primary goals, the committee recommends that the program should

- **Systematically monitor users and uses of Landsat data so that the program can evolve with changing user requirements and**
- **Consider alternative implementations that continue to enable the collection of global, moderate-resolution data with the full range of spectral capabilities.**

3

Enhancing a Sustained Land Imaging Program

Landsat has formed the cornerstone of the nation's land imaging effort, but it has never constituted the totality of that effort. Although the findings and recommendations of the committee incontrovertibly point to the need for a continuation of the critical Landsat time series, it is crucial to recognize that many other spaceborne missions have contributed greatly to U.S. imaging capabilities. For example, the Shuttle Radar Topography Mission has provided agencies and scientific users alike with near-global digital elevation data, and airborne programs continue to support focused operational uses, local scientific research objectives, and technology development. These measurements do not replace the moderate-resolution imaging of the Landsat satellites; they instead complement and add value to the core observations. Many remote sensing applications can only be done by integrating multiple data sources, and researchers routinely interpret images in the context of several types of data.[1] The committee sees a great benefit in defining the U.S. land imaging program more broadly, recognizing the substantial contributions from a diverse set of airborne and spaceborne assets. Some other types of remotely sensed data—which include finer spatial resolution, active technologies including both LiDAR and radar, and hyperspectral capability—are already being acquired by the U.S. government, the private sector, and other countries, and some could be considered for a future land imaging satellite (Table 3.1). Not all these capabilities would or could be provided directly by the U.S. government; commercial providers and international partners are essential and likely will be integral parts of the full Sustained and Enhanced Land Imaging Program (SELIP). The government would not necessarily archive all these data—indeed, not all would be available at no cost—but the data management function of SELIP could provide links to these complementary data sets.

FINE-RESOLUTION SPACEBORNE AND AIRBORNE IMAGERY

The Landsat satellites image Earth roughly weekly at moderate resolution (30 to 100 m),[2] and the historical record of Landsat data stretches back 40 years at 18-day and then 16-day revisit times (8 days with two satellites working together). This extraordinarily rich data set has led to many important studies that now monitor and explain diverse phenomena occurring on Earth's surface. Nonetheless, as understanding of these observed processes improves, both the scientific frontier and the utility of operational use have advanced such that the value of the

[1] T. Lillesand, R.W. Kiefer, and J. Chipman, *Remote Sensing and Image Interpretation,* 6th ed., John Wiley and Sons, 2007.

[2] A 15-m resolution capability was added to Landsat 7 via the ETM+ instrument but only in the panchromatic band (often referred to as the black-and-white band).

TABLE 3.1 Observing Technology and Key Observables Associated with an Enhanced Program

Observing Technology (Sensor)	Description of Data Produced	Key Observables	Typical Applications
Fine resolution optical, stereo	Optical imagery with submeter to 10-m resolution	Land cover, building footprints, transportation and utility infrastructure, coastal margins, land surface topography	Urban planning, impervious surface mapping, transportation maintenance, coastal zone management, wildlife habitat, topography, three-dimensional buildings
LiDAR	LiDAR altimeter and bathymetric measurements based on multiple returns	Land surface topography, forest canopy height and leaf area, built structures	Geomorphology and natural hazards, ice sheet volume, forest productivity and health
Hyperspectral imaging	Optical imagery with narrow spectral resolution contiguous channels	Physiological signatures of vegetation, mineralogy, snow grain size, water pollution	Land carbon fluxes, biodiversity, invasive species, snow hydrology, mineral exploration, volcano gas monitoring
SAR, InSAR	Active microwave (radar) data	Surface deformation, forest structure, soil moisture and thaw depth	Natural hazards, water management, climate impacts, deforestation

NOTE: SAR, synthetic aperture radar; InSAR, interferometric SAR.

Landsat data stream can be greatly increased by exploiting newer technologies that observe the surface at finer resolution and incorporate more of the electromagnetic spectrum.

Primary among these modalities is the ability to observe the surface at finer resolution than Landsat's tens of meters. Power, orbit, and data rate constraints restrict the total volume of data that any satellite can deliver, so it is not possible today to image the full Earth simultaneously at fine scale and rapid repeat times. Remote sensing sensor suites thus require a trade-off between spatial and temporal resolution. At the coarse end of the spatial scale, current technological limits permit the entire globe to be observed daily at spatial resolutions of 0.25 to 1.1 km, as by, for example, the NASA Earth Observing System and NOAA's Suomi NPP (National Polar-orbiting Partnership). Limiting temporal coverage to every 8 days, the globe can be observed at 15 to 100 m by Landsat 7 and Landsat 8 working together at moderate resolution with orbits offset by 8 days. Extending to finer resolutions, specific local areas of about 200 km^2 can be observed every 2 to 3 days at 0.5 to 2.6 m by commercial programs like DigitalGlobe, or the entire Earth could be observed annually if customer demand justified such a strategy. If the surface regions of interest are smaller still, airborne sensors can supply data at fine spatial resolutions and regular repeat times of hours to days. Aerial photography is a viable industry, with many companies providing fine-resolution panchromatic and multispectral images. Extending this to a national scale, the U.S. Department of Agriculture's NAIP (National Agricultural Imagery Program) makes aerial imagery available to government agencies and to the public at no charge. Similarly, the aerial imagery in Microsoft's Bing Maps is updated annually for the United States and Europe, and Google Earth provides a capability for other providers to upload imagery. A detailed summary of the spatial, spectral, radiometric, and temporal characteristics of all of the land remote sensing systems is not included in this report, but Figure 3.1 presents an abbreviated list of important moderate- and fine-resolution satellite remote sensing sensor systems from 1999 through 2015.

Landsat represents the current optimal trade-off between resolution, frequency of coverage, and global access constraints. Yet it is clear from Figure 3.1 that there are relatively few existing or proposed moderate-resolution remote sensing systems that can fill this critical need. The French SPOT 5 (2002), the Indian ResourceSat-1 (2003) and ResourceSat-2 (2011), Landsat 8 (2013), and the proposed Sentinel-2b (2014) and ResourceSat-2A are the most important operational systems. The foreign systems may provide useful data for U.S. users as long as the demands on the system are not too great. Without a Landsat-like U.S. instrument, the broad use of moderate-resolution imaging data and the gains of the exploitation of that data will suffer. The committee believes that maintaining the availability of such data is necessary if Earth is to continue to be observed frequently and with

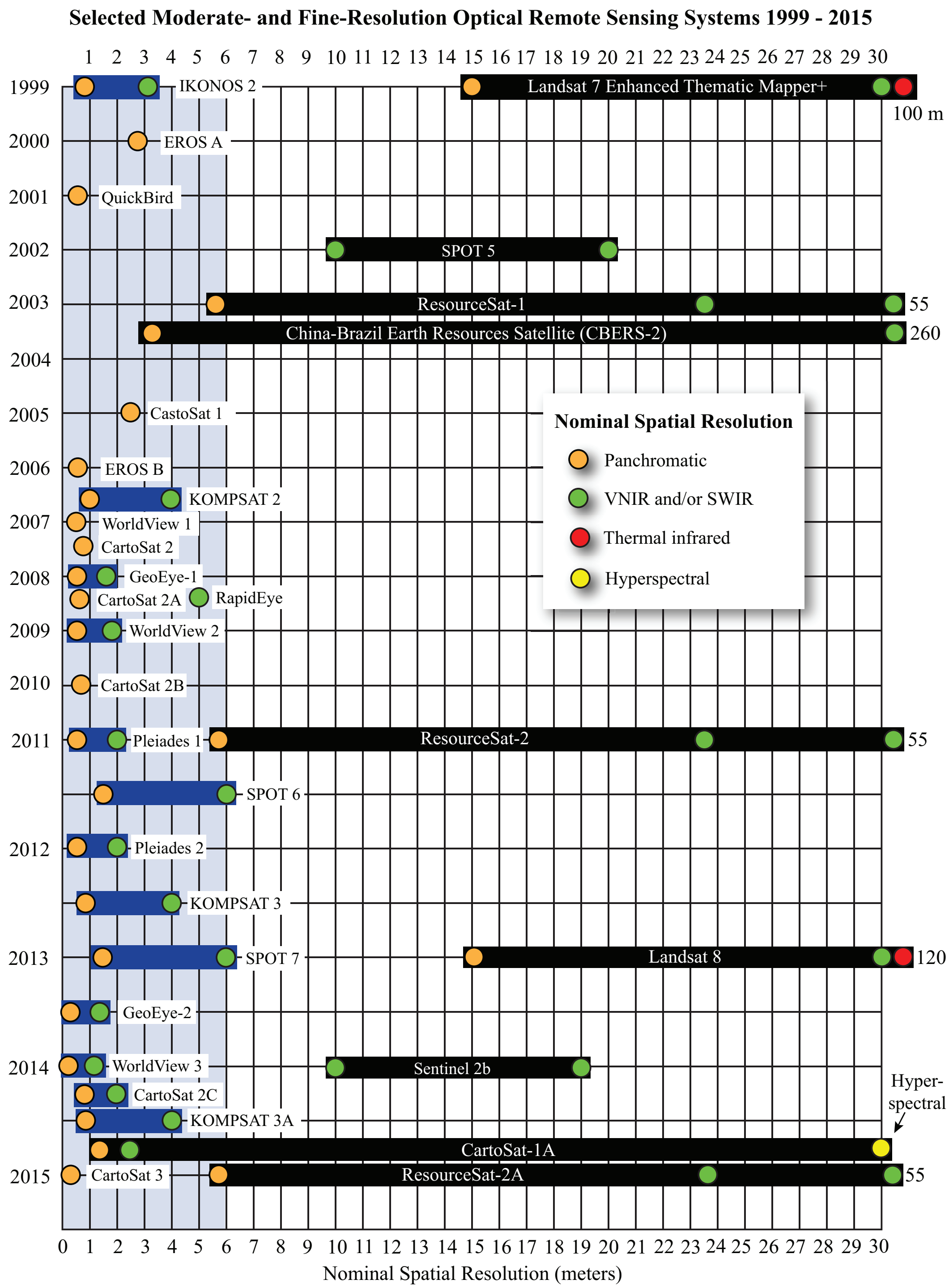


FIGURE 3.1 Characteristics of selected moderate- and fine-resolution optical remote sensing systems, 1999-2015. The spatial resolution of each remote sensing system is portrayed with the following circles: panchromatic (pan) band in orange; VNIR and/or SWIR bands in green; thermal infrared bands in red; and hyperspectral bands in yellow. There are more fine-resolution systems available than moderate-resolution (although several systems are planned for 2014-2015). SOURCE: John Jensen, University of South Carolina.

moderate resolution; it believes, further, that the usefulness of these data can be enhanced significantly if fine-resolution data are also available.

Why are there not more moderate-resolution remote sensing satellite systems available for use today? Many countries and private-market firms recognize that while moderate-resolution systems are of value, there is more commercial demand for finer-resolution panchromatic and multispectral data. Figure 3.1 shows that almost all major public and commercial remote sensing systems are migrating toward finer-spatial-resolution panchromatic and visible and near-infrared (VNIR)/shortwave infrared (SWIR) wavelength bands. Many important applications are not possible using only Landsat-like moderate-resolution data, driving a dramatic shift toward finer spatial resolution. Several important applications and data sources that require finer-scale data than Landsat 8 delivers include the following:

- *Land use/land cover.* Land cover information is categorized by the map scale at which the information is provided.[3] Remote sensor data with fine spatial resolution are required to extract high-level information about "landscape metrics."[4] Many city and county agencies throughout the United States and some federal agencies require access to land cover products at a spatial resolution finer than 2 m.
- *Building and property infrastructure.* Almost all counties in the United States collect and store property ownership information in a digital system,[5] including detailed information about each parcel's dimensions and all building footprints (perimeters). This effort requires a tremendous amount of remote sensing data collection and processing of fine-resolution imagery throughout the United States every year. Numerous government agencies, including the U.S. Census Bureau, also require building infrastructure information. Fine-resolution imagery can be used to identify the location of new residential structures and the associated road network information. This geospatial information is then conflated with postal and other sources of geospatial data to obtain accurate address information.
- *Socioeconomic characteristics.* The American Community Survey is an ongoing Census Bureau statistical survey that samples a very small percentage of the population every year.[6] Local and regional organizations use fine-resolution imagery to predict the spatial distribution of population between censuses to identify new developments or structures and to estimate the number of persons living in each dwelling unit based on building footprint and square footage estimates.
- *Transportation and utility infrastructure.* Federal and state departments of transportation rely heavily on high-resolution stereoscopic aerial photography, satellite imagery, and LiDAR data to monitor transportation infrastructure, allowing them to inventory and characterize roadways, especially to identify deteriorating infrastructure.[7]
- *Hydrology.* While moderate-resolution remote sensing data can be used to identify general stream or river centerlines, fine-resolution stereoscopic data or LiDAR data are required to precisely map drainage networks and determine the topography of floodplains for preparing digital flood insurance rate maps[8] and hydrologic models.
- *Vegetation assessment.* Moderate-resolution imagery is useful for monitoring vegetation type (e.g., forest, rangeland, wetland, agriculture), biomass, and functional health over relatively large geographic areas. Fine spatial- and spectral-resolution imagery and LiDAR data can be used to identify vegetation structure, predict watershed runoff, model urban heat islands, and describe agriculture and forest canopy biomass. Extensive remote sensing literature addresses scientific research and applications for vegetation studies based on the use of fine-resolution remote sensing data.
- *Disaster emergency response examples.* The Department of Homeland Security has significant fine-resolution data requirements, such as determining the boundary of disaster areas and vulnerable structures.[9] USGS

[3] J.R. Anderson, E.E. Hardy, J.T. Roach, and R.E. Witmer, A Land Use and Land Cover Classification System for use with Remote Sensor Data, U.S. Geological Survey Professional Paper 964, 1976.

[4] M. Herold, J. Scepan, and K.C. Clarke, The use of remote sensing and landscape metrics to describe structures and changes in urban land uses, *Environment and Planning A* 34:1443-1458, 2002.

[5] National Research Council, *National Land Parcel Data: A Vision for the Future,* The National Academies Press, Washington, D.C., 2008.

[6] U.S. Census Bureau, *American Community Survey,* available at http://www.census.gov/acs/www/.

[7] U.S. Department of Transportation, *National Consortia on Remote Sensing in Transportation (NCRST),* 2012, available at http://www.rita.dot.gov/rdt/remote_sensing.html.

[8] National Research Council, *Elevation Data for Floodplain Mapping,* The National Academies Press, Washington, D.C., 2007.

[9] U.S. Government Accountability Office, *Homeland Security: Actions Needed to Improve Response to Potential Terrorist Attacks and Natural Disasters Affecting Food and Agriculture,* GAO-11-652, 2011, available at http://www.gao.gov/new.items/d11652.pdf.

heavily relies on high-resolution remote sensing data when responding to emergencies, such as the Deepwater Horizon oil spill or Hurricane Sandy. Many other examples are described in the extensive literature on damage mapping.

LiDAR (LIGHT DETECTION AND RANGING)

Many remote sensing applications require elevation data in order to interpret spaceborne imaging data accurately. Topography is well known over much of Earth's land surface at 5- to 10-m height accuracy and 30-m data postings, but this is inadequate for evaluating such things as water flow patterns, coastal erosion and storm susceptibility, or subtle geologic processes. Existing data typically yield only a single estimate of height for each resolution element in a digital image, whereas for many applications a profile of height is critical. For example, understanding the health and evolution of forested areas requires detailed knowledge of how the biomass is distributed with respect to height. These data are currently best obtained using a profiling LiDAR instrument, which produces the finest-scale surface height measurements (at approximately centimeter accuracy) along with elevation profiles of urban and vegetated regions.

Today LiDAR data from aircraft platforms yield detailed masspoint information (i.e., *x,y* location and *z* elevation data) about the terrain and buildings, vegetation (trees, shrubs, grass), telephone poles, and roads, for example. The masspoint information can be processed to create digital surface models (DSMs) that contain information about terrain, vegetation, and building height. The vegetation and building height information can be removed from the DSM, creating a bare-earth digital terrain model (DTM), necessary for hydrologic modeling (Figure 3.2).

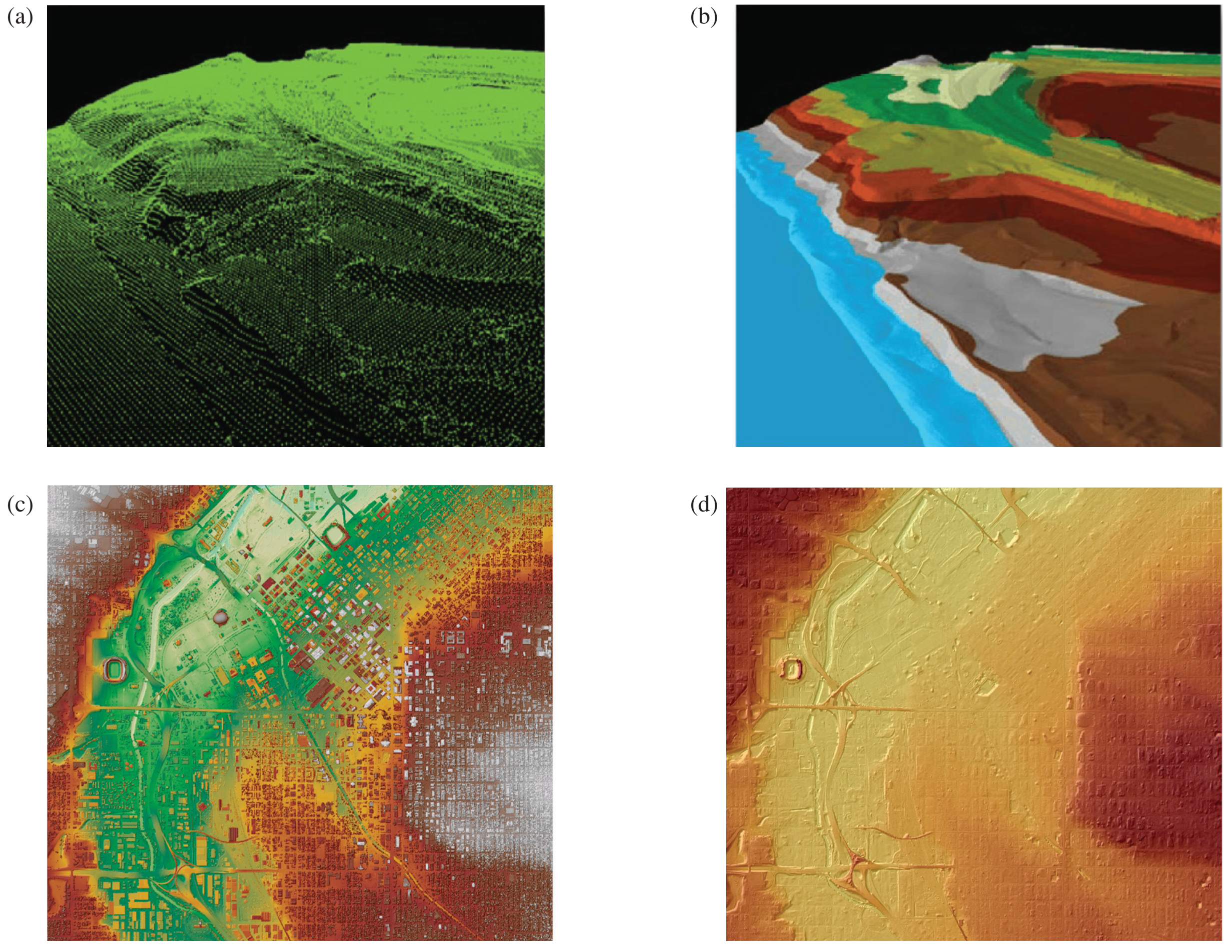
Airborne LiDAR mapping of small areas and terrestrial LiDAR scanning of even smaller footprints form a thriving commercial industry. The LIST (LiDAR Surface Topography) mission to regularly map Earth's surface at fine resolution (5 m spatial, 10 cm height) is among the recommended missions in the National Research Council report *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*.[10] Launch of the LIST mission is more than a decade away, but SELIP could include access to currently available airborne data and a plan for eventual incorporation of satellite laser altimeter information.

SYNTHETIC APERTURE RADAR

The Landsat instruments provide coverage of Earth's surface in the visible, near-infrared, and thermal-infrared sections of the electromagnetic spectrum. As such, they are primarily sensitive to the chemical composition of the surface. Characteristics of surface shape or texture, including precise measurements of deformation, are best inferred from longer-wavelength sensors operating in the microwave bands, with wavelengths from 3 to 24 cm. In particular, radar remote sensing yields these descriptors of the surface while adding the ability to acquire data when optical measurements are not possible, such as at night or during periods of clouds and inclement weather. Thus SELIP can augment the Landsat series, so that descriptors of the surface invisible to optical instrumentation can be exploited for analysis and operational capability.

Because both airborne and spaceborne synthetic aperture radar (SAR) instruments operate at rather long wavelengths, they image Earth's surface independent of most weather conditions, day or night, and provide essential capability at high latitudes and in areas with persistent cloud cover. Similarly, the longer wavelengths penetrate well into vegetation, dry soil, and dry snow. These data are sensitive to water content and surface roughness and convey important information about soil moisture. When these radar images are combined interferometrically, as described in the next paragraph, it is possible to map crustal deformation at millimeter levels so that distortions of the surface from natural hazards such as earthquakes and volcanoes, or even from variations in the flow of water or other fluids in the crust, can be visualized (Figure 3.3). Over forested areas, it is possible to map tree heights and canopy distributions, key parameters for measuring Earth's biomass and its changes. The operating wavelength is generally chosen to maximize performance for specific objectives: short wavelengths for high-resolution imaging,

[10] National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C., 2007.



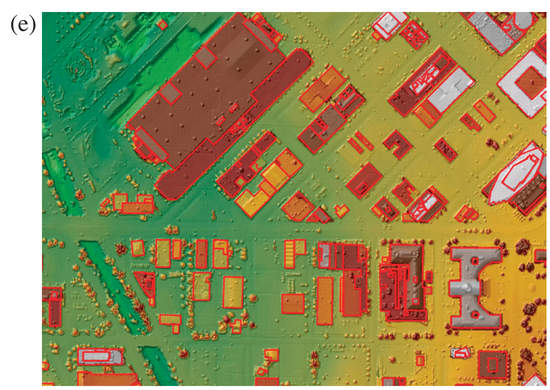


FIGURE 3.2 LiDAR information extraction: (a) LiDAR-derived masspoints of the Monterey Bay, California, shoreline viewed obliquely; (b) LiDAR-derived bare-Earth color-coded digital terrain model (DTM). (c) LiDAR-derived digital surface model (DSM) of a 7 × 7 km tile collected over Denver, Colorado, containing trees, buildings, and terrain. The LiDAR data have been shaded using LiDAR Analyst software; higher elevations are in white and lower elevations are in green. (d) LiDAR-derived DTM with all trees and buildings removed. The Bare Earth grid is automatically extracted from the LiDAR using LiDAR Analyst. (e) LiDAR-derived building footprints extracted by LiDAR Analyst as 3D Shapefiles. These files include geometric and descriptive attributes for each building such as maximum height above ground, roof type, and area. SOURCE: (a,b) Used with permission of John Copple and Sanborn Map Company. (c-e) R. Franklin, LiDAR advances and challenges, *Imaging Notes* 23, 2008, available at http://www.imagingnotes.com/go/article_free.php?mp_id=129. LiDAR Analyst is an Overwatch Textron Systems software product designed in 2004 as a plug-in for ArcGIS, ERDAS Imagine, Remote View, and ELT. Courtesy of *Imaging Notes Magazine,* Spring 2008, and Blueline Publishing, LLC, used with permission.

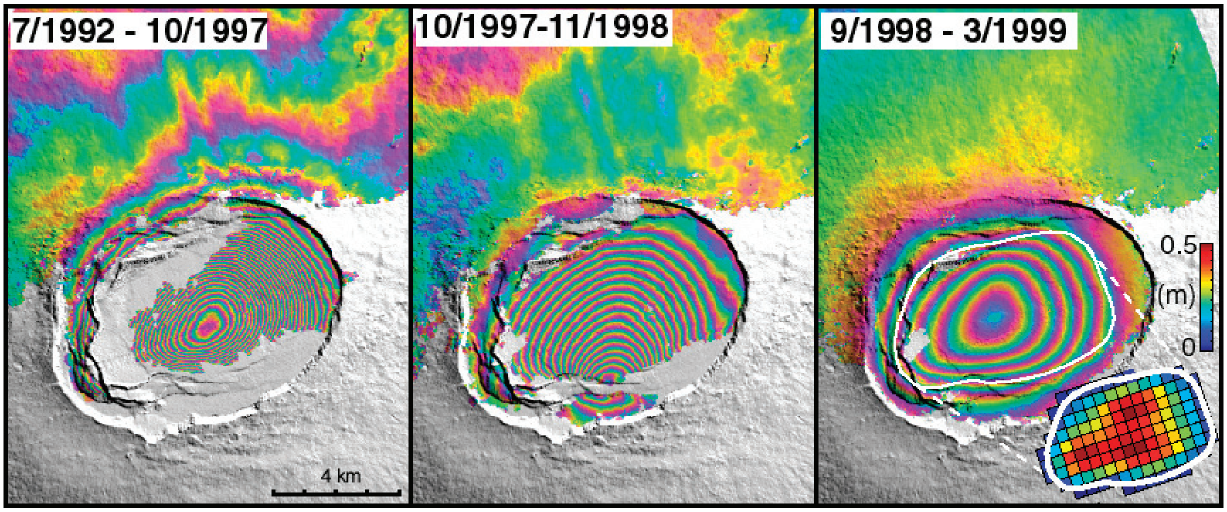


FIGURE 3.3 A time series of interferometric synthetic aperture radar (InSAR) measurements reveal variable deformation patterns from the emplacement of a dike under the flank of the Fernandina volcano, Galapagos Islands. The patterns are similar in the first and last periods, but a faulting event on the caldera rim dramatically altered the shape of the deformation in the middle time period. These patterns are diagnostic of changes in activity within the volcano. The inset at right is the inferred shape of the magma chamber. SOURCE: Reprinted by permission from Macmillan Publishers Ltd: Nature, F. Amelung, S. Jonsson, P. Segall, and H. Zebker, Widespread uplift and 'trapdoor' faulting on Galapagos volcanoes observed with radar interferometry, *Nature* 407(6807):993-996, 2000, copyright 2000.

moderate wavelengths for ocean observations, and longer wavelengths to maximize penetration into the surface cover and estimate forest biomass.

In interferometric SAR (InSAR) mode, the use of multiple antenna positions—either two antennas on a single aircraft or satellite, or one antenna in a slightly displaced position on a series of separate flight lines or orbits—delivers detailed information about surface topography, a critical parameter of the Earth system supporting many different types of investigations. Time series of such data measure surface deformation at millimeter to centimeter accuracies, permitting monitoring of crustal deformation due to tectonic forces,[11] groundwater flow, or oil and gas extraction, among others. These key measurements extend the usefulness of land imaging far beyond multispectral imaging of the surface.

The 2007 NRC decadal survey *Earth Science and Applications from Space*[12] recommended a SAR mission, Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI), but it has no target launch date.[13] Other nations have provided most of the leadership and implementation of SAR missions, so an enhanced land imaging program would benefit from including mechanisms and funding to incorporate data from airborne SAR and international SAR missions before a U.S. mission might become operational.

Table 3.2 lists the spaceborne systems that have provided the most data for SAR studies. These systems have been developed by several countries around the world and show increasing lifetime, coverage, and resolution over time. Three major civilian radar satellites currently in orbit, none of which is from the United States, are carrying out a variety of investigations of Earth, including studies of crustal deformation.

---

[11] H.A. Zebker, P.A. Rosen, R.M. Goldstein, A. Gabriel, and C.L. Werner, On the derivation of coseismic displacement fields using differential radar interferometry: The Landers earthquake, *Journal of Geophysical Research* 99:19617-19634, 1994.

[12] National Research Council, *Earth Science and Applications from Space,* 2007.

[13] National Research Council, *Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey,* The National Academies Press, Washington, D.C., 2012.

TABLE 3.2 Selected Spaceborne Synthetic Aperture Radar Systems

System	Country or Organization	Operational Lifetime	Band (nominal)	Wavelength (cm)	Spatial Resolution (m)
SEASAT	United States	1978	L-band	24	20
ERS-1/2	European Space Agency	1991-2010	C-band	6	20
JERS-1	Japan	1992-1998	L-band	24	20
SIR-C	United States	1994	C/L-band	3/6/24	20
Radarsat-1	Canada	1995-present	C-band	6	10
Envisat	European Space Agency	2002-2012	C-band	6	20
ALOS-1	Japan	2006-2012	L-band	24	20
Radarsat-2	Canada	2007-present	C-band	6	3
TerraSAR-X	Germany	2007-present	X-band	3	1-3
COSMO-SkyMed (multiple platforms)	Italy	2007-present	X-band	3	1-15

HYPERSPECTRAL IMAGERY

Finally, it is important to recognize that while Landsat produces comprehensive coverage at several distinct wavelengths, additional and stronger characteristics about surface composition follow if the reflectance spectrum is known more completely. Imaging spectrometry acquires such data at hundreds of contiguous spectral bands simultaneously. Its value lies in its ability to provide a high-resolution reflectance spectrum for each pixel in the image. Many, although not all, surface materials have diagnostic absorption features that are only 20 to 40 nm wide. Therefore, spectral imaging systems that acquire data in 10-nm bands contiguously between 400 and 2,500 nm may be used to identify surface materials with diagnostic spectral absorption features. This feature is superior to multispectral remote sensing systems that acquire data in wider, often discontinuous bands. The SELIP would benefit from exploring the advantages and practicality of adding hyperspectral analysis to the planned Landsat acquisitions.

Earth's surface consists mainly of soil, vegetation, snow, ice, and water as well as areas of built structures. Each of these constituents has properties with distinct spectral signatures, which, when measured by a hyperspectral imager, convey information about such properties as productivity, nutrient limitation, water stress in vegetation, soil mineralogy related to locations of natural resources, snow grain size and dust or soot content, and sediment and plankton abundance in water (Figure 3.4). NASA and the Department of Defense have operated airborne imaging spectrometers for more than two decades, and more recently, the National Science Foundation, commercial companies, and institutional laboratories have flown airborne instruments. For example, NASA flew the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) sensor to collect multiple flight lines of hyperspectral data over the Deepwater Horizon oil spill in the Gulf of Mexico (Figure 3.5).

Among the recommendations in the 2007 NRC decadal survey for a flight around 2020 is HyspIRI, which combines optical imaging spectrometry with multispectral thermal imagery. HyspIRI has no projected launch date. Such data are valuable for quantification of land surface composition (chemical composition of foliage, mineralogy, and other properties) and provide unique information on plant biodiversity and invasive plants. Hyperspectral imagery is extraordinarily flexible because complete spectral coverage (typically in the visible through shortwave infrared regions) is available. This allows specific regions of the spectrum to be selected for current and future data products. Imaging spectroscopy has benefited from technology improvement over the past decades, with improved optics that allow for smaller and less expensive instruments, enhanced downlink capabilities allowing exploitation of the entire spectrum, and uniform detector arrays increasing measurement accuracy, precision, and spatial registration. Several technology demonstration spectrometers have flown in Earth orbit, allowing the evaluation of spaceborne imaging spectroscopy data products, and a high-performance imaging spectrometer has flown to the Moon, demonstrating the key aspects of the capability in a prolonged spaceflight environment.

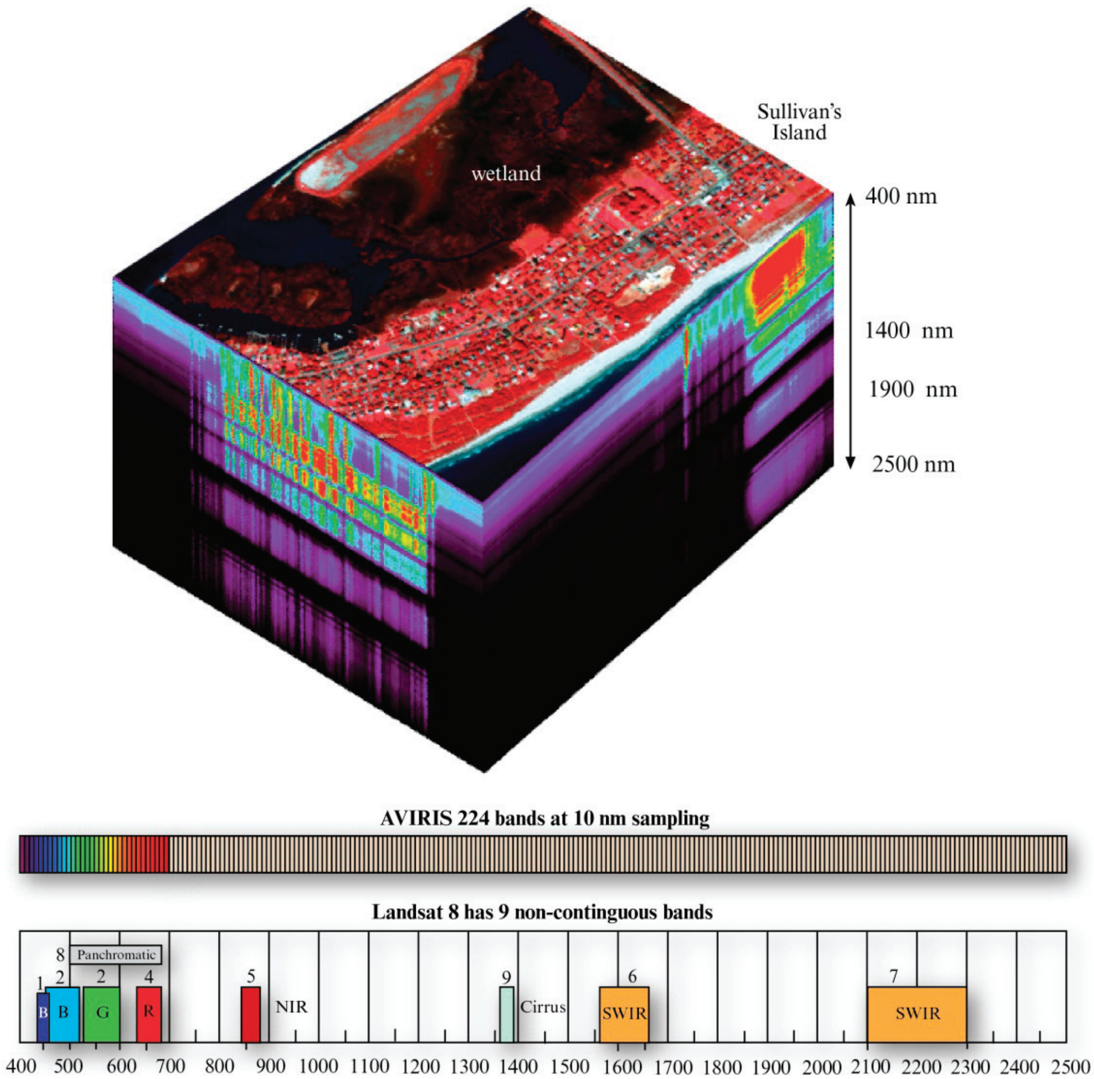


FIGURE 3.4 (a) An AVIRIS hyperspectral data cube of Sullivan's Island, South Carolina. The image on top is a color composite of just three of the available 224 bands (green, red, and near-infrared), and all of the bands are shown below in the depth of the data cube. (b) A comparison of the sensitivity of the 244 AVIRIS bands with the location of the nine Landsat 8 non-contiguous bands. SOURCE: J.R. Jensen and R.R. Jensen, *Introductory Geographic Information Systems,* Pearson Education, Upper Saddle River, N.J., page 91, Figure 3-28, 2013. (b) Courtesy of John R. Jensen, University of South Carolina.

Table 3.3 identifies characteristics of the most important current and future hyperspectral data collection systems.

COMMERCIAL AND INTERNATIONAL DATA PURCHASES

Expanding SELIP to include additional satellites providing all of the above capabilities would be prohibitively expensive given current budget constraints. Yet the committee believes that it is important to enable access to these data types in a cost-effective way, so that the full value of Landsat-class data is realized, and to enable more advanced work as enhanced capabilities allow. Including these diverse data sources would be a way to bolster a U.S.

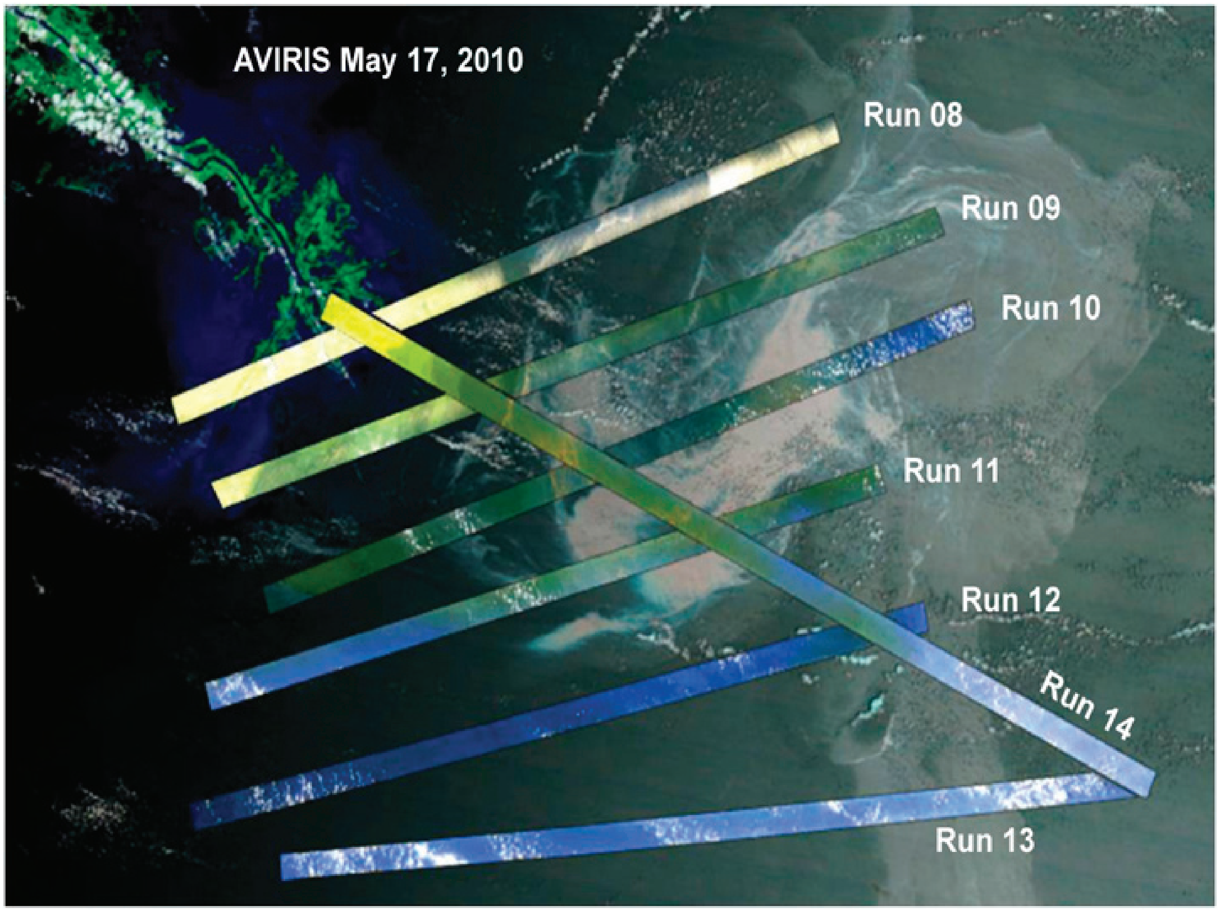


FIGURE 3.5 Seven flightlines of AVIRIS data collected on May 17, 2010, overlaid on a Landsat Thematic Mapper image of the Gulf Coast and the Deepwater Horizon oil spill. Each of the flightlines can be used to construct a datacube, similar to Figure 3.4(a). SOURCE: Courtesy of NASA/JPL-Caltech/Dryden/USGS/University of California, Santa Barbara, available at http://photojournal.jpl.nasa.gov/catalog/?IDNumber=pia13167.

TABLE 3.3 Characteristics of Selected Satellite and Airborne Hyperspectral Remote Sensing Systems

Sensor	Technology	Spectral Coverage (nm)	Spectral Interval (nm)	Number of Bands	Quantization (bits)	Instantaneous Field of View (mrad)	Total Field of View (°)
AVIRIS/ AVIRISng (airborne)	Whiskbroom linear array/ pushbroom	400-2500/ 350-2500	10/5	224/400	12	1.0	30
Hyperion (spaceborne)	linear array	400-2500	10	220	11		
CASI-1500 (airborne)	Linear (1500) and area array CCD (1500-288)	370-1050	2.2	288[a]	14	0.49	40

[a] The number of bands and the number of pixels in the across-track are programmable.

national program that ensures continuity and compatibility with the U.S. Landsat archive.[14] In particular, this could serve as a way to increase temporal and spectral coverage relative to what a baseline U.S. system might provide.

Not all data feeding the archive of the land imaging program need to be from U.S. spaceborne satellites. Other countries continue to invest in moderate-resolution satellite remote sensing systems, including SAR. In the optical domain, the European Sentinel-2, to launch in 2014, will collect all but the thermal infrared bands of Landsat, and in a wider swath for shorter revisit. The United States will have access to Sentinel-2 data under a free data policy and could complement that with data (also freely available) from a U.S.-funded thermal infrared-only small satellite. Other nations, such as India and Japan, operate land imaging programs that could potentially fill data gaps in moderate-resolution imagery. Data with fine spatial, and in some cases spectral, resolution are available commercially. This would be a comparatively low-cost way to augment a U.S. national program and ensure continuity and compatibility with the U.S. archive. Information from these other sources, if properly integrated in the U.S. imaging program, could increase temporal, spatial, or spectral coverage relative to what a cost-constrained baseline U.S. system might afford.

RESEARCH AND DEVELOPMENT COMPONENT TO ENHANCE A SUSTAINED LAND IMAGING PROGRAM

The Sustained and Enhanced Land Imaging Program would include a research and development (R&D) component with the mission of developing and testing new data products based on the core data sets of the land imaging system. This type of supporting work advances the program with improvements in technology, and experience gained during R&D facilitates iterative improvements in the land imaging program itself. The R&D component also would include development of advanced measuring technologies as well as new measuring requirements that will drive continual improvements in the core land imaging capabilities. Collaborations between the responsible federal agencies, such as USGS and NASA, and private companies will be advantageous. Furthermore, improved collaborations between NASA and USGS may result in the development of new observing technology by the NASA Earth Science Technology Office. Close collaboration between USGS and NASA will also facilitate the transition between research and operations. R&D relevant to a national land imaging program is also being done at companies such as Google and Microsoft.

FINDINGS

The committee found as follows:

- Continuity of moderate-resolution multispectral imagery with global land coverage at weekly frequency is a necessary component of a sustained and enhanced land imaging program, but it is not sufficient for monitoring the range of land surface properties that are critical for both scientific research and operational management.
- Optical imagery with fine spatial resolution and data from LiDAR, SAR, and hyperspectral instruments provide distinct and synergistic information about Earth's land surface.
- Commercial companies and other countries are a significant source of land imagery that are not available from programs operated by the U.S. government.
- Many important public and commercial applications require fine-resolution satellite and airborne remote sensor data that cannot be satisfied using moderate-resolution Landsat-8-type data alone.

RECOMMENDATIONS

The committee recommends that the Sustained and Enhanced Land Imaging Program integrate measurements from commercial partners, spaceborne sensors recommended by the 2007 NRC report *Earth*

[14] It should be noted that there are some difficulties associated with merging some data from different platforms, e.g., domestic versus international sources. Differences in calibration are often encountered and are routinely solved.

***Science and Applications from Space,* and a variety of airborne sensors and acquisitions to enable analyses not possible using only moderate-resolution multispectral data. These measurements should include, but not be restricted to, the following:**

- **Airborne and spaceborne fine-resolution remote sensing data from public and commercial sources that can be used for detailed land use and land cover, urban infrastructure, transportation, hydrology, and disaster response;**
- **LiDAR data that can be used to extract precise digital surface and terrain models, building and vegetation height information, and vegetation canopy and its internal structure information;**
- **Synthetic aperture radar (SAR) and interferometric SAR (InSAR) images at resolutions suitable for studies of deformation, elevations, and surface cover; and**
- **Hyperspectral data collection and information extraction capabilities for hydrology, ecosystem health and biodiversity, and soil science and mineralogy.**

4

Data Systems

A sustained land imaging program pays close attention not only to data acquisition, but equally to data management, data products, and data availability. Satellite data, which were once largely inaccessible and required specialized technical infrastructure to manipulate images, have evolved over the past few decades. Today, many satellite products are freely and openly available, usually via the Internet, and easily accessed by commercial and open-source software. An array of products far beyond simple imagery has been produced, such as topography, land cover, vegetation class, and vegetation performance (productivity, water use, phenology, and other attributes). For more technical users, information about algorithms, uncertainty, and ground truth are usually available. In envisioning future land imaging, end to end, the documentation of data transformations (data product generation), tracking of uncertainty, execution and documentation of calibration and validation activities (including ground truth), and planning of data availability are also core activities.

DATA AVAILABILITY

The policies for data availability have changed dramatically over the life of the Landsat program from a fee-for-service model to the U.S. Geological Survey's (USGS's) current open-access policy via the Internet. In the best sales year, approximately 25,000 images were sold. The Landsat data distribution now exceeds that number in a single day (Figure 2.1).[1]

Freely available data from USGS—not only Landsat data, but also airborne imagery and data on topography, hydrology, land cover, and so on—are widely downloaded and applied to scientific research and resource management. A number of products based on Landsat are available, along with a rich set of related map and imagery-derived products. The USGS Earth Resources Observation and Science (EROS) Center identifies several hundred current digital map and imagery products. These products span a variety of themes and mostly comprise aerial and satellite imagery, with a few dozen map products derived from imagery.

The EROS Center operates at least seven sites for downloading moderate- and high-resolution imagery and related geospatial data. GloVis[2] allows users to retrieve data in two or three steps through an interactive interface; EarthExplorer[3] provides access to many more data sets, although the search engine is less intuitive; the National

[1] See http://landsat.usgs.gov/mission_headlines2012.php.
[2] See http://glovis.usgs.gov/.
[3] See http://earthexplorer.usgs.gov/.

Map Viewer and Download Platform[4] contains data available via EarthExplorer but also contains data from the National Agriculture Imagery Program. LandsatLook[5] is a map-based interface where a user can search scene availability and view candidate scenes. Web-Enabled Landsat Data (WELD[6]) are obtainable from yet another website and include atmospherically corrected Landsat images. Landsat data are available from Landsat.org,[7] which is operated by Michigan State University, and from the Global Land Cover Facility at the University of Maryland.[8]

Moreover, several commercial companies also serve high-resolution aerial and spaceborne images, Landsat imagery, and products based on imagery (e.g., ESRI, Google, Microsoft, and Yahoo). While these sites and services offer innovative ways to search for, display, and provide images and products based on them, they lack the comprehensive access to land imaging archives that can only be offered to the public from an authoritative federal government source. These programs and others like them could be better integrated to form the basis for a coherent land imaging program.

Benefits of the current open-access policy are significant and have allowed use of the federal investment in Landsat by a vastly larger user base, including all sectors—from basic research, land management research and applications, education, citizen use, and use by the value-added sector. *Maintaining open access is critical.* Moving toward the future, the use of land imagery can be further increased, and additional value can be gained by enhancing the suite of data products, improving their documentation through metadata and uncertainty tracking, and developing even more advanced data discovery and distribution channels.

PRODUCTS DERIVED FROM LAND REMOTE SENSING

The Landsat series of satellites provides the required long-term continuity of imaging for scientific and societal benefit purposes. However, the Landsat sensor, by its nature, cannot provide all information required for land science and management. Investment in new data products must be balanced between additional advanced data products from Landsat and new data products from other emerging data sources, such as airborne LiDAR and other airborne and spaceborne sensors. Large quantities of novel data are being collected: critical near-term decisions will need to be made about investment levels to access, process, document, and distribute them. The Sustained and Enhanced Land Imaging Program (SELIP) will benefit from an effective user-oriented mechanism, through advisory committees or other structures, to prioritize different data sets and evaluate the relative importance of enhanced data products from legacy sensors compared to new techniques.

There is potential for a far greater array of derived products than are currently available. If appropriately defined and funded, sustained land imaging capabilities would enable a myriad of products and services, including many essential climate variables and climate data records. Most of the products would be difficult for users to code themselves. The complexity of the transformations needed to render some observations into useful products—which in extreme cases are millions of lines of code requiring high-performance computing—makes better infrastructure imperative. With the availability of baseline products, the population of users would also expand, driving demand for successively higher level products. The situation is not unlike the supply of "app" products for cell phones; however, without a sustained land imaging program, the product stream will diminish.

As part of an evolving imaging system, SELIP could identify critical data products and drive requirements for future missions. Because the knowledge and technology needed to produce land-surface information from imagery are sometimes formidable, it makes sense to provide such information from a data system rather than require users to undertake the transformations. Focusing on specific data products can add a great deal of rigor to the requirements definition process for follow-on missions. Management and funding models are part of ensuring that the products are produced, validated, and available for use.

USGS already distributes valuable data products derived from land imagery—for example, the National Land Cover Dataset, LANDFIRE, the Global Land Survey, and Land Surface Reflectance. The Land Surface Reflectance

[4] See http://nationalmap.gov/viewer.html.
[5] See http://landsatlook.usgs.gov/.
[6] See http://weld.cr.usgs.gov/.
[7] See http://landsat.org/.
[8] See http://www.landcover.org.

product is available for the Global Land Survey 2000, 2005, and 2010 collections and is generated on demand from Landsat 4-5 TM and Landsat 7 ETM+ data.[9] The concept would gain additional utility through a formal but open mechanism for identifying candidate products and the resources needed to produce them.

Although the concept of a climate data record (CDR) has surfaced numerous times in recent National Research Council reports,[10] the climate research and policy communities continue to struggle with an exact approach to meet this need (i.e., one that is both sufficient and cost effective). In addition, satellite-based CDRs have been further segmented into the following:

- *Fundamental climate data records (FCDRs)* are calibrated and quality-controlled sensor data together with documentation for the data used to calibrate them.
- *Thematic climate data records (TCDRs)* are geophysical variables derived from the FCDRs that have well-defined levels of uncertainty, with an ongoing program of correlative in situ measurements required for validation.
- *Essential climate variables* (*ECVs)* are atmosphere, ocean, and land measurements derived from FCDRs and TCDRs. They have to be technically and economically feasible for systematic observation and sufficient to meet the needs of the United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change (IPCC). To be useful, the ECVs must be a time series with sufficient length, consistency, and continuity to identify climate variability and change.

This report has looked at observations that would be available from SELIP from the perspective of the needs of users and engineering units (spectral, radiometric, spatial and temporal resolutions, and so on). The committee recognizes both the challenge and the need for SELIP to work with key related communities to develop an agreed-on set of FCDRs, TCDRs, and ECVs based on moderate-resolution sensors. That will mean going beyond the engineering units, such as calibrated radiance, in the existing Landsat archive, embracing more broad units—such as surface reflectance, surface temperature, cloud, and cloud shadow—and eventually evolving to more application-oriented products (i.e., ECVs). These products will also need to meet the Global Climate Observing System, First National Climate Change Communication, and IPCC requirements and be technically and economically feasible systematic observations. The Landsat Surface Reflectance product is an excellent example; it is produced routinely for selected time periods but is also available on demand for specific Landsat scenes.

ALGORITHM DEVELOPMENT AND CALIBRATION/VALIDATION

As the focus in Landsat and other space or airborne data acquisition systems evolves from providing imagery to providing higher-level data products derived from those images, a set of consequent activities becomes necessary. The first step is to develop a rigorous process for determining the required data products, similar to NASA's elicitation of requirements for Moderate Resolution Imaging Spectroradiometer (MODIS) data products or the development of the essential climate variables. Once a set of desired standard data products has been determined, the algorithm for producing the data product is selected, reviewed, and implemented. Models for this process exist in the federal and private sectors—ranging from proprietary development in house to open, competitively selected development. Regardless of the model, the selection, development, and distribution of algorithms are best achieved with freely and openly available data. Transparency of algorithms provides credibility and allows a larger community to participate in evaluation and continuous improvement.

[9] U.S. Geological Survey, *Product Guide: Landsat Climate Data Record (CDR) Surface Reflectance,* Version 2.0, 2013, available at http://landsat.usgs.gov/documents/cdr_sr_product_guide.pdf.

[10] See the following National Research Council (NRC) reports: *Climate Data Records from Environmental Satellites* (2004); *Adequacy of Climate Observing Systems* (1999); *Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring* (2008); *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (2007). Each report was published by National Academy Press (after mid-2002 The National Academies Press), Washington, D.C.

An instrument flown in a sustained land imaging program has a requirement to produce calibrated radiances. Calibration and validation of data products is critical for their effective use and credibility.[11] A strength of the Landsat program has been the radiometric calibration of the instrument, along with spatial and temporal comparisons. The development of rigorous data products requires both onboard instrument calibration and comparison to well-known ground targets. Images without rigorous calibration support limited analyses, but the associated data will not support higher-level products. An ongoing process of instrument evaluation provides validation of radiometric data products, such as reflectances, and is a basis for validation of high-level data products. However, as quantitatively derived products, such as topography, land cover, or leaf area, are developed, these products too are based on a careful and systematic program of calibration and validation against measurements made on the ground, by aircraft underflight, and by other means. The results from these calibration/validation programs contribute to credibility and are most useful when they are openly available with the data.

FINDINGS

Freely available data from the Landsat program have brought enormous benefits to science and to operational users.[12] Higher-level products continue to be developed, providing ever greater benefits to society at large.

USGS websites and other venues effectively provide access to imagery and derived products, with varying degrees of ease of use. However, the hierarchical organization and plethora of websites and interfaces make access difficult, especially for novice users who may not know which data are on which sites.

The government currently uses a number of approaches to distribute Earth observation data: dedicated federal data centers, data federations such as the Earth Science Information Partners, commercial value-added resellers, and Internet information distributors in the private and nonprofit sectors. All these mechanisms could be used in assembling an infrastructure for the SELIP, *as long as primary data and key data products remain available under an open data policy.*

The potential list of baseline products and services that land imaging could provide is much larger than the suite of products and services currently provided. However, (1) the mechanisms and procedures for introducing change are cumbersome in all agencies, so the user community cannot realistically implement new products or new algorithms for existing products; (2) similar products from NASA and NOAA are global in scale and are produced whenever and wherever the input data are available, regardless of demand; and (3) the private sector supplies some derived products of varying quality and degrees of validation.

RECOMMENDATIONS

USGS, as part of the Sustained and Enhanced Land Imaging Program, should continue to deliver derived products from imagery without explicit cost to the end users.

USGS should

- **Improve search capabilities and transparency to users and**
- **Continue to interface with the private sector to improve access to public- and private-domain land imaging data products and services.**

The Sustained and Enhanced Land Imaging Program should develop a systematic process for identifying and prioritizing a wider suite of products, including essential climate variables, that can be derived

[11] The international Committee on Earth Observing Satellites has advocated a universal validation data set for all global land cover products to increase the interoperability of data from many countries' satellites. It also emphasizes validation and accuracy assessments as a major part of a mapping program. Strahler et al., *Global Land Cover Validation: Recommendations for Evaluation and Accuracy Assessment of Global Land Cover Maps,* 2006, available at http://nofc.cfs.nrcan.gc.ca/gofc-gold/Report%20Series/GOLD_25.pdf.

[12] National Geospatial Advisory Committee-Landsat Advisory Group Statement on Landsat Data Use and Charges, September 18, 2012, available at http://www.fgdc.gov/ngac/meetings/september-2012/ngac-landsat-cost-recovery-paper-FINAL.pdf.

from moderate-resolution land imagery, and for documenting and validating algorithms, including their modifications or replacements. In doing so, the program should

- **Define criteria that government-provided authoritative data sets should meet, among them such attributes as calibration, accuracy assessment, and validation, and including ground truth;**
- **Define criteria for which products should be provided by the government and which by the private sector;**
- **Implement procedures for development, cost estimation, peer review, and the publication of algorithms that produce derived products; and**
- **Implement plans, procedures, and budgets for ongoing validation.**

5

Opportunities on the Path Forward

Following the launch of Landsat 8 on February 11, 2013, there are several options for a sustainable land imaging capability. All approaches to sustainable land imaging require addressing programmatic as well as technical design. They require stable funding to escape from the chaotic on-again, off-again funding cycle that Landsat has experienced over the past 40 years. In addition to the requirements described in Chapter 2, all approaches need to address the biggest impediment to sustainability: cost. As Table 5.1 shows, life-cycle costs for each mission since Landsat 4 were about $1 billion, when adjusted to current-year dollars. Building an exact copy of Landsat 8 might seem to be the simplest approach for Landsat 9, but such an approach is not likely to substantially lower the cost. Exact parts are not likely to all be available. Moreover, it may not be possible to procure the spacecraft or instruments from the same providers, and even if the same providers were involved, the same teams of people may not be available.

The following options represent four different ways of creating an affordable, sustainable land imaging capability. Each option focuses on one aspect of affordability, but they can be combined intelligently. The committee does not assert that these are the only options, but they are representative examples.[1]

All options could benefit substantially from the utilization of a collaborative team approach between the U.S. government and its implementation partners, whether they are domestic contractors, international partners, or other teammates. By "collaborative approach," the committee means that the government and its partners should operate as a single unit from an operations standpoint, not as employees representing separate entities each with its own unique goals and priorities. In this way, the parties are free of contractual and other impediments, such that they can truly work together to achieve fully successful solutions to problems as they present themselves with no fear of being "blamed" for any problem. This approach was recently successfully employed on the Air Force's TacSat-3 program,[2] as well as routinely in the high-resolution imaging industry.[3]

[1] The committee's recommended options are intended to apply in the timeframe after Landsat 9. However, they could also apply to Landsat 9, particularly if a decision on a successor to Landsat 8 is delayed past the fiscal year 2014 budget cycle.

[2] T. Cooley, Air Force Research Laboratory, Space Vehicles Directorate, Kirtland Air Force Base, New Mexico. "Tactical Satellite 3: Mission Overview and Lessons Learned," presentation to the meeting of experts titled "Towards the Use of Lower-Cost Platforms for the Acquisition of Environmental Data from Space," March 30, 2012.

[3] W. Scott, "Mission Assurance at DigitalGlobe: Success, Cost, and Schedule are Compatible," presentation to the 2013 Mission Assurance Improvement Workshop," April 30, 2013.

TABLE 5.1 Cost of Landsats 1 Through 8, Adjusted to 2012 Dollars

	Launch	Design Life (years)	Lifetime (years)	Original Cost ($ million)	2012 Cost ($ million)
Landsat 1	1972	1	5.5	$197 together with Landsat 2[a]	$840
Landsat 2	1975	1	6.0	$197 together with Landsat 1[a]	$840
Landsat 3	1978	1	5.1	$50[b]	$160
Landsat 4	1982	3	11.4	$538[c]	$1,280
Landsat 5	1984	3	27.7	$573[d]	$1,270
Landsat 6	1993	5	0.0	$518[e]	$820
Landsat 7	1999	5	13.8	$800[f]	$1,100
Landsat 8	2013	5		$931[g]	$930

NOTE: 2012 costs calculated from http://www.bls.gov/data/inflation_calculator.htm, using year-by-year consumer price indices.

[a] See NASA ERTS-B Press Kit (NASA News Release 74-329), January 14, 1975, see http://www.scribd.com/doc/42461911/Erts-b-Press-Kit. This value includes research and development and the launch vehicles for both Landsat 1 and Landsat 2.

[b] See Landsat Policy Issues Still Unresolved: Report by the Comptroller General to the Congress of the United States, 1978, http://gao.gov/products/PSAD-78-58.

[c] See http://archive.gao.gov/d36t11/148471.pdf.

[d] See http://www.gao.gov/products/RCED-83-111.

[e] See http://geo.arc.nasa.gov/sge/landsat/pecora.html.

[f] See http://geo.arc.nasa.gov/sge/landsat/pecora.html.

[g] See http://landsat.gsfc.nasa.gov/news/news-archive/news_0267.html.

SOURCE: Originally compiled by Tony Morse, Spatial Analysis Group, LLC, from the identified sources.

SHIFT THE ACQUISITION PARADIGM

Several of the Landsat satellites have been acquired in a very expensive way. Particularly in the case of Landsat 7 and Landsat 8, each satellite included substantial new technology, was designed afresh, was acquired one at a time using cost-plus contracts, and was managed with a philosophy of over-engineering to minimize perceived risk, with the well-intended objective of improving the chances of mission success.

An acquisition model for a cost-constrained world is quite different. Rather than acquiring satellites one-off, this model makes block buys. Purchasing multiple spacecraft at once would reduce nonrecurring engineering costs and permit the advance purchase of parts, thus reducing their cost and improving availability later in the program's life cycle. Additionally, a block-buy model would potentially enable the provision of spare spacecraft, either stored on the ground or in orbit (where the risky launch phase has been passed), which would make the program much more immune to unexpected failures. A long-term commitment would also result in the development and continuity of institutional memory in both the government agencies and aerospace contractors. This approach would be very similar to the model used by the National Oceanic and Atmospheric Administration for the provision of satellite observations to the National Weather Service for weather and severe storm forecasting.

Coupling the block-buy approach with a fixed-price contracting approach could reduce costs further. However, for a fixed-price contracting approach to be fully successful, the requirements must be well known and unlikely to be changed—for example, where the system being acquired is a copy of one that has already flown. And, after contract award, the government would need to minimize the number of contract change orders—ideally, to zero.

In the block-buy model, large-scale technological changes come with each new block, not within the block. In this regard, it is essential to only incorporate new technologies that do not compromise core operational capabilities. This could readily be done by leveraging industry, international, and/or other agency technology development activities. Additionally, each satellite in a block could accommodate a secondary instrument with a well-defined interface, on a noninterference basis, which would preserve the commonality between elements of the block while still allowing for modest, incremental technological insertion.

The acquiring entity must engage in a more collaborative relationship with the builder and be prepared to accept more perceived risk through less intrusive "light touch" oversight rather than the traditional very intrusive insight. While this seems unorthodox in light of several well-documented and high-profile acquisition failures over the past decade, it has been shown to work (for example, the Applied Physics Laboratory's New Horizons mission, the University Corporation for Atmospheric Research's COSMIC mission, the National Geospatial-Intelligence Agency's (NGA's) NextView and EnhancedView programs, the Air Force's TACSAT-3 mission, NASA's QuikScat mission, and so on), and it is particularly applicable to the block-buys-of-clones model that eschews new technology development for predictability.

INTEGRATE WITH OTHER DATA SOURCES

The Landsat satellites are not the only source of Earth imaging data available today. By including other sources under the umbrella of the Sustained and Enhanced Land Imaging Project (SELIP), not only is it possible to mitigate risk (by having other sources to fall back on in the event of a premature satellite failure), but also it enables an even more cost-effective approach where the core program is not constrained to acquire all needed data on its own. The integration can create a more robust data set by using other existing or planned data sources.

Many of the possible options were exhaustively studied by the Landsat Data Gap Study Team from 2005 to 2007 after the scan corrector failure on the Landsat 7 ETM+ instrument.[4] This excellent examination of the subject offers a framework for developing a robust and sustainable land imaging program that integrates sources of Landsat-type data from the international land imaging community. Although the United States started the Landsat series and has continued to exercise leadership over the past 40 years, leadership is not synonymous with going it alone. There is a long history of international partnering in other space endeavors. Burden sharing could take many forms: a foreign launch vehicle provided under a science-driven memorandum of understanding with no exchange of funds, instruments (such as thermal infrared, visible and near-infrared, or shortwave infrared) from an international partner, or a foreign satellite bus.

One example is the European Space Agency's (ESA's) Sentinel-2, which is planned to collect all but the thermal infrared bands of Landsat and does so in a wider swath for improved revisit.[5] NASA is collaborating with ESA to calibrate the Landsat 8 and Sentinel-2 instruments to generate comparable data products. Such an arrangement could be complemented with data (also shared) from a U.S.-funded thermal-infrared-only small satellite. Other nations, such as India and Japan, operate their own remote sensing programs, which could potentially fill some Landsat user needs, and China is emerging as an Earth observing satellite operator in the coming decade. On the Suomi NPP satellite, the VIIRS instrument collects data at greater frequency though lower spatial resolution and may be suitable for some applications, particularly when sharpened by less frequently collected but finer resolution data to enable a degree of spectral unmixing.[6] Finally, the EnhancedView contract, managed by NGA, collects commercial imagery that can be widely shared within federal government agencies, potentially satisfying some of their need for Landsat-type data, although the data from EnhancedView cannot be freely distributed to the public and, thus, does not offer the full value of a national land imaging program. None of these suggestions can replace a dedicated U.S. program for obtaining critical measurements; however, judicious use of other data sources may reduce risk, reduce cost in some cases, and enhance the SELIP.

INCREASE THE SWATH WIDTH

A potential design modification, which applies to all other options, is to increase the swath width of the sensors, with the objective of shortening revisit time, a commonly sought characteristic of any new Landsat system. Historically, Landsat has acquired data over a 185-km swath, which, for a single satellite system, yields a 16-day

[4] U.S. Geological Survey, *Landsat Data Gap Studies,* available at http://calval.cr.usgs.gov/satellite/landsat-data-gap-studies/.

[5] European Space Agency, *GMES Sentinel-2 Mission Requirements Document*, available at http://esamultimedia.esa.int/docs/GMES/Sentinel-2_MRD.pdf.

[6] B. Huang, Spatiotemporal reflectance fusion via sparse representation, *IEEE Transactions on Geoscience and Remote Sensing* 50:3707-3716, 2012.

revisit from a 705-km orbit altitude. Fortuitously, for many years we have enjoyed simultaneous coverage by both Landsat 5 and Landsat 7 (and now by Landsats 7 and 8), yielding an 8-day coverage pattern. However, flying two Landsat satellites in the future would likely be prohibitively expensive, except in cases where an earlier satellite exceeds its design life. Thus consideration should be given to increasing the swath width to reduce revisit time at far less cost than increasing the number of satellites. Landsat 8 can point its sensors off nadir ±15 degrees by a spacecraft yaw maneuver. This capability is implemented to enable data collection only for major disaster relief and recovery or other high-priority imaging.

ESA plans to fly a moderate-resolution multispectral system, Sentinel-2, with a 290-km swath width, which could improve revisit time to about 10 days with a single satellite and 5 days[7] with the planned two satellites flying concurrently. With the current 185-km swath, the nadir view angle at the swath edge is 7.5 degrees, the sensor view angle (different because of Earth's curvature) is 8.3 degrees, and the relative atmospheric path length is 1.010. With a 290-km swath, the corresponding angles are 11.6 and 12.9 degrees, and the path length is 1.026—a minor impact to angular viewing geometry at the edges of the field of view and, of course, no impact at all within the central 185-km swath for those applications that are particularly sensitive to angular viewing geometry. Generally the bidirectional reflectance distribution of most surfaces shows significant angular features at angles beyond 1 degrees from the nadir.[8] Thus, the possibility of increasing the swath width for future U.S. systems needs to be explored in more depth, as it could help considerably with the goal of a shorter revisit time at lower cost.

EMPLOY CONSTELLATIONS OF SMALL SATELLITES

Historically, every Landsat has included the full Landsat sensor suite of the time. Improved revisit times required more Landsats. Fortunately the extended life of Landsat 5 provided an 8-day revisit time, even though the original Landsat requirement was a 16-day revisit time. However, nothing compels future missions to involve only a single satellite, or for each satellite to contain the full sensor suite.

Smaller satellites can offer many benefits, either as an augmentation to a "mother ship," such as Landsat 8 (with a full sensor suite), or as an ultimate replacement. RapidEye and the Disaster Monitoring Constellation (DMC) are already examples of less costly (though less complete) land imaging satellites that could augment SELIP by providing more frequent revisit times. A small satellite carrying only a thermal infrared sensor, placed in a phased orbit with the primary Landsat, could cut revisit time in half for much less than the cost of a duplicate Landsat, with the benefit of estimating evapotranspiration for practical water resource management. Alternatively, a small satellite carrying only a simple land imaging instrument, such as a slightly enhanced Multispectral Imager (MSI), routinely flown on the DMC of imaging small satellites, would cut revisit time in half for the nonthermal imaging channels. Two such small satellites, one with thermal and the other with VNIR and SWIR, flying in conjunction with the primary Landsat, might be able to provide near full capability at half the revisit time for dramatically less cost than two full Landsats.

Small satellites also offer several other benefits. They are intrinsically resilient, enabling intelligent trade-offs of redundancy at the constellation level, as opposed to requiring full redundancy in each spacecraft, allowing for lower cost. By being simpler (often single-payload), they have lower systems engineering, integration, and test costs. Their smaller size can enable them to fly as secondary payloads, reducing launch costs. They offer improved revisit because one can afford to acquire more satellites,[9] so engineering teams can be continuously tasked instead of being organized and then dismantled for every mission. And by having more satellites, there are more opportunities for gradual introduction of new technology, enabling continuous improvement at lower cost and risk than wholesale replacement.

[7] The planned revisit time is 5 days over the equator and 2 to 3 days over mid-latitudes. See European Space Agency, ESA-NASA Collaboration Fosters Comparable Land Imagery, February 13, 2013, available at http://www.esa.int/Our_Activities/Observing_the_Earth/GMES/ESA_NASA_collaboration_fosters_comparable_land_imagery.

[8] M. von Schönermark, B. Geiger, and H.P. Röser, eds., *Reflection Properties of Vegetation and Soil—With a BRDF Database*, Wissenschaft und Technik Verlag, Berlin, 2004.

[9] The RapidEye constellation of five small satellites cost $160 million, including launch (*Space News,* May 22, 2006, available at http://www.spacenews.com/archive/archive06/Briefs_052206.html).

To minimize risk, one or more low-cost small satellites could be launched before the end of the design life of Landsat 8. Not only would this demonstrate capability, but it would also allow for cross-calibration, as is common in many other scientific endeavors (Jason-1 was calibrated by underflying the gold standard TOPEX/Poseidon, not to mention the Landsat 7 underflight of Landsat 5 and the Landsat 8 underflight of Landsat 7).

OTHER FACTORS

To sustain U.S. land imaging, one would weigh the identified alternative approaches to implementing Landsat 9 and beyond and select a combination that best suits the circumstances of the moment. Fiscal resources are likely to be the leading constraint. One such approach might be to build Landsat 9 as a clone of Landsat 8. However, so much time has passed since Landsat 8 was procured and constructed that a true clone probably cannot be built. Some parts are likely to be unavailable; government procurement rules would make sole-sourcing the same contractors difficult; and the specific teams of people involved have gone on to other projects. Nonetheless, it might make sense to use Landsat 8 as a template for the next suite of missions, even allowing for some modest technological improvements (given the impossibility of building a true clone anyway), such as increasing the swath width. In this case, the desired approach would be a block buy of several identical units, perhaps Landsats 9 through 12. The design is fixed, the parts are all bought up front, and the same team builds all four units. With a fixed-price contract, the government making no changes along the way, and a collaborative team approach following "light touch" principles, significant savings would be realizable for Landsats 10 through 12. However, Landsat 9, a near clone of Landsat 8, would cost as much as its predecessor.

Therefore, if the overarching constraint is the cost of the next Landsat, then this approach is not viable. In such a case, one is forced to look at more creative, innovative, possibly riskier approaches such as constellations of small satellites. Considerable cost savings could result, especially for the first unit(s), but this approach would require the government to step outside its comfort zone and do something totally different, driven by the unavailability of funds that would allow doing otherwise.

Regardless of the approach selected, integration of the data from Landsat 9 and beyond with data from both commercial and international sources is necessary. Given these other factors, the committee does not recommend a specific course of action. The agencies and Congress must decide which combination of options to implement.

FINDINGS

The Sustained and Enhanced Land Imaging Program will not be viable under the current mission development and management practices.

At least partly because of the unplanned, chaotic programmatic history of Landsat, the cost of each of five Landsat missions after the addition of the Thematic Mapper instrument has also been about $1 billion, when adjusted for inflation. Over the last 30 years, while there has been some technological improvement in the collection, processing, and use of Landsat data, there has been no reduction in the cost of a Landsat mission.

Building an exact copy of Landsat 8 might seem to be the simplest approach for Landsat 9, but that approach is not likely to substantially lower the cost for the next mission.

Nonetheless, options do exist to create a less costly, more robust SELIP, including the block buy of a sequence of missions, less cumbersome contracting processes, and technological innovations.

RECOMMENDATION

The Sustained and Enhanced Land Imaging Program should create an ambitious plan to incorporate opportunities to improve land imaging capabilities while at the same time increasing operational efficiency and reducing overall program cost.

The program should consider a combination of the following to increase capabilities while reducing the costs for land imaging beyond Landsat 8:

- **Shift the acquisition paradigm by means of block buys and fixed-price contracting and by collaborating with commercial and international partners;**
- **Streamline the process by which satellites and sensors are designed, built, and launched, using a single organizational unit approach (a collaborative team approach) consisting of both government employees and contractors working together as a fully integrated team;**
- **Identify foreign sources of land imaging data that complement the U.S. core land imaging requirements and seek formal data-sharing agreements with them;**
- **Consider technological innovations, such as increasing the swath width 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 a secondary payload or as a shared ride.**

Appendixes

A

Statement of Task

An ad hoc committee will conduct a study to assess the needs and opportunities to develop a space-based operational land imaging capability. In particular, the committee will examine the elements of a sustained space-based Land Imaging Program with a focus on the Department of the Interior's U.S. Geological Survey role in such a program. The committee will:

1. Identify and/or validate primary organizations and segments of society and their fundamental historical, present-day, near-future, and long-term data, information, and service requirements that need to be supported by a sustained Land Imaging Program.
2. Identify and recommend characteristics and critical program support areas expected of a sustained Land Imaging Program including, but not limited to, the continuous operation and refinement of U.S. government-owned, spaceborne land-imaging capabilities (e.g., passive, as in optical land imaging; active, as in LiDAR or SAR measurements).
3. Suggest critical baseline products and services derived from sustained land imaging capabilities, including higher-level information products such as Climate Data Records and terrestrial Essential Climate Variables.
4. Considering the requirements for an operational land imaging capability, provide recommendations to facilitate the transition of single-mission NASA research-based land imaging technology or missions to sustained USGS Land Imaging Program technology or missions, including the relationships between USGS, NASA, and NOAA in developing, maintaining and effectively utilizing land imaging capabilities.

In conducting the study, the ad hoc committee will generate recommendations based on the committee's own data gathering as well as input from the U.S. Earth science and applications community.

B

Acronyms

ACS	American Community Survey
APL	Applied Physics Laboratory
ASPRS	American Society for Photogrammetry and Remote Sensing
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible Infrared Imaging Spectrometer
BLM	Bureau of Land Management
CDR	climate data record
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COSMO-SkyMed	Constellation of small Satellites for the Mediterranean basin Observation
DESDynI	Deformation, Ecosystem Structure and Dynamics of Ice mission
DMC	Disaster Monitoring Constellation
DOD	Department of Defense
DOI	Department of the Interior
DSM	digital surface model
DTM	digital terrain model
ECV	essential climate variable
EOSAT, Inc.	Earth Observation Satellite (company)
EROS A	Earth Resources Observation Satellite
EROS Center	Earth Resources Observation and Science Center
ERS-1/2	European Remote Sensing Satellites 1 and 2
ERTS	Earth Resources Technology Satellite, also Landsat 1
ETM+	Enhanced Thematic Mapper
FCDR	fundamental climate data record
FNCCC	First National Climate Change Communication

FWS	Fish and Wildlife Service
GCOS	Global Climate Observing System
HyspIRI	Hyperspectral Infrared Imager
InSAR	interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
JERS-1	Japanese Earth Resources Satellite 1
KOMPSAT 2, 3A	Korea Multi-Purpose Satellite 2 and 3A
LANDFIRE	Landscape Fire and Resource Management Planning Tools
LDCM	Landsat Data Continuity Mission
LiDAR	light detection and ranging
LIST	LiDAR Surface Topography
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multispectral Imager
MSS	Multispectral Scanning System
NAIP	National Agriculture Imagery Program
NASA	National Aeronautics and Space Administration
NGA	National Geospatial-Intelligence Agency
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	National Polar-orbiting Partnership
NPS	National Park Service
NRC	National Research Council
OLI	Operational Land Imager
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
R&D	research and development
RBV	Return Beam Vidicon
REDD	United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
RFI	request for information
SAR	synthetic aperture radar
SEASAT	Seafaring Satellite Mission
SELIP	Sustained and Enhanced Land Imaging Program
SIR-C	Spaceborne Imaging Radar C band
SPOT 5, 6, 7	Système pour l'Observation de la Terre (System for Earth Observation)
SWIR	shortwave infrared region
TACSAT-3	Tactical Satellite 3
TCDR	thematic climate data record

TerraSAR-X	Terra Synthetic Aperture Radar X-band
TIR	thermal infrared region
TIRS	Thermal Infrared Sensor
TM	Thematic Mapper
TOPEX/Poseidon	Topography Experiment/Poseidon
UCAR	University Corporation for Atmospheric Research
UNFCCC	United Nations Framework Convention on Climate Change
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VIIRS	Visible Infrared Imaging Radiometer Suite
VNIR	visible and near-infrared region

C

Committee and Staff Biographical Information

JEFF DOZIER, *Chair,* is a professor at the Bren School of Environmental Science and Management at the University of California, Santa Barbara. He founded the Bren School and served as its first dean for 6 years. His research interests are in the fields of snow hydrology, Earth-system science, remote sensing, and information systems. He has led interdisciplinary studies in two areas: one addresses hydrologic science, environmental engineering, and social science in the water environment; the other involves the integration of environmental science and remote sensing with computer science and technology. He was a principal investigator on the Landsat 4 and 5 programs, when the satellites carrying the first Landsat Thematic Mapper instruments were launched in 1982 and 1984. He served as the senior project scientist for NASA's Earth Observing System when the configuration for the system was established. He is a fellow of the American Geophysical Union (AGU) and the American Association for the Advancement of Science (AAAS), an honorary professor of the Academia Sinica, a recipient of both the NASA/Department of the Interior William T. Pecora Award and the NASA Public Service Medal, the winner of the 2009 Jim Gray Award from Microsoft for his achievements in data-intensive science, and the 2010 John Nye Lecturer for the AGU. He earned a Ph.D. in geography from the University of Michigan. He has served on many NRC committees, including the Board on Earth Sciences and Resources, the Computer Science and Telecommunications Board, the Committee on Indicators for Understanding Global Climate Change, the Committee on Geophysical and Environmental Data (chair), the Committee on Scientific Accomplishments of Earth Observations from Space, and the Committee on Coping with Increasing Demands on Government Data Centers.

CARLOS E. Del CASTILLO, now with the NASA Goddard Space Flight Center, was a research scientist with the Johns Hopkins University Applied Physics Laboratory and the William S. Parsons Professor in the Department of Earth and Planetary Sciences. He started his career at the University of Puerto Rico studying the effects of oil pollution in tropical marine environments. Later, at the University of South Florida, his interest in organic carbon biogeochemistry and the carbon cycle led him to the use of remote sensing to study biogeochemical and physical processes in the oceans through a combination of remote sensing and field and laboratory experiments. Dr. Del Castillo has served as a project manager at the NASA Stennis Space Center and as a program scientist for Ocean Biology and Biogeochemistry at NASA headquarters. He received the William Sackett Prize for Innovation and Excellence in Research from the University of South Florida (1999), the NASA Presidential Early Career Award for Scientists and Engineers (2004), and the Emerald Honors Trailblazer Award (2007), among others. He earned his Ph.D. in oceanography from the University of South Florida. He has served as a member of the NRC

Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions and the Committee on Assessing Requirements for Sustained Ocean Color Research and Operations.

JACK D. FELLOWS is president of the EnviroGen International Foundation and G2Groups, Inc. Both of these organization focus on supporting the next generation of environmental leaders. He served as the University Corporation for Atmospheric Research (UCAR) vice president and the director of UCAR Community Programs from 1997 to 2012. Before joining UCAR, Dr. Fellows spent 13 years at the Office of Management and Budget (OMB) overseeing budget and policy issues related to the NASA, NSF, and federal-wide research and development programs. While at OMB, he helped initiate the U.S. Global Change Research Program. In 1984, he spent a year as the American Geophysical Union's Congressional Science Fellow and worked on a range of policy issues, including water resources, and helped write commercialization of land remote sensing satellites legislation that was enacted. Dr. Fellows began his career as a research faculty member at the University of Maryland, where he conducted research in the use of satellite data in hydrologic models. He has been a member of several NRC committees.

KATHLEEN O. GREEN is a consultant with Kass Green & Associates, a consultancy firm that focuses on implementing cutting-edge remote sensing and GIS. Her past endeavors include cofounding and leading Pacific Meridian Resources and serving as president of Space Imaging Solutions. She serves on the boards of several advisory committees, including the Department of the Interior's National Geospatial Advisory Committee and NASA's Applied Sciences Advisory Group, as well as the University of California at Berkeley's Foundation Board of Trustees, the College of Natural Resources Advisory Committee, and the Geospatial Information Facility Advisory Committee. She coauthored the textbook *Assessing the Accuracy of Remotely Sensed Data*. She is a past president of the American Society for Photogrammetry and Remote Sensing and the Management Association of Private Photogrammetric Surveyors. She earned a B.S. in forestry and management from the University of California, an M.S. in resource policy and management from the University of Michigan, and a Ph.D. in agriculture and resource economics from Washington University. She is a member of the NRC Committee on Needs and Research Requirements for Land-Change Modeling, and her past service includes membership of the Panel on Confidentiality Issues Arising from the Integration of Remotely Sensed and Self-Identifying Data, the Committee on Beyond Mapping: The Challenges of New Technologies in the Geographic Information Sciences, and the Committee on Licensing Geographic Data and Services.

JOHN R. JENSEN is the Carolina Distinguished Professor and codirector of the GIS and Remote Sensing Center in the Department of Geography at the University of South Carolina. His research interests are in remote sensing of the environment, digital image processing, and biogeography. He has written four textbooks on these subjects, including *Remote Sensing of the Environment: An Earth Resource Perspective*, *Introductory Digital Image Processing: A Remote Sensing Perspective* (now in its third edition), and an electronic book on geospatial processing with interactive frames of instruction and animation. He is a current member of the National Center for Geographic Information and Analysis Remote Sensing Core Curriculum Committee and a former chair of the Commission on Education in Remote Sensing and Geographic Information Systems for the International Society for Photogrammetry and Remote Sensing. Dr. Jensen is a former president and current fellow of the American Society for Photogrammetry and Remote Sensing, and he received that society's Alan Gordon Memorial Award for significant achievements in remote sensing and photographic interpretation. He received his M.S. in geography from Brigham Young University and his Ph.D. in geography from the University of California, Los Angeles. He is currently a member of the NRC Committee on Future U.S. Workforce for Spatial Intelligence, and his extensive past NRC service includes membership of the Mapping Science Committee, the Committee on Extending Observations and Research Results to Practical Applications: A Review of NASA's Approach, and the Committee on Floodplain Mapping Technologies.

DENNIS P. LETTENMAIER is the Robert and Irene Sylvester Professor of Civil and Environmental Engineering at the University of Washington, Seattle. His areas of research interest are large-scale hydrology, hydrologic aspects of remote sensing, and hydrology-climate interactions. In addition to his service at the University of

Washington, he spent a year as visiting scientist at the USGS and spent time as the program manager of NASA's Land Surface Hydrology Program at NASA Headquarters. He was a recipient of the American Society of Civil Engineers' Huber Research Prize in 1990 and the AGU's Hydrology Section Award in 2000. He is a fellow of the AGU, the American Meteorological Society, and the AAAS, and he is a member of the National Academy of Engineering and the International Water Academy. He was the first chief editor of the American Meteorological Society's *Journal of Hydrometeorology* and is the president of the Hydrology Section of the AGU. He received a B.S., an M.S., and a Ph.D. in civil engineering from the University of Washington. He is a member of the NRC Committee on the Assessment of NASA's Earth Science Programs, and he has served on many other NRC committees, including the Committee on Stabilization Targets for Atmospheric Greenhouse Gas Concentrations, the Committee on Hydrologic Science, the Survey Steering Committee for Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, and the Committee on Scientific Bases of Colorado River Basin Water Management.

BERRIEN MOORE III is dean of atmospheric and geographic Sciences at the University of Oklahoma. He also serves as Chesapeake Energy Corporation chair in climate studies, director of the National Weather Center, and vice president for Weather and Climate Programs. Most recently, Moore served as executive director of Climate Central, a nonprofit, nonpartisan think tank based in Princeton, New Jersey, and Palo Alto, California, which is dedicated to providing public, business, and civic leaders and policy makers with objective and understandable information about climate change and potential solutions. He has published extensively on the global carbon cycle, biogeochemistry, remote sensing, and environmental policy. Prior to heading Climate Central, Dr. Moore served for 20 years as the director of the Institute for the Study of Earth, Oceans and Space at the University of New Hampshire and held the position of Distinguished University Professor. He earned a Ph.D. in mathematics from the University of Virginia. His extensive NRC service includes serving as a member of the Space Studies Board, chair of the Committee on Earth Studies, and co-chair of the survey steering committee for *Earth Science and Applications from Space: A Community Assessment and Strategy for the Future*.

DIANE E. PATAKI is associate professor of biology and director of the Urban Ecology Research Lab at the University of Utah. Formerly she directed the Center for Environmental Sciences and was an associate professor of Earth system science and ecology and evolutionary biology at the University of California, Irvine. Her research focuses on ecosystem ecology, urban ecology, and global change, especially with respect to the role of plants in human-dominated and urban ecosystems. Dr. Pataki is a member of the Environmental Protection Agency's Board of Scientific Counselors and the Ecological Society of America's Science Committee, and she is director of the Steele Burnand Anza-Borrego Desert Research Center. She is a fellow of the AGU and a recipient of its Macelwane medal for young scientists. She has a B.S. in environmental science from Barnard College and an M.S. and a Ph.D. in ecology from Duke University.

DAVID S. SCHIMEL is a senior scientist at the Jet Propulsion Laboratory of the California Institute of Technology. Formerly, he was a chief science officer and principal investigator at the National Ecological Observatory Network, Inc. (NEON), where he served as CEO from 2006 to 2011. Prior to joining NEON he served as a senior terrestrial scientist in the National Center for Atmospheric Research's Climate and Global Dynamics Division and was founding codirector of the Max-Planck Institute for Biogeochemistry. His career has focused on studies of the large-scale effects of land management and climate change on ecosystem processes and has experience in managing large, complex research projects, remote sensing, data management, modeling, and the application of ecological research to science policy development. Dr. Schimel serves as the editor in chief of *Ecological Applications* for the Ecological Society of America. In 2007, he was one of the recipients of the Nobel Peace prize for his work on the Intergovernmental Panel on Climate Change report. He has authored more than 150 papers on biochemistry and climate impacts on ecosystem processes. He earned a Ph.D. in ecology from Colorado State University. He is a member of the NRC Committee on Assessment of NASA's Earth Science Programs, and he served on the Committee on Geophysical and Environmental Data, the Committee on Global Change Research, and the Committee on Atmospheric Chemistry, among others.

WALTER S. SCOTT is executive vice president and chief technical officer of DigitalGlobe, Inc. He founded DigitalGlobe in 1992 as WorldView Imaging Corporation, which was the first company to receive a high-resolution commercial remote sensing license from the U.S. government. The company later became DigitalGlobe, and with the launch of the QuickBird-2 satellite that year, offered high-resolution commercial satellite imagery. Dr. Scott also served with the Lawrence Livermore National Laboratory (LLNL), where he became program leader for Brilliant Pebbles and was responsible for creating a series of hardware prototypes and conducting flight experiments. He has also served as assistant associate director of the LLNL Physics Department and was responsible for the development of new space-related programs and identification of promising technologies. Dr. Scott was named Entrepreneur of the Year by Ernst & Young in 2004 for the Rocky Mountain region in the emerging technology category. He has a Ph.D. in computer science from the University of California, Berkeley. He served previously as a member of the NRC Committee on Earth Studies.

WILLIAM F. TOWNSEND is an independent aerospace consultant. He is also a part-time advisor with Stellar Solutions, Inc., and co-owner of Townsend Aerospace Consulting, LLC. Previously, Mr. Townsend was the vice president and general manager of the Civil Space Systems Strategic Business Unit and then vice president of exploration systems at Ball Aerospace and Technologies Corporation. Prior to his appointment at Ball, he was deputy center director and program management council chair at the NASA Goddard Space Flight Center (GSFC), where he oversaw the development, launch, and operation of all GSFC instruments, spacecraft, and missions and was closely involved with almost 60 missions during his NASA career, including more than 30 missions while at GSFC. At NASA headquarters, in the Earth Science Enterprise area, he held the positions of acting associate administrator, deputy associate administrator, deputy division director, and flight program branch chief, and he was program manager of the TOPEX/Poseidon, NASA Scatterometer, and Radarsat programs (all international Earth remote sensing missions). He has a BSEE from Virginia Polytechnic Institute. Mr. Townsend is a member of the NRC standing Committee on Earth Science and Applications from Space, is a past member of the Committee on Assessment of NASA's Earth Science Program, and also served on the Committee on Cost Growth in NASA Earth and Space Science Missions.

HOWARD A. ZEBKER is professor of geophysics and electrical engineering at Stanford University. His research involves interferometric synthetic aperture radar imaging, Earth exploration from space, satellite remote sensing, planetary science, digital signal processing for geoscience applications, and electromagnetic scattering and propagation. His research is directed at studying the surfaces of Earth and planets, especially earthquakes, volcanoes, and human-induced subsidence, and of global environmental problems, such as the movement of ice in the polar regions. Prior to joining the Stanford faculty in 1995, Dr. Zebker was a member of the technical staff at the Jet Propulsion Laboratory. He earned a B.S. in engineering and applied science from the California Institute of Technology, an M.S. in engineering from the University of California, Los Angeles, and a Ph.D. in electrical engineering from Stanford University. His prior NRC service includes membership on the Panel on Solid-Earth Hazards, Resources, and Dynamics and the Advanced Radar Technology Panel.

MARY LOU ZOBACK is currently a consulting professor in environmental Earth system science at Stanford University. Her main area of interest is active tectonics, with emphasis on the relationship between the in situ tectonic stress field and earthquake deformation. Dr. Zoback was formerly vice president for earthquake risk applications at Risk Management Solutions in Newark, California. She previously served as chief scientist of the USGS Earthquake Hazards team in Menlo Park, California, and also as regional coordinator for the Northern California Earthquake Hazards Program. She is a member of the National Academy of Sciences, a past president of the Geological Society of America (GSA), and recipient of the 2007 GSA Day Medal, the 2007 GSA Public Service Award, the Leadership, Innovation, and Outstanding Accomplishments in Earthquake Risk Reduction Award from the Earthquake Engineering Research Institute, and the AGU Macelwane Award for Young Scientists. Dr. Zoback earned B.S., M.S., and Ph.D. degrees in geophysics from Stanford University. She is a member of the NRC Disasters Roundtable Steering Committee and the Committee on Increasing National Resilience to Hazards and Disasters. Her past NRC service also includes membership of the Committee on Science, Engineering, and

Public Policy, the Survey Steering Committee for Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, and the NAS Council.

Staff

ABIGAIL A. SHEFFER, *Study Director*, joined the Space Studies Board (SSB) in fall 2009 as a Christine Mirzayan Science and Technology Policy Graduate Fellow to work on the report *Visions and Voyages for Planetary Science in the Decade 2013-2022*. She continued with the SSB to become an associate program officer. Dr. Sheffer earned her Ph.D. in planetary science from the University of Arizona and her A.B. in geosciences from Princeton University. Since coming to the SSB, she has worked on several studies, including *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*, *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*, and *The Effects of Solar Variability on Earth's Climate: A Workshop Report.*

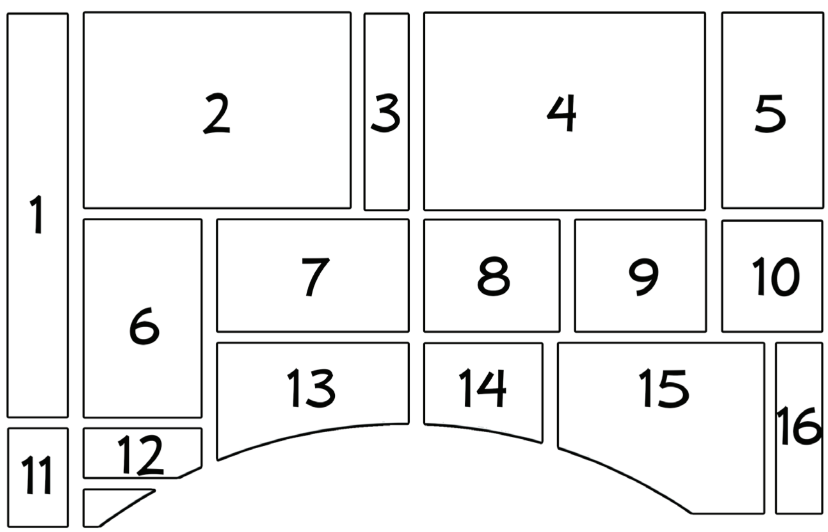
ARTHUR A. CHARO joined the SSB as a senior program officer in 1995. He has directed studies that have resulted in some 30 reports, notably the first NRC decadal survey in solar and space physics (2002) and in Earth science and applications from space (2007). Dr. Charo received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. He then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a research fellow from 1985 to 1988. From 1988 to 1995, he worked as a senior analyst and study director in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and a Harvard-Sloan Foundation Fellowship (1987-1988). He was the 1988-1989 American Institute of Physics AAAS Congressional Science Fellow. In addition to NRC reports, he is the author of research papers in molecular spectroscopy, reports on arms control and space policy, and the monograph "Continental Air Defense: A Neglected Dimension of Strategic Defense" (University Press of America, 1990).

JOSEPH K. ALEXANDER, JR., is a private consultant in science and technology policy. He was a senior program officer with the SSB from 2005 until 2013, and he served as SSB director from 1998 until November 2005. Prior to joining the National Academies, he was deputy assistant administrator for science in the Environmental Protection Agency's Office of Research and Development, where he coordinated a broad spectrum of environmental science issues involving human health and ecology and led strategic planning and implementation of research planning. From 1993 to 1994, he was associate director of space sciences at the NASA Goddard Space Flight Center (GSFC). He served concurrently as acting chief of the Laboratory for Extraterrestrial Physics. From 1987 until 1993, he was assistant associate administrator for space sciences and applications in the NASA Office of Space Science and Applications (OSSA), where he coordinated planning and provided oversight of research programs in Earth science, space physics, astrophysics, solar system exploration, life science, and microgravity science. He also served from 1992 to 1993 as acting director of life sciences in OSSA. Other positions included deputy NASA chief scientist, senior policy analyst at the Office of Science and Technology Policy, and research scientist at GSFC.

LINDA M. WALKER, a senior project assistant, has been with the NRC since 2007. Before her assignment with the SSB, she was on assignment with the National Academies Press. Prior to working at the NRC, she was with the Association for Healthcare Philanthropy in Falls Church, Virginia. Ms. Walker has 28 years of administrative experience.

MICHAEL H. MOLONEY is the director of the SSB and the Aeronautics and Space Engineering Board (ASEB) at the NRC of the National Academies. Since joining the NRC in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the Board on Physics and Astronomy, the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. In his time at the ASEB/SSB Dr. Moloney has overseen the production of more than 30 reports, including three decadal surveys (in planetary science, life and microgravity science, and solar and space physics), a prioritization of NASA space technology roadmaps, as well as reports on issues such as NASA's strategic direction, orbital debris, the future of NASA's astronaut corps, and NASA's flight research program. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the BPA and study director for the decadal survey for astronomy and astrophysics (Astro2010). With 12 years' experience at the NRC, Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anticounterfeiting technologies for currency, corrosion science, and nuclear fusion. In addition to his professional experience at the Academies, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government—including serving at the Irish Embassy in Washington and the Irish Mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin, in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

Cover Credits



1. Seattle, Washington, in false color using TM/ETM+ data (Landsat 7). From C. Small, 2006, Urban Landsat: Cities from Space, NASA Socioeconomic Data and Applications Center, Palisades, N.Y. Available at http://sedac.ciesin.columbia.edu/data/set/ulandsat-cities-from-space, accessed November 1, 2013. Courtesy of the Center for International Earth Science Information Network.

2. Mississippi Meandering (Landsat 7). Available at http://www.nasa.gov/images/content/670105main_meandering_mississippi.jpg. Courtesy of NASA Goddard Space Flight Center/USGS.

3. Cape Cod, Massachusetts (Landsat 7). Available at http://commons.wikimedia.org/wiki/File:Cape_Cod_-_Landsat_7.jpg. Courtesy of NASA.

4. Lake Manicouagan (Landsat 7). Available at http://eoimages.gsfc.nasa.gov/images/imagerecords/40000/40515/Mani_560.jpg. Courtesy of NASA GSFC Landsat/LDCM EPO Team.

5. Enhanced Landsat 8 Image, Western Australia.Western Australia. Available at http://landsat.usgs.gov/images/gallery/300_L.jpg. Courtesy of USGS.

6. Mining for Water in the Kansas Heartland (Landsat 1). Available at http://www.nasa.gov/images/content/668520main_garden-city-ks-1972-1988-2011.gif. Courtesy of NASA Goddard Space Flight Center.

7. Logging and Regrowth in Washington State (Landsat 5). Available at http://earthobservatory.nasa.gov/Features/CarbonCycle/images/washington_tm5_1984201-2010224.jpg. Courtesy of NASA Earth Observatory, image created by Robert Simmon, using Landsat data provided by the Landsat Project Science Office. Landsat is jointly managed by the U.S. Geological Survey and NASA.

8. Binhai, China (Landsat 5). Available at http://landsat.usgs.gov/images/gallery/256_L.jpg. Courtesy of USGS.

9. Binhai, China (Landsat 5). Available at http://landsat.usgs.gov/images/gallery/256_L.jpg. Courtesy of USGS.

10. Searching for Dinosaur Fossils in the Gobi Desert, Mongolia (Landsat 7). Available at http://earthobservatory.nasa.gov/Features/Fossils/Images/321.jpg. Images courtesy of Barbara Summey, NASA GSFC Visualization Analysis Lab, based on Landsat 5 data provided by the Laboratory for Terrestrial Physics.

11. Al Farafra Oasis (Landsat 7). Available at http://eros.usgs.gov/sites/all/files/external/imagegallery/2818.jpg. Courtesy of USGS.

12. Rodeo-Chediski Fire (Landsat Enhanced Thematic Mapper Plus (ETM+). Available at http://eoimages.gsfc.nasa.gov/images/news/NasaNews/ReleaseImages/20030722/rodeo.jpg. Courtesy of NASA/USGS.

13. Columbia Glacier, Alaska. Available at http://science.gsfc.nasa.gov/sed/images/featuredimage/featuredimage_272.jpg. Courtesy of NASA; images by Jesse Allen and Robert Simmon using Landsat 4, 5, and 7 data from the USGS Global Visualization Viewer.

14. Deepwater Horizon Oil Spill (Landsat 7). Available at http://eoimages.gsfc.nasa.gov/images/imagerecords/78000/78061/2010_Oil_Spill_946x710.jpg. Courtesy of NASA GSFC Landsat/LDCM EPO Team.

15. 40 Years of Recording Change, Washington, D.C. (Landsat 1). Available at http://landsat.usgs.gov/images/gallery/270_L.jpg. Courtesy of USGS.

16. Byrd Glacier, Antarctica (Landsat 7). Available at http://landsat.visibleearth.nasa.gov/view.php?id=7544. Courtesy of NASA/Jesse Allen, made from the Landsat Image Mosaic of Antarctica.