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| Description of document: | US Geological Survey (USGS) Sustainable Land Imaging (SLI) Architecture Study Team Final Report 2020 |
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# United States Department of the Interior

U. S. GEOLOGICAL SURVEY
12201 Sunrise Valley Drive
Reston, Virginia 20192-0002

In Reply Refer To: April 10, 2023

U.S. Geological Survey
Attention: Judy Cearley
Post Office Box 66783
Albuquerque, New Mexico 87193

Re: U.S. Geological Survey (USGS) Freedom of Information Act (FOIA) Tracking # DOI-USGS-2023-002326 and DOI-USGS-2023-002327 – Response

This letter is our response to your FOIA requests submitted on February 6, 2023, for the following:

> A copy of the table of contents from the Sustainable Land Imaging Architecture Study Team Final Report dated January 8, 2020, written by Doug Daniels and Jeffrey Masek.
>
> A copy of the Sustainable Land Imaging Architecture Study Team Final Report dated January 8, 2020.

Your requests were assigned control numbers DOI-USGS-2023-002326 and DOI-USGS-2023-002327. We decided to aggregate the two requests for administrative reasons due to the related subjects. See 43 C.F.R. § 2.54. Therefore, we are responding to both requests with one response.

We have enclosed one Portable Document Format (PDF) copy of the 2019 Sustainable Land Imaging Architecture Study Team Final Report, consisting of 180 pages. The record is being released to you in part. We reasonably foresee that disclosure would harm an interest protected by one or more of the nine exemptions to the FOIA's general rule of disclosure and disclosure would be prohibited by law; therefore, portions of the records are being withheld under FOIA Exemption (b)(5) ("Exemption 5"). The exempted information will not be released and has been redacted from the enclosed record.

Exemption 5 allows an agency to withhold "inter-agency or intra-agency memorandums or letters which would not be available by law to a party … in litigation with the agency." 5 U.S.C.

§ 552(b)(5). Exemption 5 therefore incorporates the privileges that protect materials from discovery in litigation, including the deliberative process, attorney work-product, attorney-client, and commercial information privileges. We are partially withholding (redacting) 146 pages under Exemption 5 because the information qualifies to be withheld under the following privilege:

*Deliberative Process Privilege*

The deliberative process privilege protects the decision-making process of government agencies and encourages the frank exchange of ideas on legal or policy matters by ensuring agencies are not forced to operate in a fish bowl. A number of policy purposes have been attributed to the deliberative process privilege, such us: (1) assuring that subordinates will feel free to provide the decisionmaker with their uninhibited opinions and recommendations; (2) protecting against premature disclosure of proposed policies; and (3) protecting against confusing the issues and misleading the public.

The deliberative process privilege protects materials that are both predecisional and deliberative. The privilege covers records that reflect the give-and-take of the consultative process and may include recommendations, draft documents, proposals, suggestions, and other subjective documents which reflect the personal opinions of the writer rather than the policy of the agency.

The portions of the 2019 Sustainable Land Imaging Architecture Study Team Final Report (SLI AST Report) withheld under the deliberative process privilege of Exemption 5 are both predecisional and deliberative in nature. They do not contain or represent formal or informal agency policies or decisions. The report is the result of an on-going Landsat Next architecture study among employees of the USGS and the National Aeronautics and Space Administration (NASA). Its contents have been held confidential by all parties and public dissemination of this information would have a chilling effect on on-going and the department's studies and collaborative efforts with other federal departments the deliberative processes; expose the department's decision-making process in such a way as to discourage candid discussion within the department, future department's studies and collaborative efforts with other federal department, and thereby undermine its ability to perform its mandated functions. The SLI AST Report is a pre-decisional and deliberative document that presents a set of options for NASA and USGS consideration in the definition of the next phase of the Sustainable Land Imaging Program to include the Landsat Next architecture. The report contains sensitive information that was provided to the AST to enable their analyses, including pre-decisional program activities, phasing assumptions, draft requirements which were later refined, preliminary budgetary profile details and assumptions, and competition-sensitive details of vendor submissions and potential commercial capabilities. Therefore, disclosure of the predecisional and deliberative portions of the report may cause public confusion by disclosing sensitive information, information would be taken out of context and could interrupt or derail standard federal departments deliberations.

The deliberative process privilege does not apply to records created 25 years or more before the date on which the records were requested.

Judy Cearley, Government Information Specialist, is responsible for this partial denial. Jennifer Heindl, Attorney-Advisor, U.S. Department of the Interior in the Office of the Solicitor was consulted on this response. NASA and the Office of Management and Budget were also consulted in the disposition of the report.

We classified you as an "other-use" requester, and you agreed to pay up to $40.00 for the processing of your request. The *search* time did not exceed your two-hour entitlement; therefore, there is no billable fee for the processing of this request.

You may appeal this response to the Department of the Interior's FOIA/Privacy Act Appeals Officer. If you choose to appeal, the FOIA/Privacy Act Appeals Officer must receive your FOIA appeal **no later than 90 workdays** from the date of this letter. Appeals arriving or delivered after 5 p.m. Eastern Time, Monday through Friday, will be deemed received on the next workday.

**Your appeal must be made in writing.** You may submit your appeal and accompanying materials to the FOIA/Privacy Act Appeals Officer by mail, courier service, fax, or email. All communications concerning your appeal should be clearly marked with the words: "FREEDOM OF INFORMATION APPEAL." You must include an explanation of why you believe the USGS's response is in error. You must also include with your appeal copies of all correspondence between you and USGS concerning your FOIA request, including your original FOIA request and USGS's response. Failure to include with your appeal all correspondence between you and USGS will result in the Department's rejection of your appeal, unless the FOIA/Privacy Act Appeals Officer determines (in the FOIA/Privacy Act Appeals Officer's sole discretion) that good cause exists to accept the defective appeal.

Please include your name and daytime telephone number (or the name and telephone number of an appropriate contact), email address and fax number (if available) in case the FOIA/Privacy Act Appeals Officer needs additional information or clarification of your appeal.

*DOI FOIA/Privacy Act Appeals Office Contact Information*

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This completes our response to your requests. If you have any questions about our response to your request, you may contact me by phone at (650) 329-4035 or by email at foia@usgs.gov.

Sincerely,

JUDY CEARLEY

Digitally signed by JUDY CEARLEY
Date: 2023.04.10 09:23:06 -07'00'

Judy Cearley
U.S. Geological Survey
Government Information Specialist

Enclosure:
AST 2019 Final Report_Redacted.pdf (180 pages)

# Sustainable Land Imaging Architecture Study Team Final Report

National Aeronautics and Space Administration

United States Geological Survey

# Preface

This document represents the final report from the 2019 Sustainable Land Imaging (SLI) Architecture Study Team (AST), conducted from August 2018 to December 2019.

# Authorship

Study Co-Lead: Doug Daniels, The Aerospace Corporation
Study Co-Lead: Jeffrey Masek, NASA Goddard Space Flight Center (GSFC)

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# Acknowledgements

The AST wishes to thank the SLI Joint Steering Group for sponsoring the 2019 AST study. We also acknowledge support from the following organizations:

- USGS Earth Resources Observation and Science (EROS), Southwest Biologic Research Station
- NASA GSFC and the Jet Propulsion Laboratory (JPL)
- NASA Earth Science Projects Division
- NASA Earth Science Technology Office
- The Aerospace Corporation
- The Landsat Science Team

# Executive Summary

## 1.1 Charter

National Aeronautics and Space Administration (NASA) and the Department of Interior (DOI)/ United States Geological Survey (USGS) chartered the Sustainable Land Imaging (SLI) Architecture Study Team (AST) 2019 to execute a feasibility study for the design and implementation approach for the second phase of a sustainable and evolvable spaceborne system to provide minimum global, continuous Landsat-quality multispectral and thermal infrared (TIR) measurements for approximately a fifteen-year period beginning in the FY26 timeframe. The study applied advancements in space systems technologies and addressed a broad set of civil land imaging needs and science applications. In doing so, the AST addressed commercial, international, and other Government providers of Earth observation data to understand these environments, assessed their merits and potential contributions, and provided business models that can be used to best exploit these capabilities.

This final report provides architecture options for NASA and DOI/USGS to inform a recommendation for an SLI architecture beyond Landsat 9.

## 1.2 Sustainable Land Imaging Science Mission Overview

Landsat imagery has been collected since 1972, resulting in the longest continuously acquired collection of space-based terrestrial observations. Landsat's mission is to monitor the extent and consequences of changes to Earth's land and coastal areas, as well as supporting the management of resources for ensuring economic and environmental quality, public health and human well-being, and national security. Whether the application is scientific, commercial, or operational, the needs are the same: a global perspective, a long-term record of observation, and well-calibrated high-resolution multispectral data (Wulder et al., 2015).

Landsat’s free and open data policy has greatly expanded the user community and revolutionized how the data can be used for a wide range of terrestrial applications. The resultant large user community and diversity of applications is of significant global and domestic economic impact. “Landsat imagery provided domestic and international users an estimated $3.45 billion in benefits in 2017 compared to $2.19 billion in 2011, with United States (US) users accounting for $2.06 billion of those benefits. Much of the societal value of Landsat stems from the free and open data policy that allows users to access as much imagery as is necessary for their analysis at no cost” (Straub, 2019).

The Earth observation capabilities offered by previous Landsat missions have ensured consistency and continuity of measurements but with incremental improvements that increased the utility of the data for science and applications. As such, numerous studies and national reports have emphasized the importance of long-term Landsat data record and Landsat’s standard for calibration including those by the National Research Council (NRC), where, for example, it is included in the 2017 Decadal Survey for Earth Science as part of the Program of Record on which the NRC’s recommendations for future measurements are based.

Looking forward, SLI must ensure long-term continuity of the multi-decadal global survey Landsat provides, in addition to evolving capability to support new and emerging science applications and measurements.

### 1.3 Study Methodology

USGS collected user needs from Federal, civil, and interdisciplinary subject matter experts (SME) including 157 unique research or operational applications, each yielding one or more moderate-resolution imagery need, to produce 379 user needs. USGS defined two quality levels for user need attributes: minimum and breakthrough. Minimum refers to the most basic data needed by a given application SME for their project or application (generally biased toward current capabilities). Breakthrough represents sufficiently improved data that would, in the best judgement of the SME, result in a significant improvement in the effectiveness of the data for their application.

To define and evaluate specific architectures, the SLI User Needs were translated to a set of draft SLI science requirements, describing spatial, spectral, radiometric, and coverage requirements. In addition to the User Needs Elicitation, these requirements were derived via assessment of Landsat and Sentinel-2 continuity and performance, input from the Landsat Science Team (LST), and other experts. Additionally, these requirements were posted for public review and comment. The draft SLI requirements are provided at two levels: threshold (generally meeting minimum user needs) and goal (additionally meeting most breakthrough user needs).

The AST used a three-phase process to establish and then down select potential architectures. Initial inputs to Phase 1 of the SLI AST 2019 study were built on the results of the SLI AST 2014 study in which over 200 concepts were evaluated to assess the relative tradeoffs of instrument characteristics, spacecraft characteristics, and mission class. The AST 2019 identified and developed 16 distinct concepts in Phase 1 that were evaluated and presented at Checkpoint (CP) 1. For Phase 2, some concepts were eliminated due to lack of overall effectiveness while others were added for further study, resulting in a total of 15 revised concepts at the conclusion of this phase. In Phase 3, five near-term missions were selected, evaluated in detail, and assembled into a series of three long-term logical roadmap options.

The architecture assessment approach revolved around the three primary tenants of the SLI program as addressed in the SLI AST 2019 charter, namely sustainability, continuity, and reliability. Sustainability is defined as the ability of the SLI program to provide the data products for the long term, without extraordinary infusions of funds, within the BG (BG) provided. Continuity is defined as ability of the SLI program to continue the long-term Landsat data record (as a function of the assessment of the minimum and breakthrough user needs, described in Section 3.2, that are achieved by a given architecture). Reliability is defined as the ability of the SLI program to be robust and not susceptible to single point failures. These three tenants were the basis for the quantitative assessment for the first two phases that allowed the down-select to the final three roadmap selections.

Finally, the cost and schedule assessment methodology for both the space and ground segments was based on existing methodologies developed by The Aerospace Corporation and depended heavily on historical data and trends to estimate the cost and schedule of the segments.

For the Ground Segment, notional ground system architecture pipelines were created for each candidate space segment architecture. These pipelines captured the flow of events and data within the major Work Breakdown Structure (WBS) components of the ground system. Staff encompassing the program management, systems engineering, and mission assurance (PMSEMA) functions were also accounted for in the notional architectures and were sized with respect to the current staffing level as well as the complexity of each notional architecture's pipeline.

### 1.4 Study Results: Overview

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# Change History Log

| Revision | Effective Date | Description of Changes |
|---|---|---|
| - | January 8, 2020 | Initial Release (Baseline) |
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# 1 FOREWORD

In accordance with the President's Fiscal Year (FY) 2014 Budget Submittal to Congress, NASA and DOI initiated a SLI cooperative venture to ensure sustained, space-based, global land imaging capabilities for the nation. In August 2018, NASA's ESD and the USGS National Land Imaging (NLI) program established the SLI AST 2019 to execute a feasibility study for the design and implementation approach of a spaceborne system to provide global, continuous Landsat-quality multispectral and TIR measurements for approximately a fifteen-year period starting in 2026.

AST 2019 activities focused on studies to define the scope, measurement approaches, cost, and risk of viable long-term land imaging systems that will achieve SLI objectives. The study was charged with identifying and evaluating a range of solutions including small dedicated spacecraft; constellation alternatives; advanced, reduced envelop instruments; integration of other land imaging data sets, as available; and possible international and private sector collaborations. The study included consideration of current and future ground system capabilities provided by commercial and public partnerships, as well as the existing capabilities established by the USGS Earth Resources Observation and Science (EROS) Center. The AST recognized that lowering SLI system costs is an important goal, and that implementing a system that stays within the allocated budget is an essential programmatic requirement for the US Government.

This report serves as the completion of the study and provides a set of viable SLI architecture concepts to be used as a basis for formulating future acquisition strategies and approaches.

## 1.1 Team Members and Affiliations

The AST 2019 was comprised of SMEs with diverse experience, spanning multiple areas of expertise. Table 1 denotes the AST 2019 core team membership, their role, and affiliation.

**Table 1. Membership**

| NASA Team Members | Organization | Role |
|---|---|---|
| Jeff Masek | NASA GSFC | AST Co-Lead; Science & Applications |
| Evan Webb | NASA GSFC | Mission Systems Engineering |
| Phil Dabney | NASA GSFC | Instrument Systems & Technologies |
| Mark Flanegan | NASA GSFC | Technology Applications & Fusion |
| Glynn Hulley | NASA JPL | Instrument Technologies & Thermal Infrared Science |
| Sergey Krimchansky | NASA GSFC | Business Models & Partnerships |
| Bob Bitten | Aerospace | Metrics, Cost & Schedule Analyst |
| Brian Markham | NASA GSFC | Calibration & Validation |
| Nipa Shah | NASA GSFC | Procurement Strategy |
| **USGS Team Members** | **Organization** | **Role** |
| Douglas Daniels | Aerospace | AST Co-Lead; Systems Architecture |
| John Dwyer | USGS EROS | Science & Applications |
| Zhuoting Wu | USGS NLI | User Needs & Applications |
| Greg Stensaas | USGS EROS | Public-Private Partnerships & Commercial Capabilities |
| Grant Mah | USGS EROS | Mission & Ground Systems |
| Chris Engebretson | USGS EROS | Data Handling; Commercial Cloud Evolution |
| Cody Anderson | USGS EROS | Calibration & Validation; Instruments |
| Dennis Helder | USGS EROS | Calibration & Validation |
| Mary Covert | Aerospace | Metrics, Cost & Schedule Analyst |
| Jon Christopherson | KBR | Commercial Capabilities |
| Emily Maddox | KBR | Administrative Management; Official Records |

Several other SMEs from NASA's ESTO, USGS NLI, and EROS Center, as well as Aerospace contributed to this study.

Finally, members of the AST contributed to authorship and review of this final report.

### 1.2 Charter

NASA and DOI/USGS chartered SLI AST 2019 to execute a study for the design and implementation approach for the second phase of a sustainable and evolvable spaceborne system to provide global, continuous Landsat-quality multispectral and TIR measurements for approximately a fifteen-year period beginning in the FY26 timeframe. The first SLI AST (AST 2014) was initiated in 2013 and culminated in the development of the Landsat 9 mission, currently planned for launch in December 2020. The AST 2014 also initiated a NASA SLI technology development effort to inform the development of future US land imaging missions beyond Landsat 9. Using the AST 2014 study results, as well as other NASA and USGS studies as an initial starting point, the AST 2019 Final Report provides architecture options for NASA and DOI/USGS to inform a recommendation for an SLI architecture beyond Landsat 9.

Specifically, the AST 2019 was tasked to execute a feasibility study for the design and implementation of a spaceborne system to provide minimum global, continuous, Landsat-quality multispectral and TIR measurements. The study applied advancements in space systems technologies, as well as addressing a broad set of civil land imaging needs and science applications collected by USGS NLI. In doing so, the AST reviewed commercial, international, and other Government providers of Earth observation data to understand these environments, assessed their merits and potential contributions, and developed business models that might be used to best exploit these capabilities. The AST studied the potential for data volume increase, by orders of magnitude, to shift the balance of investment towards the ground segment and long-term operations. Finally, the AST assessed feasibility of multi-mission science data harmonization in terms of data interoperability for science quality.

As with previous studies, the AST abided by cost constraints and this final report provides viable options within the FY19 and FY20 budget request.

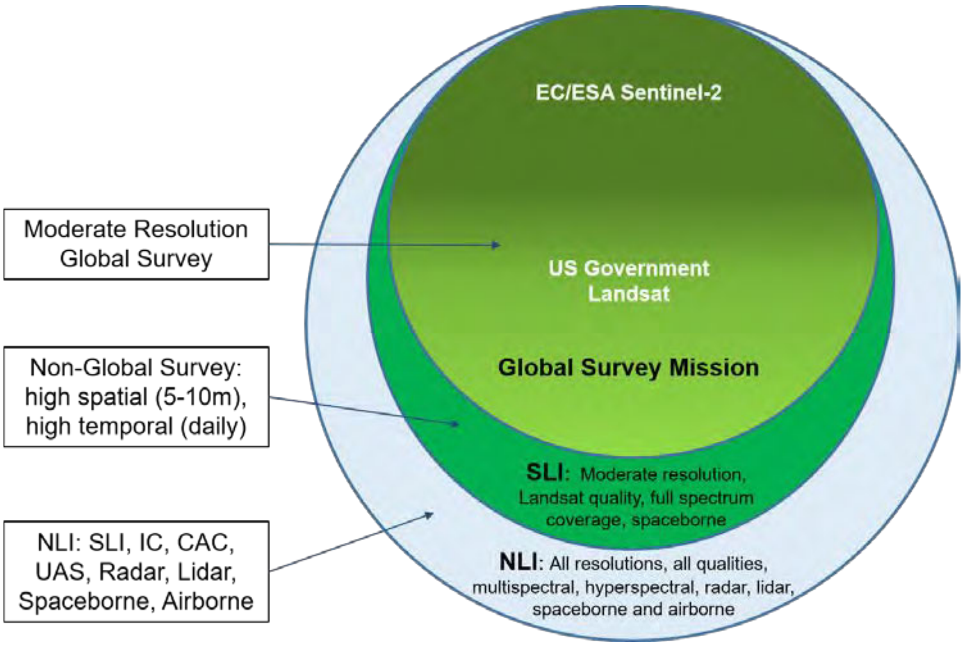
## 1.3 Programmatic Context

Landsat imagery is used for both national and global routine monitoring applications. National application examples include the National Land Cover Database, which is used to characterize land cover and land cover change, and the USDA's annual Cropland Data Layer, which provides crop acreage estimates and digital crop-specific maps. Global scale monitoring and land change applications include mapping global cropland extent, characterizing global forest extent and change, and assessing ice sheet and glacier dynamics. None of these national to global monitoring applications can exist without the continuous global survey of the Earth's surface from Landsat satellites.

SLI is a subset of the NLI capability. NLI includes all spatial resolutions, all imaging modalities (active/passive, space- and airborne), whereas SLI focuses on the moderate resolution spaceborne observing systems that provide routine monitoring of the Earth's surface (see Figure 1). SLI enables the development of a multi-decade, spaceborne system to provide users worldwide with high-quality, global land imaging measurements that are compatible with the existing Landsat record to ensure Landsat data continuity. To maintain the continuity of moderate resolution observations and allow improvement to address emerging applications, SLI needs are defined as 5 to 120 meters (m) in spatial resolution. The AST has categorized SLI user needs into two groups: 1) global survey and 2) non-global survey.

- Global survey SLI user needs are those requiring data with 10 to 120m spatial resolution and encompasses current Landsat users who require global image acquisition every two days or longer, supporting monitoring of land use/land cover (LULC), agriculture, forestry, ecosystems, water resources, geologic mapping, and cryosphere monitoring. Most of these needs are well-served by existing and planned Landsat and Sentinel-2 satellites.
- Non-global survey SLI applications are those requiring high-resolution data at 5 to 10m spatial resolution and/or requiring daily or higher observation frequency, such as emergency/disaster rapid response, water quality, coastal change, and some aspects of agriculture. In some cases (e.g. disaster response) these applications may also desire near real-time data delivery.

The AST focuses on architecture options that address the global survey needs, while seeking partnership and alternative mechanisms to meet non-global survey needs.




**NLI (outer circle) includes all resolution and sensing modalities. SLI (middle circle) is the spaceborne moderate resolution subset of the NLI. The global survey mission (inner circle) is the US Government-built subset (augmented by Sentinel-2) of SLI.**

**Figure 1. NLI and SLI Logical Relationship**

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# 2 SCIENCE MISSION OVERVIEW

## 2.1 Background

Landsat imagery has been collected since 1972, resulting in the longest continuously acquired collection of space-based terrestrial observations. In 1969, NASA initiated the Earth Resources Technology Satellite (later renamed Landsat 1), which ushered in the era of civilian remote sensing of land from space. Since then, there has been remarkable mission-to-mission consistency despite the lack of a formal government commitment to an operational Landsat program. The history of Landsat and the characteristics of specific missions have been chronicled in several previous articles listed in Further Reading (see Lauer et al., 1997; Goward and Williams, 1997; Goward et al., 2001; Sheffner, 1994; Williams et al., 2006; and Irons et al., 2012). The Landsat series has acquired data using a series of sensors. The Multispectral Scanner instrument was utilized from inception until decommissioning in August 1995. Global Thematic Mapper (TM) coverage existed from 1982 through 2012. Landsat 7 utilizes Enhanced Thematic Mapper (ETM+) coverage, starting in 1999, and Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) acquisitions started in 2013 and continue today.

Landsat's mission is to monitor the extent and consequences of changes to Earth's land and coastal areas, as well as supporting the management of resources for ensuring economic and environmental quality, public health and human well-being, and national security. Whether the application is scientific, commercial, or operational, the needs are the same: a global perspective, a long-term record of observation, and well-calibrated high-resolution multispectral data (Wulder et al., 2015). Landsat’s free and open data policy has greatly expanded the user community and revolutionized how the data can be used for a wide range of terrestrial applications. The resultant large user community and diversity of applications is of significant global and domestic economic impact. “Landsat imagery provided domestic and international users an estimated $3.45 billion in benefits in 2017 compared to $2.19 billion in 2011, with US users accounting for $2.06 billion of those benefits. Much of the societal value of Landsat stems from the free and open data policy that allows users to access as much imagery as is necessary for their analysis at no cost” (Straub, 2019).

The Earth observation capabilities offered by previous Landsat missions have ensured consistency and continuity of measurements but with incremental improvements that increased the utility of the data for science and applications. For most of the series history, two missions operated concurrently, thus providing eight-day global revisit. Periodic incremental improvements to instrument performance include increased spatial resolution, spectral coverage, signal-to-noise ratio (SNR), radiometric sensitivity, and revisit frequency. Advances in other enabling technologies such as communications and downlink, onboard storage, and flight operations have all contributed to steadily increasing volumes of global measurements.

Numerous studies and national reports have emphasized the importance of long-term Landsat data record and Landsat’s standard for calibration. In the Landsat and Beyond report, the NRC stated that “Space-based land imaging is essential to US 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.” The 2017 NRC Decadal Strategy for Earth Observations stated, “As long as it is funded, and managed as an operational program, the SLI program will support and motivate widespread usage, benefitting both the operational and scientific communities," and noted that the continuation of Landsat-class imagery as part of the Program of Record was assumed in the NRC's recommendations for future measurements.

### 2.2 The Evolution of the Remote Sensing Landscape

Nevertheless, the remote sensing landscape has changed dramatically over the last decade. First, the number of space-based Earth observation systems being deployed by the international and commercial sectors continues to increase, thereby offering the user community a growing diversity of sources of data and information. Many international systems provide science-quality observations, and an increasing fraction do so under "free and open" distribution policies. Commercial systems, while not always offering high-quality data, fill important gaps in providing high-resolution and targeted imagery. In recent years, the concept of virtual constellations (Wulder et al., 2015) has emerged whereby data collected by different systems can be used synergistically, thus driving a need for instrument and observatory cross calibration and data harmonization. Such virtual constellations minimize the costs for any given partner, since additional capability can be launched without recreating the baseline observations from scratch. Second, the way in which users analyze remote sensing imagery has evolved. The unit costs for computing and storage have dropped significantly, and science data processing algorithms are yielding new and innovative information products with greater levels of maturity. Increasingly, users are applying processing algorithms to data via cloud computing services, rather than downloading individual images to their personal workstations. Thus, the emphasis is becoming an "archive of pixels" rather than images per se.

As the SLI program moves forward, it must consider how the core global monitoring functions of a government-run system should be balanced with the emerging capabilities of the commercial remote-sensing sector and the increased number of observatories being operated by the international community. The scientific research and applications community will make use of all assets that are available, but in addition to providing the fundamental measurements there is also a need, if not an expectation, that services will be made available to enable data harmonization across multiple instruments and platforms. Landsats 7 and 8 and the EC Sentinel-2 series of satellites are already considered a virtual constellation due to their similar imaging characteristics and open data policies. The user community has articulated needs for increased revisit frequency, higher spatial resolution, and additional spectral information. At the same time, there is a recognized need for backward compatibility with the existing measurement record and continuity of spectral bands and global coverage.

This report addresses how the core government-sponsored system can advance to meet the growing needs of the user community, while leveraging new international, commercial, and technological capabilities.

### 2.3 Land Imaging Continuity Defined

The 1992 US Land Remote Sensing Policy Act (H.R.6133) stated, "it is in the best interest of the United States to maintain a permanent, comprehensive Government archive of global Landsat and other land remote sensing data for long-term monitoring and study of the changing global environment." The Land Remote Sensing Policy Act of 1992 (H.R.6133) defined continuity as "the continued acquisition and availability of unenhanced data which are, from the point of view of the user – (A) sufficiently consistent (in terms of acquisition geometry, coverage characteristics, and spectral characteristics) with previous Landsat data to allow comparisons for global and regional change detection and characterization; and (B) compatible with such data and with methods used to receive and process such data."

In 2014, the LST defined Landsat data continuity as "the collection, archival, and distribution of image data of the Earth's continents and surrounding coastal regions with the content, quality and coverage needed to map, monitor and assess the Earth's characteristics and its response to natural and human-induced change over time" (LST, 2014). To accomplish this, continuity includes: (1) long-term calibrated measurements that are consistent across the evolving instrument record; (2) a continuous record since the initiation of observations in 1972 with no significant temporal or geographic data gaps; (3) measurements that enable backward and forward assessments of the conditions and changes in the Earth's surface (a period of overlap between missions is needed to ensure measurement consistency); and (4) measurements with comparable spectral, spatial, temporal, and geographic properties that result in sufficiently consistent and accurate documentation of surface characteristic and dynamics (LST, 2014). The LST strongly endorsed the goal of Landsat data continuity as the overriding driving requirement for a future Landsat land imaging architecture. It should be noted that both sources quoted here define continuity in terms of application capabilities; in neither case is a fixed technology solution required.

The full set of 11 Landsat 8 spectral bands (provided by the OLI and TIRS instruments) defines the standard for data continuity. Near simultaneous (i.e., within a few seconds) data collection for the reflective spectral bands (VSWIR) is essential. Some separation of time between the collection of reflective band data and thermal band data is tolerable, but collection must be within a day for evapotranspiration (ET) and coastal/lake hydrodynamic applications, and seconds to use thermal data for cloud detection and clearing for reflective band images.

Eight-day repeat coverage of the global land surface is the temporal standard for continuity. When combined with imagery from the Sentinel-2 satellites, the combined constellation provides weekly cloud-free imagery in the reflective bands for most vegetated areas, which is the requirement for agricultural monitoring (Whitcraft et al., 2015). Ideally, higher frequency collections of reflected and thermal data will improve monitoring of variations in day-to-day ET rates caused by rapid vegetation growth, abrupt harvests, damaging weather events, and irrigation wetting events. Applications and studies observing intra-annual vegetation phenology such as crop monitoring and yield forecasting, tracking changes in glacier extent, tropical forest mapping, water rights monitoring, and regions with significant cloud coverage (e.g., tropics, high latitudes) benefit greatly from more frequent coverage.

The 30m resolution for reflected spectral bands is the maximum ground sample distance (GSD) and resolution for all future land imagers, whereas 120m is the maximum spatial resolution for the thermal bands. Improving the spatial resolution of future reflected bands to 10-20m would benefit most applications. Increasing thermal band resolution to 60m would enable the measurement of water consumption within many irrigated agriculture fields that are not currently resolved by the 100m Landsat 8 TIRS images, and would support better mapping of coastal water temperatures in estuaries, bays, and fjords.

Continuing the current USGS Landsat data policy of free and open access to data products is essential to the future of land imaging. Global coverage of the continental surfaces, ice sheets, coastal regions, islands, and coral reefs is required. The 24-hour latency specification for Level-1 data is suitable for most land imaging studies and applications with the notable exception of emergency response where near real time availability could be of benefit.

### 2.3.1 Importance of Calibration

A hallmark of the Landsat program is the collection of calibrated, science-quality measurements. "Science quality" means that the data collected by the Landsat series are not just pictures from space; they represent physical quantities of spectral reflectance and temperature, which may be tracked through time. The accuracy and consistency of these measurements is critical for identifying long-term changes in global ecosystems and land use, and for separating these trends from spurious variability arising solely from errors in instrumentation. The continuity of Landsat as a gold standard for calibration supports not only the Landsat science mission, but also serves as a reference for commercial and other international imagers that may not include onboard calibration hardware and protocols.

Radiometric calibration involves several related standards. *Radiometric sensitivity* is expressed as per-band SNR for the reflective bands or noise-equivalent temperature change for the TIR bands. *Absolute radiometric accuracy* requires either an uncertainty of less than 5 percent with respect to absolute spectral radiance or less than 3 percent with respect to top-of-atmosphere reflectance in the case of images for reflective spectral bands, and less than 2 percent with respect to at-sensor spectral radiance in the case of thermal bands. *Radiometric stability* governs the allowable variability in instrument response over timescales of single orbits to mission lifetime. Additional criteria describe limits on radiometric uniformity across the image, stray light, and artifacts such as coherent noise. Long-term consistency for many applications is as important as radiometric accuracy; data overlap between missions is needed for maximum data integrity.

Geometric standards involve both *absolute geodetic accuracy* (i.e. placement of observations on the ground), as well as *band-to-band registration* and *image-to-image registration* through time. Improvements in onboard hardware (star trackers, Global Positioning System) and ancillary reference data allow absolute geolocation to better than 10m for most spectral bands.

### 2.3.2 Product Harmonization

To leverage contributions from international and commercial observatories, it is critical to cross calibrate different instruments so that they can be integrated into normalized measurement records to enable time series analysis. Harmonization of these measurement records will need to account for differences in spectral bandpasses, signal-to-noise and radiometric quantization, solar illumination and viewing geometries, and GSD. Ideally the synthesis of these data records should enable backward and forward compatibility through time. Although in many cases exact matching of relative spectral response functions may be unlikely, structural bandpass adjustments or the derivation of proxy measures with known uncertainties or measurable bias may be sufficient for constructing comparable, consistent, and stable measurement records.

One example of successful data harmonization are the Harmonized Landsat 8-Sentinel-2 (HLS) products. Since the launch of the EC Copernicus Sentinel-2A in 2015, followed by Sentinel-2B launch in 2017, the combined Landsat 7 and 8 and Sentinel-2A and 2B data provides a 3-day average global revisit frequency – a significant increase in the temporal coverage to monitor the dynamic Earth surface. The Sentinel-2 satellites have spectral bands similar to Landsat 8 (excluding thermal) as shown in Figure 3. The HLS products were generated based on a set of algorithms to obtain seamless products from both sensors, including atmospheric correction, cloud and cloud-shadow masking, spatial co-registration and common gridding, bidirectional reflectance distribution function normalization and spectral bandpass adjustment (Claverie et al., 2018). Since the release of the HLS products, research studies on agriculture, vegetation, and ecosystems have found HLS data very useful in capturing key phenological events (Pastick et al., 2018), vegetation seasonality (Jönsson et al., 2018), and crop yield (Skakun et al., 2018).

Given the compatibility and opportunity for seamless harmonization between Landsat 8/9 and Sentinel-2 data, as well as the free and open Copernicus data policy, the AST considers Sentinel-2 as part of moderate-resolution land imaging data continuity.

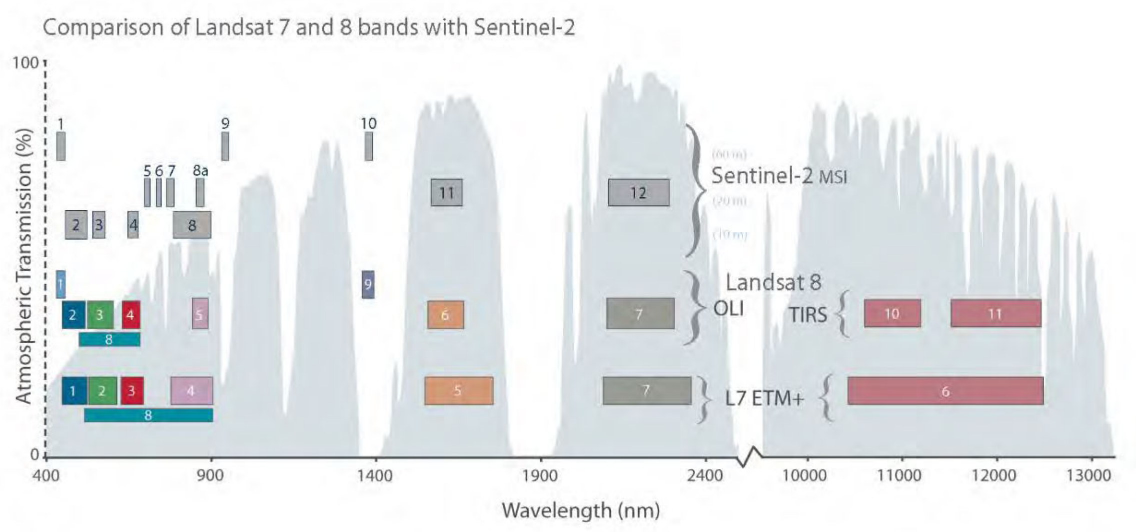


**Figure 3. Comparison of Landsat 7 and 8 bands with Sentinel-2**

### 2.3.3 New and Emerging Applications

With the increased use of Earth observation data for scientific research and resource management applications, combined with the growing number of satellite-based measurements, new applications of societal relevance continue to emerge. The increasing availability of Earth observation data is accompanied by a growing focus on developing long-term measurement records by which to assess the impacts of natural and human processes on the terrestrial environment (Carrer et al., 2018; Mitchell et al., 2017). Population growth is putting pressure on responsible stewardship of natural resources, and long-term meteorological trends and climate variability are contributing to increased frequency of natural disasters such as drought and wildfires. The development of these long-term data records involves integration of measurements acquired from different instruments and observation platforms, improved capabilities for instrument cross-calibration, and advanced algorithms for the retrieval of fundamental geophysical parameters.

Advances in instrumentation that offer data with increased spatial resolution and spectral coverage enable the application of these data to a wide range of natural resource monitoring and management issues (Rast and Painter, 2019). For example, the introduction of shorter wavelength bands provide data that can be used for water quality assessment and monitoring to address problems such as harmful algal blooms, which are human health hazards and negatively impact recreational resources (Fichot et al., 2016; Gómez Jakobsen et al.. 2018; Pahlevan et al., 2019). Narrow “red-edge” and SWIR spectral bands enable mapping of additional compositional information such as cellulosic material and that can serve as indicators of soil quality and the efficacy of soil tillage practices for nutrient preservation and erosion control (Hively et al., 2018). Improvements in SNRs have further enabled the use of these data for mapping snow/ice facies, grain size, snow cover extent, and glacier velocity (Kääb et al., 2016; Dedieu et al., 2016; Paul et al., 2016). The ability to monitor these parameters are important for understanding landscape responses to climate variability, monitoring agricultural water use, and sustainment of ecosystem services. The increasing use of TIR observations for retrieving land surface temperature (ST) has become prominent in the operational use of ET monitoring as a tool for monitoring agricultural water use consumption (Bahir et al., 2017; Martens et al., 2018), and is driving the need for thermal data to be acquired at increased temporal frequency and spatial resolution commensurate with the field scale. The AST recognizes that continuous further study is warranted as instrumentation capabilities continue to evolve.

# 3 SUSTAINABLE LAND IMAGING USER NEEDS

To develop and assess the performance of SLI architecture options, USGS initiated a study to collect current and future-looking land imaging user needs. This user needs assessment, termed the Requirements Capabilities and Analysis for Earth Observation (RCA-EO), was one of the chief recommendations from the AST 2014. User needs metrics are used to evaluate the benefits and impacts of various architecture options on specific applications, considering spatial resolution, observation frequency, and spectral characteristics. The section below briefly describes the USGS user needs study. A full report (USGS, 2018) and journal article (Wu et al., 2019) were also generated and are available upon request from USGS.

## 3.1 USGS User Needs Elicitation

USGS collected user needs from Federal, civil, and interdisciplinary SMEs who currently rely on moderate-resolution land imaging data across a wide array of applications, including: ecological and land change science; national and global agricultural and forest monitoring; natural hazards detection and monitoring for volcanoes, fire, and floods; water quality; geologic and mineral mapping; coastal change; and glacier and ice sheet studies. "User need" refers to the desired measurement or geophysical information derived from calibrated science-quality data and associated attributes. Examples of geophysical parameters include ST, land cover type, surface water extent, and burned area extent. These geophysical parameters are further defined by attributes such as spatial resolution, cloud-free observation frequency, and spectral characteristics; user needs are grouped into these three categories for analysis. Cloud-free observation frequency is defined as the interval between two dates of cloud-free data, which is distinct from the satellite revisit frequency. Satellite revisit frequency is the frequency at which a given sensor can theoretically image a location on Earth without considering usability factors such as geographic location or atmospheric condition including clouds, time of year, and the application of the data.

USGS collected user needs from SMEs using expert interview techniques (Meyer and Booker, 2001) that allowed for interactive discussions, including questions and clarifications, identification of detailed attribute values, and understanding the rationale for desired future data improvements. SMEs provided their current and future enhancement needs using their best judgement, including justifications for future measurement enhancements. USGS interviewed SMEs from 157 unique research or operational applications, each yielding one or more moderate-resolution imagery need, to produce 379 user needs.

USGS defined two quality levels for user need attributes: minimum and breakthrough. Minimum refers to the most basic data needed by a given application SME for their project or application (generally biased toward current capabilities). Breakthrough represents sufficiently improved data that would, in the best judgement of the SME, result in a significant improvement in the effectiveness of the data for their application. Structuring needs by observation quality level is a practice also used by the National Oceanic and Atmospheric Administration and the World Meteorological Organization.

Table 3 shows an example user need from the US Department of Agriculture to assess the amount of non-photosynthetic vegetation remaining in a field after harvest, a requirement for crop management and crop production analyses. The table shows how spatial resolution, cloud-free observation frequency, and spectral attributes can vary by quality level within a given user need. For example, spatial resolution shifts from 30m at minimum to 10m at breakthrough to observe smaller agricultural fields. Observation frequency shifts from two weeks at minimum to one week at breakthrough to better capture tillage and crop planting. Spectral needs shift from broad multispectral bands at minimum to narrower, multiple SWIR bands at breakthrough to capture the cellulose absorption feature and depth to identify non-photosynthetic vegetation.

**Table 3. User Need for Assessing Non-Photosynthetic Vegetation**

| User Need Level | Spatial Resolution | Cloud-Free Observation Frequency | Spectral Characteristics |
|---|---|---|---|
| **Minimum** | 30m (reflective), 100m (thermal infrared) | 2 weeks | Shortwave infrared and thermal infrared |
| **Breakthrough** | 10m (reflective), 100m (thermal infrared) | 1 week | Shortwave infrared 30-50 nm-wide bands centered near 2040, 2100 and 2200 nm; thermal infrared |

## 3.2 User Needs Findings

### 3.2.1 Spatial Resolution Needs

At minimum, 30m spatial resolution can meet 90 percent of reflective band spatial resolution needs. At breakthrough, 10m reflective band resolution can meet 86 percent of breakthrough user needs. 10m resolution data can improve crop mapping and acreage assessments and provide better discernment of field boundary and in-field variability. 10m data can also improve measurement of coastal change, glacier extent, ice sheet velocity, and differentiate cryospheric surface characteristics.

TIR needs were collected from a smaller group of users, representing only the direct TIR data usage. However, TIR data are also used indirectly to generate other products commonly needed by end users, such as cloud cover assessment, quality assessment bands (cloud and snow/ice) for Landsat Level 1 products, and higher-level products such as surface reflectance (SR) products. Among the direct TIR user needs collected, 100m TIR data can meet 77 percent of minimum needs, which the current Landsat 7/8 TIR data at 60 or 100m satisfies. At breakthrough, 30m TIR band resolution can meet 91 percent of breakthrough user needs. 30m TIR measurements enable individual field-level ET mapping and water consumption estimates associated with specific crop types. For hazards mapping, 30m TIR data improve the ability to monitor volcano dynamics, provide additional detailed information about smaller features in the flow, and improve mapping of volcanic ash and dust deposits.

In summary, most users need continuity of Landsat-like 30m reflective and 100m TIR spatial resolution to meet minimum needs for their current applications. Breakthrough levels of improvement occur at 10m reflective and 30m TIR spatial resolution.

### 3.2.2 Cloud-Free Observation Frequency

Monthly or longer cloud-free observation frequency meets 57 percent of minimum needs, which can be satisfied by the two current Landsat satellites. Weekly cloud-free observation frequency meets 71 percent of breakthrough needs, which can be satisfied by the combined two Landsat and two Sentinel-2 satellites.

Increased cloud-free observation frequency can improve land change monitoring in areas with persistent cloud cover, as well as in areas that experience frequency change such as urban, agricultural, forest, and coastal. Water resources application users need weekly or more frequent observations to map ephemeral water bodies and reservoir releases, measure water consumption, study ET, and identify changes in shoreline, wetlands, seasonal snowmelt, and freeze/thaw cycles. For water quality monitoring, weekly to daily cloud-free observations enable timely management action and response to episodic events. For hazard applications, sub-weekly to daily data support can assist in detecting and monitoring volcanic activity and fires as well as monitoring flooded areas and marine oil spills, which are critical in saving lives and property and protecting natural resources.

### 3.2.3 Spectral Characteristics

At minimum, nearly all users need continuity of some or all current Landsat spectral bands, with full spectral capability including VNIR, SWIR, and TIR bands. User needs within the geosciences, natural hazards, and cryosphere domains include additional spectral bands in VNIR, SWIR, and TIR regions (e.g., spectral resolution similar to or greater than Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER] and WorldView-3). Mid-wave infrared (MWIR; 3000–5000 nanometers [nm]) data are needed for active fire, aquatic vegetation, snow, and forest temperature mapping.

The most common breakthrough needs are red edge bands, followed by additional bands in the VSWIR regions. Figure 4 illustrates some specific, critical wavelengths identified for future Landsat spectral capabilities, along with the associated geophysical parameters, within the ultraviolet (UV), VNIR, SWIR, MWIR, and TIR regions. The spectral enhancement usage in Figure 4 shows: (a) examples of individual spectral band centers of breakthrough spectral enhancement, and (b) ideal hyperspectral needs.

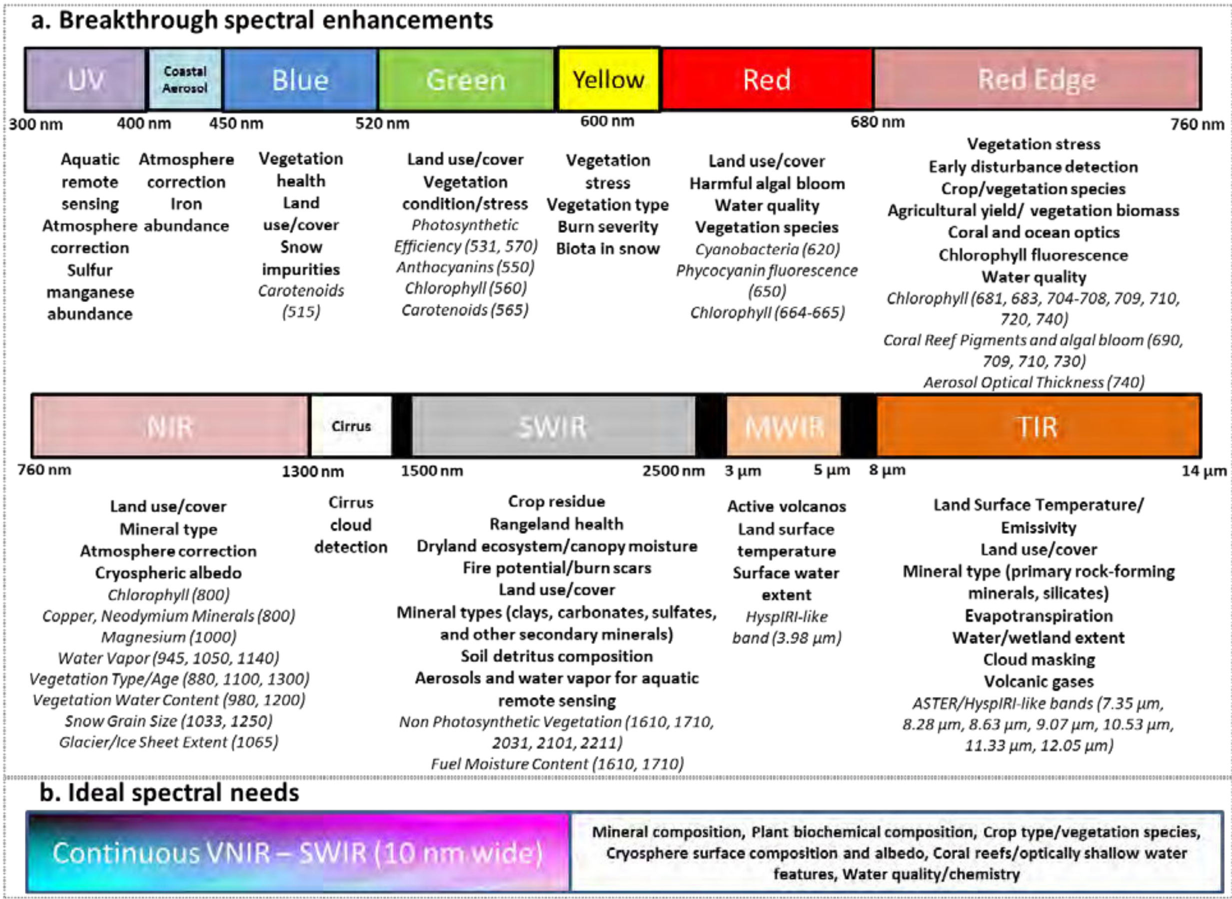


**Figure 4. Major Spectral Enhancements and Example Usage**

Red edge bands can be used to determine vegetation type and assess vegetation condition, as shown in Figure 4. Additional narrow bands in the visible range can provide vegetation functional indices related to chlorophyll, productivity, and other factors related to plant health. For water quality applications, specific narrow bands, particularly in the red and red edge portions of the spectrum, improve a variety of aquatic science measurements, including detection of phycocyanin and harmful algal blooms. Additional near-infrared (NIR) bands can enable snow grain size quantification and broadband albedo estimation. Multiple narrow SWIR bands are needed to resolve cellulose absorption features used in non-photosynthetic vegetation/crop residues mapping and management. Multiple TIR bands can provide greater accuracy in detecting Earth surface thermal anomalies, which in turn improves the accuracy of ST and emissivity products for all potential users and applications. Geologic application users identified the need for multiple narrow visible to short wave infrared (VSWIR) and TIR bands like ASTER and WorldView-3 for mineral and geochemical mapping applications. Ideally, contiguous 10nm-wide bands spanning the entire VSWIR spectral region and 5 to 8 TIR bands can satisfy a wide variety of applications.

An additional set of breakthrough user needs was collected that supports atmospheric correction, cloud mask, generation of SR products, and as auxiliary data needed for the USGS science data ground processing system. These atmospheric correction bands include water vapor, aerosols, and ozone, which if collected as part of a future Landsat capability would enable the Landsat program to be self-sufficient in producing high-level science products without auxiliary data sources and would reduce product latency. Additional details are provided in the USGS user needs study (Wu et al., 2019).

## 3.3 Other Sources of User Needs

### 3.3.1 Landsat Advisory Group Guidance

In 2018, the Landsat Advisory Group (LAG) provided recommendations for future Landsat missions beyond Landsat 9. The LAG concluded that current smallsat or cubesat systems could not meet the research and operational needs of thousands of Landsat users due to lack of spectral bands, calibration stability, or swath width, and therefore Landsat continuity is crucial. For future Landsat missions, the LAG recommended:

- Including emerging technologies to lower cost and increase temporal, spatial, and spectral resolutions;
- Improving Landsat 10 spatial resolution to 10m at a semi-weekly revisit rate at the full Landsat spectral range including 10m thermal;
- The spatial resolution of future Landsats should be no finer than 10m to be compatible with Sentinel-2, to ensure wide swath widths, and to reduce overlap with commercial data;
- Maintaining the continuity of thermal capabilities, and that additional super or hyperspectral thermal imaging options be considered. FF thermal missions and additional clouds, aerosols, vapors, ice and snow bands should be taken into consideration as well;
- Emphasizing the need to ensure interoperability between Landsat and Sentinel; and
- Investigating opportunities for public-private partnerships.

### 3.3.2 2017 Decadal Survey for Earth Science and Applications from Space

In January 2018, the National Academies of Sciences, Engineering, and Medicine released the Decadal Survey for Earth Science and Applications from Space 2017–2027 report.

The Decadal Survey placed Landsat as part of the Program of Record and emphasized the need for SLI to continue providing Landsat-class land imagery through operational Landsat missions to support operational and scientific communities. It recommended increasing synergy between Landsat and other space-based observations, as has been proven with the ESA through cross-calibration and data sharing for Sentinel-2. The 2017 Decadal Survey recommended that SLI consider following the example of Sentinel-2 for a block buy of two imagers with a wider-swath (300 kilometers [km]) and multispectral VSWIR, and thermal data that would increase the equatorial revisit frequency to two days for the HLS data. SLI also needs to recognize the increasing use of commercial systems and data opportunities in the coming decade, and the "Landsat-based" inter-calibration service will be a major contribution of NASA and USGS to the development of the commercial remote sensing sector at 5m or higher spatial scale. The 2017 Decadal Survey recommended that USGS should ensure its process for understanding user needs is continued and enhanced throughout the life of SLI. The 2017 Decadal Survey stated that the studies and surveys that USGS has completed to document the scientific and operational uses of

Landsat should be repeated at appropriate intervals so that progress can be tracked, and these studies should be broadened to incorporate other components of SLI.

### 3.4 User Needs Summary

Viewing the user needs by application area group reveals general patterns (Figure 5). Applications associated with vegetation and land cover are mostly satisfied by the existing Landsat and Sentinel-2 data sets. The primary desire for these areas is higher spatial resolution to image smaller agricultural fields and urban areas, and more frequent temporal coverage to better capture phenology (seasonal greening) and agricultural management. Some applications in terrestrial ecology could also benefit from hyperspectral data for better discrimination of vegetation type and condition. Geology and mineral mapping has a strong need for hyperspectral data to identify specific minerals and associated absorption features, but the temporal frequency can be quite low (one clear image every few years). Water quality is perhaps the most difficult application area to address. This application requires specific narrow spectral bands (or hyperspectral data) in the VNIR as well as near-daily revisit to capture water quality dynamics.

Some unmet user needs can be met by non-SLI missions. For example, the unmet water quality and agriculture application needs are suitable for commercial data use to take advantage of high temporal revisit, high spatial resolution, and increased VNIR spectral capability offered by commercial data in the future. The unmet mineral mapping needs do not require high temporal coverage, and are suitable for targeted airborne hyperspectral data collection, and can also be met by future hyperspectral missions (US or international). Finally, proposed hyperspectral missions from ESA (such as the Copernicus Hyperspectral Imaging Mission [CHIME]) or NASA (such as Surface Biology and Geology [SBG]) may also provide support for geology, water quality, cryosphere, and ecosystem needs.

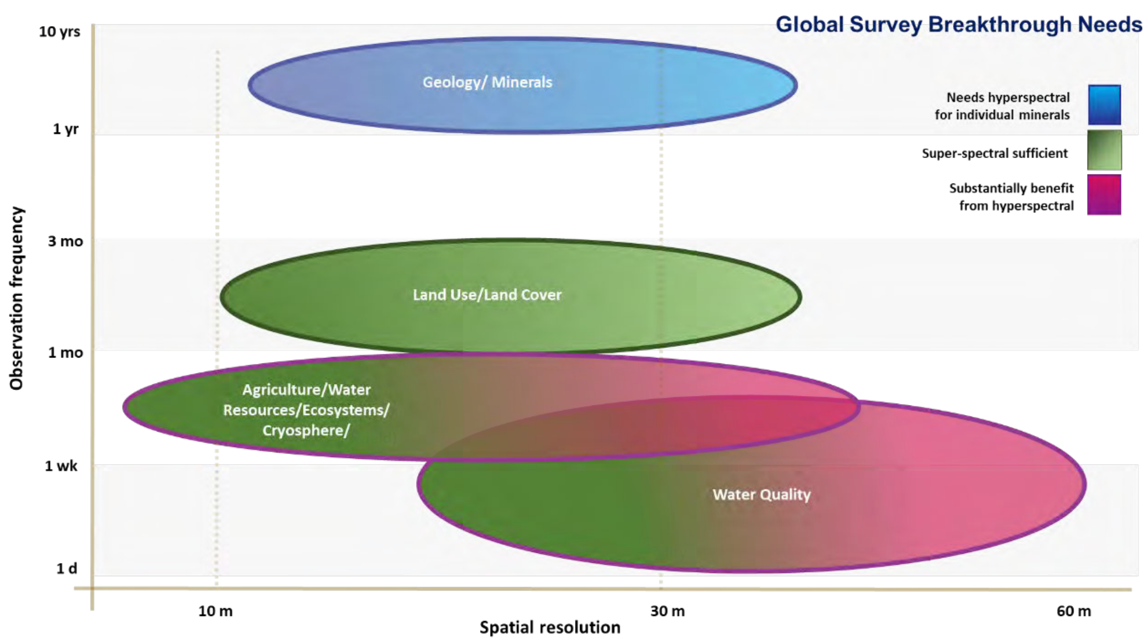


**Figure 5. SLI Spatial-Temporal-Spectral Needs by Application**

# 4 STUDY INPUTS AND LANDSCAPES

Before beginning its series of design cycles (DC), the AST formulated a comprehensive approach to identify and assess the wealth of information and publications pertaining to current and future space-borne land imaging and SLI activities. A primary lesson learned from the 2014 AST was a lack of readily available, pertinent information, including user needs, technology, and commercial landscapes awareness.

The review of background material performed by the AST 2019 directly informed assessment of key questions concerning future trajectory of user needs and science applications, commercial capabilities and market trends, space segment technologies, and ground system trends towards "as a service" capabilities.

The following sections highlight the specific inputs collected and assessed by the AST, as well as the landscapes for potential technology, commercial, and international contributions.

## 4.1 Study Inputs

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# 6 SLI ARCHITECTURE OVERVIEW

## 6.1 System of Systems Approach

In the context of this study, an architecture is defined as a set of additive "system of systems," providing a set of capabilities that collectively meet SLI goals and objectives. Specifically, the AST definition of SLI architecture includes a core SLI component comprised of the needed instruments, platforms, ground system elements, and approaches required to achieve mission requirements and long-term operations. Additionally, this architecture component incorporates risk class (reliability metrics) and business model alternatives (sustainability metrics). Other components are included in the overall architecture approach, including international measurements, such as Copernicus Sentinel-2 and Sentinel-2 Next Generation systems, and commercial capabilities for the purposes of augmenting overall measurements collected for science applications. This is depicted in Figure 13.

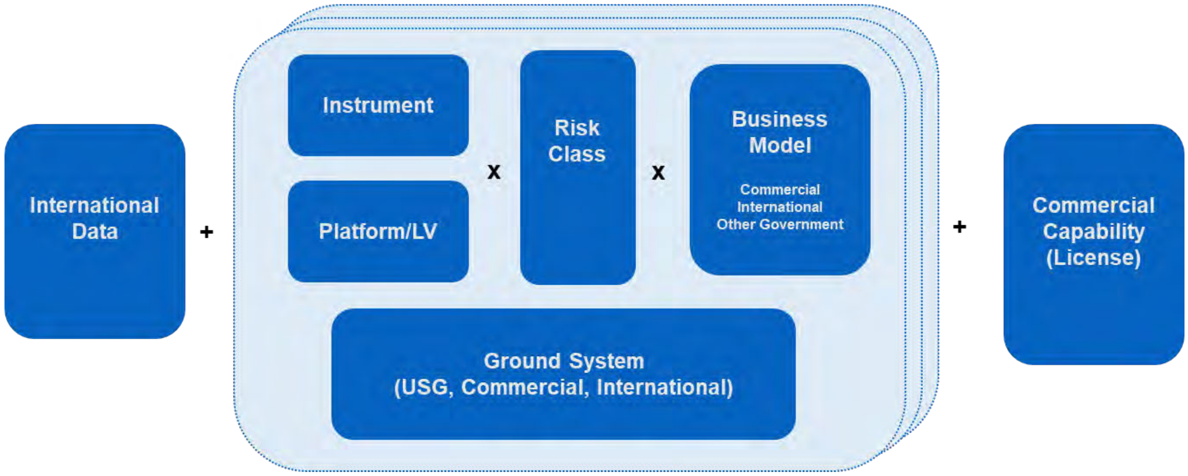


**Figure 13. Architecture Context Definition**

Within SLI, select architectures for consideration may include all or some of these elements, will evolve over time, and are comprised of existing and new capabilities.

Applying this definition, the AST vision for an SLI architecture is described in the figure below. There are multiple architecture components that contribute to the overall set of capabilities and application of new and innovative technologies and business practices over time. The most significant component is the set of SLI global survey mission implementation options. These are described in detail in Section 7. There are other system components that warrant attention and support the core survey mission. As described in Section 4.2.4, international collaboration and partnerships represent considerable opportunities for SLI to improve upon user needs satisfaction, particularly in the areas of requirements harmonization and capability phasing. The EC's Copernicus Program is a prime example of such a potential international partner. As described in Section 4.2.3, augmenting SLI data holdings with targeted sets of commercial data, particularly higher resolution VNIR measurements, may enhance some science applications.

Furthermore, an SLI capability to support relative calibration and characterization to improve data interoperability is included. As described in Section 7.8, this SLI concept provides a transfer function between diverse systems as a reference to the SLI land imaging "gold-standard." Of important note, this concept for a spaceborne transfer radiometer is not a substitute for SLI measurements. With respect to evolving innovative technologies, business models, and public-private partnerships, these often change substantially in just a few short years and therefore must continue to be studied and benefits assessed. Finally, continued collaboration with the Intelligence Community (IC) may yield common or mutually beneficial capability pathways, particularly in the area of data interoperability.

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# 9 CONCLUSION

The five-decade Landsat archive constitutes one of our longest global environmental records, and represents a landmark accomplishment of the US Space Program. Despite the tremendous success of the program for science and applications, the Landsat program has traditionally been implemented one mission at a time, with relatively little advanced planning, and often under programmatic turmoil. The initiation of the Sustainable Land Imaging Program has finally provided a basis for steady, multi-mission planning. The cooperative partnership between NASA and USGS remains essential for executing such a long-term plan.

Landsat has changed the way we view our home planet. A remarkable aspect of the system is that, as the archive lengthens, new applications come to the fore. Slow dynamics of ice sheets, ecosystems, and geologic systems only begin to "appear" when viewed across a multi-decade record of calibrated imagery. Similarly, as new technology evolves, the ability of Landsat to resolve different aspects of land change continues to improve – at finer spatial scales, finer temporal precision, and with new spectral information. While maintenance of data continuity is of paramount importance, advances in space and ground technologies also present new opportunities for SLI.

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In conclusion, NASA and USGS have a unique opportunity to take advantage of developments in space and ground systems to place SLI on a path for success for the next decades. Remarkably, after five decades of success, the best days for the Landsat/SLI program may still be in the future.

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# Appendix B Abbreviations and Acronyms

| | |
|---|---|
| ACMS | Advanced Combined Multispectral Scanner |
| ALOS | Advanced Land Observing Satellite |
| ALTIRS | Advanced Land-imaging Thermal Infrared Sensor |
| ASA | Australian Space Agency |
| ASIC | Application-Specific Integrated Circuit |
| AST | Architecture Study Team |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| ATLIS | Advanced Technology Land Imaging Spectroradiometer |
| AVIRIS | Airborne Visible/Infrared Imaging Spectrometer |
| CAC | Civil Applications Committee |
| CBE | Current Best Estimate |
| CBERS | China–Brazil Earth Resources Satellite |
| CDOM | Colored Dissolved Organic Matter |
| CDOM | Colored Dissolved Organic Matter |
| CHIME | Copernicus Hyperspectral Imaging Mission |
| CHPS | Compact Hyperspectral Prism Spectrometer |
| cm | centimeter |
| CP | Checkpoint |
| d | day |
| DC | Design Cycle |
| DNR | Dynamic Range |
| DOI | Department of Interior |
| EC | European Commission |
| ECOSTRESS | ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station |
| EnMAP | Environmental Mapping and Analysis Program |
| EO-1 | Earth Observing-1 |
| EOL | End of Life |
| EROS | Earth Resources Observation and Science |
| ESA | European Space Agency |
| ESD | Earth Science Division |
| ESPA | Evolved expendable launch vehicle Secondary Payload Adapter |
| ESTO | Earth Science Technology Office |
| ET | Evapotranspiration |
| ETM | Enhanced Thematic Mapper |
| EV | Expected Value |
| FEC | Forward Error-Correction |
| FF | Free Flyer |
| FLIF | Free Lossless Image Format |
| FMA | Four-Mirror Anastigmat |
| FOV | Field of View |
| FPA | Focal Plane Assembly |
| FPGA | Field Programmable Gate Array |

| | |
|---|---|
| FY | Fiscal Year |
| GA | Geoscience Australia |
| GFE | Government Furnished Equipment |
| GSD | Ground Sample Distance |
| GSFC | Goddard Space Flight Center |
| HgCdTe | Mercury Cadmium Telluride |
| HLS | Harmonized Landsat 8-Sentinel-2 |
| HSI | Hyperspectral Imager |
| HyspIRI | Hyperspectral Infrared Imager |
| I&T | Integration and Test |
| IC | Intelligence Community |
| ICESat-2 | Ice, Cloud, and land Elevation Satellite-2 |
| IDL | Instrument Design Laboratory |
| IIP | Instrument Incubator Program |
| IPM | Intelligent Payload Module |
| IR | Infrared |
| IS | Image-Stacking |
| ISRO | Indian Space Research Organisation |
| JPL | Jet Propulsion Laboratory |
| K | Kelvin |
| KF | Key Finding |
| km | kilometer |
| L | Landsat |
| LAG | Landsat Advisory Group |
| LAI | Leaf Area Index |
| LEO | Low-Earth Orbit |
| LMOC | Landsat Multi-Satellite Operations Center |
| LRD | Launch Readiness Date |
| LST | Landsat Science Team |
| LSTM | Land Surface Temperature Monitoring |
| LULC | Land Use/Land Cover |
| LWIR | Longwave Infrared |
| m | meter |
| MIT/LL | Massachusetts Institute of Technology Lincoln Laboratory |
| mo | month |
| MODIS | Moderate-resolution Imaging Spectroradiometer |
| MSI | Multispectral Instrument |
| MURI | Multi-band Radiometric Imager |
| MWIR | Mid-Wave Infrared |
| NASA | National Aeronautics and Space Administration |
| NDVI | Normalized Difference Vegetation Index |
| NIR | Near-Infrared |
| NISAR | NASA-ISRO Synthetic Aperture Radar |
| NLI | National Land Imaging |
| nm | nanometer |

| | |
|---|---|
| NRC | National Research Council |
| O | Option |
| OAP | Orbit Average Power |
| OLI | Operational Land Imager |
| OSC | Observing System Concept |
| PMSEMA | Program Management, Systems Engineering, and Mission Assurance |
| QWIP | Quantum Well Infrared Photodector |
| R | Roadmap |
| RCA-EO | Requirements Capabilities and Analysis for Earth Observation |
| REIS | Reduced Envelope Instrument Study |
| REMI | Reduced Envelope Multispectral Imager |
| RFI | Request for Information |
| RMA | Reference Mission Architecture |
| S | Sentinel |
| S2 | Sentinel-2 |
| SBG | Surface Biology and Geology |
| SCR | Sustainable land imaging Cross-calibration Radiometer |
| SLI | Sustainable Land Imaging |
| SLI-T | Sustainable Land Imaging-Technology |
| SLS | Strained Layer Superlattice |
| SME | Subject Matter Expert |
| SNR | Signal-to-Noise Ratio |
| SR | Surface Reflectance |
| SSR | Solid-State Recorder |
| ST | Surface Temperature |
| SWIR | Shortwave Infrared |
| TBR | To Be Resolved |
| TDI | Time Delay Integration |
| TIR | Thermal Infrared |
| TIRS | Thermal Infrared Sensor |
| TMA | Three-Mirror Anastigmat |
| TRL | Technology Readiness Level |
| UAS | Unmanned Aircraft System |
| US | United States |
| USGS | United States Geological Survey's |
| UV | Ultraviolet |
| VNIR | Visible and Near-Infrared |
| VSWIR | Visible/Near/Shortwave Infrared |
| W | Watt |
| WBS | Work Breakdown Structure |
| wk | week |
| yr | year |

# Appendix C Glossary of Terms

**Landsat data continuity** is defined as the collection, archival, and distribution of image data of the Earth's continents and surrounding coastal regions with the content, quality, and coverage needed to map, monitor, and assess the Earth's characteristics and its response to natural and human-induced change over time.

**User need** refers to the desired measurement or geophysical information derived from calibrated science-quality data and associated attributes.

**Cloud-free observation frequency** is defined as the interval between two dates of cloud-free data, which is distinct from the satellite revisit frequency.

**Satellite revisit frequency** is the frequency at which a given sensor can theoretically image a location on Earth, without considering usability factors such as geographic location or atmospheric condition including clouds, time of year, and the application of the data.

**Science quality data** means that the data collected by Landsat are not just pictures from space; they represent physical quantities of spectral reflectance and temperature that may be tracked through time.

***Minimum*** user need refers to the most basic data needed by a given application SME for their project or application (generally biased towards current capabilities).

***Breakthrough*** user need represents sufficiently improved data that would, in the best judgement of the SME, result in a significant improvement in the effectiveness of the data for their application.

***Threshold*** level draft SLI requirement is defined as the minimally acceptable performance level below which SLI fails to meet science application needs.

***Goal*** level draft SLI requirement is defined as the desirable level that greatly enhances the performance for scientific applications and remains in scope with the SLI global survey mission objective.

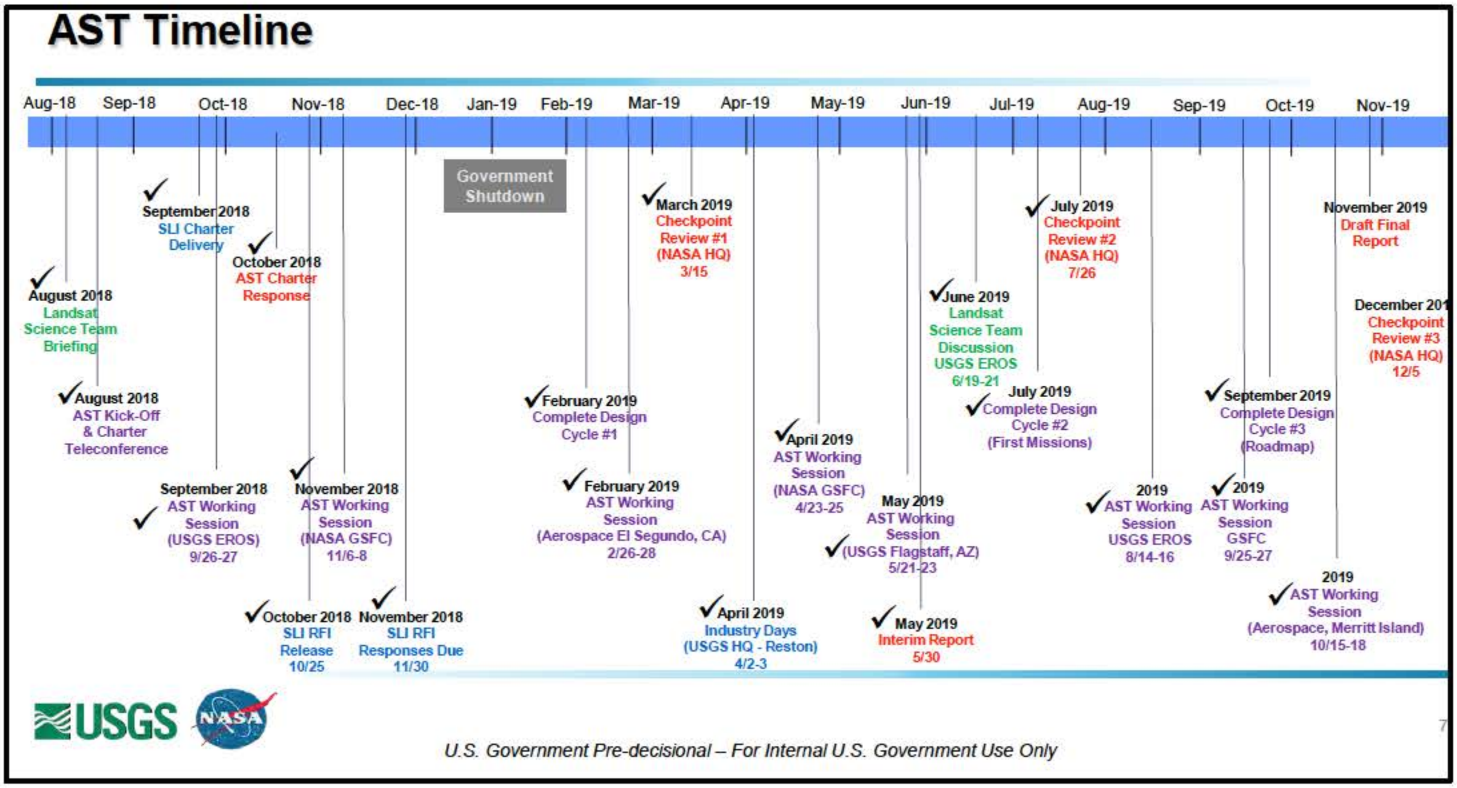
The *radiometric sensitivity* is expressed as per-band signal-to-noise for the reflective bands or noise-equivalent temperature change for the thermal infrared bands.

Absolute *radiometric accuracy* requires either an uncertainty of less than 5 percent with respect to absolute spectral radiance or less than 3 percent with respect to top-of-atmosphere reflectance in the case of images for reflective spectral bands, and less than 2 percent with respect to at-sensor spectral radiance in the case of thermal bands.

*Radiometric stability* governs the allowable variability in instrument response over timescales of single orbits to mission lifetime.

The **f-number** (*f*/N) of an optical system is the ratio of the system's focal length to the diameter of the entrance pupil ("clear aperture").

# Appendix D AST Study Timeline



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