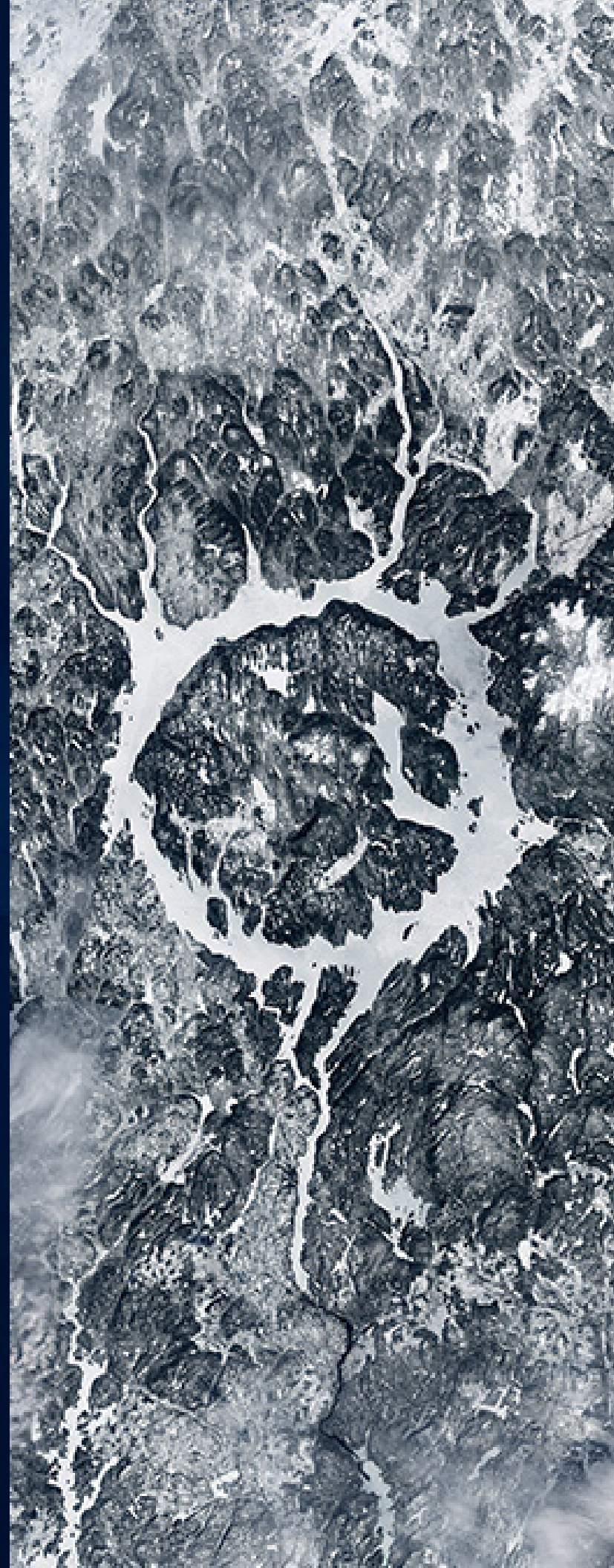


National Aeronautics and
Space Administration



CORERO

Challenges and
Opportunities for
Research in ESI



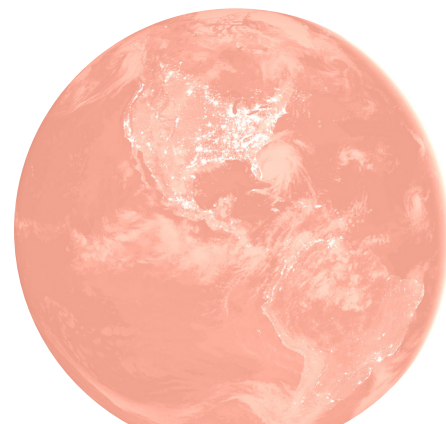
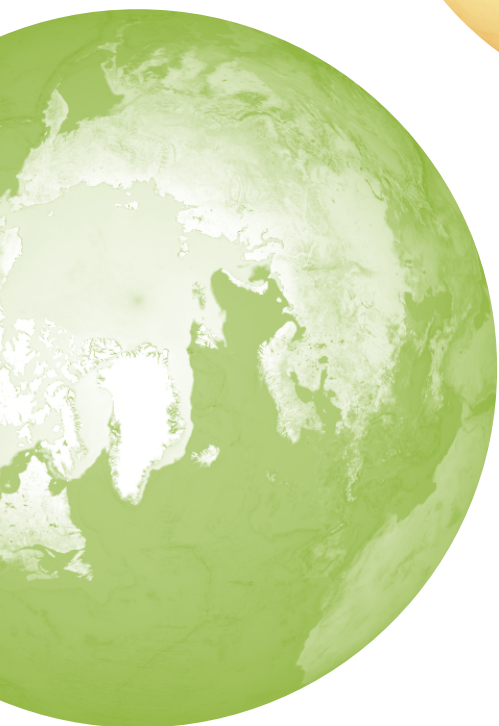
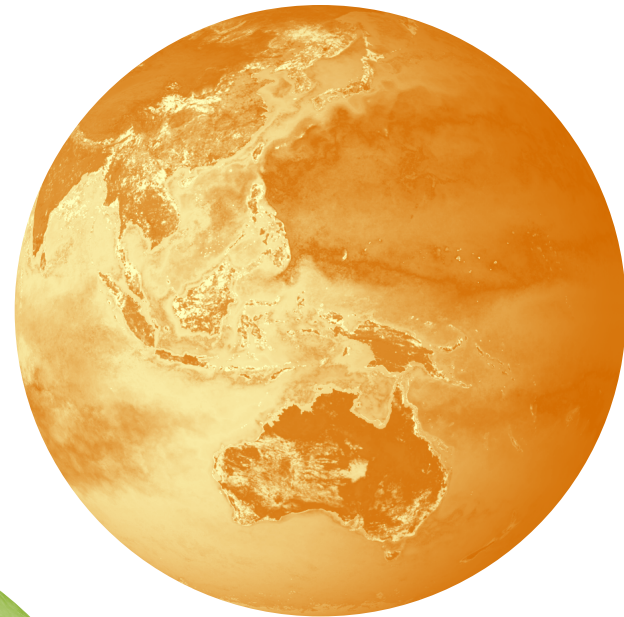
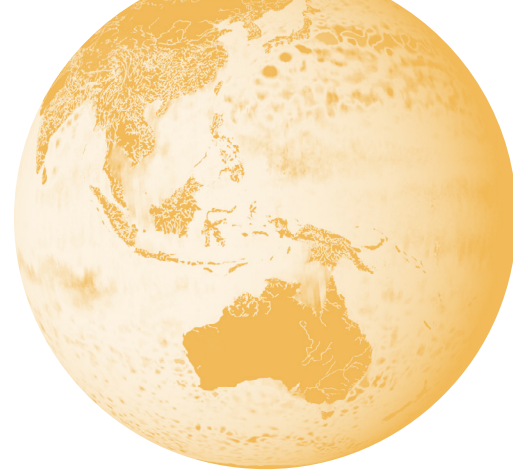
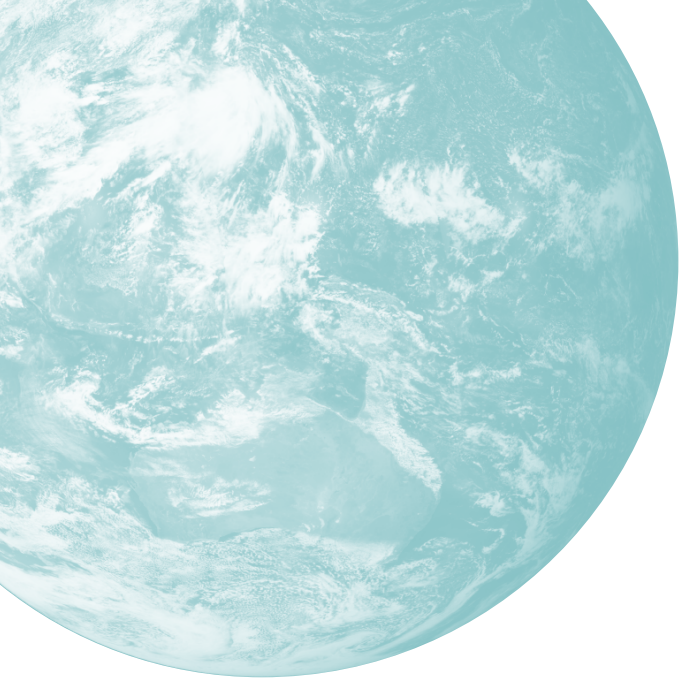
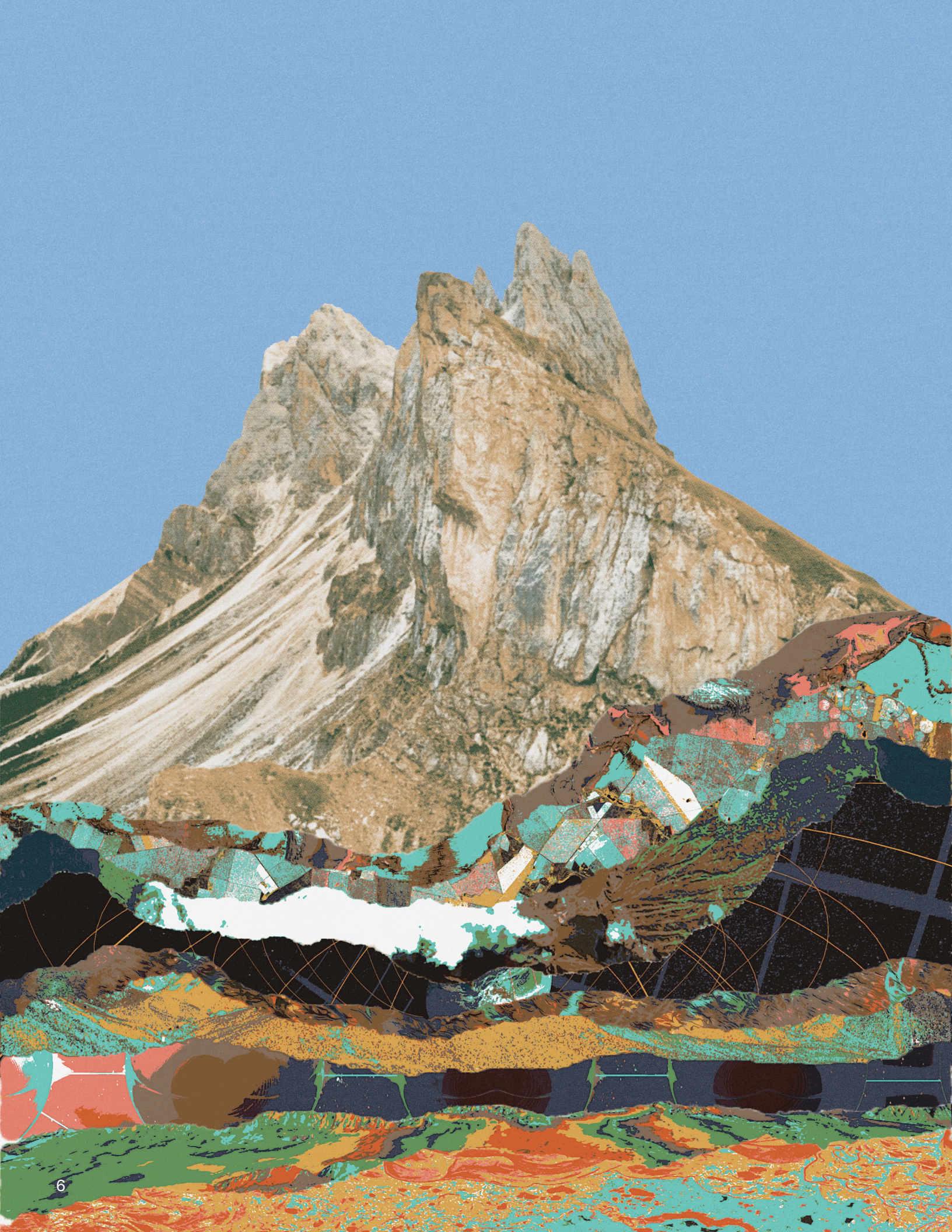


TABLE OF CONTENTS

Challenges and Opportunities for Research in ESI

Executive Summary	6
Introduction	8
Chapter 1: Key questions within the Earth Surface and Interior system	10
1.1 Surface and Near-Surface Processes	12
1.2 Tectonics and Fault Systems	20
1.3 Volcanic Systems	30
1.4 Earth's Interior Processes and Structure	38
1.5 Societal Benefits	44
Chapter 2: Observational Technology, Information Infrastructure, and Talent Pathways	54
2.1 Observational Technology	56
2.2 Modeling and Analysis Infrastructure	66
2.3 Development of Collaborations, Workforce, and Resilience	72
Chapter 3: Synopsis	80
Appendices	84



Executive Summary

This report synthesizes the state of the science and formulates key emerging challenges and opportunities in NASA's Earth Surface and Interior (ESI) research program. We show how this program has made critical contributions to the nation's economy, health, and welfare. Callouts interspersed between the subchapters highlight a sampling of NASA's exciting advances in observational technology. Chapter 1 details recent scientific achievements and discoveries. Chapter 2 describes NASA's involvement and support for the enabling technologies that led to these achievements and discoveries.

Chapter 1 is organized as follows: A diverse range of long-term, high-resolution geodetic datasets have allowed researchers to observe and quantify the response of the solid Earth to mass changes across a wide range of temporal and spatial scales, enabling forecasts of the response to flooding, droughts, coastal subsidence, and other hazards, as well as improved models of the physical properties of Earth's interior. (Ch. 1.1)

New observations of the spatial complexity of fault ruptures have driven the development of modeling approaches that can simulate such earthquakes and the other key processes acting in tectonically active regions, including diffuse damage zones, off-fault deformation, and transient signals, and leading to more sophisticated models of fault friction, stress transfer, crustal rheology and the behaviors that drive earthquake clustering. These observations and models are now integrated into the immediate post-earthquake response, providing improved situational awareness and forecasting of likely aftershocks. (Ch. 1.2)

Recent volcanic eruptions and the wide-ranging impacts of magmatic activity have underscored the need for sustained multivariate global observations (e.g., deformation, gas and aerosol emissions, thermal activity). These are

needed to illuminate the processes that drive volcanoes and to understand their cascading sets of hazards (Ch 1.3)

The discovery and characterization of magnetohydrodynamic waves in the Earth's outer core has revolutionized understanding of the dynamic coupling between the core and mantle, which governs Earth's heat distribution, plate tectonics, and the generation of magnetic field. The ongoing collection of decades-long GNSS, gravity and magnetic observations continues to be critical to the development of models of mantle rheology, elasticity, and crustal density variations. (Ch 1.4)

ESI research is essential for societal resilience and economic sustainability. The complex, highly coupled system of ESI states, changes, and feedback is best addressed by integrated multi-sensor, multi-platform constellation data and interdisciplinary collaborations. These efforts have enabled, among other accomplishments, the early detection of deformation and gas emissions associated with volcanic instability, the assessment of groundwater resources and their changes over time, and the mapping of critical mineral and energy resources. (Ch 1.5)

Chapter 2 is organized as follows. Chapter 2.1 describes advances in measurement systems, definition of the terrestrial reference frame, and methods for observing variations in the shape and radiative properties of the Earth's surface, as well as in Earth's gravity and magnetic fields. Chapter 2.2 describes the modeling and analysis advances that continue to be necessary to take full advantage of NASA's observational data, including high performance computing, data assimilation strategies, full-physics models, and the support of the human capacity to engage with them. Chapter 2.3 discusses how NASA's Earth Science to Action Strategy aligns with the goals and aspirations set out within this document, and highlights the need for Open Data and tools, stakeholder engagement, and the production of higher-order data products. A listing of all acronyms is provided after Chapter 3, which summarizes this document as a whole.

This document celebrates the successes of NASA's investments, highlights the community's ambition to power another decade of global scientific discovery and leadership, and identifies priority areas for investment to support these aspirations.

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). The colors represent elevation levels: purple for low, green and yellow for medium, and red/white for high. NASA

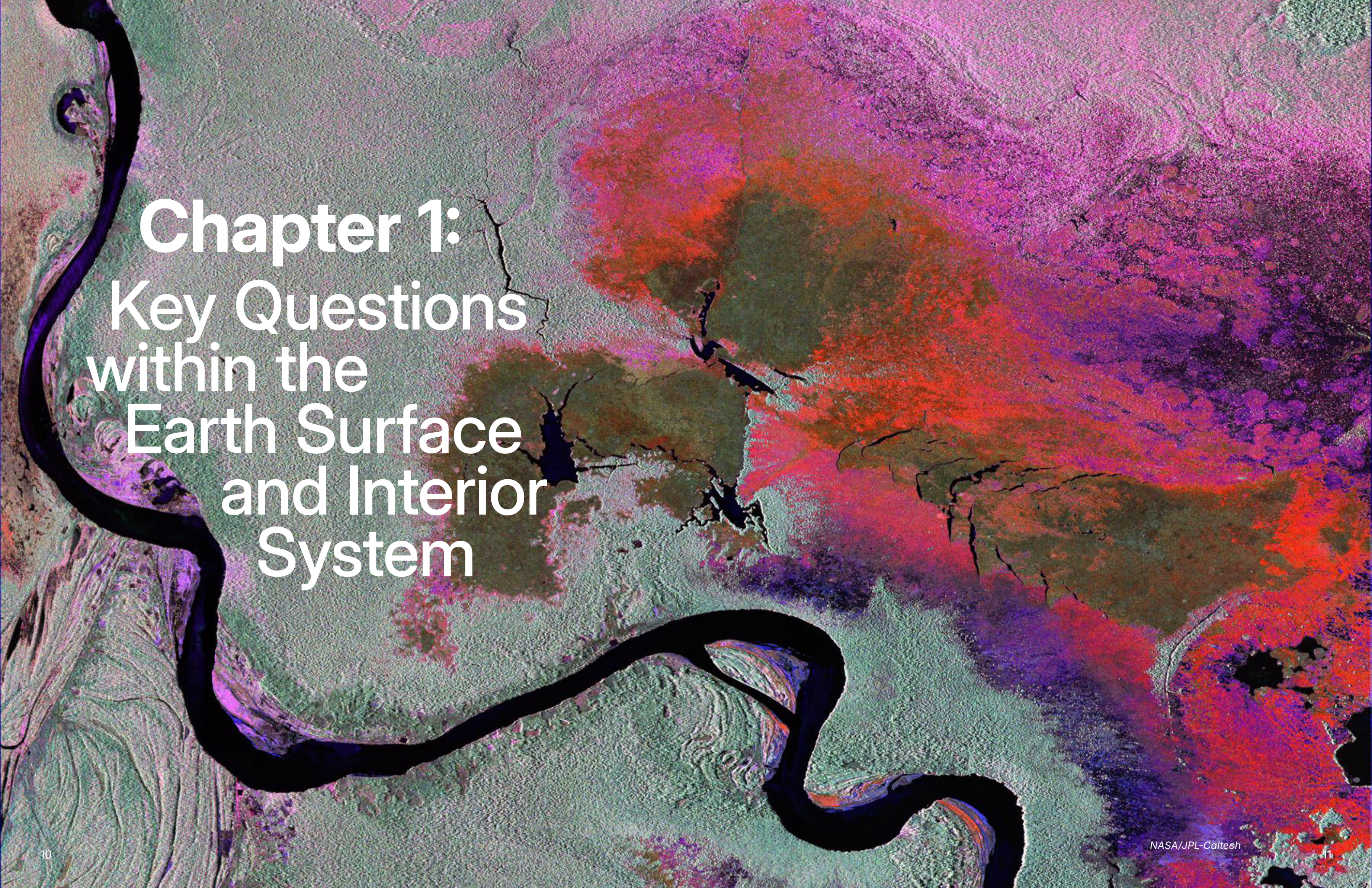
Introduction

The National Aeronautics and Space Administration (NASA) has long been at the leading edge of humanity's efforts to understand the Earth system while building a stronger, more informed and more resilient society. NASA designs and deploys a wide range of advanced remote-sensing technologies on satellite, sub-orbital, and ground-based platforms. NASA invests in the human capital, engineering and scientific developments necessary to make full use of the observations that these produce. NASA's platforms provide data that yield critical insights into the inner workings of our planet, the dynamic processes that impact its surface and interior, and the intricate interactions between them.

This document is a collaborative effort by members of the domestic Earth Surface and Interior community. It includes those who practice Solid-Earth science, with participants from academic institutions, state and federal government agencies, and private industry, reflecting a broad and integrated perspective on the key scientific challenges and their relevance to society. A committee of experts representing the research areas within ESI organized a September 2024 community workshop, solicited whitepapers, and wrote this summary document. This document celebrates the successes of NASA's investments, highlights the community's ambition to power another decade of global scientific discovery and leadership, and identifies priority areas for investment to support these aspirations.

Our report builds upon the recommendations of earlier reports in light of the scientific progress and new capabilities realized since their publication, and incorporates feedback collected from the Earth Science research community. Key previous reports include the 1989 Coolfont conference report, the 2002 *"Solid Earth Science Working Group (SESWG)"*, the 2016 *"Challenges and Opportunities for Research in ESI (CORE)"*, the National Academies' 2017-2027 Decadal Survey of Earth Science *"Thriving on our Changing Planet: A Decadal Survey for Earth Observation from Space"* (ESAS 2017), and the 2020 *"Evolving Geodetic Infrastructure to Meet New Scientific Needs."* This report focuses on science advancements since the 2016 CORE report, with an eye towards the anticipated frontiers for discovery over the next decade. The report committee also recognizes that these science advancements build on datasets and capabilities that date back much further in time.

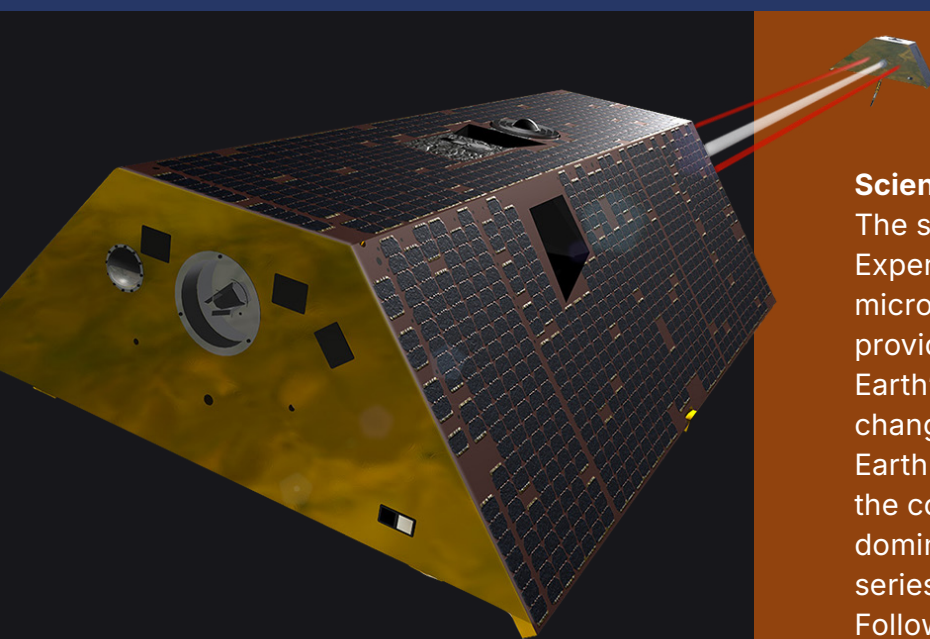
The science questions highlighted in this document intersect with critical processes within the hydrosphere, biosphere, cryosphere, and atmosphere. This document also highlights the critical role that NASA and the ESI community have played in advancing science of the Earth's Surface and Interior, in equal measure through maintaining the necessary instrumentation and infrastructure over the decadal timescales that are required for scientific advances, and in the continuous development of new technologies and methods.



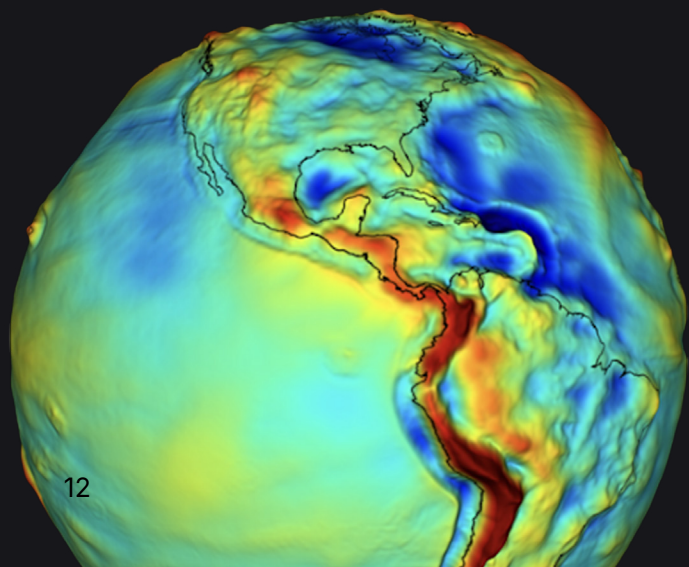
Chapter 1: Key Questions within the Earth Surface and Interior System

GRACE

Gravity Recovery and Climate
Experiment Follow-On



By measuring gravity anomalies, **GRACE** showed how mass is distributed around the planet and how it varies over time. Data from the **GRACE** satellites is an important tool for studying Earth's ocean, geology, and climate.



Science Goals:

The series of Gravity Recovery and Climate Experiment (GRACE) missions use intersatellite microwave and laser ranging systems to provide month-to-month observations of Earth's gravity field, tracking surface mass change across the planet. Studies of solid Earth behavior often require mitigation of the contribution from hydrology, which can dominate the observed signals. The mission series includes GRACE (NASA-DLR), GRACE Follow-On (NASA-GFZ), and the forthcoming GRACE-Continuity (NASA-DLR), providing an unparalleled, unifying, and continuous record of Earth's dynamic mass changes for over two decades.

Earthquakes and mass change:

Gravity measurements from the GRACE family of missions have captured long-wavelength signals from major earthquakes ($M_w \geq 8.0$), allowing estimation of their size, fault geometry, and analysis of the postseismic response. Spaceborne gravity observations complement data from GNSS and InSAR, particularly for large subduction zone events where much of the displacement occurs offshore. Gravity data has also provided insight into how rock compressibility changes with depth, through the comparison of shallow and intermediate depth events.

1.1 Surface and Near-Surface Processes

How do surface and near-surface processes interact with the rest of the solid Earth?

Key Questions

- What does observed solid Earth displacement and associated models of deformation tell us about mass redistribution and fluid flow at the surface across spatio-temporal scales?
- How does the solid Earth store and facilitate the transport of water within soils, aquifers, and other subsurface reservoirs?
- How are hazards such as landslides and sea level rise impacted by interactions between the solid Earth and mass changes in glaciers, ice sheets and permafrost?
- How do anthropogenic activities affect the surface and near-surface?
- How can we mitigate the effects of surface and near-surface signals, which are often large compared to the signals of interest described in the other chapters of this document?



The solid Earth

both influences

and responds to

other Earth Systems

Past Decade

The solid Earth both influences and responds to other Earth systems, including the atmosphere, hydrosphere, cryosphere, biosphere, and anthroposphere.

Investigations of the interactions between processes occurring at or near Earth's surface – including within soil layers, groundwater aquifers, and the shallow crust – inform assessments of natural hazards while also advancing understanding of geodynamics, climate science, hydrology, geomorphology, and ecology. Given that the response of the solid Earth to surface-mass redistribution depends on its rheology, geodetic observations of Earth's deformation also offer insights into the structure and dynamics of Earth's interior (Chapter 1.4). Displacement signals associated with hydrology are also often large relative to tectonic and volcanic signals (Chapters 1.2-1.3). Studying hydrologic signals while remaining sensitive to other types of deformation requires that we better understand and model the contribution of hydrologic variability to geodetic observations at a wide range of temporal and spatial scales.

Over the past decade, significant improvements in satellite-based geodetic monitoring, data analysis, and computational modeling have transformed our understanding of the crustal deformation, surface processes, and hazards associated with the response of the solid Earth to changes in loading and water storage. For

example, a suite of Interferometric Synthetic Aperture Radar (InSAR) missions – including Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) and satellite-based SAR platforms – has provided broad temporal and geographic coverage supporting identification and assessment of landslides and evaluation of soil moisture content. Thousands of Global Navigation Satellite System (GNSS) stations permanently deployed worldwide continuously record ground deformation due to mass redistributions within and across Earth systems (e.g., groundwater management, watershed dynamics, glacial mass loss), measuring horizontal and vertical displacement variations from several millimeters to a few centimeters over timescales of days to months. Millimeter-scale daily positioning precision and improved spatial resolution have enabled more detailed investigations of both slow, gradual surface processes (e.g., those driven by groundwater flow and sea-level rise), as well as those associated with more sudden displacements (e.g., those caused by earthquakes, storms, and landslides). The GRACE-FO mission has illuminated regional trends in freshwater storage around the globe, and is now used operationally by stakeholders seeking to better manage groundwater resources.

Advances over the last decade have been driven by improvements in data quality and by the significant expansion of the length of these data records. Long and continuous data records are critical for advancing multi-year and decadal science, including monitoring climate-driven processes, disentangling overlapping



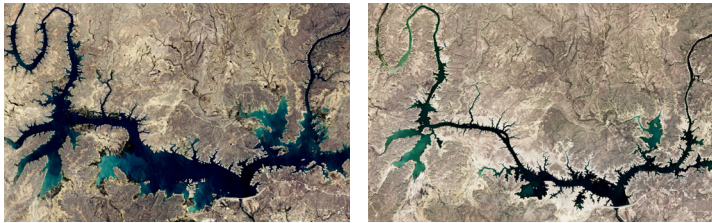
An aerial view of Strathgordon Dam in Tasmania. Adobe Stock

signals, and studying time-dependent rheology. In the western United States, for example, combinations of data from the GRACE suite of missions, continuous GNSS, and InSAR observations, all spanning more than two decades, facilitated impactful, quantitative analyses of aquifer storage and associated solid-Earth deformation driven by the severe 2011-2017 drought in California and have fundamentally transformed the understanding of water storage in soil and aquifers. The longer InSAR and GNSS data records are also advancing our understanding of sustained tectonic and non-tectonic vertical land motions in coastal areas, which contribute to relative sea-level change and add to the increasing flooding and tsunami inundation hazard impacting coastal cities.

Present Day

Today, our community continues to build on the exciting progress enabled by global monitoring of solid-Earth deformation across a range of temporal and spatial scales. By leveraging geodetic data from ground networks, airborne, and satellite-based observations (including the newly launched NASA-ISRO SAR mission, NISAR), along with emerging tools being developed by the closely-related seismology community (e.g., Distributed Acoustic Sensing), we have gained new insights into critical processes that impact society. These include the response of watersheds to heavy precipitation, the permanent loss of aquifer storage capacity during prolonged groundwater withdrawal, and the loss of fresh water to evaporation and runoff. Weekly groundwater and soil moisture drought indicators are now routinely produced based on GRACE data and provide essential and unique information about changing groundwater resource availability, as well as early warning for emergent drought and flood conditions. Additionally, high-frequency (daily and sub-daily) measurements of Earth deformation are creating new opportunities to improve assessments of flooding and drought hazards. By complementing traditional methods – particularly by providing enhanced spatial and temporal resolution – geodetic and seismic approaches are advancing the monitoring and management of water resources.

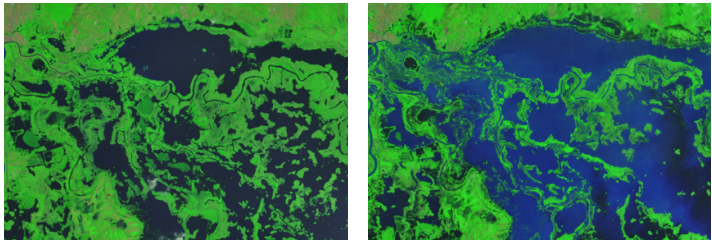
In recent years, geodetic data combined with other remote-sensing observations have been leveraged to track the effects of hurricanes



The Amistad Reservoir, which straddles the U.S.-Mexico border, has been strained by prolonged regional drought and population growth. In these images, Landsat captured the decline in water level from 2004 (left) to 2024 (right). NASA/USGS Landsat

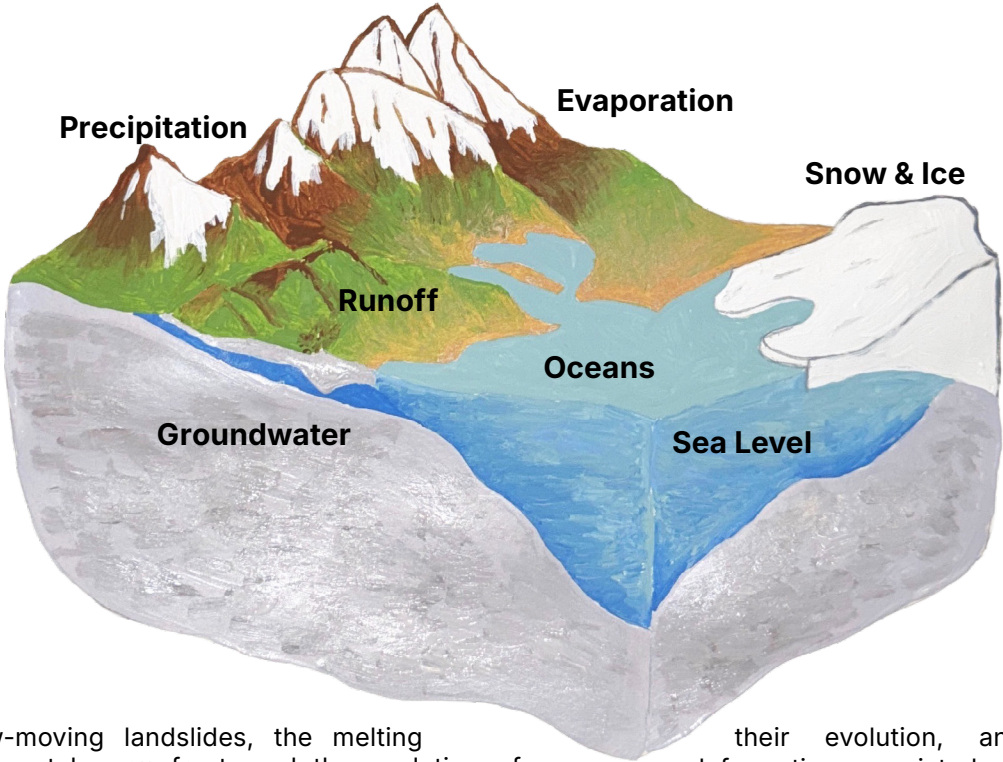


Landsat 8 captured this image of where the Zambezi river drains into the Indian Ocean on August 29, 2013. The last few decades, the Delta has been impacted by hydropower dams upstream, lessening the flow of the river and affecting the ecosystems, sediment flow, and wetland susceptibility to fire. NASA/USGS Landsat



Villages and farmland were swamped after unusually heavy rains pushed the Sinú River over its banks, seen in these false color images taken by Landsat 9 on January 23, 2026 (left) and after the flooding on February 9, 2026 (right). NASA/USGS Landsat

and atmospheric rivers on Earth's surface and interior. Yet further advancements in temporal and spatial resolution, data processing techniques, and interdisciplinary modeling could significantly elevate their scientific and societal impact. Enhancements in these areas could improve precision, operationalize hazard forecasts, and deepen understanding of Earth's interior structure, water cycle, and climate, especially through greater integration with independent datasets. Other emerging technologies, including drones and unmanned aerial vehicles (UAV), are enabling new research into finer-scale surface and near-surface processes and interactions, including erosion associated with heavy rainfall, the dynamics of



slow-moving landslides, the melting of coastal permafrost, and the evolution of mountain glaciers.

Significant advances have also been made in model development and in the analysis of cross-disciplinary data. Rapid increases in computational power and storage are enabling more sophisticated representations of solid Earth structure and deformation, including the effects of lateral structural contrasts on surface loading and the effects of poroelasticity on aquifer behavior. New developments in inverse modeling approaches, machine learning and artificial intelligence are also creating new opportunities to discover subtle patterns in data – such as time-series anomalies and trends, as well as spatial anomaly detection – and differentiate between superimposed geophysical and non-geophysical signals.

The Next Decade

Key challenges and opportunities for the next decade related to surface and near-surface processes and interactions involve the acquisition of data and development of analysis frameworks that support the scientific priorities described above:

Continuous Data Records Spanning Decades: NASA supports several critical observational platforms that enable the monitoring of global mass redistributions, surface properties and

their evolution, and solid-Earth deformation associated with surface and near-surface dynamics. Long and continuous data records are essential for evaluating long-term processes and interactions – both cyclical and secular – such as water loss during extended droughts and rates of glacial mass loss driven by both natural and anthropogenic factors.

Long and continuous data records are essential for evaluating long-term processes and interactions.

Processes occurring at and near Earth's surface span a wide range of timescales, from sub-daily to multi-decadal and beyond. Continued support of the collection of long-term records help researchers untangle these overlapping signals so that they can understand the relative contributions of tectonic activity, glacial isostatic adjustment, and drought-related solid-Earth deformation.

Sub-Millimeter Precision of Solid-Earth Deformation Monitoring: Further improvements in the precision of solid-Earth deformation measurements would significantly advance geodetic insights into solid-Earth, water, and climate sciences. An ambitious yet achievable target for the next decade is precision on the order of 0.1 mm,

which would allow separation of the various signals that contribute to geodetic time series at the level required to advance geodynamic studies, hazard assessments, and to generate high-quality groundwater and drought assessments for water-resource management and decision-making.

An ambitious yet achievable target for the next decade is precision on the order of 0.1 mm.

Sub-Daily Temporal Resolution of Solid-Earth Deformation Monitoring:

Continuous and high-rate geodetic monitoring, which exists at a subset of stations in the United States and globally, has significantly advanced our understanding of many surface processes and their interactions. Many geodetic data products are still produced at daily or longer temporal resolutions, even though the production of 5-minute or better position time series has been demonstrated. Improvements in geodetic measurement precision and processing/storage infrastructure that enable increases in the temporal resolution of routinely processed GNSS position series – from daily to hourly, or even to second-level resolution – would significantly improve monitoring of the solid Earth’s response to hurricanes, atmospheric rivers, flooding, landslides, and glacier dynamics. Production of such products in near-real time, as is already done at some sites for earthquake early warning applications, would also drive advances in operational forecasting and early warning systems.

Furthermore, enhanced sub-daily precision of GNSS positions would advance studies of Earth’s structure and rheology, particularly those focused on deformation processes occurring at sub-daily tidal periods.

Shortening the repeat times of high spatial resolution observations, such as InSAR, could further expand our capability to observe and analyze the effects of heterogeneous mass redistribution in the hydrosphere at short spatial scales and over short periods (e.g., groundwater flow, extreme weather events, landslides, glacier dynamics).

Enhanced sub-daily precision of GNSS positions would advance studies of Earth’s structure and rheology.

Enhanced Geodetic Resolution at Local and Meso Scales:

Improvements to the spatial resolution of geodetic data (including position and gravity observations) support a wide range of the scientific priorities discussed in this section. Observations at a higher spatial resolution (meter or sub-meter scale for InSAR, few km to 10’s of km for GNSS) can better capture spatial heterogeneities in snowpack, soil moisture, and groundwater storage while also enabling more accurate assessments of surface water reservoirs, glacier dynamics, and erosion. Moreover, high-spatial-resolution data are required to assess fine-scale surface and near-surface land-surface changes, such as land subsidence and sinkholes, that can affect



A GNET station weighs ice mass change in Greenland. Cornell University/Mike Willis

transportation, sewage, and drainage systems and water-supply networks.

High-spatial-resolution data are required to assess fine-scale surface and near-surface land-surface changes.

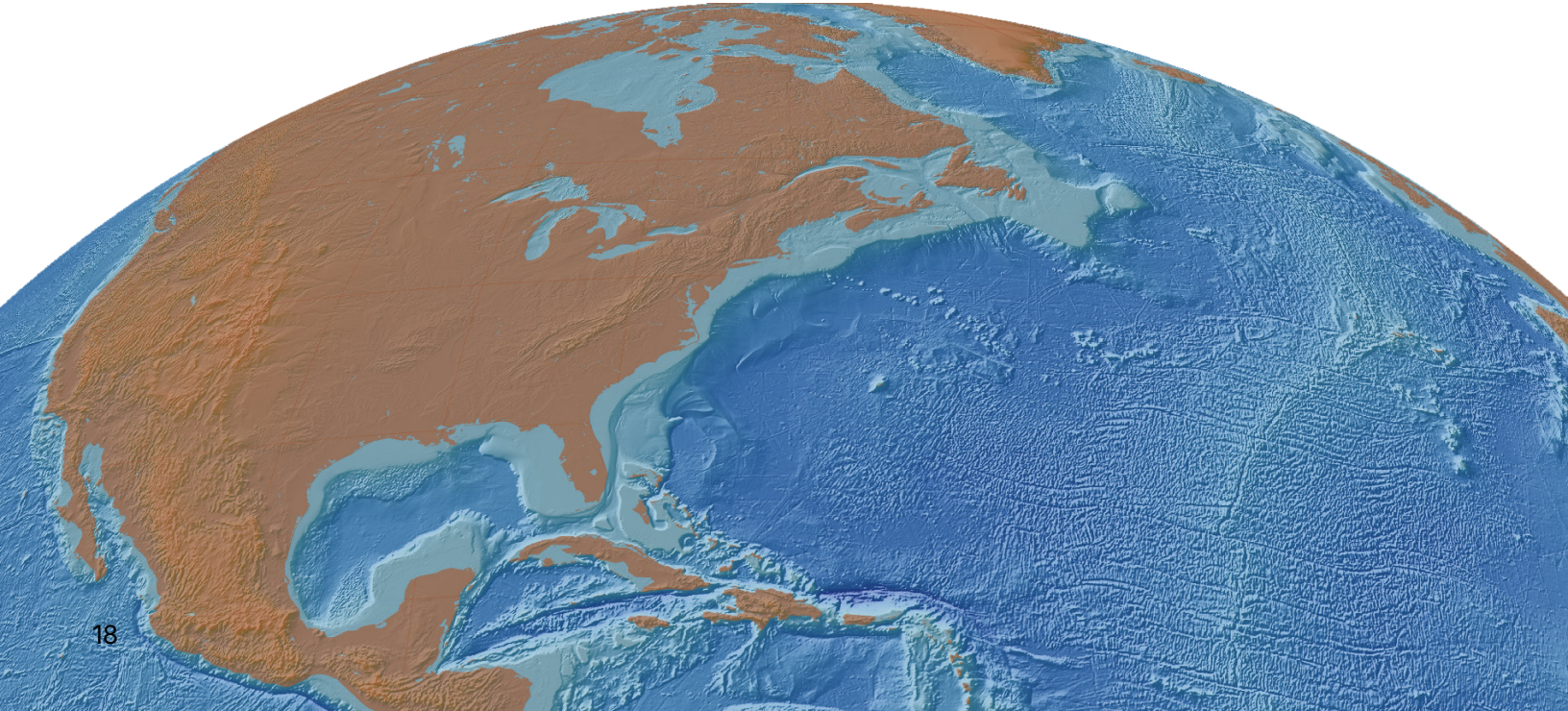
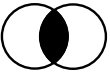
Investments in analytical technologies:

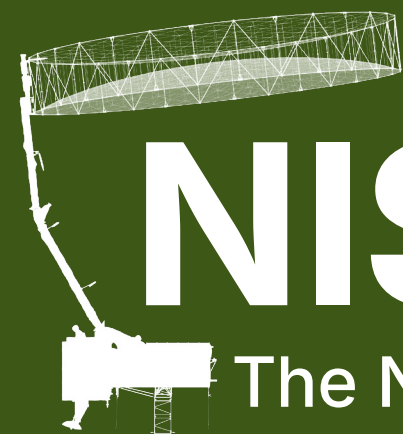
Cloud storage and modeling infrastructure, data science, machine learning, and artificial intelligence will be essential to achieving the key observational opportunities defined above: refining the separation of overlapping processes, identifying subtle patterns across diverse data streams, and connecting observations to the complex rheological behaviors that link surface processes to stress and strain of the solid Earth.

For example, in many subsurface systems where fluids are involved (e.g., groundwater or geothermal reservoirs) deformation driven by changes in pore fluid pressure and thermo-mechanical processes is superimposed on

deformation due to variations in loading. To fully leverage the diverse and complementary datasets that can inform such studies, it is critical to develop numerical methods that can ingest and assimilate a wide range of data types (such as GNSS, gravity, InSAR, and DAS) and that are consistent with the state-of-the-art geophysical and hydrological models. This latter task requires the development of stronger connections across disciplines and specialties (e.g., connecting modeling experts with data experts; connecting hydrologists with geodesists).

Refining the separation of overlapping processes, identifying subtle patterns across diverse data streams, and connecting observations to the complex rheological behaviors that link surface processes to stress and strain of the solid Earth.





NISAR

NISAR measures Earth's changing ecosystems, dynamic surfaces, and ice masses providing information about biomass, natural hazards, sea level rise, and groundwater, and will support a host of other applications.

The NASA-ISRO SAR (NISAR) Mission

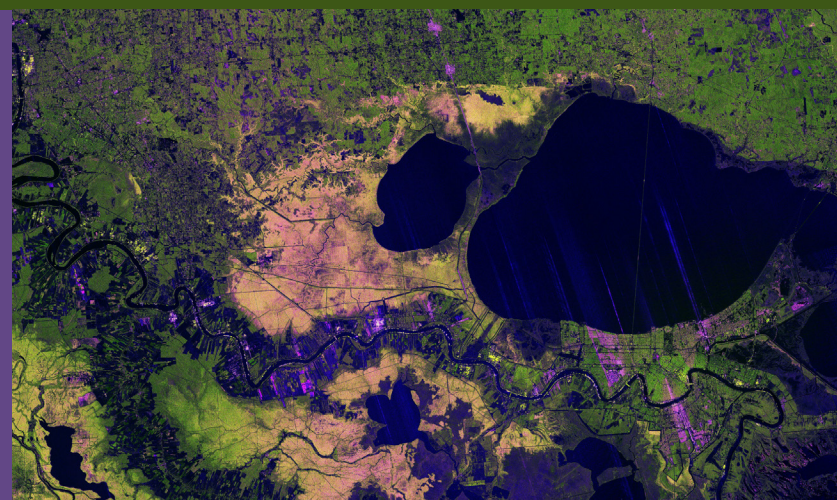
Science Goals:

The NASA-ISRO SAR (NISAR) mission uses microwave imagery to measure the changing surface of our dynamic planet. NISAR provides information about the entire seismic cycle, volcanic activity, landslides, sea level rise, changes in water storage, and other natural hazards. NISAR employs two different microwave wavelengths (S- and L-band) and observes Earth's land and ice-covered surfaces globally every 12 days from 2 directions over its baseline 3-year mission, and also observes the sea surface near coastlines and in response to events offshore. Imagery before, after and during the evolution of an event is required for InSAR, necessitating persistent, global observations.

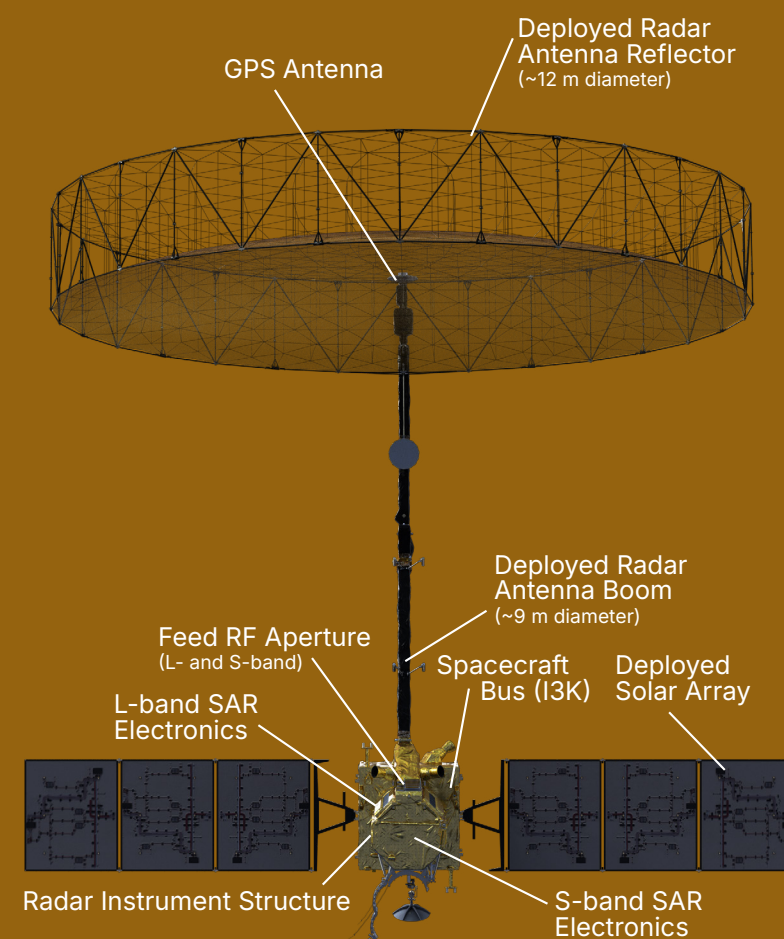
Expanding the reach of InSAR:

NISAR's dense time series and the high coherence achievable with L-band imagery extends solid Earth research into even heavily vegetated regions that have thwarted InSAR research in the past. NISAR's Open Data/Science policies and production of accessible, analysis-ready data expand the range of users who can use NISAR data in their research and applications. In the regions where both S- and L-band data are acquired, often at multiple polarizations, new frontiers of InSAR data analysis will be opened for researchers to explore.

This false-color NISAR image depicts an eruption in Ethiopia. NASA/JPL-Caltech



NISAR captured this image of the Mississippi River Delta region in southeastern Louisiana on Nov. 29, 2025. NASA/JPL-Caltech

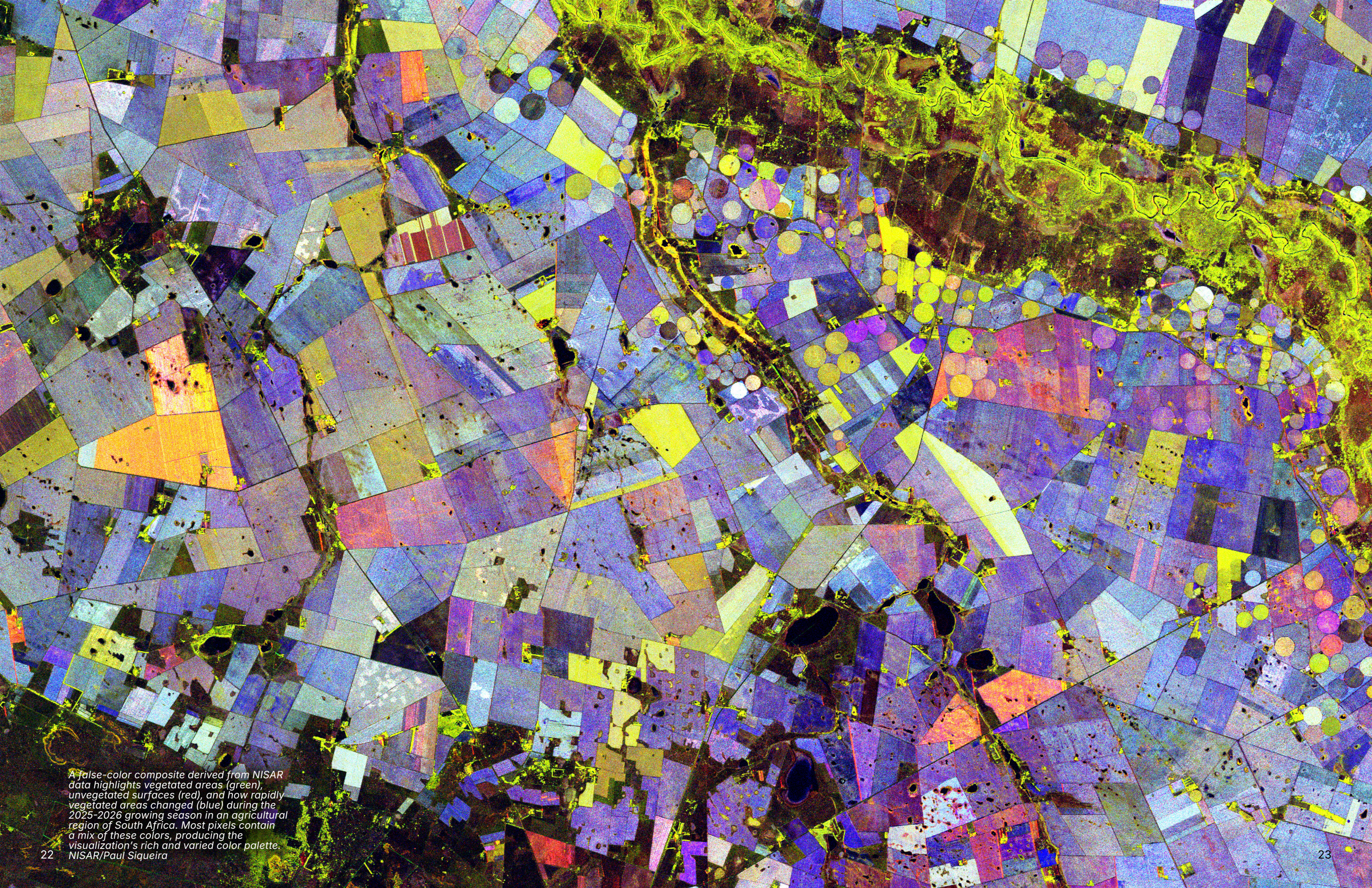


1.2 Tectonics and Fault Systems

What is the nature of crustal/mantle deformation and the implications for related hazards?

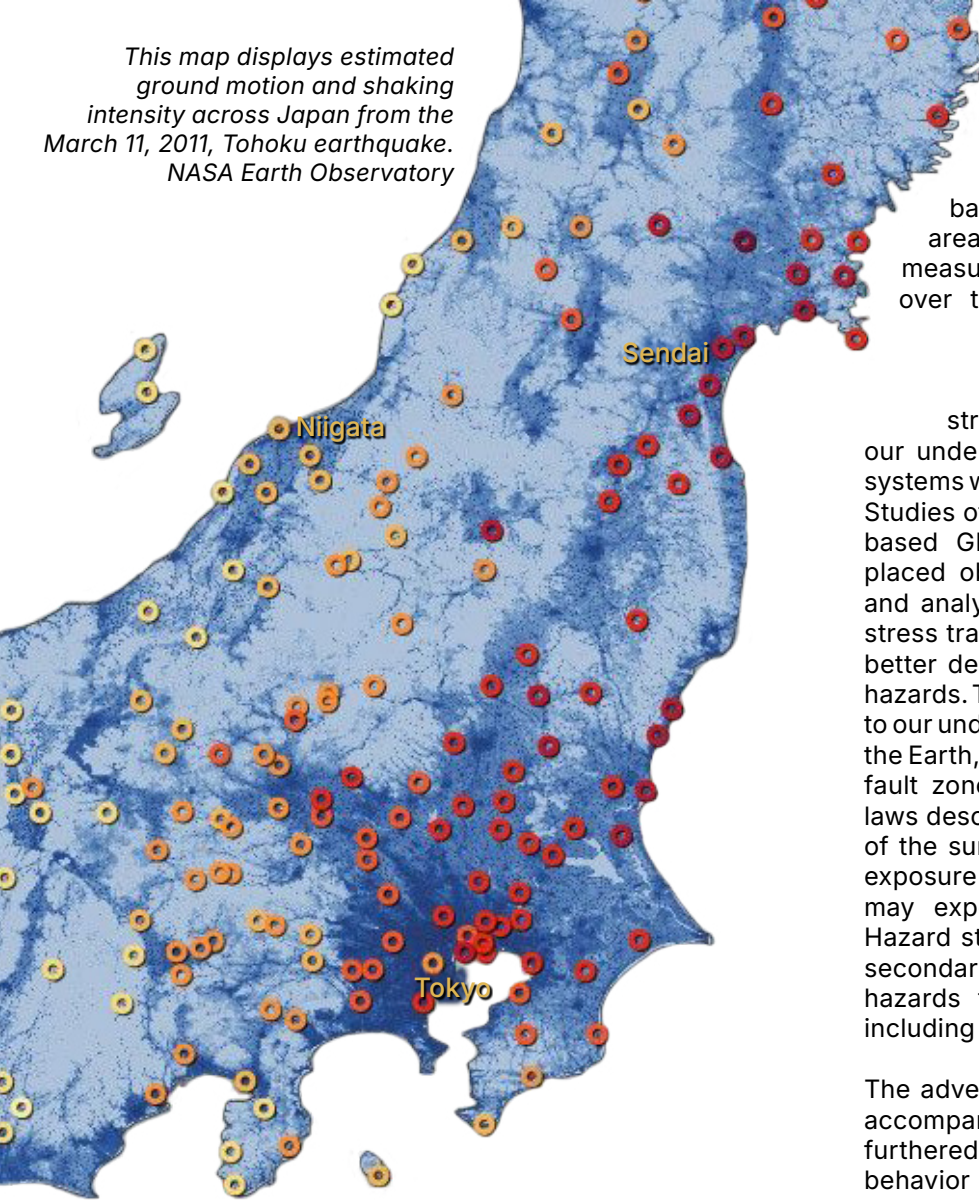
Key Questions

- How do plate boundaries and plate interiors evolve over time scales of seconds to millennia?
- What are the underlying mechanical properties of the lithosphere, asthenosphere and fault zones?
- What role do fault creep, off-fault deformation, strain partitioning, and other types of complexity play in our understanding of the earthquake cycle and associated hazards?
- How do multiple sources of deformation interact in tectonically active systems?
- How can we leverage current understanding and resources to improve our response to earthquakes and associated cascading hazards?



A false-color composite derived from NISAR data highlights vegetated areas (green), unvegetated surfaces (red), and how rapidly vegetated areas changed (blue) during the 2025-2026 growing season in an agricultural region of South Africa. Most pixels contain a mix of these colors, producing the visualization's rich and varied color palette. NISAR/Paul Siqueira

This map displays estimated ground motion and shaking intensity across Japan from the March 11, 2011, Tohoku earthquake. NASA Earth Observatory



Past Decade

Earthquakes, the processes that drive them, and the hazards that accompany them have captured our interest for as long as societies have settled along active plate boundaries. Space-based and airborne geodetic data have revolutionized our understanding of the characteristics of earthquakes, the driving mechanisms behind them, and other types of deformation associated with tectonically active plate boundaries. These data also have enabled detailed studies of earthquakes within plate interiors and other areas that experience less frequent seismicity, but where exposure to the hazards of strong ground motion is particularly large when it occurs.

Catalogs of instrumentally-observed earthquakes now cover over a century, and field work has extended our knowledge of fault behavior

back thousands of years in select areas. Satellite gravity and radar altimetry measurements constraining the geoid over the oceans have revolutionized the measurement of large-scale bathymetry and seafloor structure, which has greatly improved our understanding of oceanic plate boundary systems which host great offshore earthquakes. Studies of individual earthquakes using space-based GNSS, InSAR and gravity data have placed observed fault rupture characteristics and analysis of post-seismic deformation and stress transfer into a broader context, allowing better description and quantification of future hazards. These analyses have been foundational to our understanding of the state of stress within the Earth, friction laws that apply to the complex fault zones beneath the surface, constitutive laws describing the brittle and ductile rheology of the surrounding crust, and the fragility and exposure of the built environment in areas that may experience earthquakes in the future. Hazard studies have also addressed the many secondary but potentially equally devastating hazards that accompany large earthquakes, including landslides, liquefaction and tsunami.

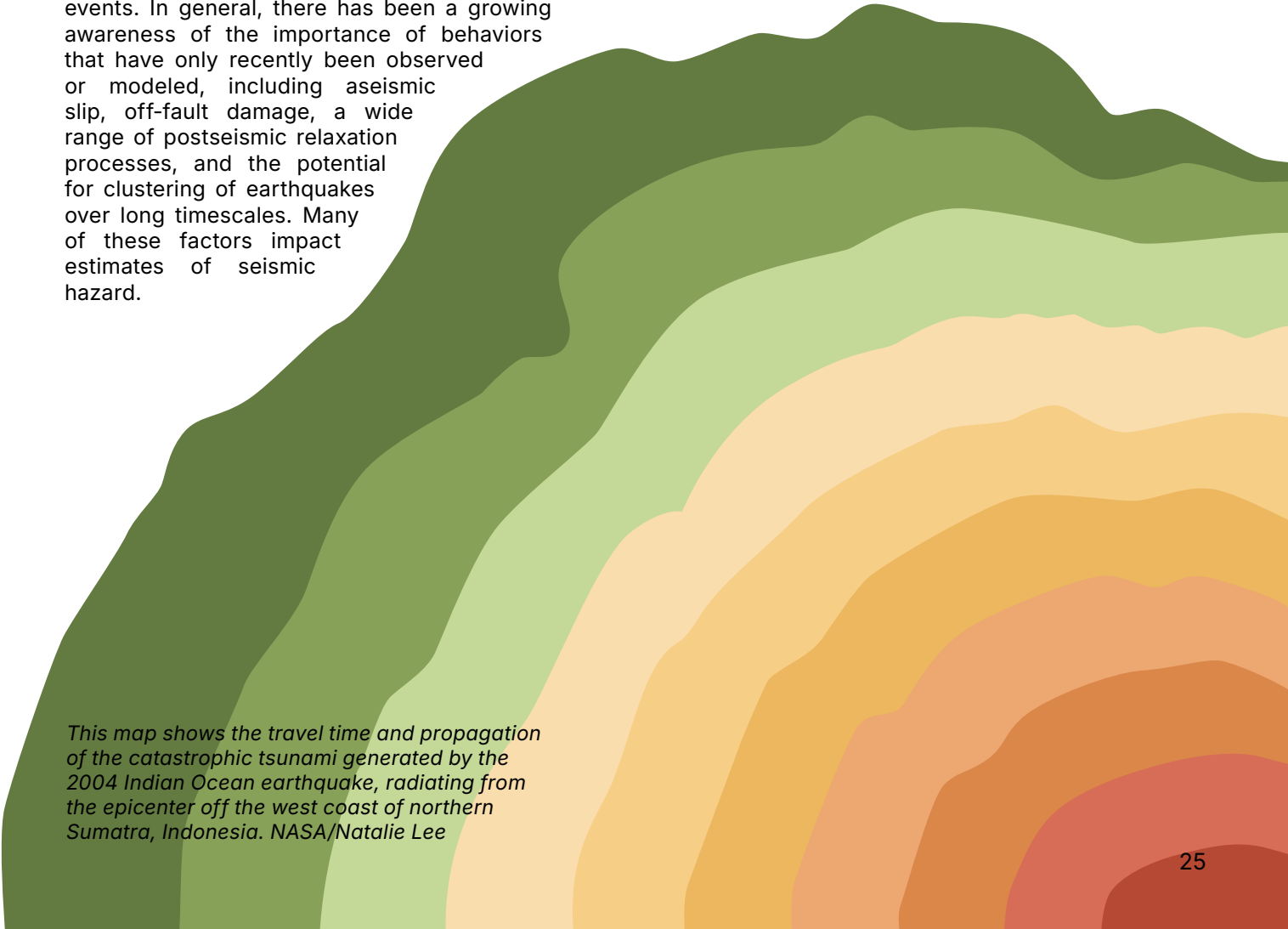
The advent of new types of observations was accompanied by surprising discoveries that furthered our understanding of earthquake behavior at the extremes of the seismic cycle. The 2011 Magnitude 9 (M9) Tohoku earthquake in Japan was a horrific example of how secondary hazards such as tsunami, combined with exposure of the built environment, can lead to disaster. Some of the first-ever measurements of coseismic seafloor displacement showed offsets as large as 30 m. Slip on the subsurface fault is inferred to have exceeded 60 m. GNSS-based observations of strain in the Tohoku area had led to suggestions that the area could be susceptible to extreme events of this sort — agreeing with historical indicators of large tsunami on land that were more widely appreciated after the event. Unfortunately, this information was not incorporated into earthquake hazard assessments until after the disaster, emphasizing the need for more streamlined and timely communication of research results to a wide range of stakeholders. Studies of recent earthquake ruptures with InSAR and high-resolution imaging geodesy using optical sensors, including the 1992 M7.2 Landers, 1999 M7.1 Hector Mine, 2010 M7.2 El Mayor, 2016 M7.1 Kumamoto, 2016 M 7.8 Kaikōura, and 2019

M6.4 & M7.1 Ridgecrest earthquakes, revealed the great complexity of earthquake ruptures and broad, distributed zones of diffuse damage and secondary faulting.

On the other end of the spectrum of fault behaviors, denser geodetic networks with stations within a few kilometers of the fault in some cases have allowed observations of a different type of fault-zone activity: aseismic fault creep transients (also known as slow or silent earthquakes). One of the most significant early observations of these was made along the northern Cascadia subduction zone, with evidence of fault slip equivalent to a ~M6.7 earthquake occurring over the course of about a week at regular intervals of a little over a year. Such activity was consistent with emerging new models of fault friction behavior, which drove rapid development of theoretical and physical approaches that could reproduce and explain these transients. Similar observations have now been made in many subduction zone environments around the world, as well as along strike-slip fault zones such as the San Andreas. In some areas, it is now possible to forecast the likely onset time of these slow slip events. In general, there has been a growing awareness of the importance of behaviors that have only recently been observed or modeled, including aseismic slip, off-fault damage, a wide range of postseismic relaxation processes, and the potential for clustering of earthquakes over long timescales. Many of these factors impact estimates of seismic hazard.

Present Day

Today, advances in geodetic observations have allowed researchers to resolve progressively smaller and more subtle signals associated with all phases of the seismic cycle, while computational approaches have rapidly advanced to simulate the behavior of the Earth system, with all its complexity. We now have access to decades-long InSAR time series with approximately fortnightly temporal sampling, at more than one wavelength, over much of Earth's land surface, and an expanded set of GNSS observations that have been upgraded to high-rate, multi-constellation, and near-real-time capability. The availability of long and temporally dense, global InSAR time series now permits us to go beyond plate boundaries, into plate interiors, to detect the secular motions of tectonic plates and eventually improve global plate motion models that also incorporate distributed intraplate deformation. Together, these platforms observe a wide range of behaviors that are key to seismic hazard estimates, including the long-term deformation across plate boundaries and



This map shows the travel time and propagation of the catastrophic tsunami generated by the 2004 Indian Ocean earthquake, radiating from the epicenter off the west coast of northern Sumatra, Indonesia. NASA/Natalie Lee

deep into plate interiors, potential interactions between earthquakes on nearby faults, and the aftershock and postseismic deformation histories after individual events. The ability to study progressively smaller earthquakes means that we can analyze a much larger number of events and comprehensively search, often aided by machine learning approaches, for patterns in their occurrence that would otherwise be impossible to detect.

Improved InSAR coverage and capabilities have also enabled research into areas where rapid land-cover changes or other factors, such as the lack of GNSS infrastructure, have inhibited such studies in the past. InSAR researchers can now work in some of the most rapidly changing landscapes on the planet, including agricultural areas. However, these new capabilities are accompanied by challenges—InSAR data are also sensitive to variation in vegetation properties and soil moisture—in addition to displacement of the ground surface. While fault zones often serve as hydrologic barriers in the landscape, with differences in vegetation sometimes quite apparent across the fault, researchers must take care to not attribute ecosystem-related signals to displacements across the fault zone.

There have also been significant advances in the area of earthquake early warning and

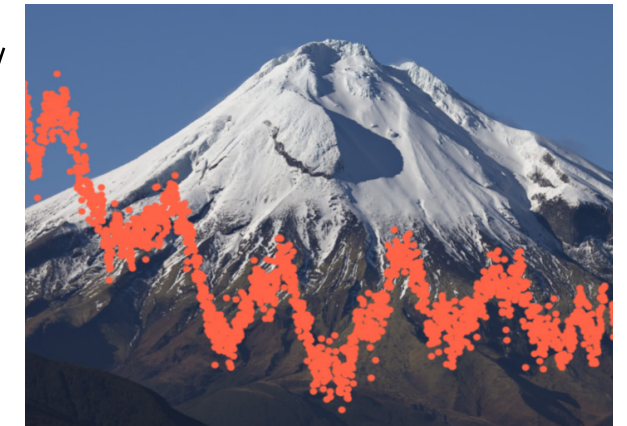
rapid source characterization in support of earthquake response and operational aftershock forecasting. Earthquake early warning relies on rapid characterization of the size and location of the fault plane after the earthquake has already begun (but before the most damaging shaking hits a population center). Early warning systems that use high-rate GNSS data have been demonstrated around the world, including in the western United States. Where available in near-real time, the use of GNSS data results in better magnitude estimates of large events and finite fault models, with accompanying improvements in models of stress drop and aftershock likelihoods. Since the 2014 M6.0 South Napa earthquake, the USGS has been demonstrating the use of GNSS data in their earthquake response, with several geodetic data streams being used operationally in the 2020's. Rapid acquisition and interpretation of remote-sensing imagery has also allowed for the prompt creation of fault rupture and damage proxy maps that are invaluable in the early response to earthquakes and other natural disasters. Investments in GNSS have enabled detection of ionospheric perturbations due to tsunami generated by large, subduction zone earthquakes, providing unique, near-real-time global detection and forecasting capabilities associated with these often devastating hazards.

The Next Decade

Denser observations in space and time: Future advances are limited by our ability to resolve and separate subtle deformation signals that overlap in space and time due to the wide range of processes active within the solid Earth and its shallow subsurface (e.g., tidal load responses, seasonal hydrologic cycle, seismo-volcanic events and precursors, human activity). Many of these processes probe interior structure and constitutive properties. However, we are challenged by current limits in spatial and temporal resolution. For instance, within the context of specific existing InSAR constellations, observations are made at the same local time of day and thus alias any physical process that responds to solar tides. Dense temporal sampling is essential for identifying and separating their respective deformation signatures. Denser observations in space and time will also allow for better mitigation of many of the error sources, such as those due to variability in the troposphere or ionosphere, that can obscure the effects of smaller phenomena.

Improving precision: Small events, or small variations in the deformation field associated with larger events, can be windows into the underlying forces that drive the tectonic system and allow the study of highly variable fault and rock properties. Lowering the detection threshold further also means that we can better assess correlations with non-tectonic forces that could contribute additional spatial-temporal variability in loading along fault systems. Improved observations likely will allow us to observe new behaviors, such as the widening spectrum of fault creep and aseismic transients, that fall outside the early ideas of how fault zones accumulate and release stress. Measurements of off-fault behavior (including high-resolution scanning with cm-scale pixels), damage, and fault creep provide insight into the physics of how the upper few km of the crust accommodate and partition strain. These new observations inform hazard estimates and earthquake-early-warning efforts based on increasingly realistic models of fault and material behavior, which themselves have benefited from advances in high-performance computing and data-assimilation techniques that can support the necessary level of detail and ingest the rapidly expanding volumes of data.

Dense temporal sampling is essential for identifying and separating their respective deformation signatures.



Geodetic time series can help researchers disentangle effects of hydrologic loads on volcanic processes. Dave Young, graphic by NASA

Lowering the detection threshold further also means that we can better assess correlations with non-tectonic forces that could contribute additional spatial-temporal variability in loading along fault systems.



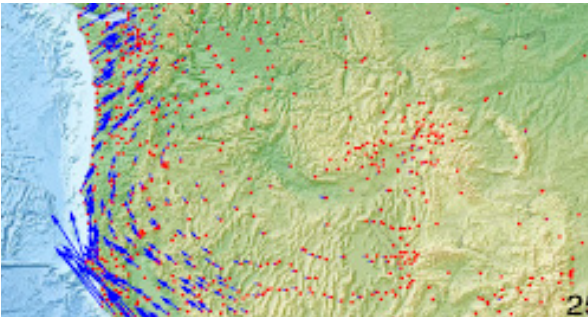
InSAR and GNSS-constrained displacement in California. Cornell University/Rowena Lohman

Most of the world's plate boundaries and the greatest earthquakes and associated hazards occur under the oceans. To make substantial progress in understanding these offshore systems requires the use of remote sensing and space geodetic systems tailored to the ocean environment. The development of novel GNSS-acoustic systems can greatly advance our understanding of earthquake cycle processes in subduction zones globally. GNSS/A relies on surface vessels acoustically communicating with seafloor assets, which either echo (in two-way systems) or time (in one-way systems) the received pulse, enabling determination of point positions on the seafloor. In recent years, autonomous surface vehicles have been put to the task of surveying seafloor beacons. Determining their position while in active survey mode outside of coastal areas requires robust methods of precise point positioning in the open ocean.

Constraints on multiple components of deformation: Three-dimensional deformation observations from satellite imaging are another growing need. Inversions for characteristics of the subsurface based on observations at the surface are often ill-posed problems with non-unique solutions. The existence of constraints on more than one component of the deformation field, as are available at the limited number of sites with GNSS observations, greatly enhances our ability to narrow down potential fault zone behaviors, as well as to distinguish fault-related displacements from those related to groundwater withdrawal, landslides, or other factors. Even when data from different, overlapping passes of the satellite are combined, allowing for slightly different viewing geometries, the difference in time between those observations introduces another potential source of uncertainty. Cross-correlation (pixel-tracking) of both SAR and optical imagery provides a measurement of how the surface moves in the horizontal dimension, complementing the near-vertical range observations from InSAR, albeit with much lower precision than line-of-sight InSAR observations. Proposed new styles of InSAR constellations, such as those with a receive-only companion satellite, address this limitation, provide precise observations of multiple components of the deformation field at the same time, and would allow optimal combinations of GNSS and InSAR.

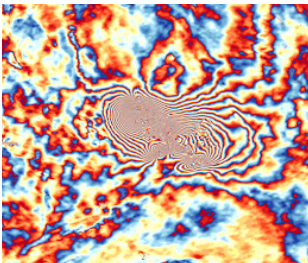
Corrections for the ionosphere and troposphere: It has been recognized since the beginning of the satellite geodesy era

The development of novel GNSS-acoustic systems can greatly advance our understanding of earthquake cycle processes in subduction zones globally.



GNSS observations of the complex displacement field in Cascadia. USGS

Proposed new styles of InSAR constellations, such as those with a receive-only companion satellite, address this limitation, provide precise observations of multiple components of the deformation field at the same time, and would allow optimal combinations of GNSS and InSAR.



Sentinel-1 interferogram spanning the 2019 Ridgecrest, CA, earthquake. European Space Agency

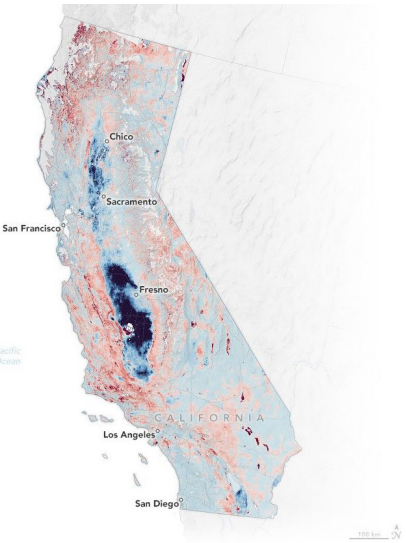
that one of the largest sources of systematic noise in current InSAR and GNSS observations stems from spatio-temporal variability in the propagation delay between the satellite and the ground associated with the ionosphere and troposphere. Modeling of these delays, including efforts to leverage numerical weather models, is an ongoing research area, with iterations that have resulted in improvements to the numerical weather models themselves and that have required reprocessing of GNSS data for each new version of ITRF. Any methodological advances that can reduce or remove the propagation effects directly will open new vistas in the use of deformation

studies to discover, quantify and interpret subtle changes due to aseismic transients, magma migration in the subsurface, or changes in aquifer state.

Spanning the spectrum of spatio-temporal scales: Earth's surface deformation, including that associated with tectonic and non-tectonic processes, evolves over a wide range of spatio-temporal scales. Understanding processes that vary over decadal timescales requires integration of data from multiple observation systems and sensor platforms. For tectonic systems, this includes multi-decadal postseismic relaxation processes following large earthquakes, long-term slow-slip transients, and spatio-temporal changes in fault coupling through the earthquake cycle of partially coupled faults. At locations that have hosted GNSS stations over long timescales, the availability of daily and sub-daily position estimates allows separation of co- and post-seismic signals during the period when the relevant behaviors have the strongest variability, and when observing and characterizing deformation behavior best informs models of fault and crustal rheology. However, these GNSS sites are often so sparse that spatial aliasing (e.g., variations with depth, lateral structure) still limits our ability to understand and interpret these signals. Imaging geodesy (e.g., InSAR) provides sufficient spatial coverage, but has typically involved near-weekly observations that do not generally allow separation of the co-seismic signal from the most informative portion of the post-seismic displacement history. Proposed InSAR constellations that include the ability to acquire sub-weekly to daily observations would be a major advance in this area.

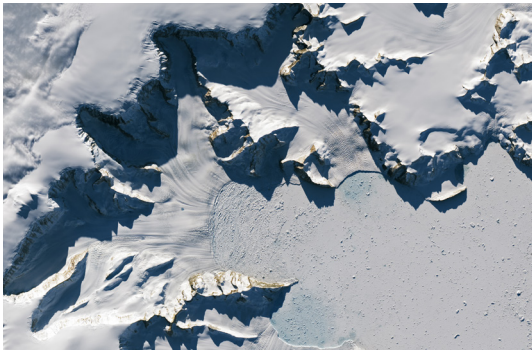
Observations spanning decades: Important contributions to surface deformation also include elastic loading, thermoelastic strain and poroelastic deformation associated with hydrology (Chapter 1.1), short-term weather events, annual to decadal climate variations, deformation in response to changes in sea level and the distribution of ice sheets and glaciers, as well as human activity. The response of the Earth to these loads, including the occurrence of triggered earthquakes, can help us understand properties and behaviors of rocks and faults that are not otherwise observable. Continuity of observation over multiple decades, such as already available for some GNSS networks (and being approached with InSAR in selected areas), is critical to these efforts.

Proposed InSAR constellations that include the ability to acquire sub-weekly to daily observations would be a major advance in this area.

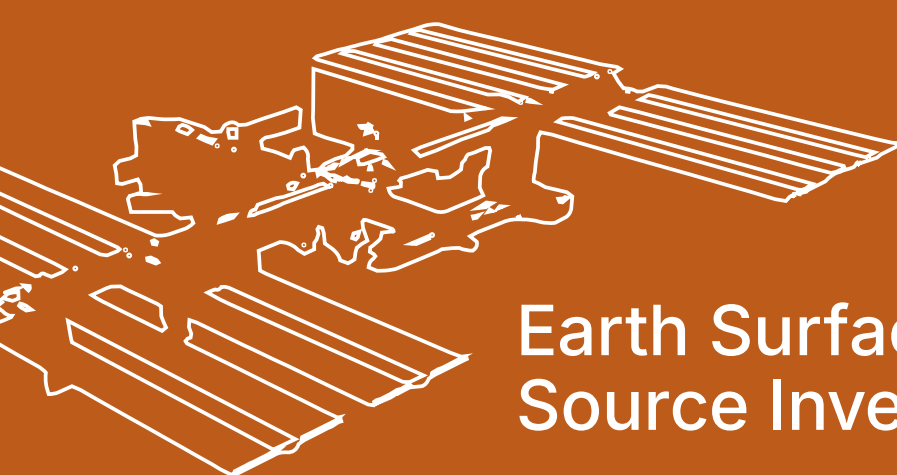


A map of California's vertical land motion: areas shown in blue are subsiding, with darker blue areas sinking faster than lighter blue ones. Areas shown in dark red are rising the fastest. NASA Earth Observatory

Continuity of observation over multiple decades, such as already available for some GNSS networks (and being approached with InSAR in selected areas), is critical to these efforts.



Landsat 8 captured the scale of the loss of Hektor's grounded ice on the eastern Antarctic Peninsula in early 2024. NASA Earth Observatory



EMIT

Earth Surface Mineral Dust Source Investigation

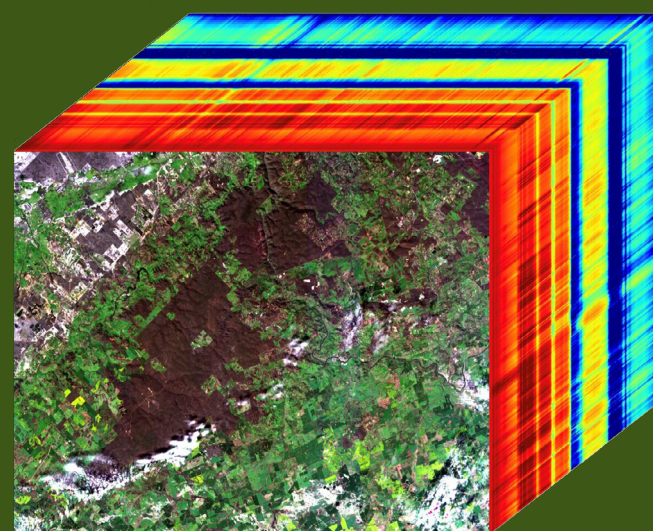
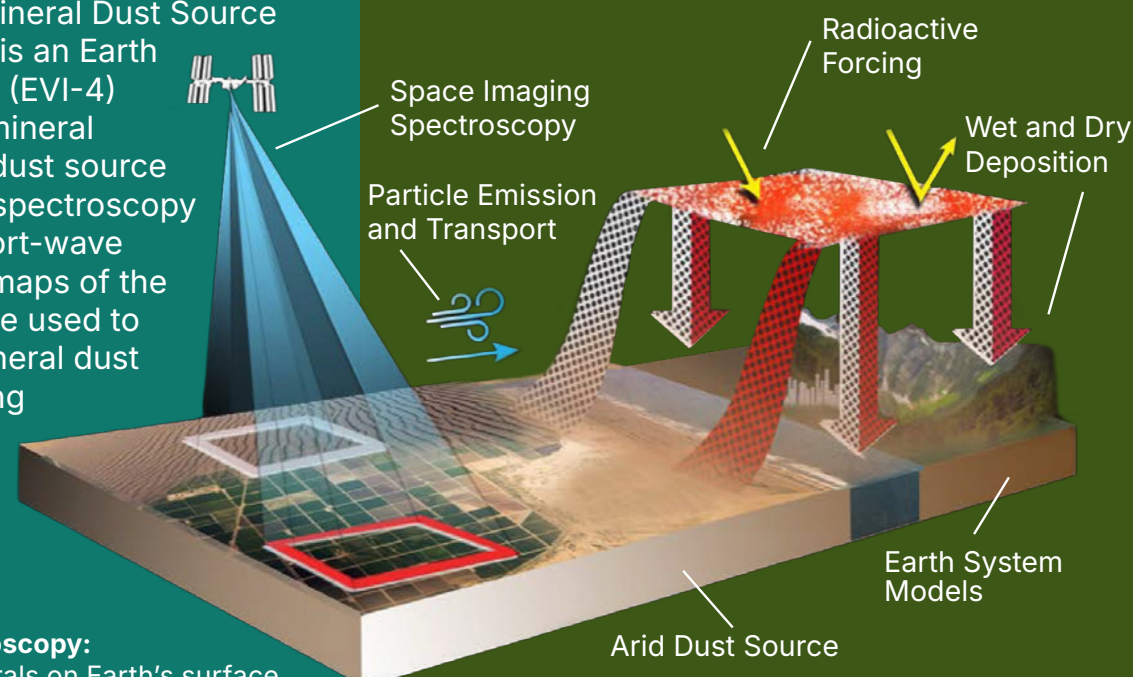
The Earth Surface Mineral Dust Source Investigation (EMIT) is an Earth Ventures-Instrument (EVI-4) Mission to map the mineral composition of arid dust source regions via imaging spectroscopy in the visible and short-wave infrared range. The maps of the source regions will be used to model the role of mineral dust in the radiative forcing (warming or cooling) of the atmosphere.

EMIT's Imaging Spectroscopy:

The distribution of minerals on Earth's surface can provide insight into volcanic systems, resources, and climate studies. EMIT is an imaging spectrometer that measures a spectrum for every point in an image. Sunlight reflected from minerals on the Earth's surface is imaged by a telescope and spectrometer system onto a detector area array that includes the visible (380nm) and short wavelength infrared (2500nm) parts of the spectrum.

The Science of Spectroscopy:

From its vantage point on the International Space Station, the imaging spectrometer for NASA's EMIT mission collects data that allows researchers to distinguish between the 10 most common surface minerals that are mobilized as dust in arid regions. One application is the identification of rare-earth elements and lithium-bearing minerals, including within areas that were previously mined for other elements and then abandoned. EMIT observations of alteration mineralogy in hydrothermal systems may enable tracking of subsurface magmatic changes.



The image at the front of the cube shows a mix of materials in western Australia, including exposed soil (brown), vegetation (dark green), agricultural fields (light green), a small river, and clouds. The rainbow colors extending through the main part of the cube are the wavelengths of light (in nanometers), or spectral fingerprints, from corresponding spots in the front image. NASA EMIT

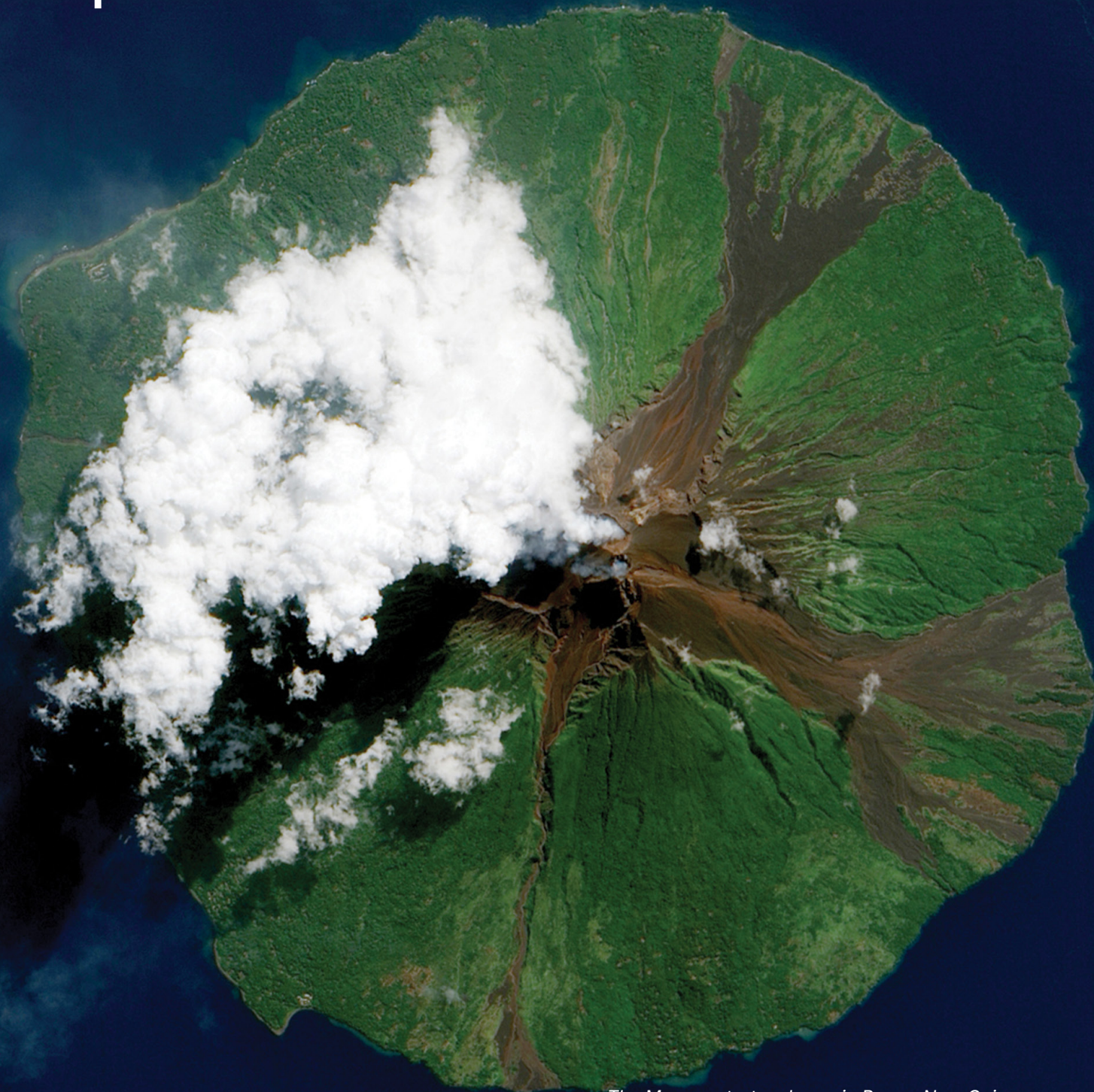
1.3 Volcanic Systems

How do magmatic systems evolve and interact with their environment?

Key Questions

- What processes precede, accompany, and follow different types of volcanic eruptions and how do we mitigate their associated hazards?
- How do different environmental settings (e.g., tectonic, subglacial, subaerial, submarine) and their changes impact volcanic behavior?
- How do magmatic, tectonic, and hydrothermal interactions drive the formation and distribution of mineral resources?

At the heart of volcanology lies a fundamental challenge: understanding the states and processes that drive volcanoes through transitions, from dormancy and quiescence to unrest, and, at times, to eruptions.



The Manam stratovolcano in Papua New Guinea, as seen from space on June 16, 2010. On June 16, the volcano released a thin, faint plume as clouds clustered at the volcano's summit. NASA's Earth Observatory

Introduction

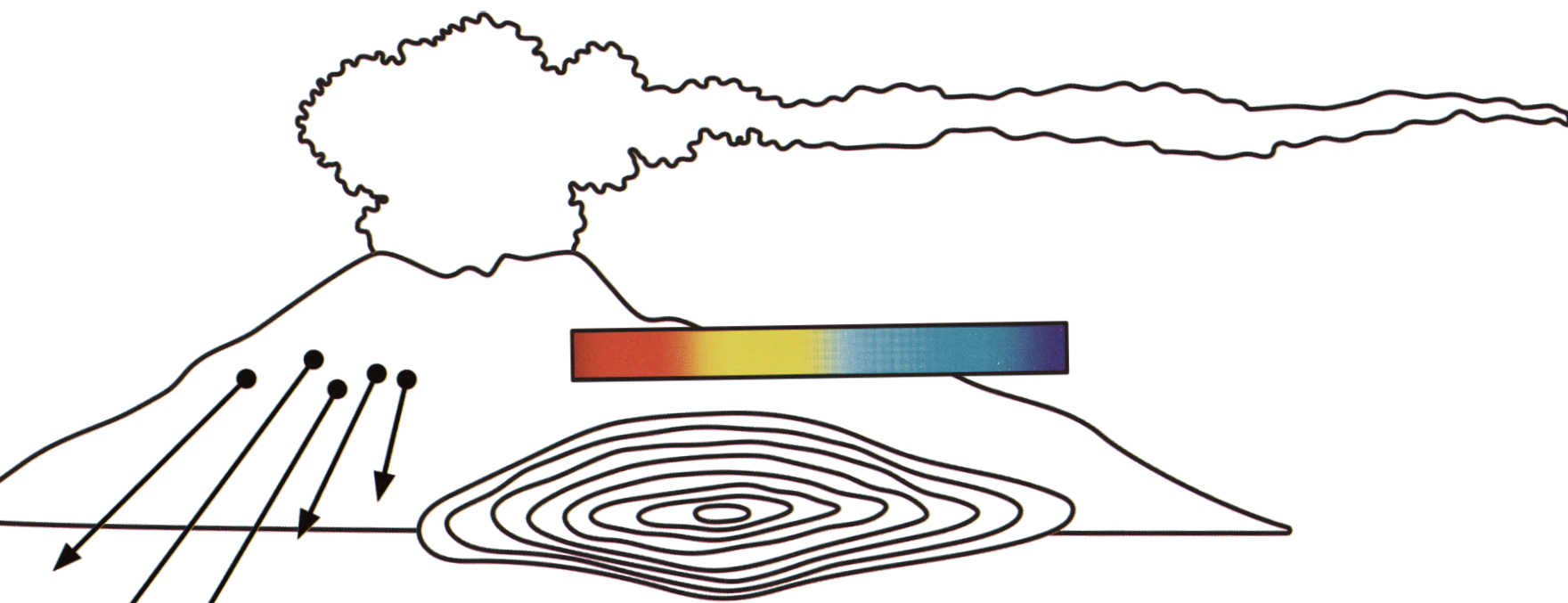
Magmatic systems are powerful agents of planetary change, shaping Earth's landscape, influencing climate, supplying geothermal energy and mineral resources, and posing a multitude of hazards to communities worldwide. Understanding the various processes driving subaerial, submarine, and subglacial volcanic activity requires an integrated approach that connects long-term geological change with short-term transient behaviors across multiple observables. At the heart of volcanology lies a fundamental challenge: understanding the states and processes that drive volcanoes through transitions, from dormancy and quiescence to unrest, and, at times, to eruptions. What determines whether an eruption will be effusive or explosive? How does magmatic system behavior control the likelihood, style, composition, frequency, and intensity of volcanic activity? How do volcanic systems evolve over millions of years? These questions define the essence of volcanoes as dynamic systems, evolving for instance through caldera formation, lava lake activity, dome growth, and complex cycles of magma intrusion and withdrawal.

The importance and potential for monitoring volcanoes globally gained worldwide attention with the devastating 1985 Nevado del Ruiz eruption. More recently, the 2022 Hunga Tonga-Hunga Ha'apai eruption (Tonga) injected an unprecedented volume of water vapor into the

stratosphere and also triggered a tsunami that propagated across entire ocean basins. Similarly, the unanticipated 2011 Nabro eruption (Eritrea) underscored the critical role that remote sensing can play, as it detected sudden massive sulfur dioxide emissions that subsequently altered global weather patterns. The 2021 Tajogaite eruption (Canary Islands, Spain) highlighted the unpredictable impacts of volcanic events, as it generated massive lava flows that destroyed entire villages and generated ash plumes impacting air travel and agriculture. The 2025 seismic unrest near Santorini (Greece) is a recent and well-documented example of seismicity connected to volcanism, and how subtle movements of magma, gas, and bedrock might herald future activity in a geologically complex region. At the same time, widespread thermal unrest has become a critical indicator of impending explosions—among the most unpredictable volcanic hazards, as tragically exemplified by the catastrophic 2014 Ontake (Japan) and 2019 Whakaari / White Island (New Zealand) eruptions.

The impacts of volcanic activity do not end with an eruption. Large eruptions can unleash subsequent landslides, lahars (fast-moving flow of water mixed with volcanic debris), pyroclastic flows (extremely hot, fast-moving clouds of gas, ash, and volcanic rock fragments), and atmospheric disturbances that affect global weather, sometimes for years. Even long after eruptions subside, residual heat, toxic gas emissions, and unstable terrain continue to pose





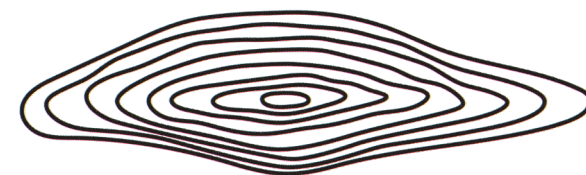
threats (e.g., the 2021 Tajogaite eruption, La Palma, Canary Islands, Spain). Some of the most devastating volcanic hazards, such as debris avalanches and lahars, can occur independently of eruptive activity, emphasizing the need for a holistic understanding of magmatic systems—not just to forecast eruptions, but also to anticipate their long-term consequences.

Past Decade

Over the past decade, advances in satellite remote sensing (deformation, topography change, thermal sensing, gases) and in-situ airborne eruption plume analyses have revolutionized volcanic monitoring, providing an unprecedented view of magma movement and evolution, gas emissions, heat transfer beneath the Earth's surface, and processes on the surface and in the atmosphere. As the examples cited above illustrate, these breakthroughs have bridged multiple scientific disciplines, including volcanology, tectonics, climate science, and atmospheric chemistry, offering fresh insights into how volcanic systems evolve. Technological and analytical improvements have also enhanced the accuracy and completeness of magmatic system inventories, enabling better detection and characterization of surface expressions of volcanic and hydrothermal activity. The improvements in observations and the emergence of longer time series have, in turn, spurred the development of deterministic physics-based models that have the potential to improve forecasting of volcano dynamic behavior and eruptions.

Present Day

Advances in **deformation monitoring** have significantly improved our understanding of magmatic processes and transitions. A decade ago, gaps in satellite interferometric synthetic aperture radar (InSAR) coverage limited our ability to systematically monitor deformation. Today, an international constellation of satellite sensors (particularly Sentinel-1 and NISAR) provides roughly weekly global coverage, enabling systematic inventories of volcanic deformation, though complete integration of deformation data with other geophysical observations, and improved hazard assessment frameworks, is a potential not yet fully exploit-

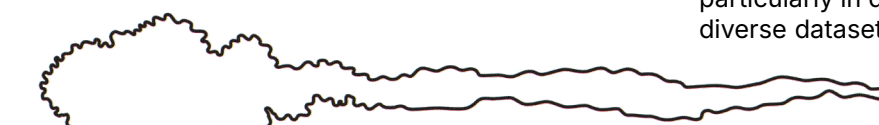


ed. **Topography observations** play a critical role in both understanding volcanic systems through mass conservation in holistic volcano models, but also in forecasting and measuring lava and other flows (pyroclastic, lahars, avalanches) and for large-scale topography change (sector or caldera collapse). Over the past two decades, the spatial coverage and resolution of global

topographic mapping have advanced rapidly, but capabilities for detecting change remain limited, typically to around 12 meters in spatial resolution. Recent developments in targeted, higher-resolution crewed (i.e., UAVSAR-Ka band GLISTIN-A and QUAKEs-I) and uncrewed airborne imaging have provided compelling examples of the power of detailed, frequently-acquired, local topographic information in rapidly changing environments. As such, they inform the spatio-temporal resolution and precision needs for future global topography observations.



New **thermal observation** methodologies now quantify the thermal signatures of magmatic-hydrothermal processes across timescales from decades to days, and spatial scales from km² to m². Increased automation now allows researchers to analyze long-trending datasets (e.g., MODIS, ASTER) integrated with newer, higher-resolution data sources (e.g., VIIRS, ECOSTRESS). These improvements have refined our ability to detect thermal anomalies associated with volcanic activity, hydrothermal alterations, and pre-eruptive heating—essential for tracking subtle but critical changes in magmatic systems.



Significant progress in **volcanic gas monitoring** has enabled global inventories of sulfur dioxide (SO₂) emissions, improving our ability to track volcanic gas flow rates even in minimally instrumented or unmonitored locations. Advances in satellite-based gas detection (e.g., TROPOMI and ASTER inventories) have provided new insights into the role of volcanic emissions in atmospheric chemistry, though large discrepancies between ground and space sulfur dioxide (SO₂) observations of dense, low-altitude plumes pose challenges. Additionally, semi-automated tools such as Plume Tracker have enabled better analysis of gas-to-particle conversions in open-vent plumes. New methodologies for carbon dioxide (CO₂) emissions monitoring have complemented improved ground-based networks and new instruments have made it possible to quantify major volcanic CO₂ emission events via spaceborne spectroscopy. However,

challenges remain—high atmospheric CO₂ backgrounds complicate direct measurements, prompting innovative detection proxy approaches such as tracking plant responses to elevated CO₂ near quiescent flank gas seeps. Another challenge is the measurement of near-real-time injection altitudes—still the largest problem in modeling the dispersion of volcanic plumes (gases, aerosols).

Advances in land surface spectroscopic analysis have further enhanced our understanding of volcanic systems. Over the past decade, researchers have identified specific mineral compositions and their relative abundance using visible to short-wave infrared (SWIR) and thermal infrared (TIR) spectroscopy. These capabilities have been particularly valuable in detecting geothermal and hydrothermal alteration minerals, helping researchers estimate the age, intensity and type of volcanic activity.

Going beyond the leaps in observational capabilities, increased computational power and more realistic physics-based models have enabled **data-model fusion strategies**. The integration of near-real-time observational data into forecasting models will improve eruption forecasts. These advances allow us to track magmatic processes and predict transitions in volcanic activity. However, challenges remain—particularly in developing models that assimilate diverse datasets, and account for uncertainties.

Despite these obstacles, the field has made substantial progress toward linking observational data with predictive modeling, bringing us closer to real-time, physics-based forecasting of volcanic activity.

The Next Decade

The complex dynamics of magmatic systems, as well as their surface expressions, require us to push the limits of individual sensors and platforms. Successful approaches will require well-coordinated sensor constellations and integration of observations from multiple satellite-based techniques with ground-based networks.

Deformation and Topography: Accurately mapping displacements caused by magmatic system pressurization and magma subsurface movement and surface changes due to lava flows, dome growth, flank collapses, and

landslides demands high-resolution deformation and topographic measurements. The ability to resolve both large-scale regional movements and localized subsurface processes, such as hydrothermal circulation and magma accumulation; and above ground processes, such as lava and other flows, is crucial for refining eruption forecasts and assessing the broader implications of volcanic unrest.

InSAR provides unparalleled spatial coverage and precise ground displacement measurements but struggles to approach the daily temporal resolution that is necessary during volcano eruption response. In contrast, continuous GNSS observations offer high-precision data at discrete points, and excel at capturing rapid, small-scale deformation. Progress in volcano science and applications requires continuous improvement in meter-scale, daily surface deformation observations, particularly during highly dynamic events. Such observations should be able to integrate with existing decadal time scales to track inter-eruption and pre-eruption transient deformation.

The need for high precision topography with global coverage suggests the need for a mission, such as the proposed Surface Topography and Vegetation (STV) mission, that leverages multiple technologies, possibly with a combination of satellite and suborbital platforms. A promising advancement that can provide regional remote sensing coverage with high sampling cadence is the development of sub-orbital High-Altitude Pseudo-Satellite (HAPS) platforms, which can deliver near-continuous, high-resolution imaging, filling the gaps between satellite overpasses and enabling real-time hazard assessments.

Thermal Remote Sensing: Interpreting thermal anomalies, unrest, and lava flows relies on satellite-based thermal observations with enhanced spectral, spatial, and temporal resolution. Future monitoring systems should integrate advanced sensors covering visible to shortwave infrared (VSWIR), mid-wave infrared (MWIR), and thermal infrared (TIR), with high radiometric sensitivity for subtle temperature changes and a broad dynamic range for both eruptive events and background conditions. Expanding TIR bands will also improve mapping of silicate (e.g., feldspar) and other minerals, as well as volcanic glass, aiding geological and mineral exploration, as well as contributing to other applications relevant to natural hazards

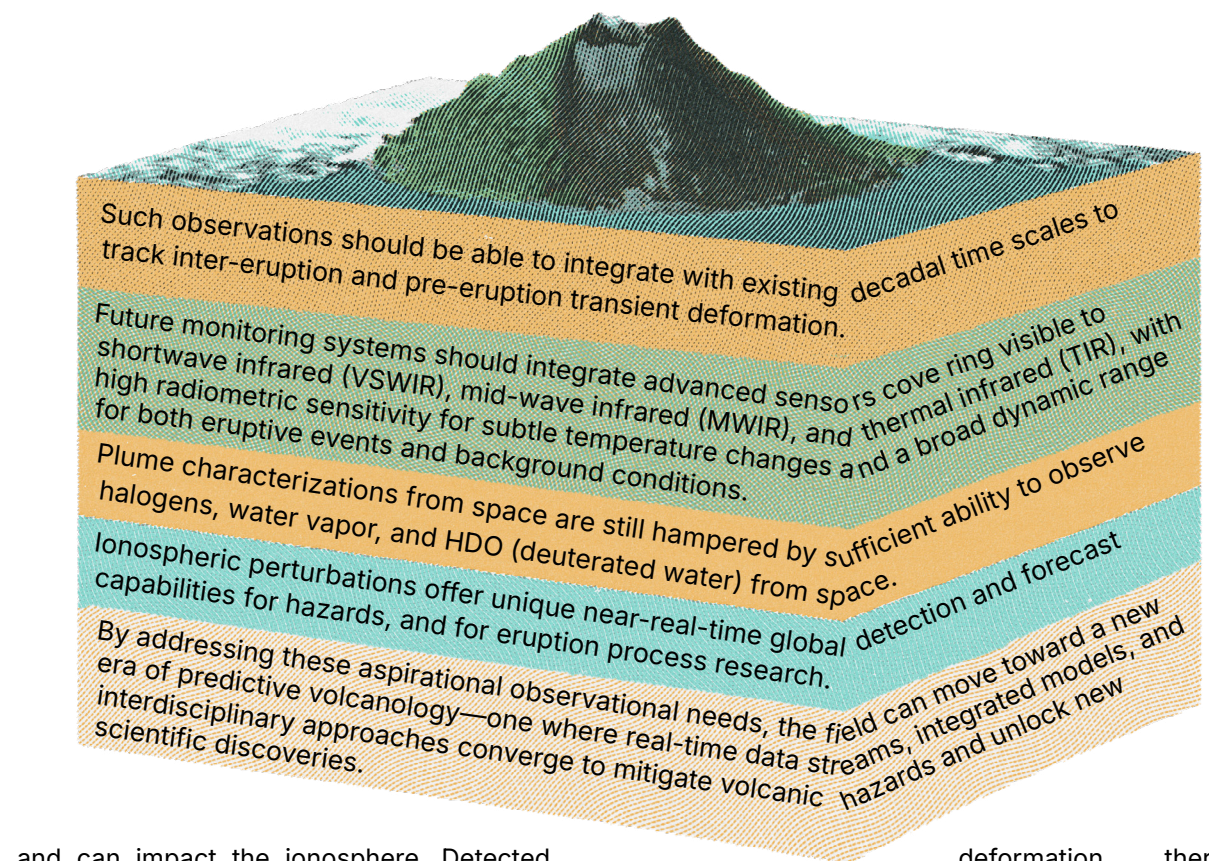
and societal impact, such as the detection of wildfires.

Thermal monitoring is limited by spatial and temporal resolution. Meter-scale imaging is needed for identifying smaller and lower-temperature thermal anomalies and geothermal fields; these data would also improve tracking of the location and evolution of large lava flows. Global thermal coverage should balance broad surveillance with targeted monitoring of high-risk areas for response efforts. An optimal strategy combines geostationary satellites for continuous monitoring and polar-orbiting satellites for high-resolution imaging, ensuring rapid and comprehensive coverage.

Beyond resolution, improving radiometric calibration and atmospheric corrections is crucial for accurate satellite-based temperature measurements. Advanced algorithms should account for atmospheric interference and separate temperature signals from emissivity variations, enhancing the interpretation of volcanic surfaces. Correcting for ozone (O3) and water vapor (H2O) in the thermal infrared is especially important for precise geologic mapping and hazard assessment.

Gas and Particulates: Simultaneous tracking of CO2, SO2, water vapor, and secondary (i.e., sulfate) aerosols, either on single platforms or by constellations, will enable detections of changes in subsurface processes and aid in tracking ageing plumes as they begin dispersing globally. Plume characterizations from space are still hampered by sufficient ability to observe halogens, water vapor, and HDO (deuterated water) from space. Their detection (pioneered by JAXA's GOSAT), could provide enormous specificity in fingerprinting volcanic process changes if observed at under-km-scale spatial footprints. Detections of short-and long-term CO2 soil degassing using plants as proxy sensors through both adverse and fertilizing effects may become constrained enough to enable earlier detections of deep intrusions and magma ascent.

Ionospheric disturbances: Co-Volcanic Ionospheric Disturbances (CVIDs) and Traveling Ionospheric Disturbances (TIDs) have been detected from multiple volcanic events over the past decade. Large explosive eruptions and some of the resulting tsunamis may cause atmospheric pressure, acoustic and gravity waves that travel both horizontally and vertically,



and can impact the ionosphere. Detected by remote sensing in combination with ground networks (e.g., GNSS), these ionospheric perturbations offer unique near-real-time global detection and forecast capabilities for hazards, and for eruption process research.

In combination, different observables may provide more comprehensive characterizations of these inherently multivariate phenomena. For example, CVIDs coupled with global infrasound networks and stratospheric water vapor pulse detections may trace and characterize blue-sky events like the 2022 Hunga-Tonga Hunga Ha'apai eruption. Digital-twin modeling of plume dispersion and gas emission can improve understanding and forecasting of volcanic processes and their impacts in closer to real-time, making them more relevant to geohazards applications.

Towards a next-generation observational framework: The next decade of research in magmatic systems anticipates a transformation in the way we collect, integrate, and interpret observational data. Scientific advancement and hazard mitigation require high-resolution, high-frequency global observations that capture both large-scale and localized volcanic phenomena in near-real-time. The integration of multiple remote sensing techniques—spanning

deformation, thermal, gas, and mineralogical analyses—and the development of new analytical methods will provide a more holistic view of magmatic processes, enabling better insights into how magmatic systems change and reach tipping points. Constellation architectures that combine satellite, airborne, and ground-based platforms will enable such coordinated observations, and will necessitate advances in international data standards, assimilation and fusion to drive advancements in near-real-time physics-based modeling.

Advancing our ability to monitor magmatic systems will not only enhance eruption forecasting and hazard assessment but also deepen our understanding of volcanic processes and their interactions with the broader Earth system. The fusion of state-of-the-art remote sensing, advanced data assimilation, and machine learning-driven pattern recognition will enable unprecedented insights into how magmatic systems evolve over time. By addressing these aspirational observational needs, the field can move toward a new era of predictive volcanology—one where real-time data streams, integrated models, and interdisciplinary approaches converge to mitigate volcanic hazards and unlock new scientific discoveries.

GNSS

Global Navigation Satellite System

A Critical Enabling Technology:

The global system of constellations which make up GNSS underpins the science goals of ESI at all temporal and spatial scales, both through the measurement of displacements upon the Earth's surface, as well as the critical role that GNSS plays in most forms of navigation and positioning of the global constellation of satellites. Advances in GNSS support applications including meteorology, soil moisture and groundwater mapping, evaluation of earthquake and volcanic hazards, and earthquake and tsunami early warning.

Developing and advancing GNSS into the future:

NASA has been heavily involved in the support and advancement of GNSS since its earliest days. NASA laid the groundwork for the International GNSS Service (IGS), establishing global collaborations and standards amongst hundreds of organizations. NASA developed key hardware, such as the TurboRogue receiver and choke ring antennas, and shaped the development of spaceborne GNSS receivers on satellite missions such as TOPEX/Poseidon and GRACE. NASA's development of the GipsyX software and the Precise Point Positioning analysis method has enabled millimeter-level accuracy in positioning and has revolutionized both scientific and commercial GNSS applications worldwide. NASA is leading the way on installing laser ranging reflectors on the GPS Block III satellites to better tie this constellation to the terrestrial reference frame.

1.4 Earth's Interior Processes and Structure

How do Earth's interior structure and dynamics evolve and interact with the surface, ocean, and atmosphere?

Key Questions

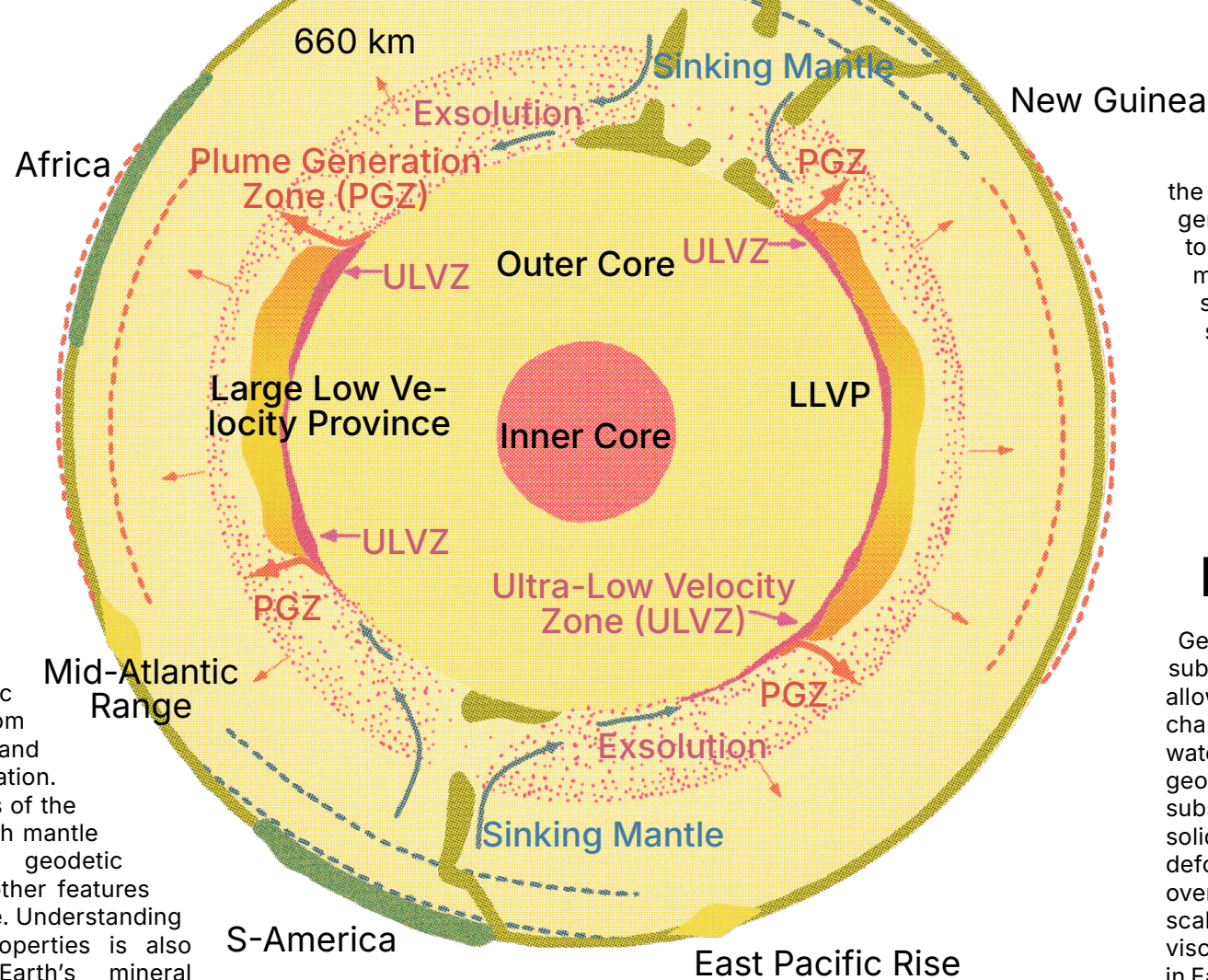
- What are the structure and dynamics of Earth's crust, mantle and core?
- What is the rheology of the mantle, and how does it deform in response to surface loading?
- How do core-mantle interactions affect Earth's rotation, orientation, and geomagnetic variability?
- What sources and processes contribute to geomagnetic field variations, and how are they coupled with other Earth systems?
- How does the geomagnetic field protect Earth's habitability?

Introduction

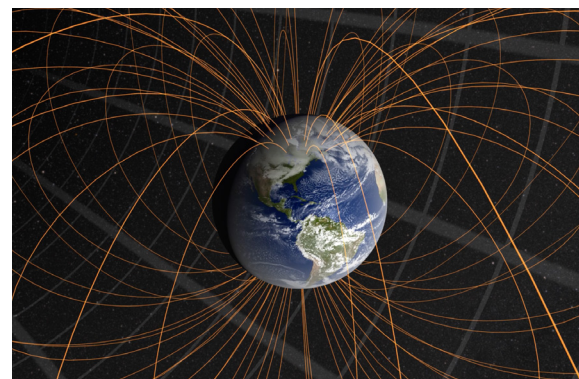
Mantle and core processes shape Earth's surface and interior. Convection of Earth's mantle is responsible for the distribution of Earth's heat, water, and critical elements, contributing to the evolution of continents, driving plate motion and dynamics of the core, and, ultimately, giving rise to many of the resources that sustain our society today. Convection within the Earth's core sustains our magnetic field, which protects life from harmful solar radiation, and provides navigational information. Thermomechanical properties of the crust control the coupling with mantle dynamics and impact the geodetic observations, hazards, and other features we can observe at the surface. Understanding crustal composition and properties is also essential for exploring Earth's mineral resources, and critical for novel modes of magnetic navigation that operate when GNSS is compromised.

While seismology, in particular using tomographic approaches, has been very successful in mapping wave speed heterogeneity tied to thermal and compositional variations inside Earth's deep interior, these ultimately involve assumptions of elastic behavior and static density variations, which are complicated by the presence of anelasticity (across a broad spectrum of transient behavior)—and convective flow. The relation between the driving forces of deformation and the observed displacement and gravity change (e.g., post-glacial rebound, hydrological and tidal loading) provides insight into the rheology of the crust and mantle. Throughout Earth's interior, elastic, frictional, viscoelastic, and plastic properties display substantial lateral and radial variations that remain active areas of inquiry.

The geodetic (GNSS, gravity, altimetry) study of Earth's dynamic surface as discussed in Chapter 1.1 provides insight into Earth's mantle structure and dynamics. The dynamic nature of Earth's core is primarily revealed through



Global modeling of magnetic signals from internal and external sources, inference of core structure, simulation and assimilation of geodynamo models and geomagnetic observations feed our understanding of the origin of Earth's magnetic field and its temporal variation.



A simple visualization of Earth's magnetosphere near the time of the equinox. NASA/Goddard Space Flight Center Scientific Visualization Studio

the actively changing magnetic field that it generates, and whose structure is accessible to satellite observation. Global modeling of magnetic signals from internal and external sources, inference of core structure, simulation and assimilation of geodynamo models and geomagnetic observations feed our understanding of the origin of Earth's magnetic field and its temporal variation. This has implications beyond the dynamical processes in the core, as these widely interact with other Earth systems.

Past Decade

Geodesy provides a window into Earth's subsurface structure and rheology, which allows us to disentangle the effects of mass changes due to atmosphere, ocean, surface water, and interior fluids, and motions of geophysical fluid systems in the surface/subsurface and of the outer core relative to the solid mantle. For example, GNSS-measured deformation in response to glacial unloading over a wide range of spatial and temporal scales has revealed the heterogeneous viscosity structure of Earth's mantle. Changes in Earth's gravity field, shape, and rotation (e.g., length-of-day), are all impacted by changes in the angular momentum of the fluid components of the Earth system (including the atmosphere, outer core, and surface hydrology), variations in the long-term distribution of mass (e.g., due to an earthquake), and deformation due to ocean tides, and seasonal and multi-annual hydrological load cycles. These variations can be leveraged to study the Earth's interior, such as in recent studies that use GNSS observations of ocean tidal loading to constrain lateral contrasts in elasticity and density structure within the crust and upper mantle. Additionally, geodetic and seismic data are being applied to the study of poroelasticity in aquifer systems, with important implications for water-resource management and sustainability.

Nearly three decades of continuous magnetic measurements made by low-Earth-orbit (LEO) satellites have resulted in high-resolution and time-varying global geomagnetic field models. Geomagnetic variations beyond the spatial resolution limit (<1000 km) set by the crustal magnetic field can be detected, and ocean-tide induced magnetic anomalies are now part of e.g., Swarm Level-2 products. Substantial

progress was made in numerical geodynamo modeling, and the resultant large numerical datasets for different model settings have been used to derive scaling laws and statistics that have allowed breakthroughs in geomagnetic data assimilation to probe core processes. The state of science has leapt forward from inferring two-dimensional core flow beneath the core-mantle boundary to quantifying three-dimensional core flow structure, resulting in the discovery of core waves, gyres and jets, crucial for understanding the dynamical balance that controls magnetic field generation and its variation. Data assimilation has advanced from conceptual studies to a mature technology for estimating the four-dimensional core state and predicting geomagnetic variations on sub-decadal time scales. The International Geomagnetic Reference Field (IGRF), updated every 5 years, serves broad science needs, and societal needs from resource exploration to alternative navigation systems.

Present Day

Earth is deforming over a wide range of temporal scales associated with tidal forcing and changes in surface loads due to ice, water, mantle convection, tectonics and erosion/deposition. The style of deformation is fundamentally controlled by a broad spectrum of rheological behaviors that describe processes that manifest themselves at time scales from periods of planetary orbits to the nearly instantaneous seismic disturbances.

ice
water
mantle convection
tectonics
erosion / deposition

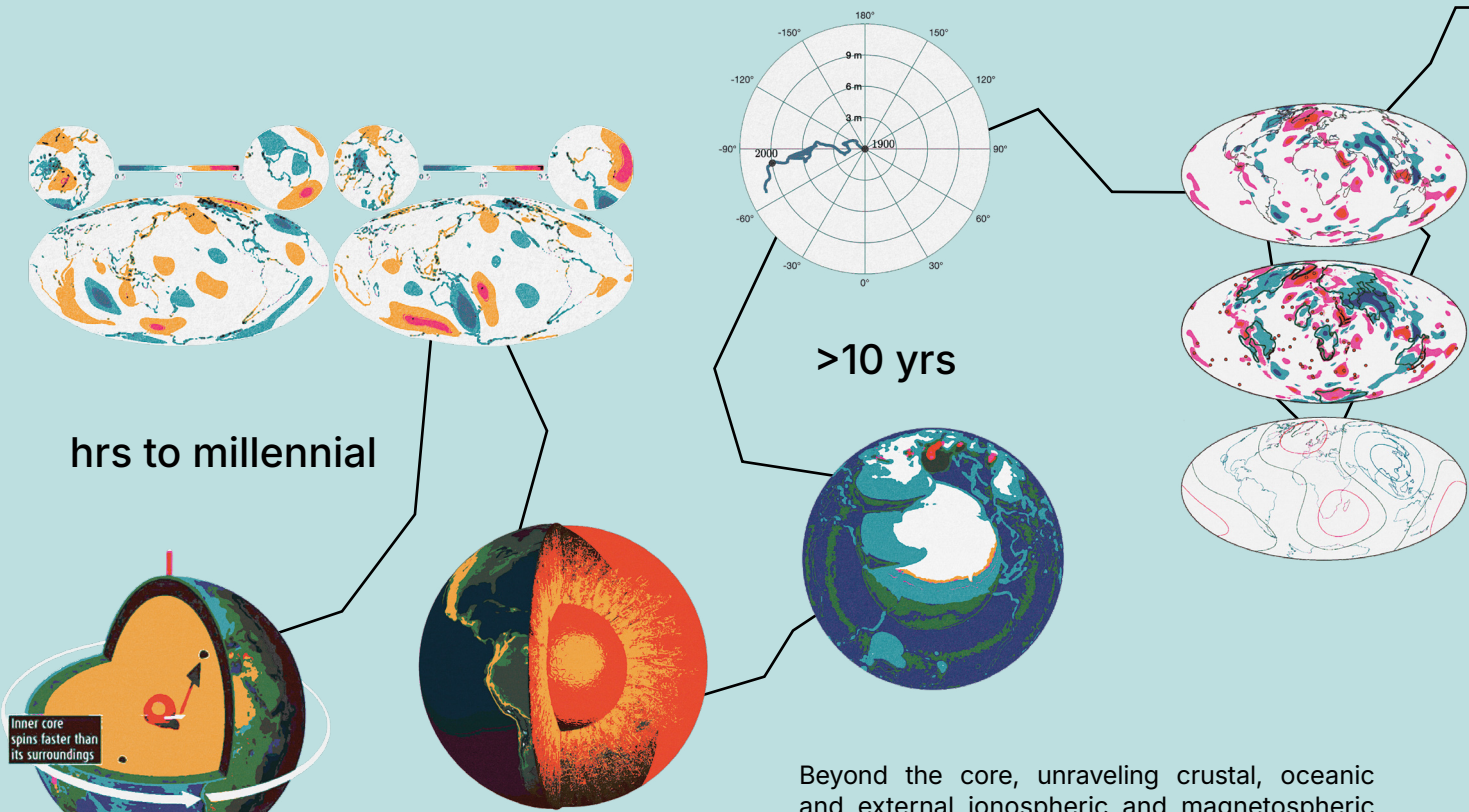
Geodetic observations of deformation at different timescales, both spatially diffuse and highly localized, have allowed the separation of the contributions of elastic, frictional, viscous, and transient behaviors, reconciling different estimates of apparent mantle viscosities and apparent lithospheric elastic thicknesses. For

example, transient creep may play an important role across the timescales relevant for the study of glacial isostatic adjustment (GIA). Deglaciation due to climate change gives us changes in sea-level in a manner that can only be predicted if we understand the response of the solid Earth to processes occurring on time scales from the catastrophic collapse of an ice sheet down to the slow melting of an entire ice cap over many thousands of years. Both thermodynamic (pressure, temperature, composition) variations inside the Earth, and the frequency and stress and history dependence of the forcings, need to be accounted for in simulating GIA-related processes. Powerful new theories have emerged that allow us to use geodetic observations for what is being termed "tidal tomography."

Continuous high-quality geomagnetic, geodynamic, and geodetic measurements have revealed sub-decadal (~6 year) oscillatory signals in the geomagnetic field, surface deformation, time-variable gravity, length-of-day (LOD), and polar motion. These co-varying signals indicate that different Earth systems may oscillate synchronously. This drives multidisciplinary efforts to understand cross-coupling among different Earth systems, from the deep interior to surface geophysical fluid systems, and a search for as yet unknown internal or external excitation mechanisms. Recently, combinations of satellite laser ranging (SLR) and GRACE observations detected a gravity anomaly that is consistent with a phase transition episode

within the deep mantle that spanned several years. Separation of the effects of a signal like this from contributions from surface water mass changes or flow in the core is only possible when there are decadal-length time series available.

An emerging development is the use of geomagnetic measurements for remote sensing the dynamic state of geophysical fluid systems. Magneto-tomography has discovered long-theorized high-frequency magnetohydrodynamic (MHD) normal modes superimposed on the slowly varying outer core state. These normal modes reveal the dynamical state of Earth's core and provide a revolutionary new tool for investigating how the magnetic field is generated and evolves on broad time scales. Magnetometric remote sensing of the oceans uses magnetic signals induced by aperiodic oceanic motion for improving estimates of ocean transport properties and the oceanic heat budget. Data assimilated within ocean circulation models improve ocean state estimates, with important applications for the study and mitigation of natural hazards (e.g., tsunami warning). Geomagnetic modeling and data assimilation are facilitating the development of precise magnetic navigation systems that will remain fully operational when GNSS is compromised or unavailable. Ultra high-resolution regional and global crustal magnetic models enable accurate



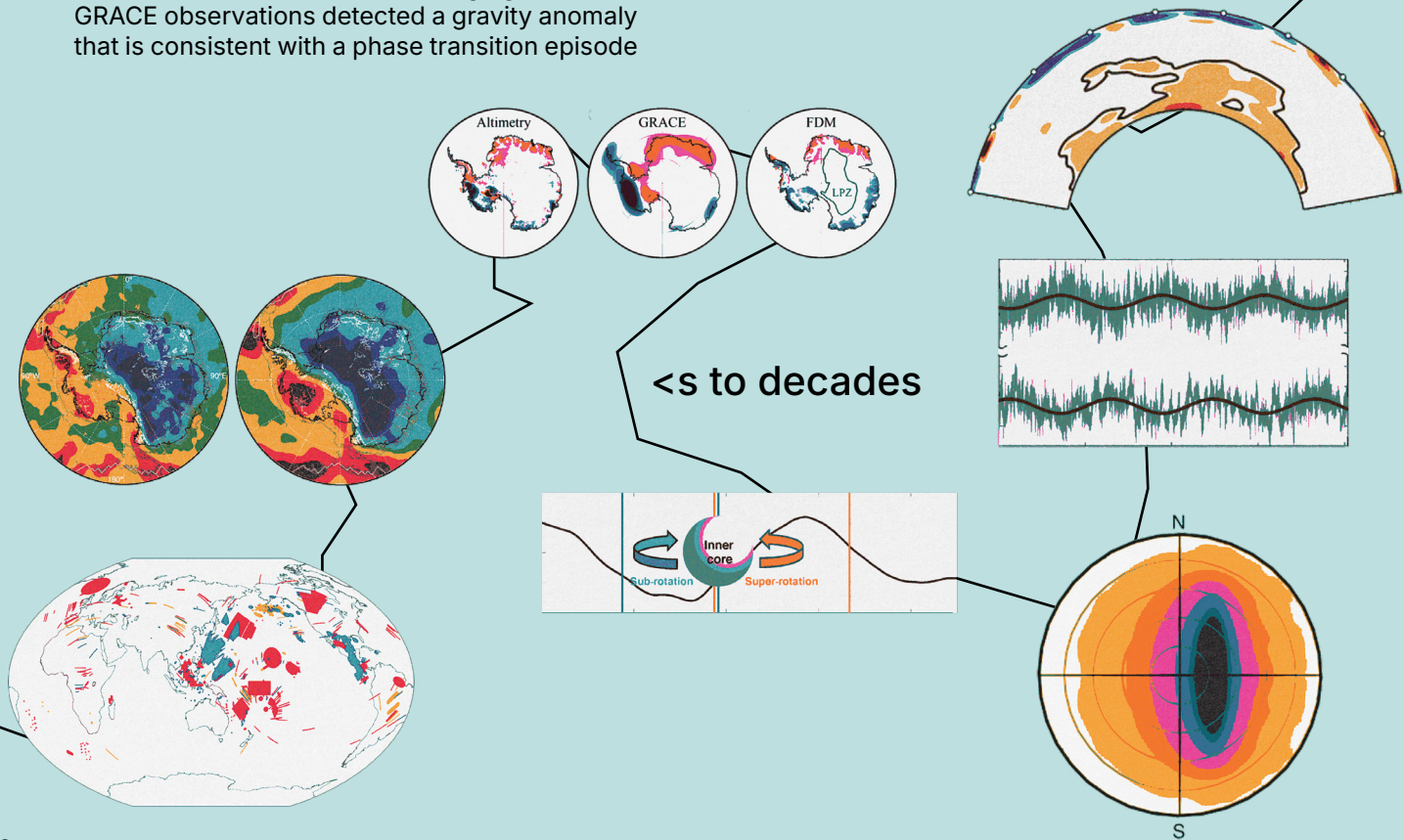
forecasts of geomagnetic secular variation in both field intensity and direction, which is of significant societal importance.

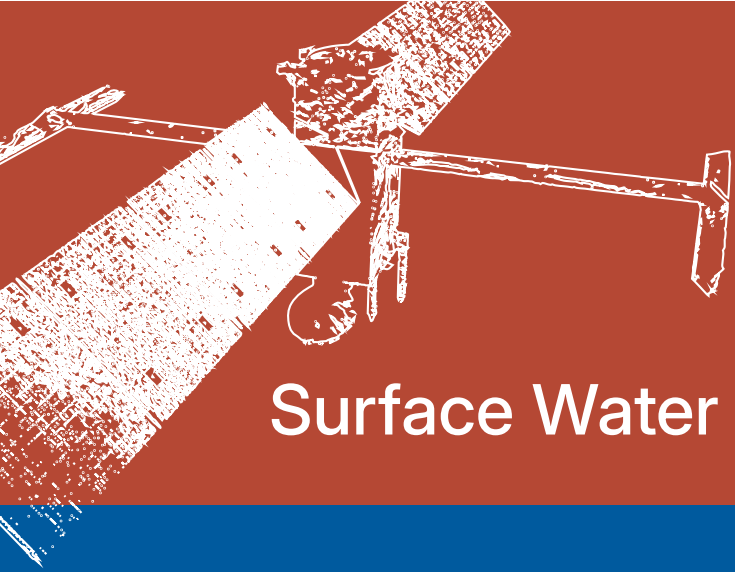
The Next Decade

The achievements in the past decade, and the emerging and rapidly developing knowledge and new capabilities have well positioned the ESI community to address the key questions listed at the beginning of this chapter. Geodetic characterizations of crust and mantle deformation behavior will rely on continuously improving analysis, modeling, and sensing systems, be they GNSS, gravity, or altimetry based. Geomagnetic and geodetic investigations into the structure and evolution of the state of Earth's core will require a quantitative understanding of the newly discovered magnetohydrodynamic waves and modes in the core. Lower mantle density and thermal structure impacts the geomagnetic secular variation, and angular momentum exchange in the core-mantle system excite Earth rotation and orientation variations on time scales of several years and longer. Accurately predicting the secular variation of earth rotation and orientation fits into broad science research while serving societal applications.

Beyond the core, unraveling crustal, oceanic and external ionospheric and magnetospheric magnetic sources is important for understanding lithospheric properties (e.g., via mantle induction) and practical applications (e.g., magnetic-based navigation systems). Estimating volumetric oceanic transport properties and oceanic heat content is critical for understanding climate variations. Determining ionospheric and magnetospheric current systems is necessary for understanding Sun-Earth interactions and their impact on life on Earth.

Accompanying these opportunities are several imminent challenges, many of which are similar to those identified in previous chapters. Addressing the scientific problems outlined in this chapter requires continuity of long-term global monitoring and improvements in spatial, temporal and spectral resolution, at a cost that is sustainable over time (Chapter 2.1). For example, separation of the effects of internal and external magnetic sources requires long-term global geomagnetic measurements and high-resolution geomagnetic field models. Model biases due to substantial differences between numerical parameters and Earth's core conditions remain to be quantified, which could be tackled with next-generation geodynamo models for asymptotically close or even comparable to Earth's core conditions (Chapter 2.2). Addressing infrastructure needs and the pipeline of human talent will be vital in order to sustain and expand NASA's core capabilities in ESI science (Chapter 2.3).





SWOT

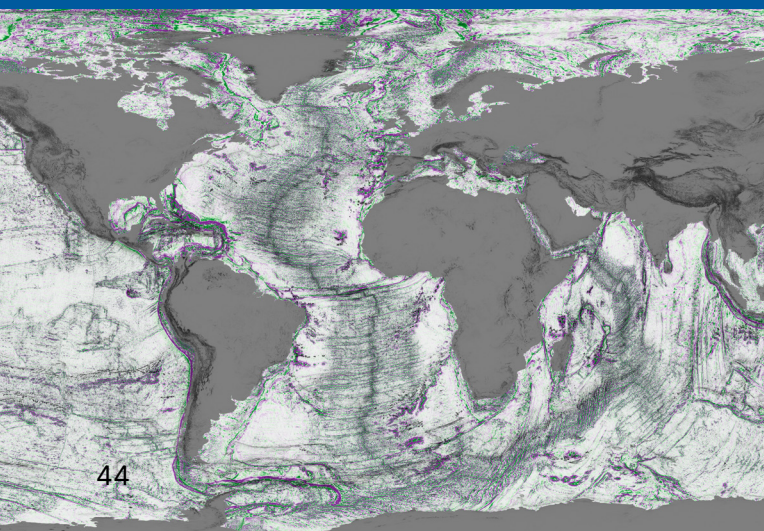
Surface Water and Ocean Topography

Science Goals:

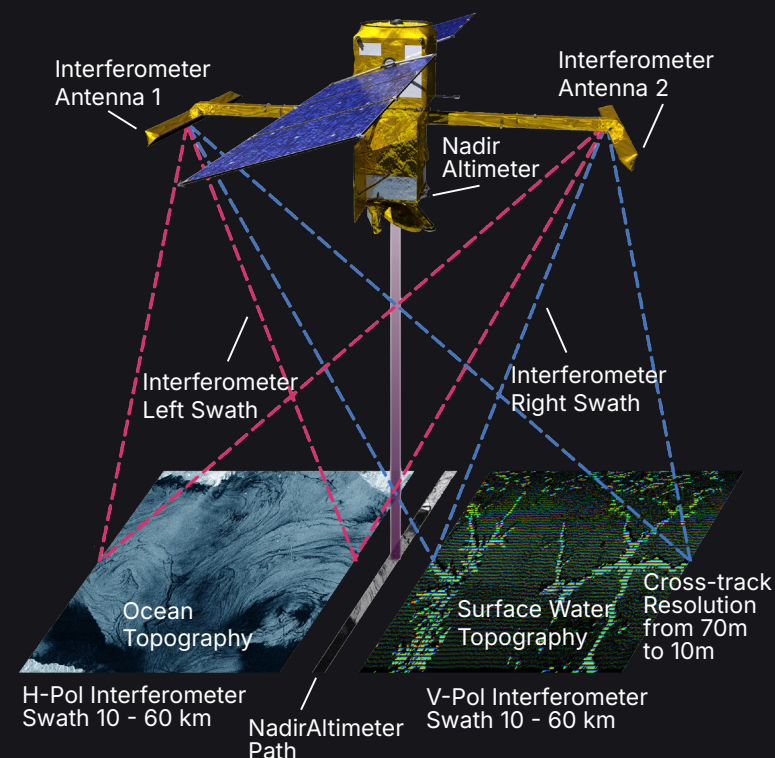
The NASA-CNES swath altimetry SWOT mission uses a radar interferometer to measure the surface topography of oceans, rivers, and lakes globally. It also measures the marine gravity field at a high (4 km) spatial resolution. Small gravity anomalies help map the 75% of the seafloor that remains uncharted by ships. Notable discoveries include abyssal hills—the most common landform on Earth; canyons along continental margins; and the bathymetry of approximately 60,000 undersea volcanoes.

A Swath of Applications:

Bathymetry and seafloor roughness influence ocean circulation, mixing, climate, and marine ecosystems. SWOT data improve tsunami hazard forecasts by mapping deep-ocean features that direct wave energy; enhance inertial navigation using the marine gravity field. SWOT data also support a range of practical uses, such as planning submarine cable routes, mapping of rivers, lakes and floods on land, refining tidal models, and evaluating territorial claims to the seabed under the United Nations Convention on the Law of the Sea.



Designed to make the first-ever global survey of Earth's surface water, the Surface Water and Ocean Topography, or SWOT, satellite will collect detailed measurements of how water bodies on Earth change over time. The satellite will survey at least 90% of the globe, studying Earth's lakes, rivers, reservoirs, and ocean at least once every 21 days to improve ocean circulation models, and weather and climate predictions, and to aid in freshwater management around the world.



A global seafloor map created using data from the SWOT (Surface Water and Ocean Topography) satellite to identify deep-sea features. Purple colors indicate regions with rapid elevation changes, such as seamounts and abyssal hills, while green areas represent more uniform regions. NASA/Goddard Space Flight Center Scientific Visualization Studio

1.5 Societal Benefits

How do Earth Surface and Interior's science and observations benefit humanity?

Key Objectives

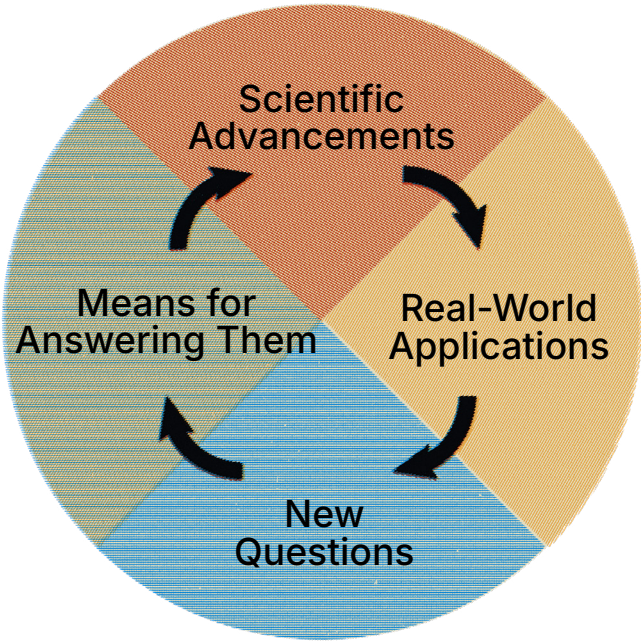
- Inform timely detection, characterization, forecasting, and mitigation of natural, anthropogenic, and cascading hazards.
- Improve discovery, characterization, and management of natural resources, including critical minerals, energy, and water resources.
- Advance precise navigation systems, including geodetic and geomagnetic-based approaches.
- Quantify vertical land motion, particularly along coasts, its contribution to inundation, and its impact on coastal communities and infrastructure.
- Empower decision-makers with trusted, actionable ESI information to improve situational awareness and advance resilience.
- Strengthen the workforce of the future to support national competitiveness.

Introduction

Societal Relevance of ESI observations

ESI science has a pivotal role in determining how we meet pressing societal challenges, from mitigating the risks associated with natural hazards to promoting sustainable resource management and supporting climate adaptation strategies. Research that is inspired by user and community-member needs fosters a “virtuous cycle,” wherein scientific advancements are directly aligned with real-world applications, which then sparks new questions and the means for answering those questions.

Research that is inspired by user and community-member needs fosters a “virtuous cycle,” wherein scientific advancements are directly aligned with real-world applications, which then sparks new questions and the means for answering those questions.



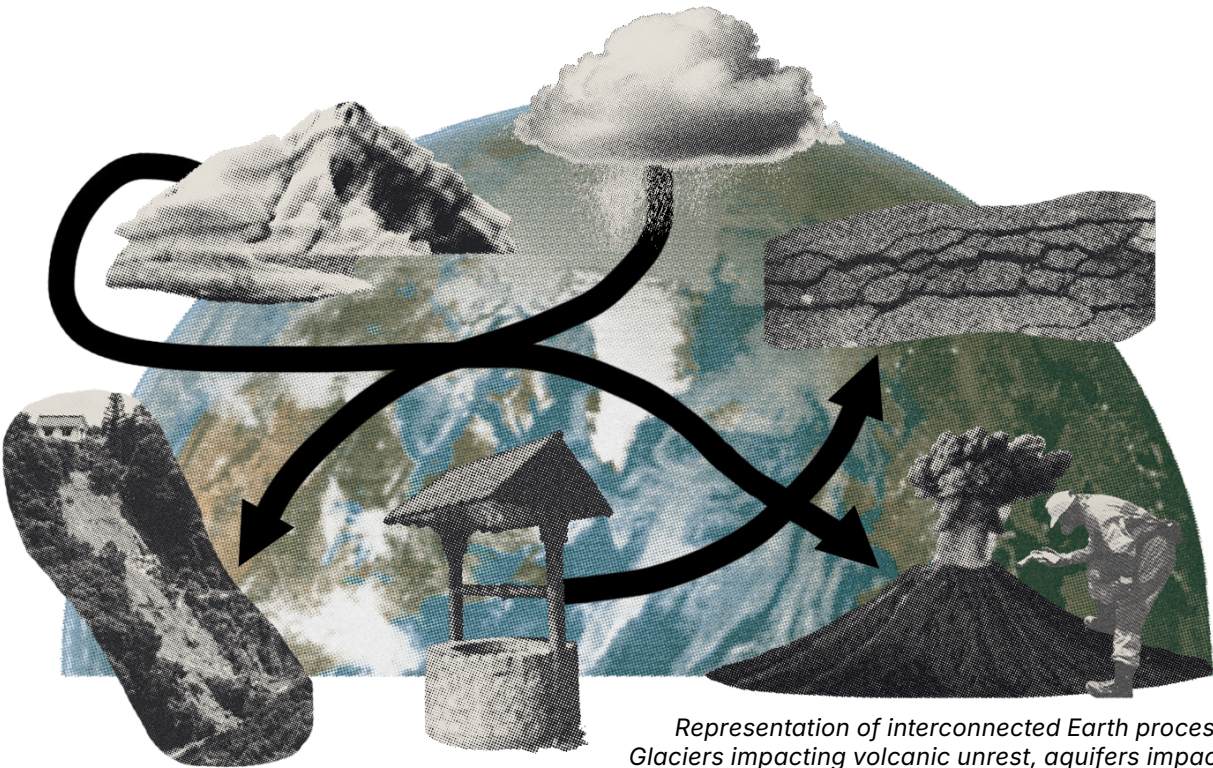
The societal relevance of solid-Earth science is evident across a range of critical applications. For example, the prediction of secular variations of the geomagnetic-field is critical for the development of the International Geomagnetic Reference Field (IGRF) model, which is widely used in both scientific research and industrial applications, and supports navigation, satellite operations, and geophysical surveys. The IGRF is an essential tool for agencies such as the National Geospatial-Intelligence Agency (NGA) highlighting the broad utility of solid-Earth science in national security and strategic planning.

Through these contributions, solid-Earth science not only advances our understanding of the planet but also provides tangible benefits that enhance societal resilience and sustainability. It underpins efforts to forecast and respond to geohazards such as earthquakes, tsunamis, and volcanic eruptions, thereby enhancing public safety and disaster preparedness. Solid-Earth science supports the sustainable management of vital natural resources, including groundwater, minerals, and energy, ensuring their availability

for future generations. Additionally, solid-Earth science helps to address the environmental impacts of human activities, such as land subsidence caused by groundwater extraction and seismic events induced by resource exploitation.

Past Decade

Over the past decade, NASA's missions have provided essential measurements of changes to Earth's surface, offering unprecedented insights into processes that affect both natural environments and human infrastructure. A major achievement has been the successful integration of multisensor platforms, including GNSS, InSAR, and GRACE, revolutionizing the way landscape deformation and subsurface processes are monitored. This integration has improved the detection, measurement and characterization of geohazards and enhanced



Representation of interconnected Earth processes: Glaciers impacting volcanic unrest, aquifers impacting infrastructure damage, and rain impacting landslides. Adobe Stock, Florian Schwandner

resource assessments. One example is the characterization of vertical land motion along coastlines, which is now performed with a steadily growing set of observation types that include GNSS, InSAR, high-resolution digital elevation models, optical imager, and LIDAR. The deployment of the EMIT and ECOSTRESS sensors on the International Space Station was a milestone for imaging spectroscopy of the Earth's land surface at high resolution. Both sensors support a variety of research and applications ranging from detection of methane and volcanic gas emissions, to hydrothermal processes leading to volcano instability and landslides, and to identification of energy, mineral and water resources.

There has also been a notable enhancement in understanding of interactions within the Earth system. Research has increasingly focused on the coupling between solid-Earth processes and hydrological, cryospheric, and atmospheric systems. This interdisciplinary approach has shed light on complex feedback mechanisms and cascading hazards, such as how tectonic activity can influence hydrological cycles (and vice versa) or how glacial melting impacts seismicity or volcanic unrest. These insights are critical for anticipating the broader impacts of environmental changes and natural disasters.

The development and application of artificial intelligence (AI) in geoscience represent another

key milestone. AI-driven tools have proven effective in processing large datasets, identifying subtle patterns, and enhancing predictive models for natural hazards. This technological advancement has accelerated the pace of discovery and improved the accuracy of efforts to forecast aftershocks, volcanic eruptions, and other geohazards.

In addition to scientific and technological progress, there has been an expanded focus on stakeholder engagement. Programs like the Advanced Rapid Imaging and Analysis (ARIA) project, and Observational Products for End-Users from Remote Sensing Analysis (OPERA) project exemplify this shift by providing actionable geospatial products that support situational awareness, disaster response, resource management, and policy development. By aligning scientific outputs with the needs of decision-makers and communities, these initiatives ensure that research has a direct and meaningful societal impact.

Present Day

Today, it is widely appreciated that the complexity of Earth's dynamic systems and their relationship to socially relevant applications requires that we acknowledge and address the coupling between such systems and acquire

the data necessary to understand them. The intricate interactions between the solid Earth, hydrosphere, atmosphere, and cryosphere are difficult to disentangle due to their complex feedback loops and overlapping temporal and spatial scales. Moreover, cascading hazards – such as earthquakes triggering landslides or volcanic eruptions influenced by climatic shifts – add additional layers of complexity that are challenging to model accurately.

While solid-Earth science provides critical insights into resource management (e.g., subsidence associated with groundwater) and some types of natural hazards (e.g., volcanic unrest, likelihood of aftershocks following an earthquake), these insights must also be effectively communicated to, and then utilized by policymakers, emergency managers, and the broader public.

The growing influence of anthropogenic activities has introduced further complications. Activities such as groundwater extraction, resource exploitation, and large-scale infrastructure projects have been linked to induced seismicity and land subsidence, blurring the lines between natural variability and human-induced changes. These impacts have challenged efforts to establish natural baselines of behavior and have complicated the interpretation of geophysical data. Where available, combinations of independent observations with sufficient spatial and temporal resolution have facilitated such efforts, such as the use of GNSS, gravity and space-based geodetic imaging to study groundwater withdrawal in California during recent droughts and recovery periods. Such data are now used operationally by state-level decision makers in Arizona and California as part of their efforts to manage freshwater resources in an era of expanding agricultural activity and finite resources.

Similarly, synergies have been exploited between spectral data collected at VSWIR and TIR wavelengths with InSAR and Lidar data collected over the same areas of the Earth.

Together, these datasets can be useful for monitoring slope (in)stability, including those related to permafrost change in arctic coastal areas, as well as for landslide and debris flow potential after wildfires and volcano sector or edifice collapse. VSWIR hyperspectral data have been used to map the distribution of char materials from recent wildfires in the western United States, as well as the moisture state of vegetation and soils. This information has helped forecast the accumulation of fuels that could feed future fires, particularly those along the Wildland-Urban interface. Similar data from airborne platforms was used to rapidly characterize damage to structures after the devastating 2025 fires in Los Angeles.

While solid-Earth science provides critical insights into resource management (e.g., subsidence associated with groundwater) and some types of natural hazards (e.g., volcanic unrest, likelihood of aftershocks following an earthquake), these insights must also be effectively communicated to, and then utilized by policymakers, emergency managers, and the broader public. Today, efforts to enhance societal engagement are focusing on the development of effective frameworks for translating complex scientific findings into actionable policies and decision-making tools. There have been deliberate efforts to engage with community members and the general geohazards communities of practice to incorporate their needs into scientific research agendas. As one example, the development of the NISAR mission included a series of stakeholder workshops aimed both at achieving a better understanding of their needs and how NISAR data could benefit them, but also at educating them about the tools that are available to facilitate their own direct use of this data post-launch. The OPERA Surface Displacement (DISP) products were generated with these users in mind, along with the development of a portal hosted by the Alaska Satellite Facility Distributed Active Archive Center (DAAC) that allows users to visualize and interact with InSAR-based displacement rates and time series without any specialized training or computational resources.

In the rapidly evolving landscape of Earth science, training in the analysis of data and use of cyberinfrastructure continues to present notable challenges. Many Earth science practitioners face difficulties in adopting modern computational workflows, particularly

those involving advanced cyberinfrastructure like cloud computing. These workflows, while powerful, often come with steep learning curves and complex technical requirements that can be barriers to entry. To address this, NASA and other agencies have supported the development of accessible training programs (e.g., for the processing of GNSS and InSAR data) and user-friendly cloud-hosted platforms designed to lower these barriers. Such resources empower scientists to harness the full potential of modern computational tools, enabling more efficient data processing, analysis, and collaboration across disciplines. Today, NASA data are more widely utilized than ever before, both domestically and internationally. Geodetic data inform the USGS earthquake response, the management of water resources, and planning for coastal resilience. Multi- and hyper-spectral data support the search for new resources, a better understanding of the response of the landscape to extreme weather events, and the interplay between fires, vegetation and landslides.

The Next Decade

The evolving landscape of solid-Earth science presents numerous opportunities to address the problems described above and build upon previous successes. It is critical to maintain a strategic focus on making progress on problems that face society, and prioritizing observational strategies, technology and analytical tools that are needed to make progress on these problems. Gaps continue to exist in public understanding of how solid-Earth science contributes to disaster mitigation and sustainability efforts. As a result, there is an urgent need to communicate the societal impact of these data, including how these data are used to address hazards and opportunities associated with changes driven by both natural forces and human activities.

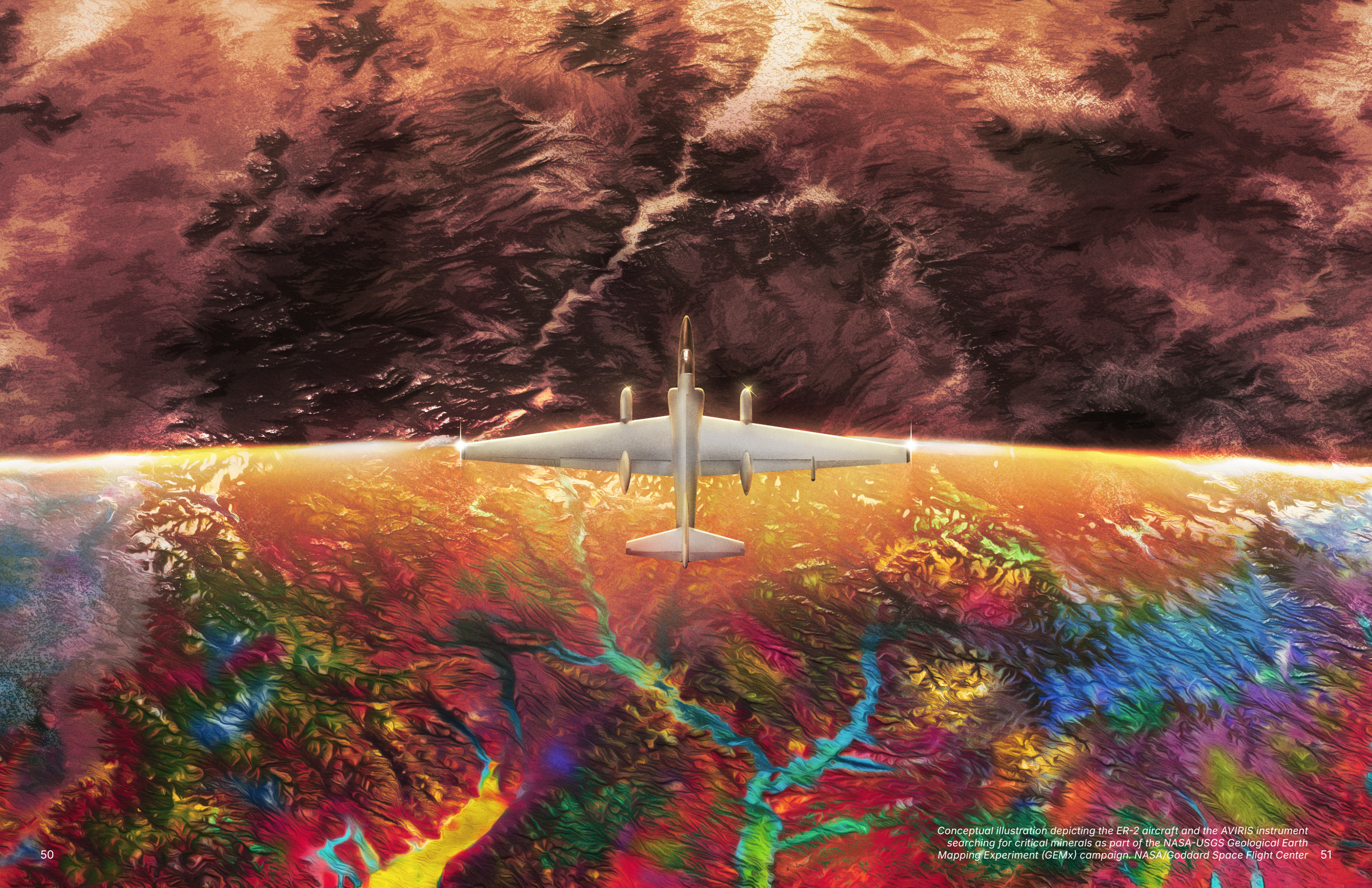
For instance, as landcover is changing due to environmental shifts, there can be new opportunities to map mineral deposits using NASA platforms. This is especially true of areas which are remote or otherwise inaccessible, and for which only remote sensing data can provide such compositional information. Mineral and energy resource assessments, and the search for new sources of critical- and energy-related minerals require accurate mineral maps of the earth's surface. These maps can help guide more detailed geologic mapping and further on

the ground exploration and resource extraction. The growing utilization of water resources represents another critical area of opportunity. Geodetic data can inform water management and decision making around reservoir operations, such as balancing drought risk with the risk for flooding and damage to infrastructure during extreme weather events. Geodesy's sensitivity to regional groundwater storage can be used in combination with hydrologic modeling and data assimilation to explore and forecast how a watershed may respond to a rapid influx of water, such as floods after periods of drought, and rapid snowpack melting. Investigating load-induced Earth deformation at the time scales of individual storms (such as was performed for Hurricanes Harvey and Sandy) is a relatively new research direction, with direct societal relevance to the study of potential inundation along coastlines.

There is also room for growth in our ability to forecast and assess natural hazards. Our very limited understanding of the precursors and physical mechanisms driving phenomena like earthquakes, landslides, and volcanic eruptions seriously constrain our forecasting capabilities. Without a clearer grasp of these processes, it remains challenging to anticipate when and where hazardous events might occur and to warn the public in a timely manner. There remains a lack of robust models that can effectively integrate diverse observational data with advanced computational techniques, such as machine learning and physics-informed neural networks (PINNs). These approaches hold great promise for improving the accuracy of geohazard forecasts, yet there is a need for improvement before they can effectively capture the complex, nonlinear interactions that govern natural events.

It is critical to maintain a strategic focus on making progress on problems that face society, and prioritizing observational strategies, technology and analytical tools that are needed to make progress on these problems.

The data required to address societal needs ranges from the development and deployment of new sensors to the enhancement of temporal



and spatial sampling of existing technologies. TIR data can provide accurate surface temperatures, allowing monitoring of urban heat island effects and permafrost thaw in the Arctic which can release methane. Satellite-based monitoring of the complex interplay between geological activity and atmospheric composition, while transformative, still faces capability gaps. Current satellite missions are unable to routinely monitor multiple key parameters, such as carbon dioxide (CO₂) and sulfur dioxide (SO₂) emissions from volcanic systems and separate them from methane (CH₄) and other greenhouse gases from anthropogenic sources such as dairy farms and landfills. Building on the successes of VSWIR and TIR measurements for geologic, snow/ice, mineral mapping, gas/aerosol plume and vegetation studies will require a new spaceborne sensor such as the proposed Surface Biology and Geology (SBG) mission. SBG would provide temporally comparable VSWIR and TIR data acquired from two different platforms.

The development of very-low-Earth-orbit (VLEO) satellites promises to revolutionize crustal and magnetic-field mapping by offering unprecedented spatial resolution. These advancements will enhance our ability to monitor subtle changes in Earth's surface and interior, providing critical data for both scientific research and practical applications. In parallel, emerging sensor technologies in other allied communities, such as DAS, are transforming existing communication infrastructure into dense seismic monitoring arrays, including in more inaccessible regions such as on the seafloor. Such synergies can leverage NASA resources and deliver additional value beyond what can be achieved through NASA-supported data alone.

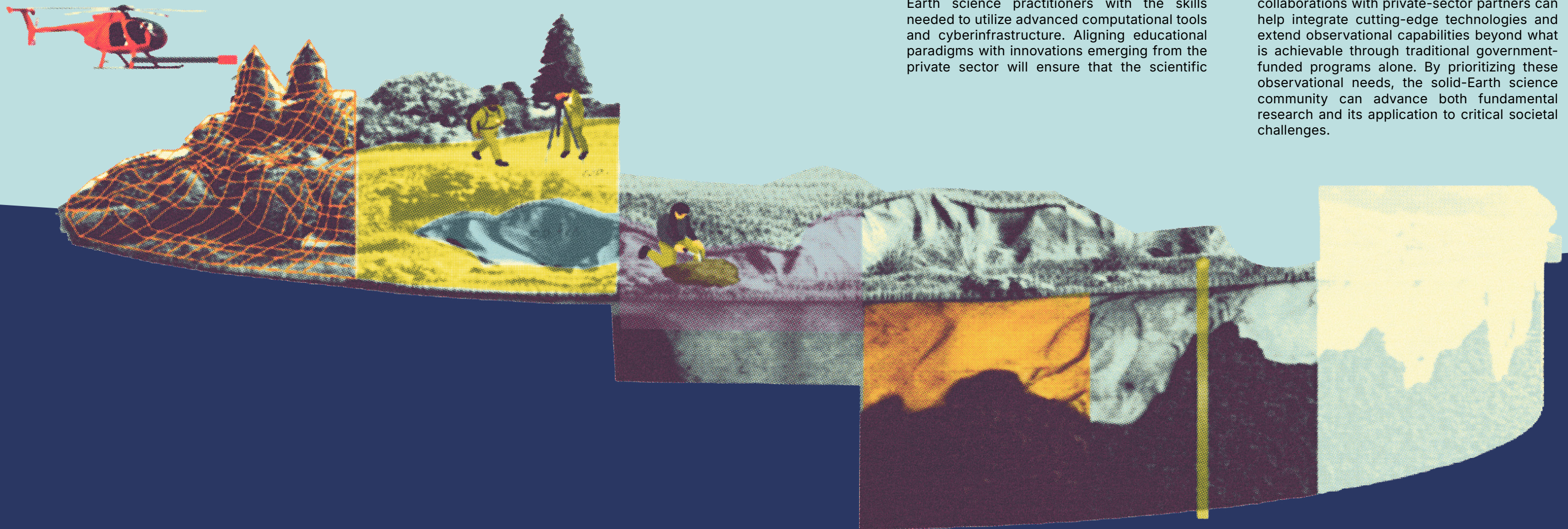
To maximize the value of these diverse observational data, there is a pressing need for improved interdisciplinary data integration. Creating infrastructure that facilitates the combination of datasets from multiple

sources—such as InSAR, GNSS, and optical remote sensing platforms—will enable a more holistic view of Earth system processes that can be more easily integrated by end-users who are trying to understand the impact of droughts, potential inundation along coastlines, or other complex phenomena. Enhancing real-time data fusion capabilities is particularly important for supporting rapid disaster response and decision-making, where timely, integrated information can significantly improve outcomes. Strengthening stakeholder engagement is also crucial for aligning research priorities with societal needs throughout the value chain. By actively involving communities, policymakers, and other stakeholders in the research process, scientists can ensure that their work has meaningful, real-world impact and garners broad public support.

To fully realize these opportunities, it is essential to invest in rejuvenating the workforce. This includes the development of targeted training programs designed to equip Earth science practitioners with the skills needed to utilize advanced computational tools and cyberinfrastructure. Aligning educational paradigms with innovations emerging from the private sector will ensure that the scientific

workforce remains agile and adaptable in the face of rapidly evolving technologies. Additionally, fostering collaboration between academia, industry, and government will promote the development of interdisciplinary expertise and encourage the translation of scientific discoveries into practical applications.

Finally, accelerating innovation and discovery and ensuring the broad utility and impact of observational data requires a commitment to data accessibility, training, and Open Science. Support for tutorials and training workshops aimed at the full range of the NASA community, from students and early career researchers to more senior scientists, can ensure that the workforce is able to fully utilize NASA's investment in new observation and take advantage of the most state-of-the-art analytical approaches (including modeling, machine learning, etc.). Promoting open access platforms for data sharing will enable the scientific community to leverage these resources for an ever-growing range of research applications. Fostering collaborations with private-sector partners can help integrate cutting-edge technologies and extend observational capabilities beyond what is achievable through traditional government-funded programs alone. By prioritizing these observational needs, the solid-Earth science community can advance both fundamental research and its application to critical societal challenges.



Observational Technology, Information Infrastructure, and Talent

Pathways

Chapter 2:

NASA AIRBORNE SCIENCE PROGRAM



A conceptual illustration of the NASA Earth Science Airborne Program fleet. NASA

Furthering and advancing the use of satellite data:

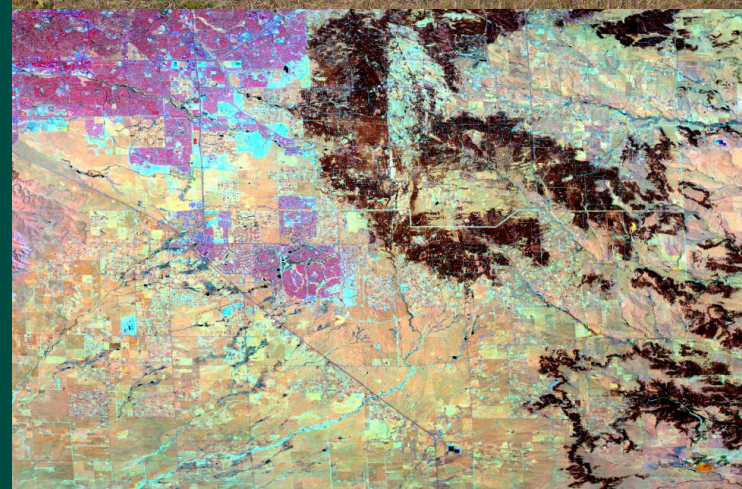
The NASA Airborne Science Program (ASP) operates, maintains, and grows a family of airborne platforms to support NASA science. ASP meets NASA's evolving needs by advancing new capabilities for a variety of ranges, altitudes, speeds, agility, capacities, and concept-of-operation scenarios. In partnership with the private sector, ASP enables technology maturation through sub-orbital testing of new instrument technologies and algorithms, including SBIR investments in high-altitude platform systems (HAPS), and in autonomous low-altitude drone technology for solid Earth hazards mapping and science.

A composite image taken by the ASP's MASTER instrument in April 2026 to evaluate the mineral composition of the ground beneath: each color in the image corresponds to a different material with unique reflective, emissive, and thermal properties. NASA/EPIC Lab

Primary Objectives:

One of the key supported capabilities is the collection of calibration and validation data for Earth-observing satellites. Airborne platforms also provide the opportunity to collect spatially and temporally targeted, high-resolution measurements of processes over small scales that can then be co-analyzed with global satellite observations.

The Costa Rica Airborne research on forest Ecosystem Response to volcanic emissions (CRATER) team poses with the S2 Black Swift uncrewed aerial system in front of the Rincon de la Vieja volcano. NASA/Milan Loiacono



2.1 Observational Technology

Developing Next-Generation Observing Systems to Address ESI Science Priorities

Key Objectives

- Improve the temporal, spatial, and spectral range and increase the sensitivity of geodetic, geomagnetic, and spectroscopic imaging of Earth's surface and interior through next-generation instruments and integration of constellations of ground, airborne and space systems.
- Accelerate rapid and agile architecting, prototyping, and demonstration.
- Promote interoperability through standards and agreements.
- Quantify vertical land motion, particularly along coasts, its contribution to inundation, and its impact on coastal communities and infrastructure.
- Address space-to-ground download bottlenecks and explore onboard processing.
- Develop agile tasking capabilities that enable rapid response and situational awareness after major natural and anthropogenic disasters.

Introduction

NASA has long been a leader in the use of space and suborbital assets to address fundamental questions about the processes operating in and on the Earth, many of which are of critical societal importance. The scientific questions raised in Chapter 1 can be answered through measurements of the Earth’s surface, solid and fluid; the temporal changes in these surfaces; the radiative emissions from the surface and medium between Earth and Space; and the gravity and magnetic potential fields of the Earth. In the next decade, it is critical that we ensure the continuity and accuracy of these measurements, while improving their quality in ways that will allow researchers to answer these pressing questions.

Rapid temporal repeats, high spatial resolution, and broad spectral coverage are some of the key areas where improvements in observations can impact science and application outcomes. Other themes that bind the development and deployment of geo-observation systems are the need for continuity (including the ability to combine legacy and leading-edge data), and for approaches that facilitate the integration, fusion, assimilation, and joint inversion of disparate and heterogeneous data sets.

Rapid temporal repeats, high spatial resolution, and broad spectral coverage are some of the key areas where improvements in observations can impact science and application outcomes.

The measurement systems described in this chapter differ greatly in their capabilities and limitations. Microwave systems (0.3-15 GHz: P- to Ku bands) can acquire data at night and in nearly all weather conditions, including dense cloud cover, but their interactions with atmospheric water vapor and the ionosphere introduce effects that must be accounted for in analyses. Optical signals are less affected by atmospheric refraction, but signals can be entirely blocked by clouds and dense aerosols. Precise satellite-to-satellite tracking systems (e.g., GRACE family of missions) are highly sensitive to changes in the gravity field, while SLR (with its long history of observations) contributes ob-

servations of the longest spatial-wavelength components of the gravity field and center-of-mass variability. Very high-altitude satellites such as GNSS have low sensitivity to Earth’s gravity field but provide excellent positioning capability due to the large number of dedicated satellites and the large networks of ground receivers.

Over the last decade, the Earth Surface and Interior (ESI) community has made great progress in many areas that were described as high priorities within the most recent Decadal Survey (ESAS 2017), as well as in areas that were then seen as future opportunities. Reference frames have improved both in long-term secular stability and in our ability to capture their short-term variability. Earthquake early-warning systems using both seismic and geodetic data have been deployed, and seafloor geodetic systems (e.g., GNSS-acoustic, ocean-bottom pressure sensors, direct path ranging), although limited in number, have been used for critical earthquake studies. Strides have been made in automated InSAR processing, particularly with openly accessible Sentinel-1 observations, and routinely generated InSAR products are now being used in earthquake, volcanic, and hydrologic studies. Airborne observations from NASA UAVSAR and point clouds from uncrewed aerial vehicles and drone imaging are regularly being generated, but their integration into synoptic products is still an area of active development.

Reference Frames and Earth Orientation Parameters

Reference frames tie together the measurements from the systems that observe the wide variety of solid Earth phenomena and establish the basis for temporal and spatial comparisons. The relationship between the celestial and terrestrial coordinate systems (in the form of time-dependent Earth Orientation Parameters), provides valuable information about global-scale mass movement, loading, and deformation. All measurements in the Earth reference system have differing requirements for the accuracy of the frame, i.e., low-resolution imagery may only need tens of meters accuracy, while studies of long-term sea-level rise require improvement from the current ~0.5 mm/yr stability of the terrestrial reference frame to a target goal of 1mm/decade stability, proper-

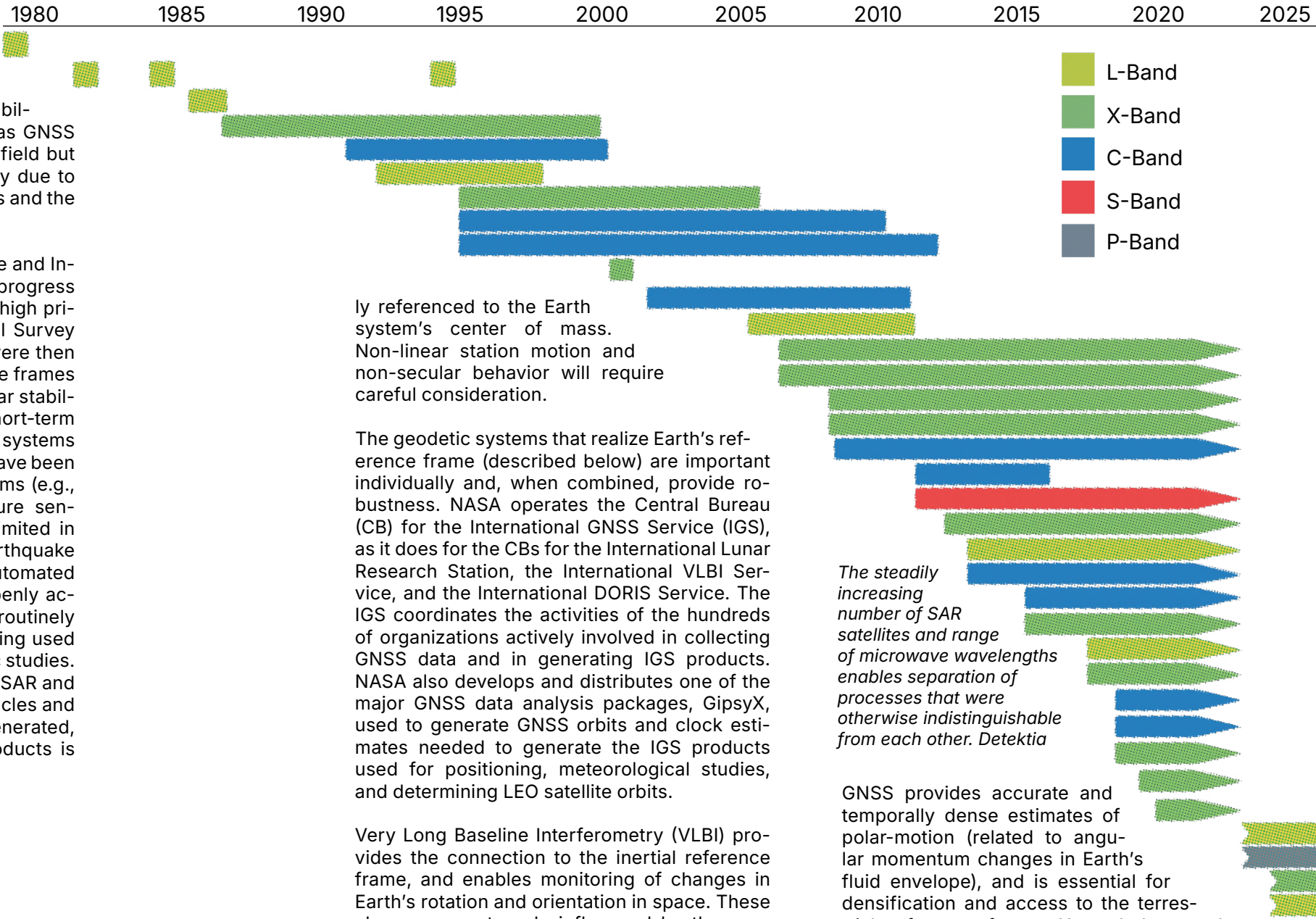
ly referenced to the Earth system’s center of mass. Non-linear station motion and non-secular behavior will require careful consideration.

The geodetic systems that realize Earth’s reference frame (described below) are important individually and, when combined, provide robustness. NASA operates the Central Bureau (CB) for the International GNSS Service (IGS), as it does for the CBs for the International Lunar Research Station, the International VLBI Service, and the International DORIS Service. The IGS coordinates the activities of the hundreds of organizations actively involved in collecting GNSS data and in generating IGS products. NASA also develops and distributes one of the major GNSS data analysis packages, GipsyX, used to generate GNSS orbits and clock estimates needed to generate the IGS products used for positioning, meteorological studies, and determining LEO satellite orbits.

Very Long Baseline Interferometry (VLBI) provides the connection to the inertial reference frame, and enables monitoring of changes in Earth’s rotation and orientation in space. These changes are strongly influenced by the coupling between the fluid outer and solid inner cores to the mantle, and are critical for any navigation outside the local Earth system (e.g., for lunar and planetary navigation). Improvements to atmospheric-delay modeling, densification of the network of very-wide bandwidth systems, and protection of the microwave frequency band are needed to improve VLBI accuracy and exploit the engineering gains embodied in the VLBI Global Observing System (VGOS). SLR provides the most robust access to Earth’s center-of-mass motions and variability in dynamic oblateness. Higher network density, range bias reduction, and multi-satellite analysis are needed for improved SLR accuracy. The Space Geodesy Satellite Laser Ranging (SGSLR) system will be critical to meeting these goals.

GNSS provides accurate and temporally dense estimates of polar-motion (related to angular momentum changes in Earth’s fluid envelope), and is essential for densification and access to the terrestrial reference frame. Upgraded ground and satellite antenna calibrations, orbit modeling, improvements to ties between observa-

Upgraded ground and satellite antenna calibrations, orbit modeling, improvements to ties between observation systems, and improved atmospheric delay modeling are needed to support each of these geodetic systems, which may necessitate improvements to the frames themselves.



tion systems, and improved atmospheric delay modeling are needed to support each of these geodetic systems, which may necessitate improvements to the frames themselves.

Earth Surface Deformation and Change

InSAR has progressed over the past three decades from a series of research-focused SAR missions (e.g., ERS-1/2, JERS, RADAR-SAT-1/2, ENVISAT, ALOS-1/2, TerraSAR-X, COSMO-SkyMed) to missions providing systematic observations (e.g., Sentinel-1, NISAR). Commercial satellites have added opportunistic acquisitions that supplement space-agency mission observation plans, particularly for time-sensitive events (e.g., earthquakes, floods, and volcanic eruptions). UAVSAR observations have covered many targets of interest with campaigns of repeat observations that have provided both higher resolution imagery than satellite platforms, but also the potential to acquire SAR observations from different viewing geometries (e.g., along east-west flight paths). The NISAR mission, launched in 2025, is the first SAR mission that includes L- and S-band radar observations. NISAR observations will follow a systematic, global acquisition plan over land and coastal waters, with at least two observations of any location during any 12-day period.

High-resolution (<10m spatial resolution; <1m precision and accuracy; ~daily targeted sampling) bare-earth baseline digital elevation models (DEMs) are required for the generation of topography change products and their many applications (e.g., lava flow thickness, coastal storm surge flooding and erosion, glacier and

permafrost change). For over two decades, satellite laser altimetry has offered high precision (<1m), locally dense but synoptically sparse observations providing key insights into Earth's surface morphology over land, including bare land height and vegetation complexity. Additionally, a long history of airborne laser altimeter data continues to support various scientific and societal applications. Over the oceans, sea surface topography via radar altimetry measures the steric contributions to sea level change, and indirectly to the topography of ridges, trenches, and transform faults on the ocean floor, at scales that complement the still relatively sparse directly observed ship-based tracks.

Currently, ICESat-2 and GEDI are NASA's primary satellite laser altimeters. These systems play a crucial role in calibrating DEMs, which in turn helps InSAR missions with terrain corrections. SAR missions can also produce high-resolution, accurate topographic data (e.g., ~1 m vertical accuracy at 12 m spatial sampling for the TanDEM-X mission from the German Aerospace Agency). Airborne single-pass InSAR topography from NASA's UAVSAR Ka-band GLISTIN-A is capable of 3 m spatial sampling with a few meters precision that is most suited for low-vegetation topography change. The airborne QUAKES-I stereo-imager provides wide swath meter-level measurement of topography and associated color imagery but is best suited to areas without dense vegetation.

Radiative and Reflective Properties

Mapping of the surface at wavelengths from the ultraviolet through thermal infrared enables re-

search within a wide suite of topics, including volcanology, mineral exploration, and landslide hazards. Compositional information derived from such data include accurate mineral maps over exposed soils, rocks, and other geologic materials. In addition, measurements from these systems are sensitive to gas emissions and can be used to address the magnitudes of sources of these emissions. For instance, the Geological Earth Mapping Experiment (GEMx) was a joint USGS/NASA mission that utilized NASA aircraft to map the potential for lithium, aluminum and rare earth elements in the western United States. In combination with InSAR and lidar data, these observations can also help monitor slope (in)stability, informing the potential for landslides, both volcanic and terrestrial. Debris-flow potential can also be assessed after wildfires.

VSWIR hyperspectral data, in particular, can be used to map the extent of wildfire char and the moisture state of vegetation and soils, thereby evaluating the accumulation of fuels for future fires. Additionally, the incorporation of high-resolution mapping of mineralogy and chemistry along fault zones and recent earthquake ruptures can provide useful information on fault strain rates and, as in the case of TIR, when hydrothermal fluids are involved, identify additional targets for mineral resource exploration, and evapotranspiration.

Gravity Field

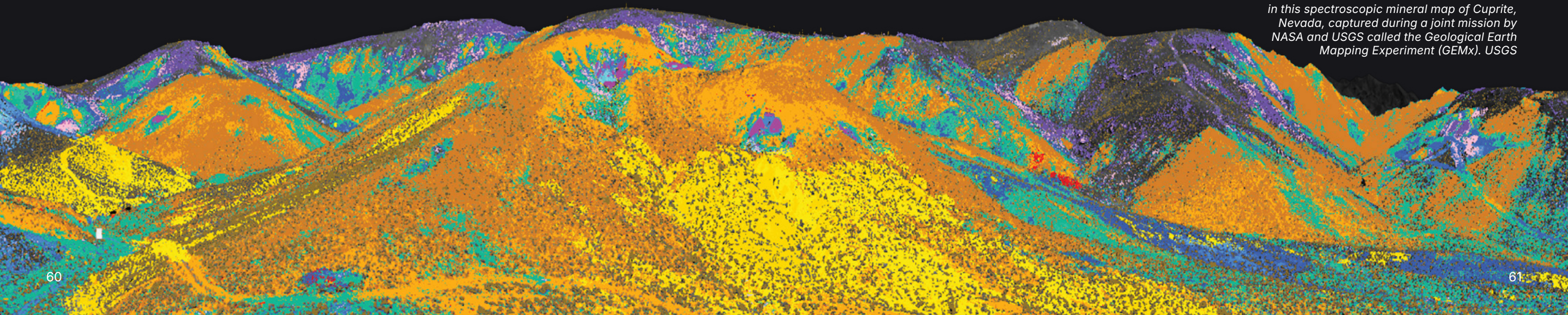
Space-based measurements of the gravity field and sea surface altimetry each have decades-long data records, which are further complemented by extensive GNSS ground networks that provide calibration and ancillary

measurement types. A mature community of users have developed sophisticated processing algorithms that determine the shape of Earth's fluid envelope under the influence of Earth's gravity and rotation (a gravitational equipotential known as the geoid). The last decade has witnessed major advances in modeling, with high-resolution geoid, high-resolution DEMs, ocean tides, non-tidal ocean loading, ice sheet evolution, glacial isostatic adjustment (GIA) and 3D earthquake models all now routinely generated while continuing to be improved. Important technological strides include SWOT, satellite-to-satellite laser ranging interferometers, and quantum gravimeters for airborne and terrestrial gravity mapping.

Global gravity-change measurements by the GRACE (2002–2017) and GRACE-FO (2018–present) missions have provided innumerable insights into hydrological, cryospheric, and oceanographic processes (at long spatial wavelengths) and have illuminated interior processes such as the earthquake seismic cycle. Ongoing research and development in spaceborne gravimetry data processing and estimation algorithms have led to continued improvement in the mass-change products derived from GRACE and GRACE-FO data, which has furthered both their scientific value and their societal impact.

Despite all these advancements, time-variable gravity studies suffer from geocenter uncertainty and remain limited in spatio-temporal resolution. Gravity change is linked to position change and both need to be appropriately reconciled. With static geoid models, the largest uncertainty is in the 40–100 km wavelength range. Large gaps exist between the terrestri-

Various minerals are revealed in vibrant detail in this spectroscopic mineral map of Cuprite, Nevada, captured during a joint mission by NASA and USGS called the Geological Earth Mapping Experiment (GEMx). USGS



al and airborne measurements of gravity with large uncertainties in the coastal geoid due to altimetry dependence on density assumptions for topography above the geoid and sensitivity to density errors from lakes, ice sheets, and errors in the DEMs. Relative sea level measurements still suffer from a lack of co-location of GNSS and tide gauges, and reduced accuracy of radar altimetry near the coast.

Magnetic Field

Space-based magnetic measurements in the post-MagSat era have been provided by the international community, including the current Swarm mission and Macau Science Sats, and ESA's proposed NanoMagSat. These magnetic observations have supported a wide range of studies, including those of the Earth's sea-floor. Over the oceans, most remote-sensing methods only see the water surface, but gravity and magnetic fields are sensitive to integrated properties and can extend the measurement of crustal deformation and characteristics beyond exposed land. While progress is being made using data from modern satellite-magnetic surveys (e.g., the extracted ocean tidal magnetic signals are now a high-level data product of ESA's Swarm mission), observational configurations aimed at extracting oceanic signals require further study and implementation.

Magnetic navigation capability is of national security importance, serving both civilian and military purposes when GNSS-based systems are compromised or unavailable. These applications share the challenges of geomagnetic data assimilation and field modeling, but they

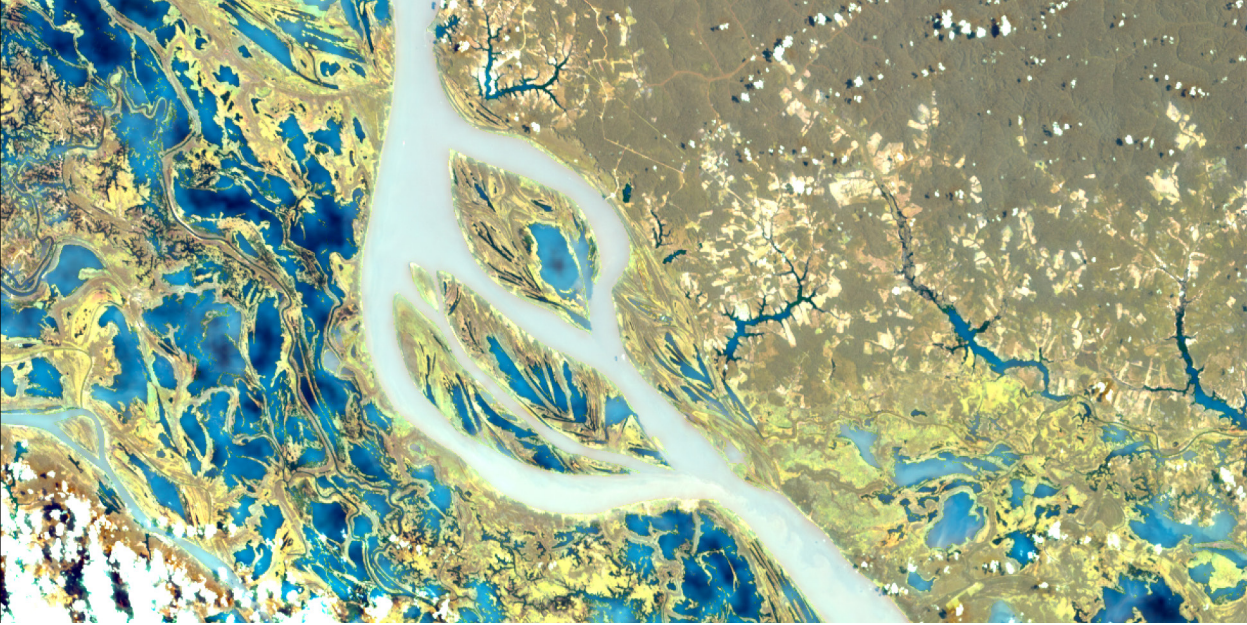
also require capabilities in accurate forecasting of geomagnetic field variations on decadal time scales. Magnetic measurements from satellite constellations and land-based magnetometers along the coasts and on oceanic islands will require integration to provide sub-100 km spatial and sub-hourly temporal coverage.

Outlook

Across the "measurement systems" described above, a new portfolio of platforms and instrumentation is needed for many applications, with the ability for more frequent, high spatial resolution surveys in areas with rapid change and for event response. The next decade will see the development of new sensors and sensor types which will deliver lower-cost GNSS systems, low-power atomic clocks, gyroscopes, and quantum entanglement systems, to name but a few. The community must harness improvements in instrumentation and processing techniques, while ensuring continuity of observations by meaningfully connecting to legacy data. The next decade will benefit from an increasing diversity of new delivery systems, including long-haul, multisensor platforms, commercial vehicles, CubeSats, High Altitude Platform Systems (HAPS) systems, and other suborbital assets.

InSAR

Following the last Decadal Survey's (ESAS 2017) recommendation for Surface Deformation and Change (SDC) as a Designated Observable (DO) that would follow NISAR, consid-



NASA's EMIT instrument captured this hyperspectral image of the Amazon River in northern Brazil on June 30, 2024. NASA

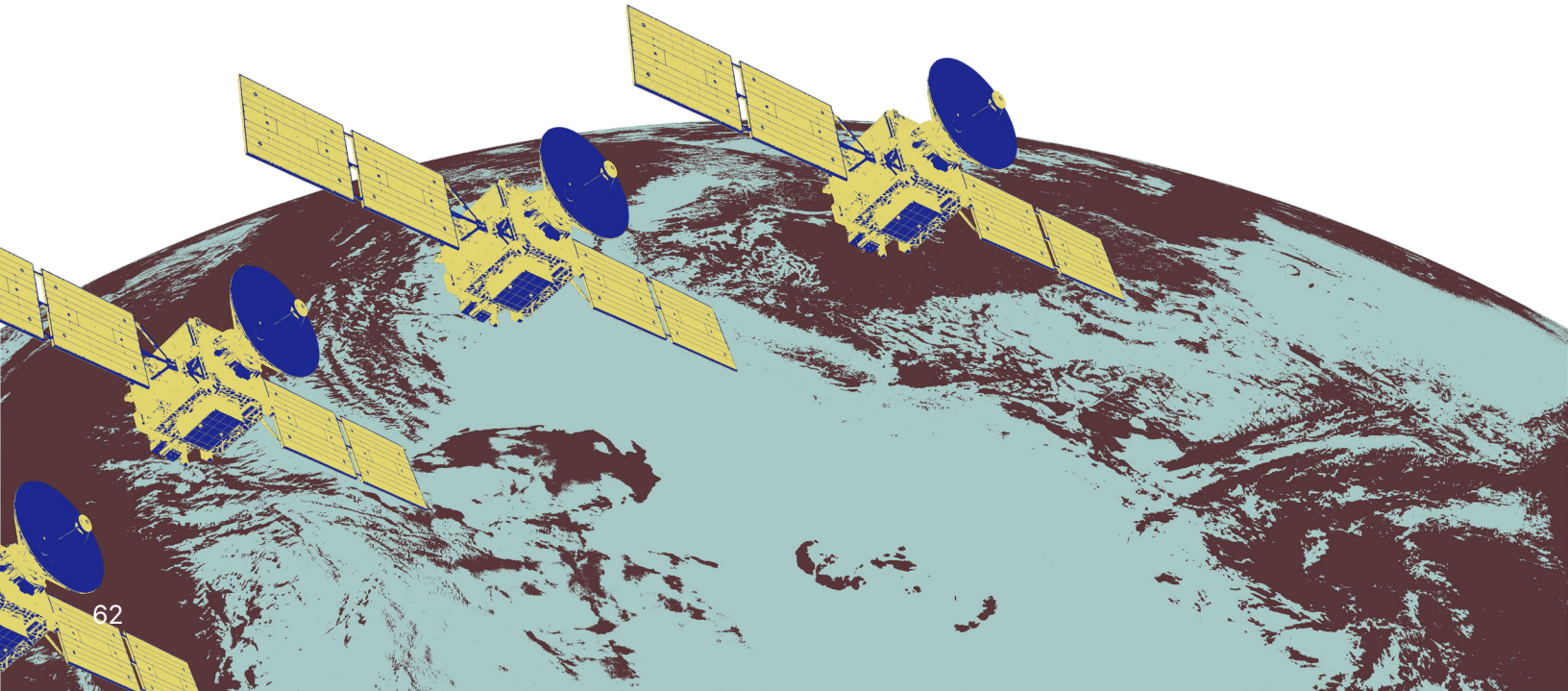
erable research into sensors, architectures, and partnerships has been carried out by NASA. A thorough analysis has led to a wide variety of observing system options, at L-band, that would serve the needs of the broader science community. Options range from NISAR-like satellites co-orbiting with a planned ESA ROSE-L system (four satellites total, each in 12-day orbits) to a constellation of small satellites with narrower swaths than those of NISAR, but that retain the flexibility to focus on a single swath over a target of interest in order to achieve daily repeat sampling. Other options would reduce the impact of tropospheric effects or add along-track sensitivity that would support generation of 3D displacement fields.

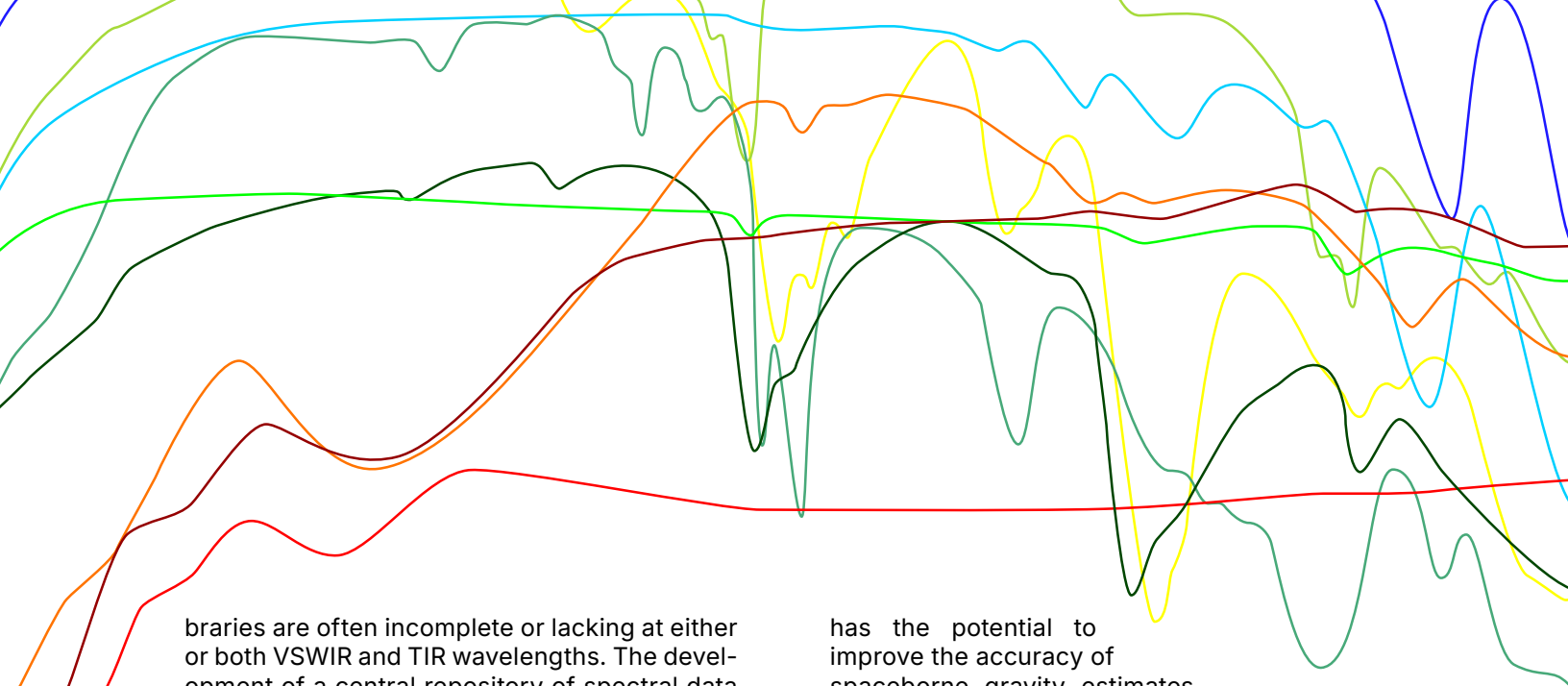
Stereo-imaging

The combination of stereo-imaging with radar and lidar can produce the global bare Earth topography required for the generation of topography change products as described above. Frequent topography sampling over extended time series will address crustal and surface processes across geologic and geomorphic time scales. At local and regional scales, airborne platforms can provide targeted higher-resolution topography, while the need for equivalent observations on a global scale, and thus from space, has motivated NASA's Surface Topography and Vegetation (STV) incubation study.

Imaging spectroscopy

The EMIT and ECOSTRESS sensors on the International Space Station (ISS) were milestones for imaging spectroscopy of Earth's land surface and subsequent applications. Both sensors serve as precursors to the planned Surface Biology and Geology (SBG) mission which would launch a VSWIR hyperspectral imaging spectrometer as well as a TIR multispectral instrument. Such joint observations could help determine which building materials can help minimize urban heat island effects, identify unregulated mining sites, and examine the composition of mining talus. How best to combine VSWIR and TIR surface emissivity observations is an area of active research. For example, how does vegetation cover impact the comprehensive and quantitative mapping of minerals in partially exposed soil, rock, and regolith? Conversely, how can vegetation impacts be used to derive underlying geophysical and geochemical state changes? Estimates (such as those that will be made by SBG or potential airborne campaigns) of dry (non-photosynthetic) and green vegetation cover, and their water and nitrogen content, will help inform how vegetation cover affects mineral mapping in soils and other geologic substrates. Currently, spectral library data for many critical minerals and other materials are difficult to obtain, and their characterization in spectral li-





libraries are often incomplete or lacking at either or both VSWIR and TIR wavelengths. The development of a central repository of spectral data with standards for publishing metadata would ensure these data are easy to find and use. These spectral libraries should also include optical constants and multiple textural characteristics and grain sizes at all wavelengths.

Gravity and GNSS

The time series of gravimetric observations will be extended with the launch of components of the Mass-Change and Geosciences International Constellation (MAGIC), including GRACE-C (polar MAGIC pair, scheduled for 2028) and the Next-Generation Gravity Mission (NGGM, inclined MAGIC pair) missions with a staggered deployment of the two satellite pairs. The future MAGIC missions will advance our ability to monitor hydrological and cryospheric processes and our understanding of a full range of processes associated with the earthquake seismic cycle (inter-, pre-, co-, and post-seismic). Investments in Quantum Gravity Gravimeter (QGG Pathfinder) for the future will enhance spatio-temporal resolution. There is an expectation that ground-based GNSS networks will continue to expand and be much less expensive with the new generations of multi-GNSS, multi-frequency chips. Seafloor geodetic techniques are expected to contribute to increased global coverage across the full range of ocean depths.

Geocenter motion measurement and the accurate alignment of space geodetic systems (SLR, VLBI, GNSS and DORIS) will be facilitated by missions such as ESA's GENESIS, which have the goal of realizing the terrestrial reference frame with an accuracy of 1 mm and its changes to within 0.1 mm/yr. Quantum technology

has the potential to improve the accuracy of spaceborne gravity estimates through its uses in quantum gradiometers or quantum accelerometers. Reduced Size, Weight and Power (SWaP) in key components will facilitate the implementation of spaceborne gravimetry using constellations of SmallSats, further expanding the set of tools available to researchers.

Magnetic field

The current key geomagnetic missions (e.g., ESA's Swarm) will sunset within a decade. Currently planned post-Swarm magnetic satellite missions will not provide the data needed to sufficiently advance high-resolution crustal-field modeling. This shortcoming represents a significant gap that could severely limit future research in key areas of crustal, lithospheric processes, and cryospheric research, as well as in the emerging and rapidly developing field of precise magnetic navigation, an alternative positioning and navigation technique that uses magnetic field anomalies when GNSS or other methods are unavailable (including for underground drilling and infrastructure projects). Improved geomagnetic measurement and ultra-high resolution modeling on a global scale will give rise to precise magnetic navigation systems, allow for monitoring of volumetric ocean-transport processes, and enable the design of effective early-warning systems for hazardous tsunami waves.

NGA is supporting activities (MagQuest) to build domestic geomagnetic data acquisition capabilities. Now is the time for NASA to bring together the internal and external field communities (leveraging synergies with the heliophysics and planetary science communities) to

codesign missions that enable state-of-the-art studies on all geomagnetic field sources. Satellite magnetometry, including gradiometric surveys, can provide high spatial resolution coverage, while ground observatory data can reveal high-temporal-frequency variations. Constellations of different platforms will be key to achieving this objective. Additional opportunities from low-Earth orbit satellites (200–300 km altitude, e.g., DiscSat), CubeSats and magnetometers onboard other satellites (e.g., CryoSat, GOCE, Iridium) can enhance the scientific return of magnetic field missions and provide a safety net for global main field modeling.

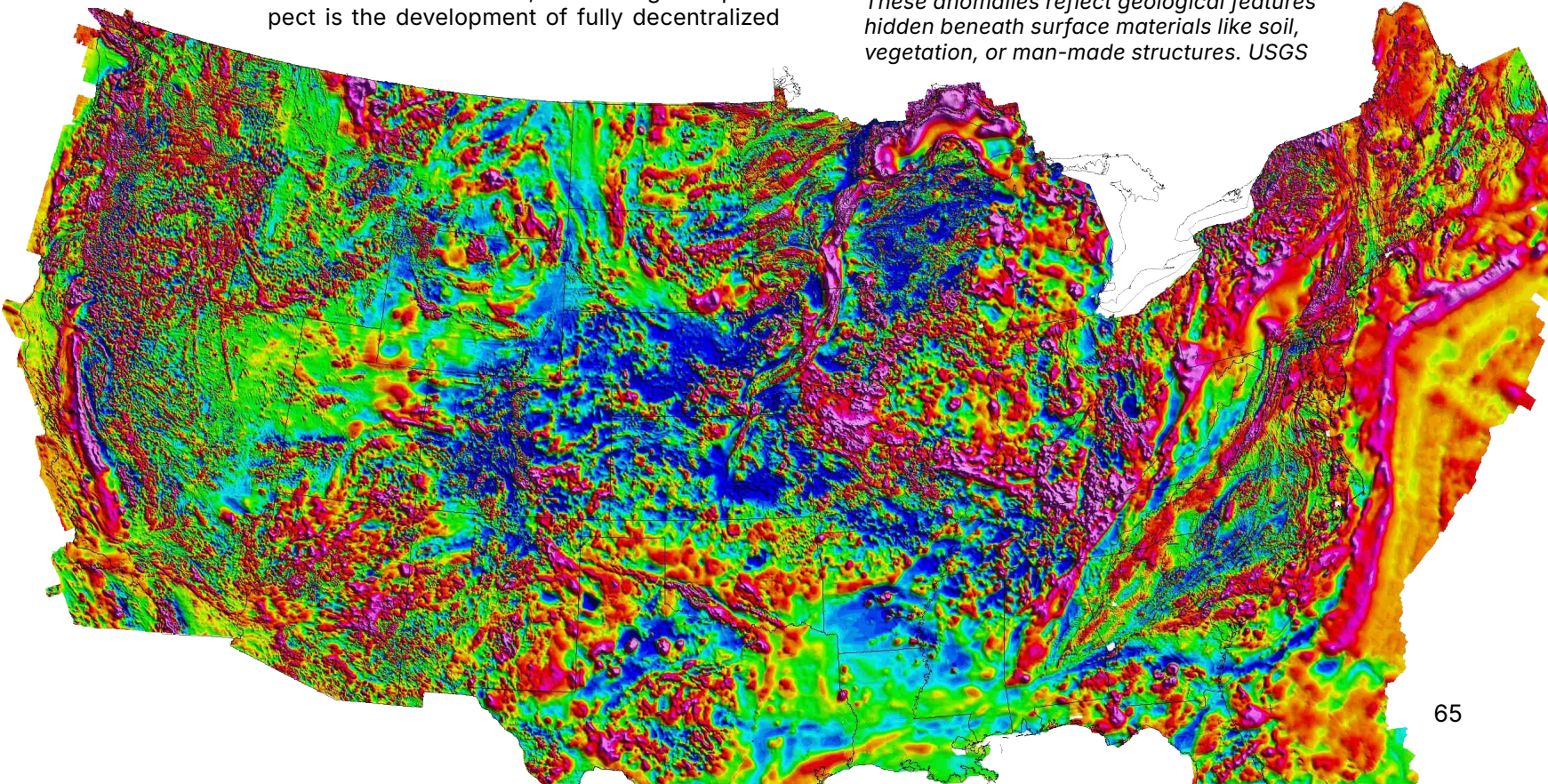
Space communications and signal integrity

In an increasingly crowded Earth and space environment, challenges will include active jamming and spoofing of VLBI and GNSS signals, passive radio frequency interference, and leaky ultra-wide-band communication systems. Mitigation strategies will be required to ensure the robustness of all deployed systems, supported by investments in quantum encryption and related technologies. Commercially developed sensors and platforms require calibration and validation to ensure fitness for purpose, and care must be taken to develop Findable, Accessible, Interoperable, and Reusable (FAIR) data formats, and exchange standards and analysis code. In this context, an exciting new prospect is the development of fully decentralized

physical infrastructure networks (DePINs). Built on blockchain technology for trust-worthiness validation, secure exchange, and the promise of “federated” learning, with crypto-economic incentives, ground-based geodetic (GNSS) networks have lately become fully operational. Similar technologies involving both physical and digital resources may soon take to space and integrate Earth observation across all components of the measurement system. Care must be taken to capture, curate, and archive all data for scientific applications, which may include post-processing.

Whatever the future of observational technology (the “hardware”) that applies to the science questions posed in Chapter 1, massive amounts of new data will be generated that will require data and modeling systems maintenance, system integrity assurance, and investments in advanced modeling and analysis infrastructure (the “software”), further discussed in Chapter 2.2. Equally critical will be the judicious stewardship of community facilities and supranational networks of human resources (the “middleware”), sustained by accessible educational and outreach programs for cohort-forming workforce development across collaborating government agencies, industry, and the private sector, as discussed in Chapter 2.3.

A colorful map illustrates variations in the distribution and type of magnetic minerals, primarily magnetite, within the Earth's crust. These anomalies reflect geological features hidden beneath surface materials like soil, vegetation, or man-made structures. USGS





Continued progress over the next decade requires harnessing ever-expanding computational capabilities, emerging hardware, and increasingly sophisticated software approaches.

This graphic represents the difference between binary bits and qubits. Binary bits, the basic unit of information for traditional computing, process information sequentially using 0s and 1s. Qubits, the basic unit of information for quantum computing, can represent 0s, 1s, or both simultaneously; this allows quantum computers to process a vast amount of possibilities in parallel. NASA/Allison Li

2.2 Modeling and Analysis Infrastructure

Transforming Observations into Understanding and Action

Key Objectives

- Match growing needs in data analysis infrastructure, algorithms for post-processing
- Harness revolutions in computing (CPU, GPU, TCU, Cloud and Quantum)
- Support modeling frameworks and data assimilation strategies that include advances in machine learning and artificial intelligence and digital twins

The last decade has seen tremendous growth in the spatial coverage, temporal span, resolution and quality of geosciences data. These efforts have led to the development of Earth system “digital twins”, a framework for representing, monitoring, modeling, and forecasting terrestrial processes. Such frameworks enhance our understanding of the underlying mechanisms and feedbacks, and allow us to assess their impact on human and ecosystem health and wellbeing. Continued progress over the next decade requires harnessing ever-expanding computational capabilities, emerging hardware, and increasingly sophisticated software approaches.

The era of big data and Earth system models presents opportunities and challenges to advance the science and applications outlined in Chapter 1. Large data volumes from current and future satellites, such as EMIT, SWOT and NISAR, suborbital and airborne platforms (e.g., AVIRIS, UAVSAR/AirSAR-NG), and in-situ land stations and marine instrumentation (some with tremendously high data rates, like Distributed Acoustic Sensing), present formidable challenges. End-users in both the scientific and applications communities need fine spatial resolution over large areas, with dense temporal sampling over long timespans, at low latency, during rapidly evolving natural and anthropogenic processes.

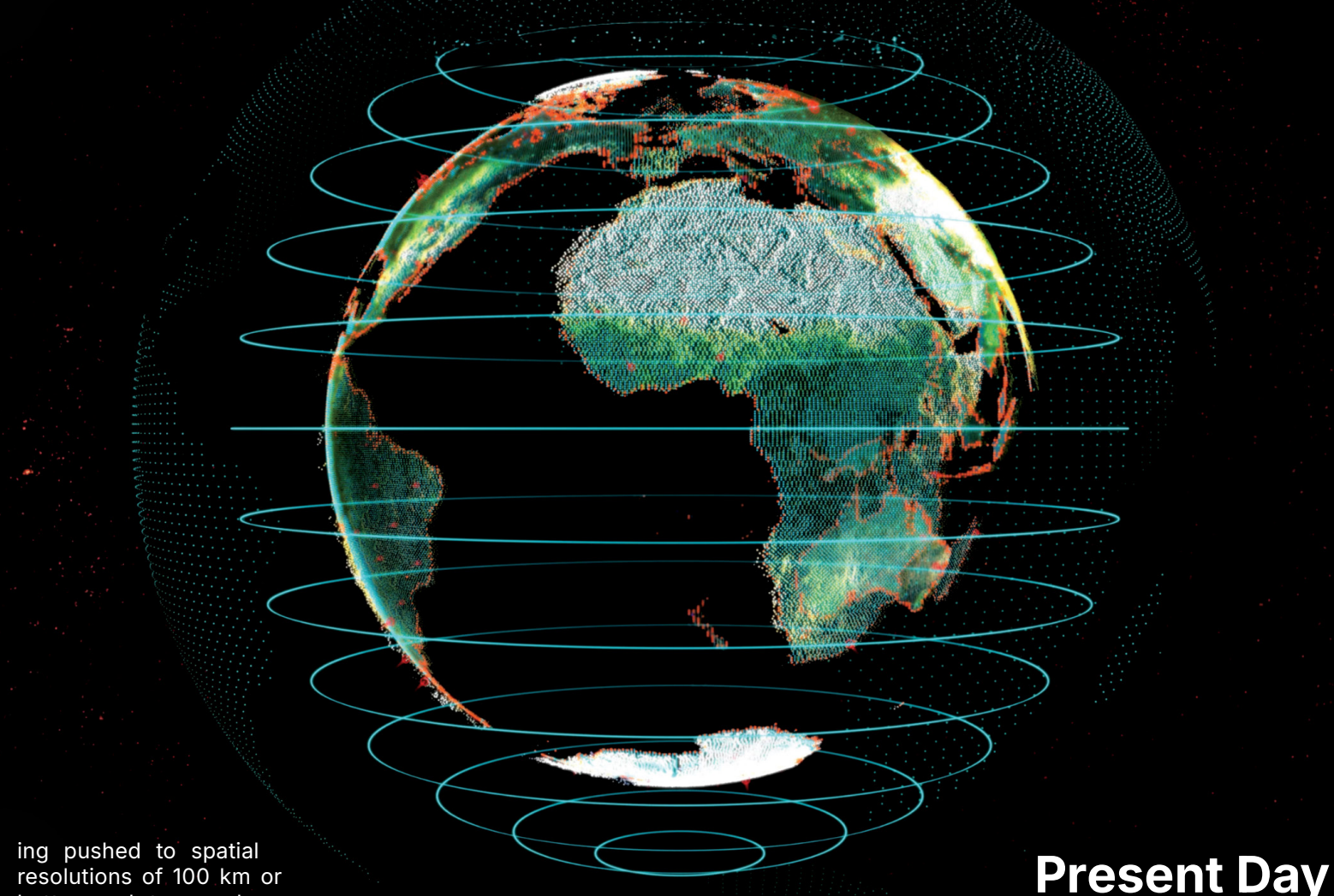
Past Decade

The continuously growing data records have yielded new discoveries, both through improved resolution (more samples in space and time, and in different parts of the electromagnetic spectrum) and extended observation continuity (longer time series, larger areas). For example, the decade-long InSAR time series made possible by ESA’s Sentinel-1 InSAR satellites since late 2014, combined with more sporadic InSAR data as well as GNSS time series over the previous two decades, has enabled the study of time-variable tectonic and hydrologic processes with increasing sophistication. Combinations of decadal-scale geodetic observations with other types of measurements, such as thermal-anomaly time series from NASA’s MODIS instrument, have led to new physical models for magma transport and storage at volcanoes. High-resolution ionospheric, lithospheric, and global magnetic field modeling studies have highlighted the complex interactions between

surface observables and core dynamic processes.

Modeling has allowed us to fully realize the potential of the rich datasets acquired by NASA over the past decade. Spectroscopic modeling of Earth’s surface radiative properties with measurements of the EMIT mission helps map the availability and location of critical minerals. Geomagnetic field modeling, both of internal and external origins, are be-

GRACE (2002-2017), GRACE-FO (2018-present). These time series of gravity data have been, and their successors will be, essential in mapping and understanding global variability in the hydrosphere, cryosphere, and geosphere systems (e.g., glacio-isostatic adjustment, large undersea earthquakes monitored throughout the seismic cycle). They are routinely assimilated into hydrological models for the ongoing monitoring of shallow groundwater and soil-moisture drought indicators.



ing pushed to spatial resolutions of 100 km or better and temporal resolution of sub-hourly intervals. These advances utilize a gradiometer (along-track from a single satellite, or cross-track with constellations), and day-side magnetic data (doubling the local time coverage compared to using only night-side data).

A last example are the global mass-change observations from satellite-gravity missions

Present Day

We are challenged in how we access large data archives, how we extract the data products at the needed level, and how we model these data. Different operational models exist for getting the desired products to the relevant communities, ranging from simply providing the data and analysis tools, to making specific higher-level products available, to offering Cloud-based on-demand

processing in ways that are defined and managed by the end-user.

Depending on the scale and volume of the archived data, and the storage size of the raw and processed data, solutions will vary. However, for large data archives (e.g., the NISAR mission) it is more economical to maintain data archiving and analysis capabilities relatively “close-by”. As an example, since 2021 the Satellite Needs Working Group (SNWG) has funded the Observational Products for End-users from Remote Sensing Analysis (OPERA). The project has developed a range of SAR and optical imagery-based surface-deformation and hazard-related products aimed at a broad range of end-users and community stakeholders. Efforts like OPERA both serve to expand the number of users who are able to leverage NASA-based data products in their work, and can reduce costs through limiting the need for individual users to egress the much larger, raw data files that they are interested in.

In response to obvious needs, our modeling capabilities continue to grow. Community software packages such as those maintained by the Computational Infrastructure for Geodynamics (CIG), the Community Surface Dynamics Modeling System (CSDMS), or the Ice-sheet and Sea-level System Model (ISSM), allow local to global models of solid-earth deformation in response to earthquakes, mass loading, and interactions with the ice dynamics from both glaciers and polar ice caps. Several additional commercial and open source software packages address a host of specific processes, including mass wasting, lava flows, volcano dynamics, tsunami modeling, and hydro-geodesy problems, to name but a few. The extent to which the latter adhere to Open Science practices, or are broadly accessible, in the case of commercial packages, limits their broad use by the community.

The ESI community is well positioned to benefit from advances made in Artificial Intelligence (AI). The pace of development of Machine Learning (ML) and Deep Learning (DL) is explosive. In the area of atmospheric and climate modeling, Google’s NeuralGCM and GraphCast, Microsoft’s ClimaX, NVIDIA’s FourCastNet, and Huawei’s Pangu-Weather, are poised to change the ways in which we approach scientific problems such as numerical weather forecasting and long-term climate modeling. With the alluring economic opportunities that these privately

funded developments have entailed for new researchers, continued care is required to maintain a thriving scientific professional community that remains well versed in both “data” and “domain” science, across government laboratories, academia, and private industry.

Opportunities and Challenges

The huge growth in data volumes and types poses an ever-increasing burden on mission design and operation, analysis and modeling, and non-scientific end-users. As hardware and machine architecture continues to evolve rapidly, software will need to do more than “keep up”. As an example, in GNSS processing, the iterative nature of improvements results in the need to completely reprocess the entire global dataset for each version of the ITRF. For large data volumes, a major challenge lies in the detection of unexpected or anomalous transient signals. Opportunities lie in the ability to develop anomaly detection tools that are embedded or easily applied on adjacent large processing infrastructure. Robust anomaly detection should move beyond single sensors or single satellites (e.g., constellations of multiple SAR satellites measuring contemporaneously, from different angles, and with short re-visit times) and include, to the extent possible, other types of data such as GNSS, multispectral, thermal, gas, precipitation, and soil-moisture time series. These remote-sensing observables need to be integrated with in situ data streams. For example, separating atmospheric phase anomalies from volcano deformation hidden in InSAR time series in the era of ‘big data’ presents a real challenge, potentially requiring ML/AI to enable detection and provide early warning of impending geohazards.

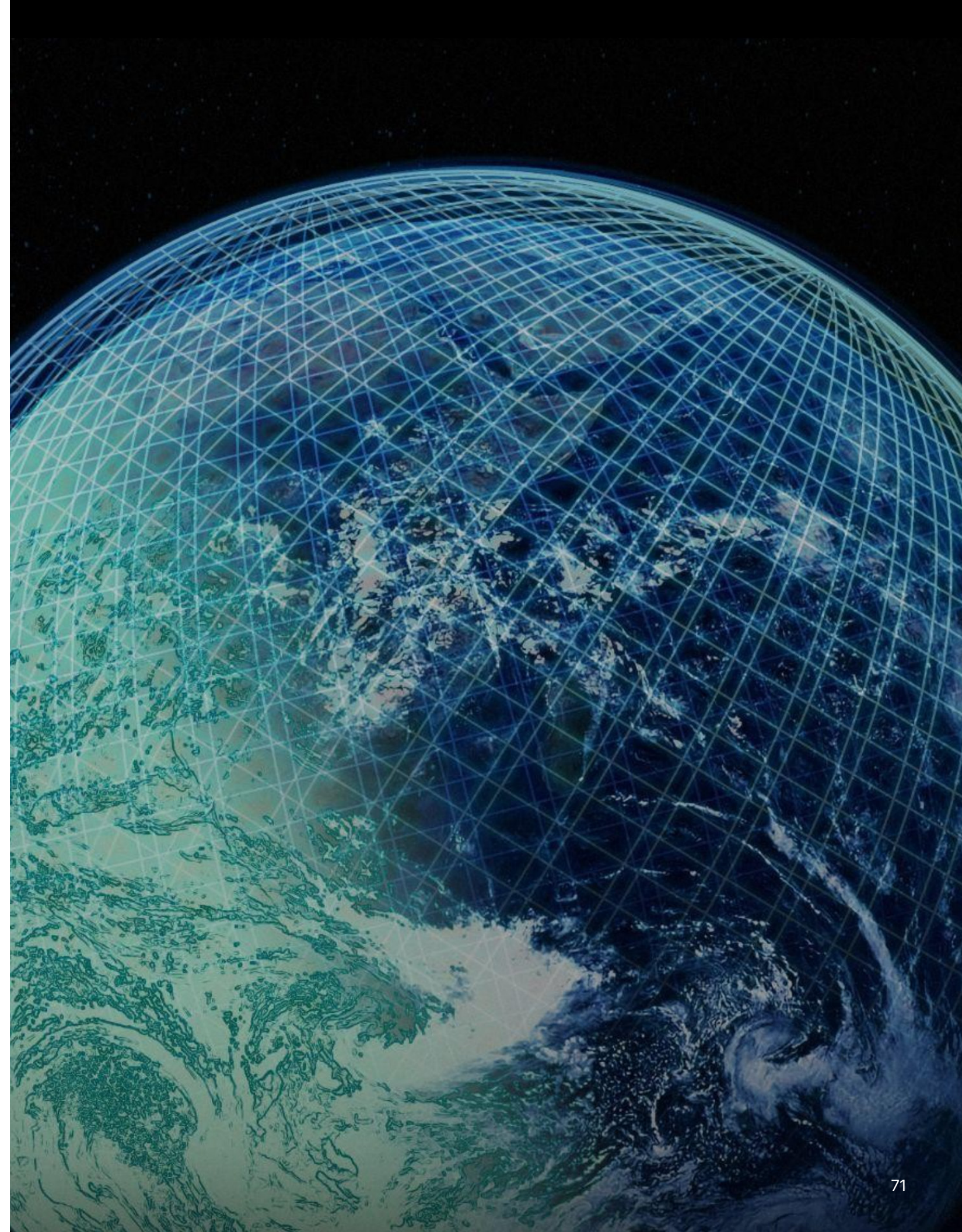
In the area of geomagnetic data assimilation and geodynamo modeling, pushing the numerical modeling closer to core conditions comes at the cost of substantially increasing storage requirements (by at least three orders of magnitude) and computing time (by as many as five orders of magnitude). Direct numerical simulations at these scales require innovative algorithms to harness advances in parallel computing in order to be feasible. Assimilation of geomagnetic observations into the next generation of geodyna-

mo models to provide core state estimates will increase the computational requirement by at least another two orders of magnitude. Efforts need to focus on designing new assimilation schemes, and on developing reduced-order systems to model the dominant core-dynamical processes with far less computational expense than direct numerical geodynamo modeling.

Outlook

Despite substantial progress over the past two decades, investment in open source, community-led modeling infrastructure continues to be needed to keep pace with the needs of the scientific community. Beyond the well-developed CIG, CSDMS, ISSM, and other community-based modeling codes, multi-physics numerical methods combining thermal, solid, and fluid mechanics are needed to support a variety of ESI focus areas, including magmatism, shallow fluid processes, permafrost, and anthropogenic contributions. As forward and inverse (e.g., adjoint-state) models that include more realistic, time-dependent full-physics, become computationally more expensive, and as statistical parameter identification and characterization methods, become impractical, the need for data-science approaches and “surrogate” models is expected to grow. At the same time, the need for quality-controlled, unbiased, generalizable, training and verification data will continue to grow.

How can NASA manage the interactions between end-users and modeling and computational infrastructure? Large modeling capabilities with well-written, well-documented, and well-maintained code (Findable, Accessible, Interoperable, Reusable) are the key to collaborative Open Science and verifiable results. In some cases, such as lava flow modeling, infrastructure such as Volcanology Infrastructure for Computational Tools and Resources (VICTOR), which integrates leading software into a unified framework for model comparison and validation, can facilitate science, accessibility, and applications. Such a framework connects researchers with access to the software, comprehensive documentation and workforce training, resources, and standardized datasets (such as topography). The next chapter addresses some of the challenges and opportunities that arise in this context.





2.3 Development of Collaborations, Workforce, and Resilience

Creating pathways to Open Science and empowering the future workforce

Key Objectives

- Big data allows us to answer critical ESI questions, while also uncovering new areas of inquiry that can be resolved with additional data acquisition, computation, data storage, and networking technology.
- Open Data and Open Science policies promote high-level data products that can be easily disseminated to and used by non-experts.
- Development of a skilled workforce and professional networks is critical to the nation's economic and strategic security.
- Engagement with domestic and international partners is also critical, creating new opportunities that benefit both parties.

Developing and maintaining an integrative infrastructure for the advancement and application of ESI science is closely aligned with the objectives and methods of NASA's Earth Science to Action Strategy for 2024-2034. We seek to achieve a self-sustaining "Virtuous Cycle" which encompasses the collection and dissemination of open and big data for fundamental research and applied science, through domestic and international collaborations, and to maintain a connection to end users via open source community software and public education. This cycle begins with sensor development and data acquisition, flows through collaborative analysis and software development, and culminates in tools, insights, and education that feed back into improved data collection and community engagement.

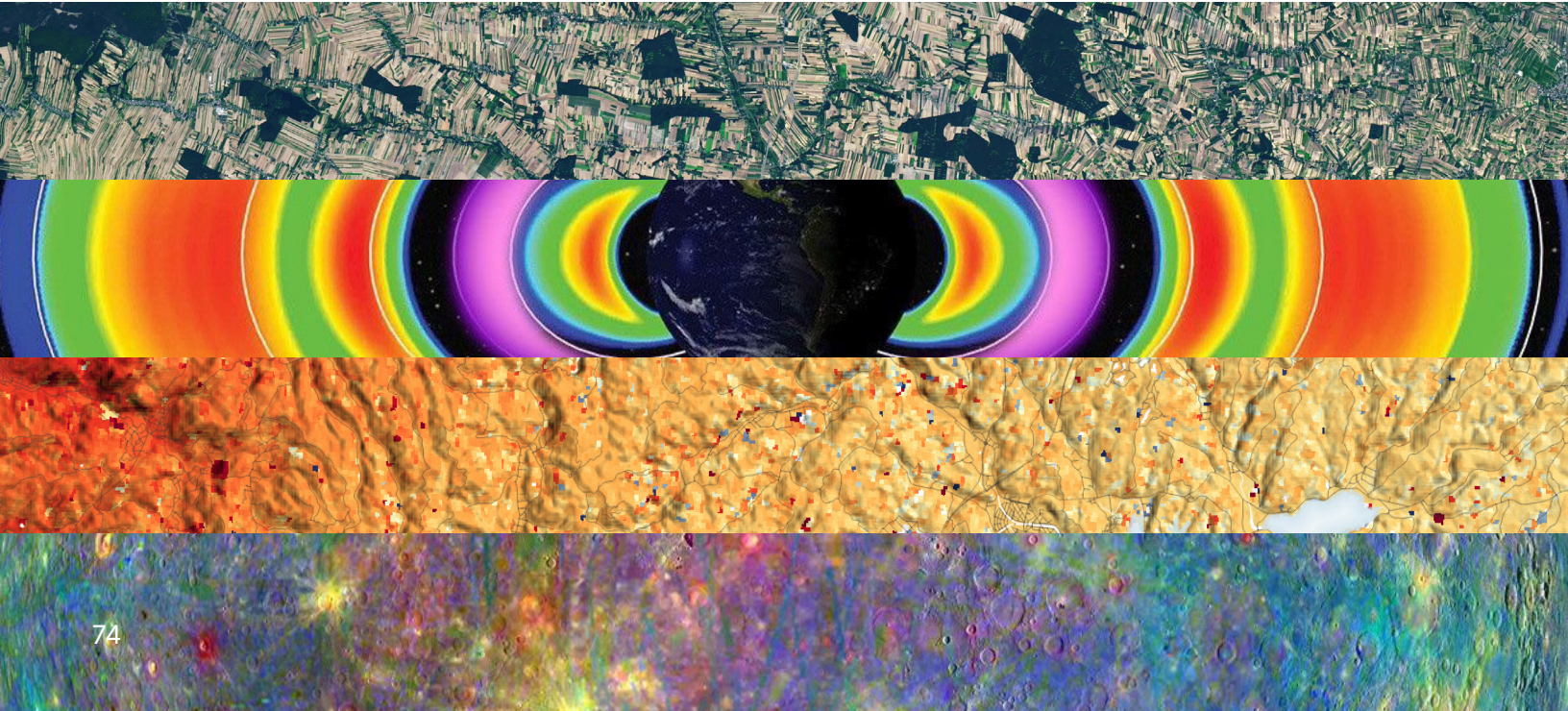
Advancing ESI science relies on the acquisition, integration, and modeling of geodetic, geomagnetic, seismic, spectral, and many other kinds of observations.

The virtuous cycle depends on the infrastructure and workforce while also contributing to its sustainability. Societal benefits, scientific discovery and user needs should guide the prioritization of the various functions and outputs of the integrative infrastructure. For example, accessible data, open software tools, and a highly skilled workforce are necessary infrastructure components, and having these will facilitate

further advanced models and tools, an expanded user base, and training of the next generation of experts. The commitment to Open Data and software and the peer-review process remains fundamental to the research community and is essential for reliable calibration and verification to ensure the advancement of scientific knowledge. The integrative infrastructure needed to advance ESI goals will also develop a well-trained workforce capable of serving the needs of private industry and commerce.

Advancing ESI science relies on the acquisition, integration, and modeling of geodetic, geomagnetic, seismic, spectral, and many other kinds of observations, in a coherent theoretical framework, by geodesists, seismologists, geophysicists, remote-sensing scientists, and other geoscience experts. With increasing spatial and temporal resolution of various observation types, there is an increasing need to archive, process, and integrate vast datasets. Similarly, incorporating advanced and more complex models requires the usage of advanced computation techniques and vast computation power, as shown in Chapter 2.2. This is true both of "traditional" domain-science modeling approaches and of emerging "data-science" techniques (e.g., machine learning and artificial intelligence, which are both data and computational power-hungry). ESI research depends on digital networks and computational infrastructure to support the increasing demand to explore big data and generate more complex and realistic models, often in a time-sensitive manner (e.g., anomaly and transient detection for

Geodetic, geomagnetic, seismic, and spectral representations. NASA Earth Observatory, NASA/Goddard Space Flight Center/Kristen Perrin, NASA



The earthquake that struck western India on January 26, 2001, was the country's strongest in the past 50 years. This perspective view of the Rann of Kachchh in India shows the area of the earthquake's epicenter in the lower left corner. The cyan area in the foreground represents water that flooded previously dry areas following the earthquake. The image combines radar data from the Shuttle Radar Topography Mission with Landsat satellite imagery. NASA/JPL/NIMA

hazard forecasts, scenario testing for disaster response). These scientific and technological advances require a highly trained workforce to process and integrate big data and to develop advanced models for scientific applications and societal benefit. Equally vital will be those able to assume roles as translators of science into public knowledge, policy, decisions, and action – educators, communicators, science journalists, community outreach specialists.

Past Decade

Rapid developments in computation, data storage, and networking technologies over the past decade provided the needed infrastructure to expand observational and modeling capabilities used for ESI science. An eightfold expansion of the US cloud computing market between 2010 and 2025 has changed the nature of computation and data storage in all aspects of life, including the science world. The introduction of serverless computing in 2014 enabled users to run large computations without hardware limitations. High Performance Computing (HPC) centers also contributed to rapid growth in data storage and computation capabilities. Large datasets and extensive computations have migrated to the Cloud or HPC centers at many NASA facilities, academic, and research organizations.

Open Data and open source policies have continued to contribute significantly to the fast ex-

pansion of geodetic and remote-sensing data use over the past decade. Open Data policies have been adopted by most space-geodetic communities (e.g., VLBI, GNSS, gravity missions) since the early days of space geodesy in the 1980s. Landsat was among the earliest NASA sensors to be transferred into joint administration with the USGS as an operational global mapping tool and its data became freely available in 2008. In contrast, InSAR data had restricted availability for decades. A major shift occurred in 2017 when the European Space Agency (ESA) adopted an Open Data policy for Sentinel-1 SAR data, which are acquired over all continental areas worldwide every 6 or 12 days. This wealth of openly available data spurred the development of new and efficient InSAR time-series techniques and their applications to monitor surface deformation in challenging areas. Open source policies also enabled the development of software suites for data processing and modeling. Examples include the ISCE and MintPy packages for InSAR data processing, and community models developed by Computational Infrastructure for Geodynamics (CIG). In contrast, similar Open Data policies have not yet been applied to the new and growing data sources of high-resolution optical and SAR imagery acquired by commercial satellites. To explore the potential applications of such data, NASA acquired a limited quantity of commercial satellite imagery and provided it to researchers via the Commercial Smallsat Data Acquisition (CSDA) Program.

Expanding the use of ESI observations to other Earth science fields as well as to engineering and city-planning applications requires the production of high-level data products that can be easily used by non-experts. High-level positioning products have been produced for several decades by several GNSS data processing centers, including the Jet Propulsion Lab (JPL), SCRIPPS Orbit and Permanent Array Center (SOPAC), and Nevada Geodetic Laboratory (NGL). However, InSAR data processing centers were developed only in the past decade, mainly thanks to the wealth of Sentinel-1 data, leading to the production of a wide range of data products. The Alaska Satellite Facility (ASF) offers on-demand Cloud-based processing of Sentinel-1 data that can generate terrain-corrected georeferenced SAR images, interferograms and time series products (velocity maps). The Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) in the UK developed the Looking Inside the Continents from Space Synthetic Aperture Radar (LiCSAR) system and developed tools to generate geocoded interferograms, coherence maps, and velocity maps of wide tectonically active areas, mostly along plate boundaries. NASA's Advanced Rapid Imaging and Analysis (ARIA) data processing center and Observational Products for End-Users from Remote Sensing Analysis (OPERA) program were formed to exploit radar and optical remote sensing, GNSS, and seismic observations for hazard science and response. High-level InSAR products were also generated by commercial companies tasked by national agencies to generate maps of crustal movements.

International collaborations have been essential for the development of NASA satellite missions and the expansion of geodetic research in particular. Over the past decade such collaborations have enabled the development of the following missions: Gravity Recovery and Climate Experiment—in collaboration with the

German Aerospace Agency (DLR); GRACE-FO—in collaboration with German Research Centre for Geosciences (GFZ); NASA-ISRO SAR (NISAR)—collaboration with the Indian Space Agency (ISRO); and the Surface Water Ocean Topography (SWOT)—in collaboration with the Centre National d'Etudes Spatiales (CNES) with contributions from the Canadian Space Agency (CSA) and the United Kingdom Space Agency. The Sentinel-6A/Jason-CS mission is a collaboration with ESA to collect data on Earth's sea level and climate change. The international collaboration between NASA and ESA has provided access to the Sentinel-1 SAR data archive through the ASF Distributed Active Archive Center (DAAC). Interagency collaboration between NASA and USGS supported the development of the Landsat satellite missions, under which Landsat-8 and Landsat-9 have been operating reliably for the past decade. The Sentinel-6A/Jason-CS mission development includes an interagency collaboration with NOAA.

Advancing ESI science relies on a reliable professional workforce at various levels of expertise, including geodesists, Earth scientists, engineers, computer scientists, and technicians. Ongoing professional development for students and researchers is regularly offered by The Earthscope Consortium, which formed as a merger of UNAVCO and IRIS, and has continued their activities. Over the past decade, many geodesists reached retirement age. At the same time, student enrollment in geodesy and Earth sciences continues to decline in the US and the Western world. This situation has led to a shortage of geodesy experts, according to a white paper titled "The Geodesy Crisis". The National Geospatial Agency funded a training program via the multi-university Geomatics Emerging Scientist Consortium for Geomatics Education, Research, and Capabilities Enhancement (GEO-ESCON) consortium. The situation in adjacent areas, e.g., the geomagnetic, spectrometry, and thermal infrared-sensing communi-

ties, is similarly dire and in need of rejuvenation.

Societal benefits of ESI science mainly center on hazard and safety assessments and Earth resources (Chapter 1.5). To increase government funding and public support, knowledge sharing with stakeholders is essential, including decision-makers, local, state, and federal government agencies, and the general public. Much of the knowledge has been disseminated in peer-reviewed literature and via official reports and via traditional and social media. Over the past decade, sharing ESI research knowledge with the public often happened after the occurrence of natural or human-made disasters, such as the 2014 South Napa earthquake, the 2015 Nepal earthquake, the 2021 Surfside building collapse, and the 2023 Türkiye-Syria earthquake sequence.

Present Day

The present day reflects a decade of tremendous progress in the computation of complex, interrelated processes that involve the solid Earth. From magnetohydrodynamic simulations of the geomagnetic field, through its interaction with the induced and ionospheric fields, which includes inverse-modeling, adjoint modeling, and data assimilation techniques, to coupled ice-sheet-ocean-atmospheric, and now land-surface interactions, development has come from advances in theory and computational hardware. Both CPU-based and GPU-based processing, on massively parallel and sequential systems are relevant in this space. Increasingly, hardware may be leading where software may follow, leading to questions of

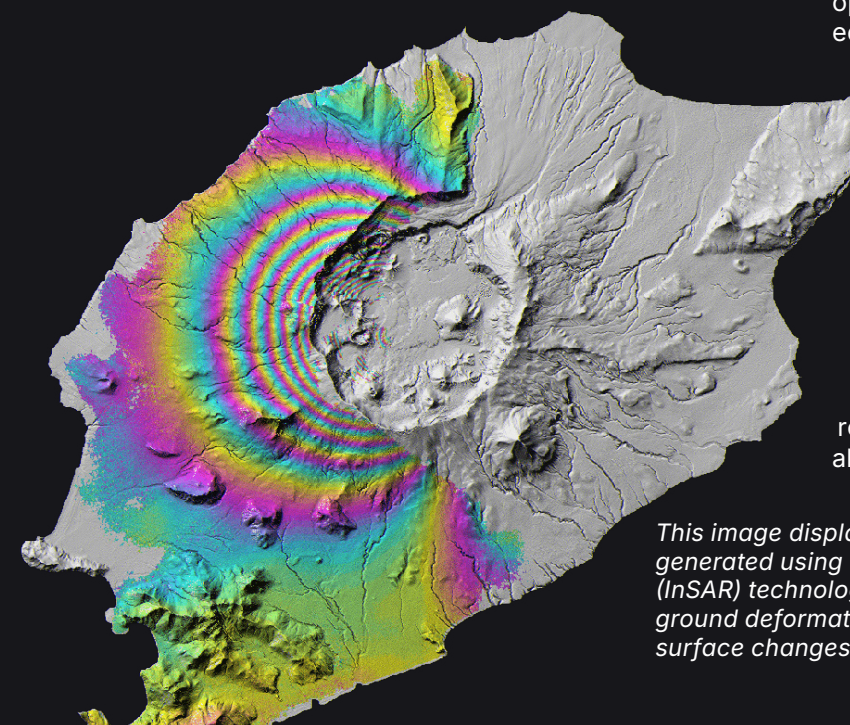
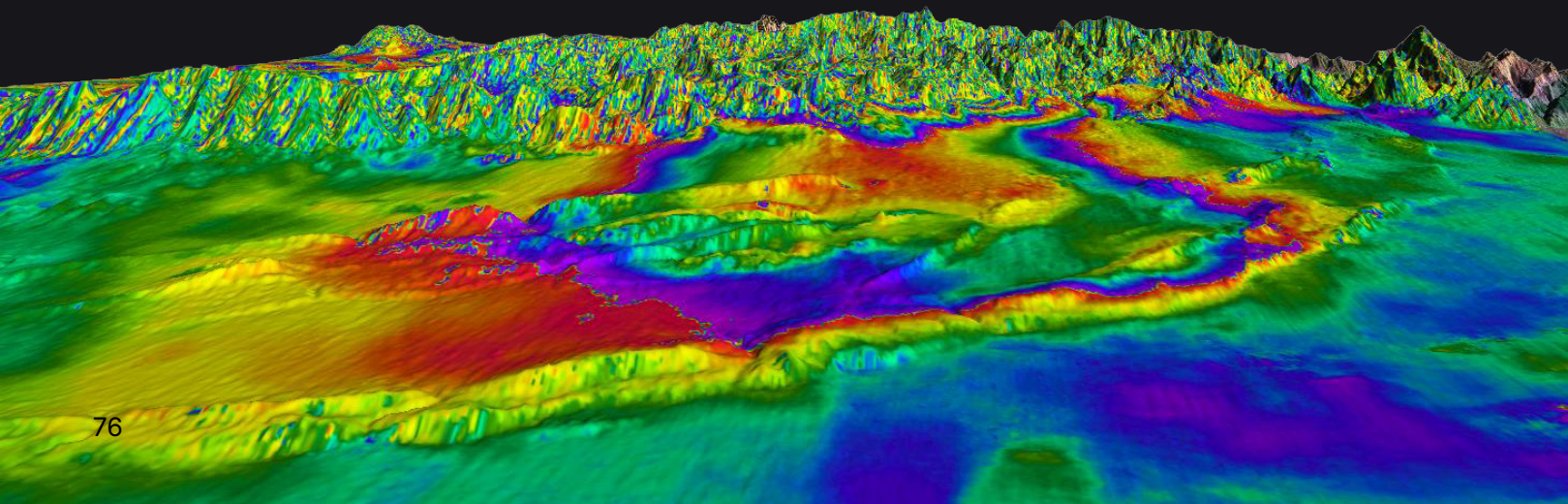
how science might dictate the future of computation and how the emergence of AI could provide new opportunities to leverage big data for advancing our understanding of various Earth processes.

The emergence of larger and more sophisticated models stimulates innovations in modeling and computational infrastructure. Effectively managing the interactions between end-users and infrastructure is an emerging challenge. Large modeling capabilities with well-written, well-documented, and well-maintained code are key to collaborative Open Science and verifiable results following Findability, Accessibility, Interoperability, and Reusability (FAIR) standards. Establishing integrative infrastructure that connects researchers to software, documentation, training, and standardized data sets ensures accessibility and facilitates the advancement of Earth science and its myriad applications.

The Next Decade

Over the next decade, hardware development is expected to continue developing at a rapid rate to meet the growing demands of ESI science to acquire big data, store them, move toward near-real-time processing, and construct more complex and realistic models. Hardware development will see significant advancements in semiconductors, computing, and AI accelerators. At the same time, quantum computing will progress to creating breakthroughs with complex simulations. The rise of AI and ML accelerators will drive the development of next-generation GPUs and TPUs (Tensor Processing Units), optimizing deep-learning models for Cloud and edge computing. Edge-AI processors will become more widespread, enabling smart devices to process data locally without relying on cloud infrastructure.

Data storage technology will evolve significantly over the next decade to meet the growing demands of AI, big data, and high-performance computing. Traditional storage solutions such as Solid-State Drives (SSDs) will continue to improve. Breakthroughs in AI-driven storage optimization will enable intelligent data management, reducing redundancy and improving retrieval speeds. The rise of computational storage,



This image displays an interferogram of Mount Okmok in Alaska, generated using Interferometric Synthetic Aperture Radar (InSAR) technology. The colored bands, or "fringes," represent ground deformation, allowing scientists to measure subtle surface changes with precision down to millimeters. NASA

where processors are embedded within storage devices, will minimize data processing bottlenecks and enhance performance for AI workloads. Cloud storage will continue to expand, with advancements in distributed and decentralized storage networks ensuring greater security, redundancy, and cost-effectiveness. *The modern workforce will need access to such cloud resources to fully utilize the rich catalog of NASA data.*

An alternative model for **data storage and computation** has recently developed in the form of Decentralized Physical Infrastructure (DePIN), which leverages blockchain, distributed computing, and tokenized incentives to create and manage real-world infrastructure in a decentralized manner. Unlike traditional centralized infrastructure—such as cloud storage, energy grids, telecommunications, and sensor networks—DePIN operates on a peer-to-peer model, where individuals or organizations contribute hardware resources and are rewarded for their participation. *This approach enhances scalability, security, and accessibility while reducing reliance on large corporations and single points of failure.*

Over the next decade, NASA, ESA, and several other national space agencies are expected to uphold **Open Data and open source policies**, which are essential for ensuring broad user access and maintaining consistent standards for data and derived products. However, there are still a number of national space agencies and commercial operators with restrictive data policies. *NASA's current efforts to expand access to restricted datasets obtained by other national space agencies and commercial satellite operators will hopefully encourage the wider adoption of Open Data policies worldwide.* The broader scientific community could assist these efforts by identifying areas of collaboration.

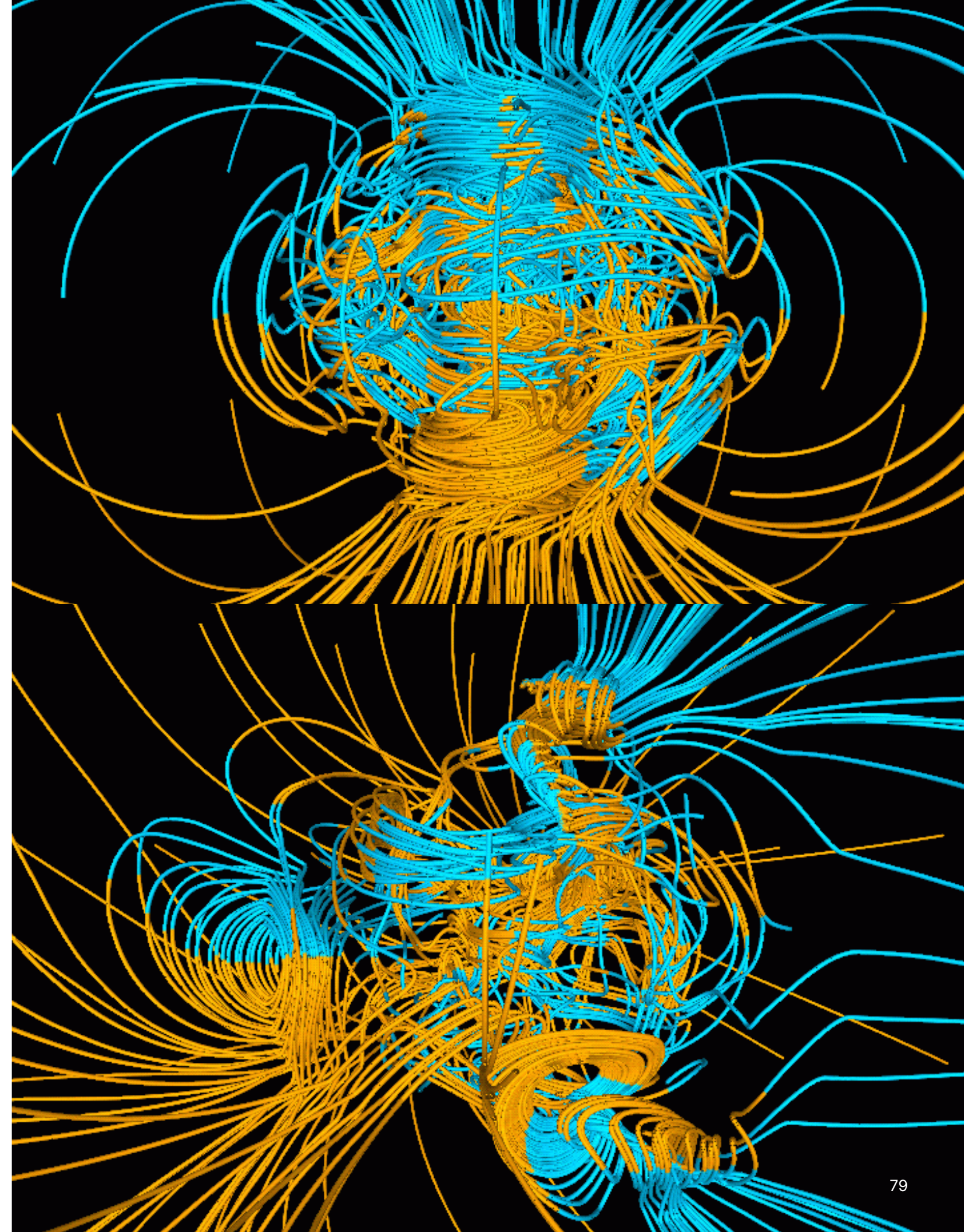
The development of **data processing centers** over the past decades has helped researchers, agencies, and the public access high-level data products useful for science and society. With increasing computation and storage capability, the current processing centers will be able to produce, deliver, and develop more high-level data products. As each data center applies different methods to different data subsets, results may vary from one data processing center to another. *Setting standards among the centers to obtain results with similar confidence levels will be immensely impactful.*

The small and declining number of experts in geodesy, geomagnetics, and geophysics in the U.S. **workforce** poses risks for the successful future of fundamental solid-Earth science, and its downstream applications for hazard forecasting, disaster response, resource management and exploration, and public education. A national assessment of agency and private-sector capacity-building needs, such as the one performed by the National Academies' for mineral resources, could aid agency decisions to support institutions in the recruitment and training of students and early-career employees. A multifaceted approach towards recruitment and training students and early-career employees should be pursued, with the awareness that some must be eligible for future U.S. government positions, including those that require security clearance.

Students are more likely to develop an interest in geodesy and other geosciences via their studies in related fields, such as in environmental change, geohazards, satellite navigation, etc., especially those with clear societal impacts. Rebranding academic programs, e.g., from "geodesy" to "geospatial engineering," might appeal to a broader set of prospective students. Adherence to Open Science practices, providing citizen-science opportunities, and organizing skill-building workshops will likely prove useful for raising awareness about geoscience careers and allowing students and the workforce to expand their knowledge and competencies. Knowledge of fundamental geoscience can be a great benefit to a variety of careers in the private sector. Upon entering the workforce, intentional mentoring by senior scientists will be essential for the continued development and sustainability of the observing systems and capabilities on which solid-Earth research depends.

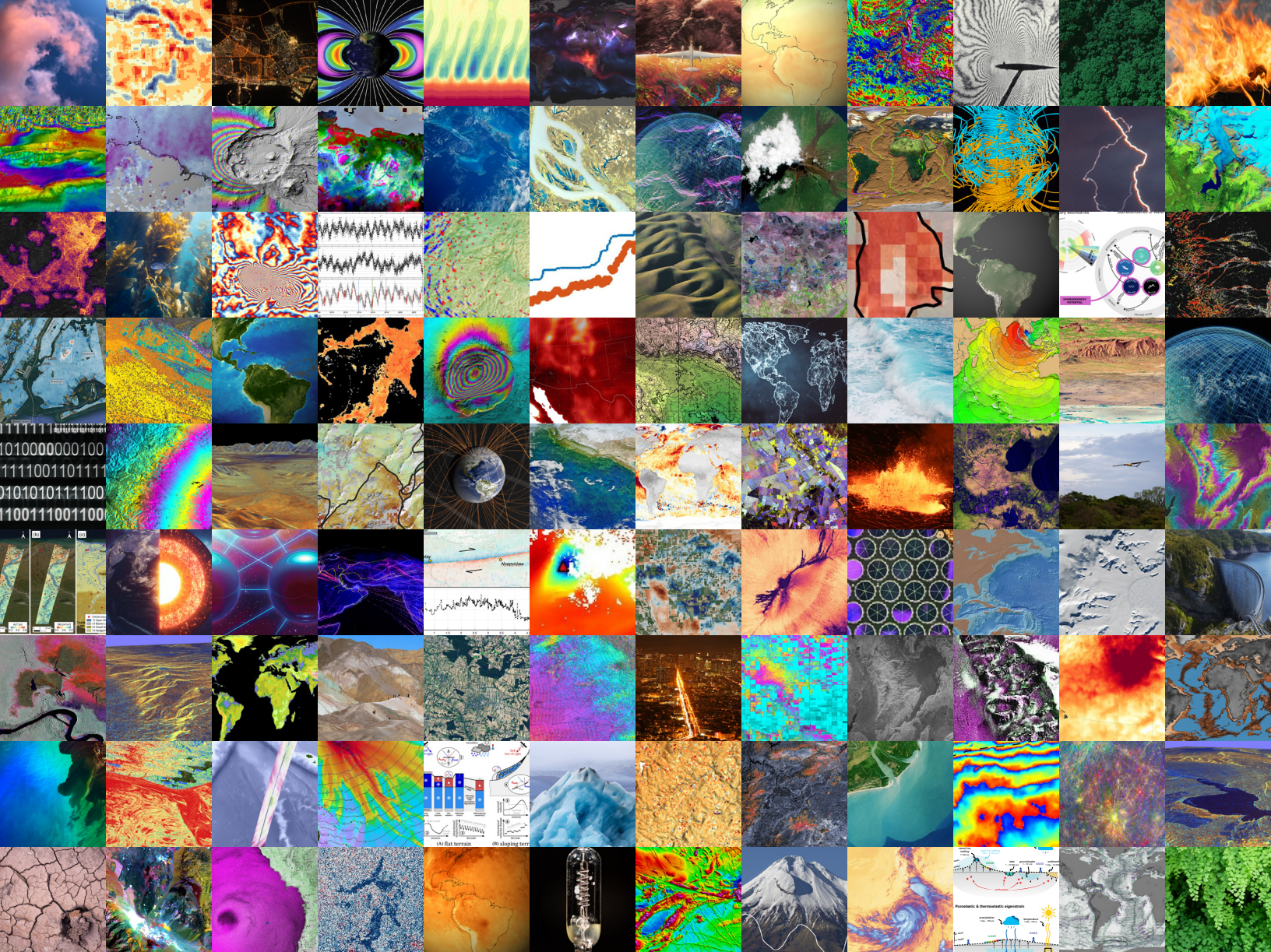
A computer simulation of Earth's magnetic field in a period of normal polarity between reversals (top) and during the upheaval of a reversal (bottom). The lines represent magnetic field lines: blue when the field points towards the center and yellow when away. The dense clusters of lines are within Earth's core.

Los Alamos National Laboratory/U.S. Department of Energy



SWOT captured this image of the Yukon River and nearby lakes on June 18, 2023 as it passed over Alaska. NASA/JPL-Caltech

Chapter 3: Synopsis



A deeper understanding of our home planet is essential to improve our resilience and our ability to thrive as a society. Achieving crucial insights into the Earth system, guided by the scientific challenges described in this report, requires a strong and diverse portfolio of data, technology, analysis tools, and a skilled workforce. It is imperative for us to embrace these complex challenges and opportunities.

The Earth's complex geophysical processes rarely occur in isolation, frequently overlapping in time and space. Observational and analysis capabilities are advancing at an unprecedented pace. Our workforce needs ongoing, continuous development to keep and grow the momentum of discovery and innovation.

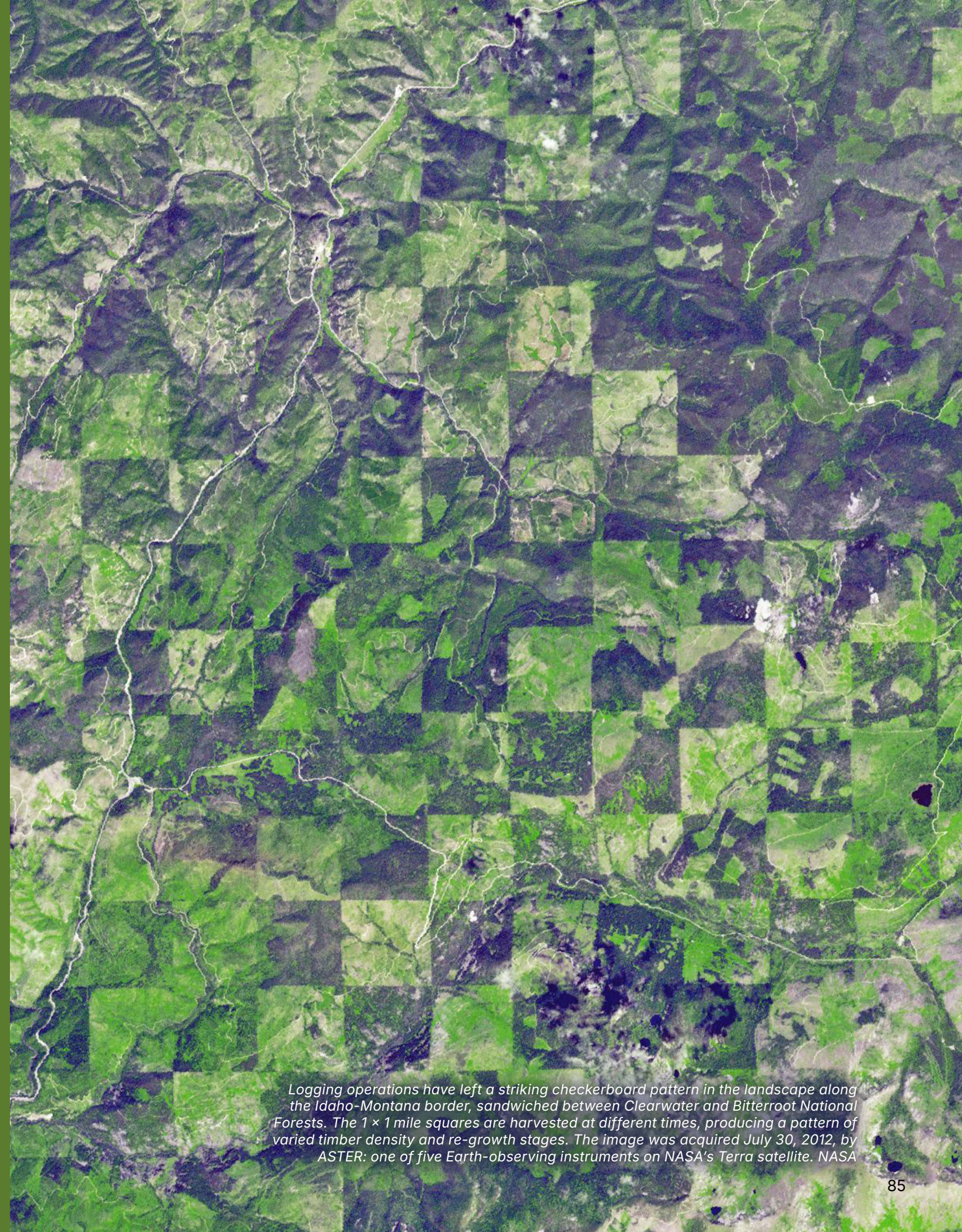
This report comes in the wake of a series of National Academies' Decadal Surveys. Our community remains strongly supportive of their recommendations. The National Academies' 2017-2027 Decadal Survey of Earth Science has many essential components that continue to be endorsed by the community and that are at various stages of development. The primary components from the 2017 Decadal Survey that directly advance the ESI community are the Surface Deformation and Change (SDC), Surface Topography and Vegetation (STV), Mass Change (MC), and Surface Biology and Geology (SBG) Targeted and /or Designated Observables. Going into the next decade, the need to support science and societal resilience using spaceborne data from these Designated Observables has only become more pressing.

This report has the following primary findings:

- Advancing our understanding of the many complex, interacting processes within the Earth system (e.g., separation of different post-seismic processes) requires enhanced temporal, spatial, and spectral resolution and better coordinated observations through satellite constellations. While missions with regular, global, observation plans are foundational, we increasingly need the added capability to provide targeted, higher-resolution, near-real-time data for transient events. To enable baseline distinctions of change, it is critical to maintain continuity of densely sampled observation time series, across the lifetime of multiple missions. This drives the need for cross-platform integration of data and calibration, consideration of evolving instrument capabilities, and the necessary data systems to harvest and interpret the resulting complexity of data across multiple observational solutions. The integration of such complex, multi-sensor observations is ideally considered at the formulation stage, addressing cross-calibration/validation and interoperability from the start.
- The portfolio of technology should deliver a suite of observations that include both active and passive measurement types conducted from space, suborbital and ground assets. Such technology will encompass a range of cost, complexity, and capabilities, supported by the agency and its partners throughout the mission innovation lifecycle. Each mission is expected to push technological boundaries through a range of platform solutions, including investments in physical and virtual constellations where these make sense to meet mission objectives.
- Across all scientific subdisciplines represented in this report, the rapidly increasing quantity and growing quality of data must be supported by excellence in analytical tools and computational resources. A framework that facilitates interpretation and integration of data, and that provides predictions, their uncertainties, and other information, requires innovation in computation, integration, and assimilation algorithms, and will support leaps in scientific advancements and Earth action uses, such as decision support tools.
- To meet the future needs of our society, the next generations of leaders and scientists will need to be recruited and prepared. The National Academies of Sciences, Engineering, and Medicine "Evolving the Geodetic Infrastructure to Meet New Scientific Needs" 2020 report discusses current challenges in recruitment and retention of the geodesy workforce, and similar themes exist in other areas of ESI. The provision of modern, state-of-the-art computational and analytical resources to the community, and dedicated training in their use, can help with maintaining this workforce and ensuring their success. However, education and engagement at the K-12 level and sustained mentoring of early-career researchers is a critical component of any plan to maintain a vibrant, innovative community of scientists in the future.

The strategies and observations outlined here, by building upon the scientific challenges and opportunities described in this report, directly support NASA's 2024 Earth Science to Action strategy, providing tools and opportunities that can enable solutions and discovery throughout the mission and innovation lifecycle, for the benefit of all.

Appendices

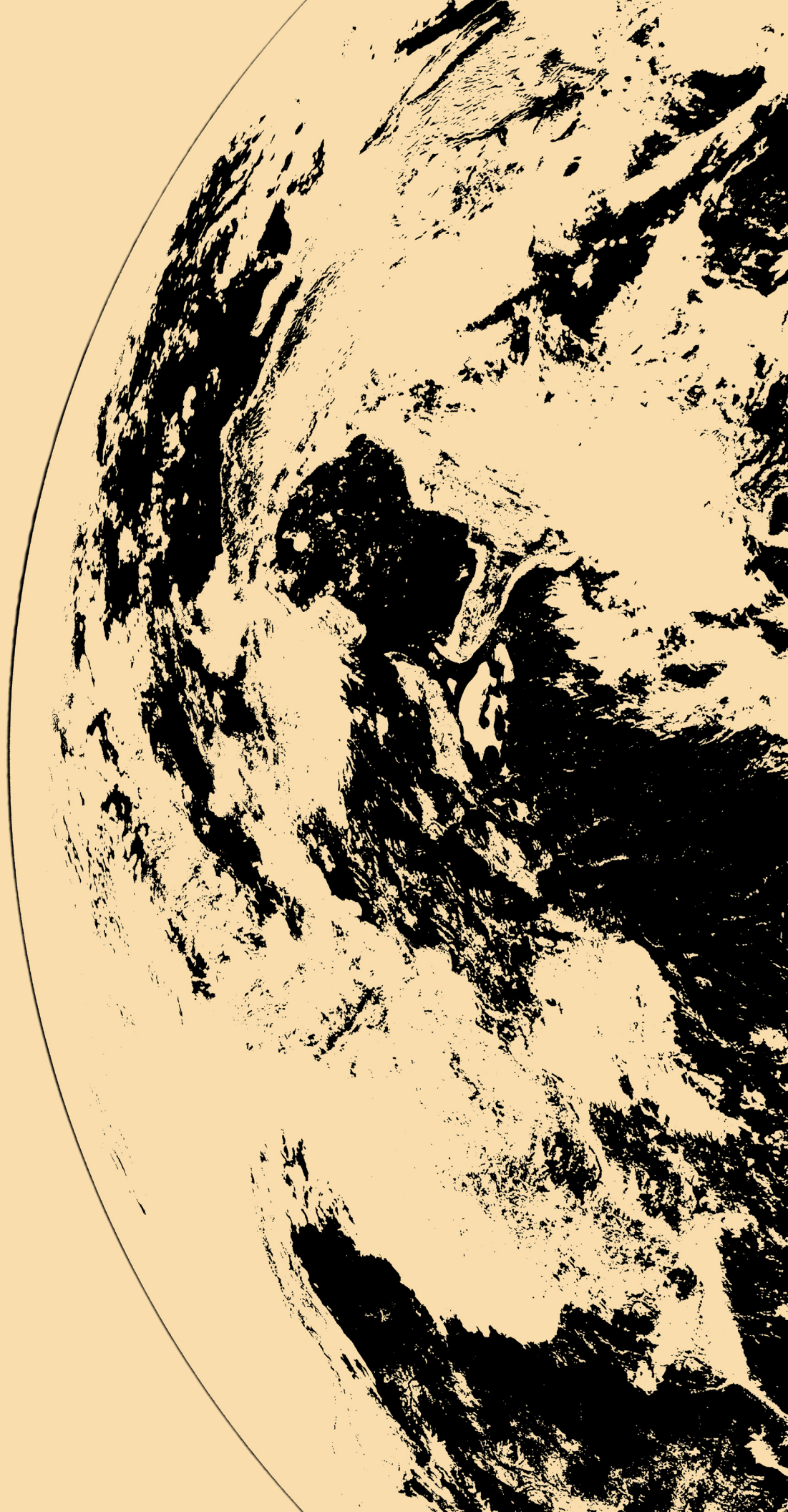


Logging operations have left a striking checkerboard pattern in the landscape along the Idaho-Montana border, sandwiched between Clearwater and Bitterroot National Forests. The 1 × 1 mile squares are harvested at different times, producing a pattern of varied timber density and re-growth stages. The image was acquired July 30, 2012, by ASTER: one of five Earth-observing instruments on NASA's Terra satellite. NASA

Mapping of Technology to Objectives

Observable Processes	Yesterday	Today	Tomorrow	Surface Processes	Tectonics and Fault Systems	Magmatic Systems	Earth's Interior	Societal Imperatives
Terrestrial Reference Frame (TRF)	SLR - International Laser Ranging Service (ILRS) VLBI - International VLBI Service (IVS) GNSS - International GNSS Service (IGS) DORIS - International DORIS Service (IDS)	SLR - International Laser Ranging Service (ILRS) VLBI - International VLBI Service (IVS) GNSS - International GNSS Service (IGS) DORIS - International DORIS Service (IDS)	SLR & SGSLR - International Laser Ranging Service (ILRS) VLBI - International VLBI Service (IVS) GNSS - International GNSS Service (IGS) DORIS - International DORIS Service (IDS) Spaceborne Co-Location - GRITSS, GENESIS					
Surface Deformation	InSAR Sentinel-1 UAVSAR (airborne) GNSS International GNSS Service (IGS) Plate Boundary Observatory Pixel Offset by SAR or Imaging	InSAR NISAR UAVSAR (airborne) ALOS PALSAR GNSS International GPS Service (IGS) Network of the Americas Pixel Offset by SAR or Imaging	InSAR ROSE-L Surface Deformation and Change (SDC) InSAR Constellation AirSAR-NG (airborne) GNSS International GNSS Service (IGS) Network of the Americas					
Topography	SAR TanDEM-X SRTM Stereographic Mapping	Radar TanDEM-X Lidar ICESat-2, GEDI LVIS (airborne) Stereoinaging Maxar (Polar Geospatial Center) QUAKES-I (airborne) Point Cloud Imaging	Radar Surface Topography and Vegetation (STV) TanDEM-X Lidar Surface Topography and Vegetation (STV) ICESat-2, GEDI, EDGE LVIS, CASALS (airborne) Stereoinaging Surface Topography and Vegetation (STV) Maxar (Polar Geospatial Center) QUAKES-I (airborne)					
Geomagnetism	Magnetic Field SWARM, Champ, Sac-C	Swarm	MagQuest (NGA), NanoMagSat (France)					
Gravity Field	Satellite-to-Satellite Ranging GRACE	Satellite-to-Satellite Ranging GRACE-FO	Satellite-to-Satellite Ranging GRACE-C NGGM					
Surface Composition	VSWIR AVIRIS (airborne) TIR HyTES, eMAS, MASTER (airborne)	Imaging Spectroscopy VSWIR EMIT AVIRIS (airborne) Imaging Spectroscopy TIR ECOSTRESS HyTES, eMAS, MASTER (airborne)	Imaging Spectroscopy VSWIR SBG-VSWIR AVIRIS (airborne) Imaging Spectroscopy TIR OTTER SBG-TIR HyTES, eMAS, MASTER (airborne)					
Gases	Total Column Spectroscopy GOSAT, GOSAT-2, OCO-2, OCO-3, TanSat Imaging Spectroscopy ASTER, OMI, MODIS, VIIRS, MASTER (airborne)...	Total Column Spectroscopy GOSAT, GOSAT-2, GOSAT-GW, OCO-2, OCO-3, TanSat Imaging Spectroscopy ASTER, OMI, MODIS, VIIRS, MASTER (airborne)...	Total Column Spectroscopy GOSAT, GOSAT-2, GOSAT-GW, OCO-2, OCO-3, TanSat Imaging Spectroscopy ASTER, OMI, MODIS, VIIRS, MASTER (airborne)...					

ACRONYMS



List of Acronyms

ASF	Alaska Satellite Facility
AI	Artificial Intelligence
CO2	Carbon Dioxide
CH4	Methane
CIG	Computational Infrastructure for Geodynamics
CSDA	Commercial Smallsat Data Acquisition (NASA program)
CSDMS	Community Surface Dynamics Modeling System
DAAC	Distributed Active Archive Center
DAS	Distributed Acoustic Sensing
DEM	Digital Elevation Model
DePIN	Decentralized Physical Infrastructure Network
ESAS 2017	2017-2027 Decadal Survey for Earth Science and Applications from Space, National Academies of Sciences, Engineering, and Medicine
ESI	Earth Surface and Interior (NASA Program)
FPGA	Field Programmable Gate Array
GEO-ESCON	Geomatics Emerging Scientist Consortium for Geomatics Education, Research, and Capabilities Enhancement
GIA	Glacial Isostatic Adjustment
GPS	Global Positioning System
GSD	Ground Sample Distance
HAPS	High Altitude Platform System
HDO	Deuterated H2O
H2O	Water
HPC	High Performance Computing
IGRF	International Geomagnetic Reference Field
IRIS	Incorporated Research Institutions for Seismology
InSAR	interferometric synthetic aperture radar
ISSM	Ice-sheet and Sea-level System Model
JPL	Jet Propulsion Laboratory
LEO	Low Earth orbit
LOD	Length Of Day
MHD	Magnetohydrodynamic
ML	Machine Learning
MWIR	Mid-wavelength Infrared
NGL	Nevada Geodetic Laboratory
O3	Ozone
OPERA	Observational Products for End-Users from Remote Sensing Analysis
PINN	Physics-Informed Neural Network
SAR	Synthetic Aperture Radar
SBIR	Small Business Innovation Research program
SLR	Satellite Laser Ranging
SGSLR	Satellite Geodesy Satellite Laser Ranging
SNWG	Satellite Needs Working Group
SO2	Sulfur Dioxide
SOPAC	SCRIPPS Orbit and Permanent Array Center
SV	Secular Variation
SWaP	Size, Weight and Power
SWIR	Short Wavelength Infrared
TIR	Thermal Infrared wavelength
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar (NASA)
UAV	Unoccupied Aerial Vehicle

VICTOR	Volcanology Infrastructure for Computational Tools and Resources
VSWIR	Visible and Short Wavelength Infrared
VLBI	Very Long Baseline Interferometry
VGOS	VLBI Global Observing System
VLEO	Very Low Earth Orbit

List of Missions and Instruments

ALOS-1	Advanced Land Observing Satellite - 1
ALOS-2	Advanced Land Observing Satellite - 2
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
COSMO-SkyMed	Constellation of Small Satellites for the Mediterranean basin Observation
CryoSat-1	Cryospheric Satellite - 1
CryoSat-2	Cryospheric Satellite - 2
DORIS	Doppler Orbitography and Radiopositioning Integrated on Satellite
ECOSTRESS	Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station
EMIT	Earth Surface Mineral Dust Source Investigation
ENVISAT	Environmental Satellite
ERS-1	European Remote Sensing Satellite - 1
ERS-2	European Remote Sensing Satellite - 2
Genesis	(ESA)
GEMx	Geological Earth Mapping Experiment
GLISTIN-A	Glacier and Ice Surface Topography Interferometer
GNSS	Global Navigation Satellite System
GNSS/A	Global Navigation Satellite System / Acoustic
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
GRACE	Gravity Recovery and Climate Experiment (NASA & DLR)
GRACE-FO	GRACE Follow-On (NASA & GFZ)
GRACE-C	GRACE Continuity
GOSAT	Greenhouse gases Observing SATellite (JAXA)
GEDI	Global Ecosystem Dynamics Investigation
ICESat	Ice, Cloud and land Elevation Satellite
ICESat-2	Ice, Cloud and land Elevation Satellite - 2
Iridium	Iridium satellite constellation
ICEYE	ICEYE corporation and satellites
ISS	International Space Station
JERS	SAR mission
Landsat	Successor(s) to Earth Resources Technology Satellite
MAGIC	Mass-Change and Geosciences International Constellation
MagQuest	Magnetic Quest
MagSat	Magnetic Satellite
MERMAID	Mobile Earthquake Recorder for Marine Areas by Independent Divers
MODIS	MODerate resolution Imaging Spectroradiometer
NanoMagSat	Nano MagneticThe Satellite (ESA)
NGGM	Next-Generation Gravity Mission (ESA)
NISAR	NASA ISRO Synthetic Aperture Radar
QGG	Quantum Gravity Gravimeter
QUAKES-I	Quantifying Uncertainty And Kinematics of Earth System Imager
RADARSAT	Radar Satellite
RADARSAT-2	Radar Satellite - 2
ROSE-L	Radar Observing System for Europe in L-band (ESA)
SRTM	Shuttle Radar Topography Mission

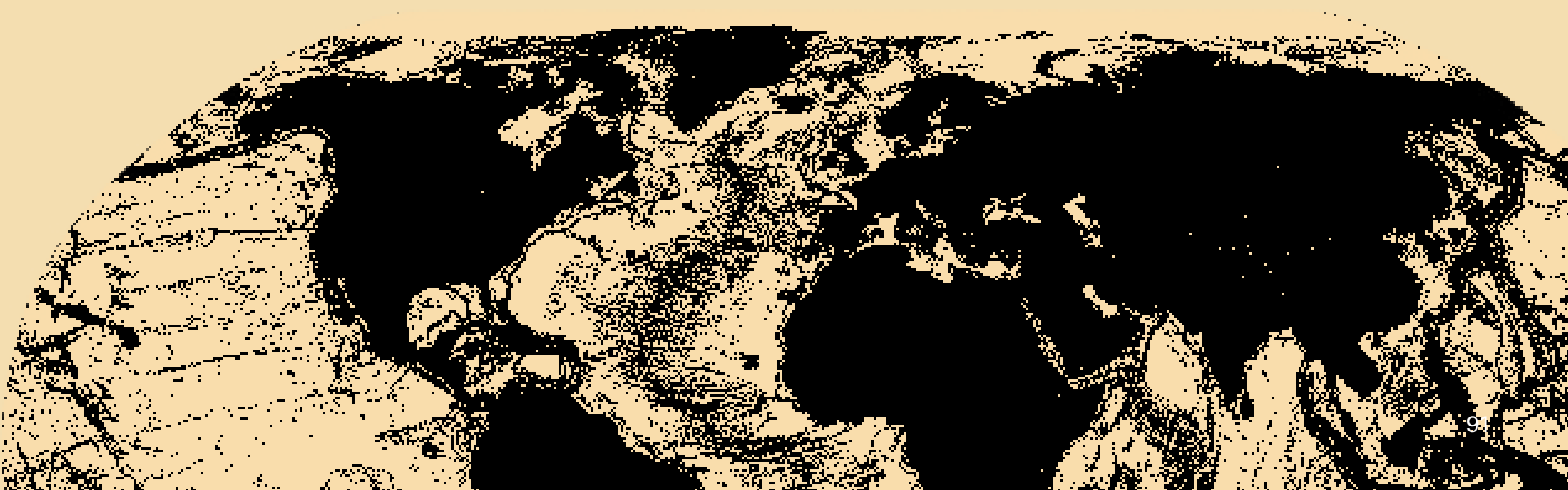
SWOT	Surface Water Ocean Topography
SDC	Surface Deformation and Change
STV	Surface Topography and Vegetation (NASA incubation study)
Swarm	The Swarm Constellation (ESA)
Sentinel-1	The Sentinel-1 constellation (ESA)
SBG	Surface Biology and Geology
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement
TerraSAR-X	Terra Synthetic Aperture Radar-X
TROPOMI	TROPOspheric Monitoring Instrument
VIIRS	Visible Infrared Imaging Radiometer Suite

List of Institutions

BGS	British Geological Survey
CNES	Centre National d’Etudes Spatiales (France)
CSA	Canadian Space Agency
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
ESA	European Space Agency (EU and associated countries)
GFZ	Geoforschungszentrum (Potsdam, Germany)
ISRO	Indian Space Agency (India)
JAXA	Japan Aerospace Exploration Agency (Japan)
NASA	National Aeronautics and Space Administration (USA)
NGA	National Geospatial-Intelligence Agency (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NSF	National Science Foundation (USA)
USGS	United States Geological Survey

Image Credits

Page 1	NASA/JPL-Caltech
Pages 2-3	NASA/USGS Landsat
Page 4	NASA/SWOT, NASA/Goddard Space Flight Center Scientific Visualization Studio, NASA/PACE, NASA/Goddard Space Flight Center Scientific Visualization Studio, NASA Earth Observatory
Page 6	NASA/Milan Loiacono
Page 9	NASA
Page 10-11	NASA/JPL-Caltech
Page 12	NASA/JPL-Caltech, NASA

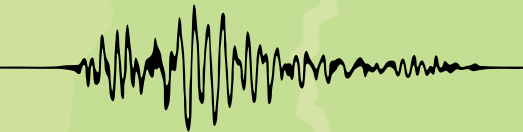


Page 14	Adobe Stock
Page 15	Adobe Stock
Page 16	NASA/USGS Landsat
Page 17	Concept - Cornell University/Rowena Lohman, Artist - NASA/Natalie Lee
Page 18	Cornell University/Rowena Lohman
Page 19	Cornell University/Mike Willis
Page 20	NASA/JPL-Caltech
Pages 22-23	NISAR/Paul Siqueira
Page 24	NASA Earth Observatory
Page 25	NASA/Natalie Lee
Page 26	NASA/Natalie Lee
Page 27	Dave Young, graphic by NASA, Cornell University/Rowena Lohman
Page 28	USGS, European Space Agency
Page 29	NASA Earth Observatory
Page 30	NASA/JPL-CalTech, NASA EMIT
Page 32	NASA's Earth Observatory
Page 33	NASA, NASA Earth Observatory, GNS Science/EQC/Karen Britten
Page 34-35	NASA/Natalie Lee
Page 37	Image: NASA/JPL/NIMA/MITI, Graphic: NASA/Natalie Lee
Page 38	NASA, Adobe stock
Page 40	University of Oslo/Reidar G. Trønnes, NASA/Goddard Space Flight Center Scientific Visualization Studio
Page 44	NASA/Goddard Space Flight Center Scientific Visualization Studio, NASA/ Yeosang Yoon
Page 47	Adobe Stock, Florian Schwandner
Pages 50-51	NASA/Goddard Space Flight Center
Pages 52-53	USGS
Pages 54-55	Adobe Stock
Page 56	NASA, NASA/Milan Loiacono, NASA/EPIC Lab
Page 59	Detektia
Pages 60-61	USGS
Page 62	Adobe Stock, graphic by NASA/Natalie Lee
Page 63	NASA
Page 64	NASA
Page 65	USGS
Page 66	NASA/Allison Li
Pages 68-69	Adobe Stock
Page 71	NASA OPERA
Page 72	NASA/Reto Stöckli, graphic by NASA/Natalie Lee
Page 74	NASA Earth Observatory, NASA/Goddard Space Flight Center/Kristen Perrin, NASA
Page 75	NASA/JPL/NIMA
Page 76	NASA/JPL/ESA
Page 77	NASA
Page 79	Los Alamos National Laboratory/U.S. Department of Energy
Pages 80-81	NASA/JPL-Caltech
Page 85	NASA
Page 92-95	NASA/Natalie Lee
Page 96-97	NASA/Natalie Lee

Community Input

In early 2024, NASA Earth Surface and Interior program leadership approached two co-leads and requested that they form a committee to plan a community workshop, determine modes of receiving community input, and agree on a process for writing the report. The committee was comprised of sixteen Earth science researchers from academic institutions, NASA research centers, and the United States Geological Survey. The September 2024 workshop included options for in person and remote participation, and brought together a mix of plenary sessions, poster sessions, and breakout groups, where participants worked on shared documents to outline opportunities, challenges, and future directions. Federal employee (USGS, NASA) committee members participated representing themselves as individual subject matter experts with their professional opinions alone, but not representing the U.S. Federal Government or their respective agencies.

To widen participation, there was the opportunity to provide feedback online and via a solicitation for white papers. After the white papers were received, the committee formed groups responsible for writing each section. Each section reflects current and future areas of research, and is augmented with background and context about the role of NASA in each area. A subset of the writing team worked to harmonize the style of the various sections and to compose the Introduction (Chapter 0) and Summary (Chapter 3). Finally, the writing team solicited short highlight pieces from community members involved in some of the areas of NASA's largest investments over the past decade.



Committee White Papers:

These White Papers were seeded by the September 2024 CORE 2.0 workshop's breakout groups.

- Andrea Donnellan, Paul Lundgren, "Surface Topography and Deformation"
- Társilo Girona, "Advancing Understanding and Monitoring Capabilities of Volcanic and Magmatic Processes"
- Thomas Herring, "Reference frames, Earth orientation and rotation"
- Thomas Herring, "Forgotten Topics"
- Weijia Kuang, Hao Cao, Jon Aurnou, Terence Sabaka, Kyle Gwirtz, "Probing Covariation of Earth Systems via Geomagnetic Investigation"
- Rowena Lohman, "Open Science"
- Paul Lundgren, Társilo Girona, Thomas Herring, Frederik Simons, Grace Bato, "Analysis Infrastructure"
- Hilary Martens, Shimon Wdowinski, Roland Bürgmann, Rowena Lohman, ESI CORE Team, et al., "Interactions Between Systems and Cascading Hazards"
- Frederik Simons, "Sensors/Hardware/Observational Capabilities/Decentralized Physical Infrastructure"
- Shimon Wdowinski, Hilary Martens, Thomas Herring, Bernard Hubbard, "Surface and near-surface processes and interactions"



Community White Papers:

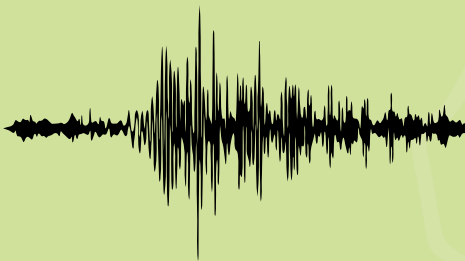
These White Papers were contributed by the Science Community

- Patrick Alken, Weijia Kuang, Gary Egber, “Future Long-term Sustainable Missions for Exploring Earth’s Magnetic Field”
- Hao Cao, Weijia Kuang, Jonathan Cheng, Jon Aurnou, “Revealing whole Earth dynamics through geomagnetism: From core to magnetosphere”
- Arnaud Chulliat, “Satellite Geomagnetism at a Crossroads: Advancing Crustal Field Modeling and Magnetic Navigation”
- Tim Dixon, “A SAR Constellation”
- William Frank, Andrew Newman, Joan Gomberg, Meng Wei, James Foster, Mark Zumberge, Laura Wallace, “Seafloor geodesy to image subduction zone dynamics from the trench to the arc”
- Junle Jiang, “Satellite Remote Sensing and Geodesy for Hazard Monitoring, Resource Management, and Geoscience Advances in Oklahoma”
- Chi-Yu King, “A Research Program on Earthquake Precursors?”
- Bryant Loomis, Srinivas Bettadpur, David Wiese, “Science grade quantum gravity gradiometer for mass change”
- Brent Minchew, “The promise of emerging observational technology: Vastly improved temporal resolution and other benefits”
- Leonid Petrov, “Removing the roadblock for improving the accuracy of reference frames”
- Jeanne Sauber-Rosenberg and Scott Luthcke, “Advancing topography and surface change observations with present and future laser altimetry missions”
- Jeanne Sauber-Rosenberg, “The Solid Earth Response to Earthquake Cycle Processes using MAGIC”
- SDC Study Team, “Surface Deformation and Change (SDC) - Part 1: Science and Applications”
- SDC Study Team, “Surface Deformation and Change (SDC) - Part 2: Observing Capabilities and Systems”
- Tara Shreve, “Applications of InSAR and GRACE for improved groundwater management”
- David Sibeck, “Observations from low-altitude spacecraft relevant to Heliophysics”
- John Tarduno, “Evolution of the Core, Geodynamo, Magnetosphere and Habitability”
- Robert Tyler, “Magnetometric Remote Sensing in Ocean/Climate Studies”
- Florian Schwandner and Tarsilo Girona, “Community priorities in magmatic-volcanic system research”

CORE 2.0 Committee

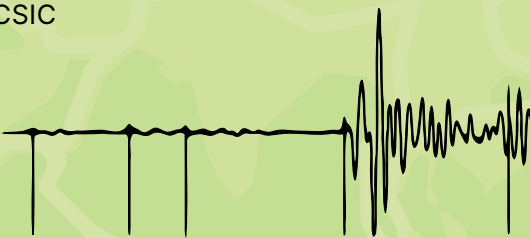
Committee Leads:

Rowena B. Lohman, Cornell University, Committee Co-Chair
Florian M. Schwandner, NASA Ames Research Center, Committee Co-Chair
Mark Simons, California Institute of Technology, Committee Chapter 1 Lead
Frederik J. Simons, Princeton University, Committee Chapter 2 Lead



Committee Members:

Jonathan M. Aurnou, University of California Los Angeles
Roland Bürgmann, University of California Berkeley
Andrea Donnellan, Purdue University
Lucy M. Flesch, Purdue University
Társilo Girona, University of Alaska Fairbanks/Geosciences Barcelona, CSIC
Thomas A. Herring, Massachusetts Institute of Technology
Bernard E. Hubbard, USGS Geology, Energy & Minerals Science Center
Weijia Kuang, NASA Goddard Space Flight Center
Bryant D. Loomis, NASA Goddard Space Flight Center
Paul R. Lundgren, NASA Jet Propulsion Laboratory
Hilary R. Martens, University of Montana
Diego Melgar Moctezuma, University of Oregon
Shimon Wdowinski, Florida International University



Production Team:

Milan Loiacono, Production Editor
Natalie Lee, Production Graphic Designer

Special Contributors:

Felix W. Landerer, NASA Jet Propulsion Laboratory
Bjarke Nilsson, Danmarks Tekniske Universitet
David Sandwell, University of California San Diego
Yao Yu, University of California San Diego



Ex-Officio (NASA Headquarters):

Lucia S. Tsaoussi (former ESI Focus Area Lead)
Kevin A. Reath (former Geosphere Lead)
Gerald W. Bawden (former NISAR Lead)
Benjamin R. Philips (former ESI Focus Area Lead)



External Reviewers:

Timothy Dixon, University of South Florida (permission sought)
Michael M. Watkins, California Institute of Technology (permission sought)
Jeffrey T. Freymueller, Michigan State University (permission granted)
Susan Owen, formerly at the Jet Propulsion Laboratory
Geoffrey Blewitt, University of Nevada, Reno





National Aeronautics and Space Administration

Mary W. Jackson NASA Headquarters
300 E Street SW (Hidden Figures Way)
Washington, DC 20546
nasa.gov/centers/hq

nasa.gov

NP-2026-09-6861-HQ