Evolving the Geodetic Infrastructure to Meet New Scientific Needs (2020)

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EVOLVING THE
GEODETIC INFRASTRUCTURE
TO MEET NEW SCIENTIFIC NEEDS

Committee on Evolving the Geodetic Infrastructure to Meet New Scientific Needs

Board on Earth Sciences and Resources

Committee on Seismology and Geodynamics

Division on Earth and Life Studies

A Consensus Study Report of
The National Academies of
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Cover: Front: Illustration of the Icesat-2 satellite measuring sea ice thickness, an important climate change variable, in the Arctic. The sea ice height measurement depends on cm-accuracy laser range measurement as well as cm-accuracy tracking using the Global Navigation Satellite System (GNSS) and Satellite Laser Ranging (SLR) of the geodetic infrastructure. Back: The four geodetic measurement techniques of the geodetic infrastructure: Very Long Baseline Interferometry (top left), GNSS (top right), SLR (bottom left), and Doppler Orbitography and Radiopositioning Integrated by Satellite (bottom right). Images courtesy of NASA.

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the content of the report nor did they see the final draft before its release. The review of this report was overseen by DANNY REIBLE, Texas Tech University, and KEITH CLARKE, University of California, Santa Barbara. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

APPENDIXES

Summary

Satellite remote sensing is the primary tool for measuring global changes in the land, ocean, biosphere, and atmosphere. Over the past three decades, active remote sensing technologies have enabled increasingly precise measurements of Earth processes, allowing new science questions to be asked and answered. As this measurement precision increases, so does the need for a precise geodetic infrastructure.

The connections between the geodetic infrastructure and science applications are illustrated in Figure S.1. The geodetic infrastructure (level 1) comprises four measurement techniques used to accurately determine the Earth's orientation in space, its gravitational field, the trajectories of satellites in orbit around the Earth, and the positions of reference points on the Earth. Data from these reference points are used to define the terrestrial reference frame (level 2), a set of coordinates and velocities of stable reference points on the surface of the Earth, which are used to define the locations of all other sites. Other geodetic products (e.g., orbit determination; level 3) are used to generate and interpret high-precision data from Earth-orbiting missions (level 4). These missions provide the connection between the terrestrial reference frame and the geophysical observables (level 5), which are needed to help answer science questions (level 6).

Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (NASEM, 2018; referred to hereafter as the Decadal Survey) identified high priority questions and associated space observational requirements to support Earth system science and applications for 2017–2027. Many of the science questions in the Decadal Survey can be supported by the existing geodetic infrastructure, as long as it is maintained. However, other science questions require enhancements to the infrastructure. For example, active remote sensing systems at the core of the National Aeronautics and Space Administration (NASA) program—such as Jason-3, NASA-Indian Space Research Organisation Synthetic Aperture Radar, Ice, Cloud, and land Elevation Satellite 2, Gravity Recovery Climate Experiment Follow On (GRACE-FO), and Surface Water Ocean Topography (SWOT)—often require more accurate timing and orbit information to achieve their threshold science requirements. Understanding and implementing improvements to the geodetic infrastructure and terrestrial reference frame is urgent because high-precision data needed for Decadal Survey science questions are already flowing from satellites in orbit.

At the request of NASA managers, the National Academies of Sciences, Engineering, and Medicine established a committee to summarize progress in maintaining and improving the geodetic infrastructure and to identify improvements to the geodetic infrastructure to meet new science needs laid out in the Decadal Survey. The committee tasks are given in Box S.1 and the responses to these tasks are summarized below.

TASK 1: PROGRESS IN MAINTAINING AND IMPROVING THE GEODETIC INFRASTRUCTURE

The committee's first task was to summarize progress and future aspirations for maintaining and improving the geodetic infrastructure, as detailed

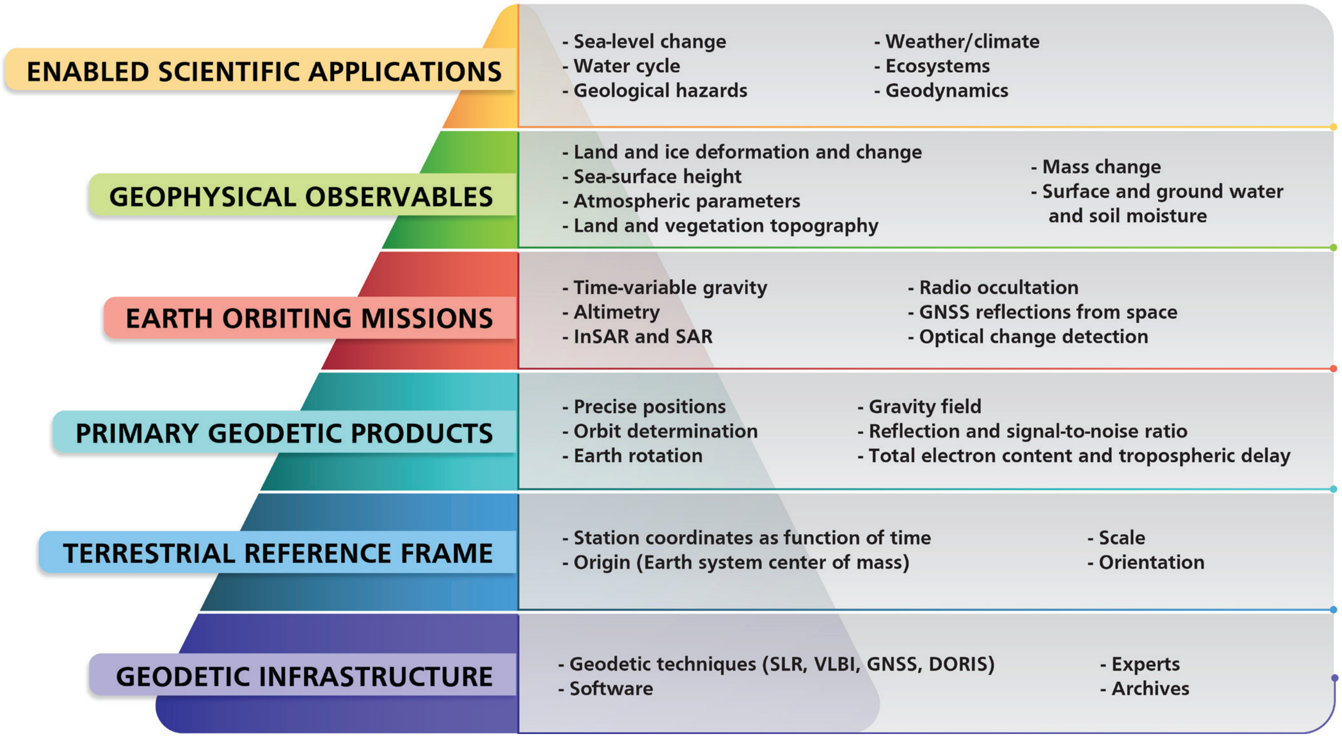

FIGURE S.1 Illustration of how the geodetic infrastructure is connected to enabled scientific applications. NOTE: DORIS = Doppler Orbitography and Radiopositioning Integrated by Satellite; GNSS = Global Navigation Satellite System; InSAR = Interferometric Synthetic Aperture Radar; SLR = Satellite Laser Ranging; VLBI = Very Long Baseline Interferometry.

in the recommendations in *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* (NRC, 2010). The geodetic infrastructure includes the measurement systems and facilities that allow continuous collection of data at the reference points that define the terrestrial reference frame, as well as international geodetic services that play a role in the measurement systems or produce enabling data sets or models. Four complementary measurement techniques are used to define the reference frame parameters (origin, orientation, and scale), with each technique bringing specific strength to the reference frame definition:

1. Very Long Baseline Interferometry (VLBI), which provides information on Earth orientation angles and scale.
2. Satellite Laser Ranging (SLR), which provides information on the location of the center of mass of the Earth and scale. SLR is also a passive backup tracking method that can be used for orbit determination when other instruments (e.g., GNSS) fail.

BOX S.1
Committee's Tasks

1. Summarize progress in maintaining and improving the geodetic infrastructure, as detailed in the recommendations in *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* (NRC, 2010), and aspirations for future improvements through, for example, new technology and analysis.
2. Identify science questions from the 2018 Decadal Survey on Earth Science and Applications from Space (NASEM, 2018) that depend on geodesy, and describe the connections between these questions, associated measurement requirements, and geodetic data.
3. Discuss the elements of these science questions that drive future requirements for the terrestrial reference frame, Earth orientation parameters, and satellite orbits, and identify what geodetic infrastructure changes are needed to help answer the questions.
4. Identify priority improvements to the geodetic infrastructure that would facilitate advances across the science questions identified in Task 2.

3. A network of Global Navigation Satellite System (GNSS) stations, installed much more densely over the globe than the small number of VLBI and SLR sites. The density of this network allows tens of thousands of GNSS receivers on spacecraft, aircraft, ships, and buoys, and in local geodetic arrays to access or connect to the International Terrestrial Reference Frame (ITRF). The GNSS network also makes a vital contribution to the measurement of polar motion.
4. Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), which is mainly used to compute accurate orbits of altimetric spacecraft and to enhance the global distribution of ITRF positions and velocities.

A large number of U.S. federal agencies contribute to the development and maintenance of the geodetic infrastructure. NASA operates a set of VLBI and SLR sites and hosts a few DORIS sites. The U.S. Naval Observatory supports the operation and upgrade of U.S. VLBI stations and provides Earth orientation parameters that describe irregularities in the rotation of the Earth. NASA, the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration's National Geodetic Survey, and the U.S. Geological Survey operate about one-quarter of the GNSS sites that form the core of the International GNSS Service. The National Geospatial-Intelligence Agency maintains a Global Positioning System (GPS) tracking network. In addition, U.S. federal agencies make substantial contributions to the international geodetic infrastructure through participation and leadership in international geodetic services.

The committee asked the above U.S. agencies to present their progress in and aspirations for maintaining and enhancing the geodetic infrastructure. Since the NRC (2010) report *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* was published, several agencies have upgraded their networks (e.g., by replacing datums and upgrading GNSS sites to allow real-time streaming). Progress has been slower in modernizing VLBI and SLR systems. The committee found three areas of concern. First, the precision of the next-generation VLBI and SLR systems has not been validated with long-term data-driven studies (as opposed to simulation) in the refereed literature. Second, few VLBI or SLR stations have been added to complement and increase the density of the international geodetic network, especially in the southern hemisphere, leading to greater errors in the north-south location of the center of mass of the Earth. Third, a unified, highly accurate, national GNSS observing system has not been developed that could both (a) serve as the U.S. realization of and connection to the ITRF and (b) support the Decadal Survey science questions. Most of the geodetic networks operated by U.S. agencies have upgraded their GPS systems to receive signals from multiple satellite systems (multi-GNSS) or have clear plans to do so. However, plans to support the software and associated products (orbits and clocks) and models (e.g., location of antenna phase centers) needed for multi-GNSS data streams are not clear.

A broader concern is that, with an aging workforce and declining number of graduates trained in geodetic techniques and models, the United States risks losing its leadership role in geodesy or even its ability to meet the needs of U.S. geodesy programs. It is also at risk of losing redundancy (and hence validation capability) in the highest-grade geodetic data analysis software, independently written and maintained by more than one research group.

TASKS 2 AND 3: DECADAL SURVEY SCIENCE QUESTIONS THAT DEPEND ON THE GEODETIC INFRASTRUCTURE

Task 2 was to identify science questions in the Decadal Survey that depend on geodesy and to describe the connections between these questions, associated measurement requirements, and geodetic data. The committee selected a range of science questions that depend primarily on maintaining the current geodetic infrastructure (weather and climate and ecosystems) or on improving its capabilities (sea-level change, terrestrial water cycle, and geological hazards). Those science questions were discussed at a 2-day workshop in February 2019 attended by geodesists working to maintain and improve the geodetic infrastructure and discipline scientists seeking to answer questions that require an accurate terrestrial reference frame. Together, they identified what specific aspects of the geodetic infrastructure need to be maintained or improved to help answer the science questions being considered (Task 3). The science questions and their geodetic needs are summarized below.

Sea-Level Change

Sea level is a leading indicator of climate change because its long-term change is driven mainly by the amount of heat being absorbed by the oceans and the amount of land ice being melted by a warmer atmosphere and oceans. Monitoring sea-level changes at global to regional scales, understanding the causes of these changes, and projecting how sea level might change in the future are critical for mitigating adverse impacts on coastal infrastructure, ecosystems, and human society. A precise geodetic infrastructure is essential for studies of (1) absolute sea-level change (sea level measured with respect to the Earth's center of mass or other suitable reference surface), which is important for understanding climate change; and (2) relative sea level (sea level measured with respect to the possibly moving land surface), which is important for assessing the impacts along the coasts.

All of the measurements of sea-level change and its components (ocean thermal expansion, ice sheet and glacier mass change, land water hydrology, vertical land motion, and the effects of melting ancient and modern land ice) require a terrestrial reference frame that is accurately defined as a function of time. The terrestrial reference frame needs to have an accurately defined origin and be free of drifts and other errors, lest they create errors in the satellite measurements that could be misinterpreted as climate signals. This will become particularly challenging as the Earth's shape and gravity field change due to climate change. Of particular concern is the movement of the Earth's center of mass relative to the reference frame origin as the ice sheets melt, which could amount to several centimeters over the course of a century. In addition, geodetic sites near areas of ice mass loss may show anomalous motion and should be treated carefully if used to define the reference frame. It is also important to be able to reconstruct the terrestrial reference frame back in time, so that sea level measurements made a century from now can be compared to sea-level measurements made today or 25 years ago.

Terrestrial Water Cycle

Observing and understanding the water cycle and changes in the water cycle are essential for protecting this life-enabling resource both now and in the future. High-precision geodesy has become an important tool for hydrologists, climate scientists, and water managers, enabling a range of studies, including (1) elastic loading caused by changes in terrestrial water storage; (2) aquifer-system compaction and land subsidence caused by groundwater overdraft; (3) surface-water monitoring to support science, water management, and flood forecasting; and (4) water-cycle monitoring to track changes in total water storage and measure water cycle components (soil moisture, snow water equivalent, and vegetation water content).

The main geodetic focus of terrestrial water cycle applications is the ability to monitor absolute vertical deformation at local, regional, and continental scales. In the United States, this monitoring ability requires a backbone of core GNSS sites having a spacing of ~40 km and weekly Interferometry Synthetic Aperture Radar (InSAR) and altimetry acquisitions. Swath altimetry (e.g., SWOT) is needed to frequently measure surface water level (lakes and rivers), and is calibrated using tide gauges tied to the terrestrial reference frame by GNSS. The orbits of the InSAR and altimetry satellites rely on well-distributed GNSS stations at the surface of the Earth, as well as a stable and accurate terrestrial reference frame. Monitoring the water mass changes in the larger basins requires monthly time-variable gravity measurements from GRACE-type missions with support from the SLR network. Timely production and distribution of water cycle products relies on open data, accurate/open software, and a skilled workforce.

Geological Hazards

Earthquakes and volcanic eruptions open a window on processes operating within the Earth. They are also capable of great destruction, which has led to substantial efforts to forecast their occurrence and mitigate their impacts (e.g., reinforcing buildings to withstand expected shaking). Because earthquake and volcanic cycles occur on hundred- to thousand-year time scales, global and long-duration observations are needed to capture enough partial cycles to understand and model the underlying physical processes and so advance forecasting. The required measurements include surface deformation, time-variable gravity, surface topography, sea surface tsunami waves, and surface cover and atmospheric changes. All of these measurements depend on maintenance and moderate improvements of the geodetic infrastructure.

The surface deformation measurements depend on a global backbone of GNSS sites that is augmented with higher spatial resolution, but less frequent (weekly) InSAR measurements. The combined system should be able to monitor global plate motions at mm/yr accuracy with local strain rate measurements at sub 50 nanostrain/yr precision, which requires a slight enhancement in the GNSS network. Approximately 40 km or better spacing of geodetic-quality GNSS stations is needed for monitoring tectonically and volcanically active sites in North America. Accurate and near-real-time satellite orbits and clocks are needed for both long-term monitoring and disaster mitigation. A time-dependent terrestrial reference frame combined with time-dependent gravity will be needed to track deformations from major tectonic events, especially in ocean areas not monitored by GNSS and InSAR. Ocean GNSS sites, with real-time data delivery, can increase the accuracy of tsunami forecasts as well as provide platforms for seafloor geodesy. All of these applications rely on open data as well as accurate/open software and a skilled workforce to deliver reliable products in a timely manner.

Weather and Climate

The atmosphere is a complex system that varies spatially at length scales ranging from meters to the circumference of the Earth and time scales ranging from minutes and weeks (weather) to years and longer (climate). Understanding and predicting weather and climate requires high spatial and temporal sampling using a wide variety of sensitive terrestrial and space-based sensors combined with large numerical models that assimilate these data. Science applications that rely on maintenance or enhancement of the geodetic infrastructure include (1) improving weather models, and (2) monitoring climate and reducing uncertainty in climate projections.

These applications use ground-based GNSS to measure total column water vapor over land as well as space-based GNSS radio occultation to measure the vertical structure of the atmospheric water vapor and temperature over both land and ocean areas. The measurements rely on accurate clocks and orbits of the GNSS constellations, which in turn rely on the geodetic infrastructure. The sheer number of radio occultations per day requires a fully automated system with frequent updates of clocks and orbital information. Maintaining absolute accuracy over perhaps hundreds of years will require a stable terrestrial reference frame, accurate orbits for the GNSS satellites as well as the low-Earth orbiting satellites, and a consistent approach to antenna models and data processing.

Ecosystems

Ecosystems supply the services upon which all life depends. Understanding how ecosystems are changing and how these changes influence the Earth system are important for sustaining life on the Earth. Ecosystem science topics that use active remote sensing, and thus rely on the geodetic infrastructure, include (1) vegetation dynamics; (2) lateral transport of carbon, nutrients, soil, and water; (3) global soil moisture; and (4) permafrost and changes in the Arctic.

The main geodetic tools used to investigate ecosystems are (a) Synthetic Aperture Radar (SAR) and InSAR for estimating changes in vegetation land cover, lidar for measuring vertical biomass structure, bare-earth topography, and surface motion associated with erosional and depositional processes; and (b) GNSS-derived total column water vapor and radio occultation for measuring atmospheric water vapor and soil moisture. These tools rely on accurate satellite orbits and clocks and thus depend on maintaining the current accuracy of the geodetic infrastructure and terrestrial reference frame. The application of GNSS to ecosystem science is emerging, and so the signal-to-noise ratio from GNSS ground stations will need be archived to support future research. Sustained gravity measurements are also a priority. New geodetic needs include increasing the number of GNSS stations across environmental gradients and placing the stations at locations with tide gauges and soil moisture sensors. In addition, many more radio occultation measurements are needed to support water vapor observations.

TASK 4: IMPROVEMENTS TO THE GEODETIC INFRASTRUCTURE

Task 4 was to identify priority improvements to the geodetic infrastructure that would facilitate advances across the science questions summarized above. These improvements cover five main areas: (1) accuracy and stability of the terrestrial reference frame; (2) accuracy and stability of satellite orbits; (3) accuracy of the global-scale gravity field; (4) augmentation of the GNSS station network; and (5) analytical support for an enhanced geodetic infrastructure.

Most of the passive satellite systems recommended in the Decadal Survey rely on moderately accurate (<1 m) and near-real-time satellite orbits that are enabled by the continued maintenance of the geodetic infrastructure. In contrast, all of the active sensors that measure height (radar and laser altimetry), surface deformation (SAR), or path delay (radio occultation) require three-dimensional orbit accuracies that are better than or equal to the accuracy of the geophysical observable. For all of the satellite systems, active or passive, the availability of accurate orbits has enabled fully automated processing and accurate geolocation, which increases the exploitation of the large data sets being collected by Decadal Survey missions.

The accuracy and stability of satellite orbits relies on the accuracy and stability of the terrestrial reference frame, which is derived from the geodetic infrastructure. The committee identified three areas of improvement in the geodetic infrastructure needed to help answer the Decadal Survey science questions:

1. **Finalize deployment and testing of next-generation VLBI and SLR systems and complete deployment of multi-GNSS receivers to achieve a balance of geodetic measurement techniques between the northern and southern hemispheres, document the errors in the systems, and improve the ability to estimate their positions accurately and automatically.**
2. **Increase the capabilities for measuring the center of mass motions expected over the next 100 years, due to the melting of the Greenland and Antarctic ice sheets.**
3. **Work with the international community to implement a fully time-dependent terrestrial reference frame that will accommodate sudden, annual, and long-term changes in the locations of the fundamental stations.**

The most stringent requirements for enhancements to the accuracy and stability of the terrestrial reference frame are driven by science questions related to sea-level change, ice-mass loss, and land-surface deformation associated with (a) the movement of water over the surface of the land, cryosphere, and oceans; and (b) the elastic and viscoelastic response of the solid Earth to water loading, earthquakes, and volcanic eruptions.

Ground-based GNSS receivers are essential for achieving the Decadal Survey science objectives related to sea level, cryosphere, weather, climate, geological hazards, and ecosystems. The density of core GNSS stations in the United States needs to be increased in high priority regions, including plate boundary zones to capture the earthquake cycle, coastlines to capture land motion that could affect sea-level impacts and coastal ecosystems, and regions with substantial terrestrial water storage. In addition, the United States will need to work with the International GNSS Service to deploy additional GNSS sites in remote, rapidly deforming areas, such as the perimeters of the ice sheets that deform by changes in mass loading. Such sites need good stability of geodetic monuments, long duration, and high data rate and availability. The U.S. stations should be considered part of the U.S. geodetic infrastructure, open to everyone, and thus have long-term financial support. Many of these stations already exist, but the infrastructure is aging and users cannot rely on their continued operation by NSF.

Maintaining and enhancing the geodetic infrastructure to compute the terrestrial reference frame, satellite orbits, and other products requires complex software systems developed over decades by teams of scientists and engineers. The software systems ingest both the raw measurements from the geodetic infrastructure and models for the deformation of the Earth and for propagation of the electromagnetic waves through the ionosphere and atmosphere. Support for software is critical for using GNSS data to calibrate and validate future satellite missions. The most important aspects of this activity are that all of the raw data are completely open and that cross-checking occurs by at least two independent groups using largely independent and open software.

An important component of both the GNSS and InSAR infrastructure is the development of new software delivery tools to make these data seamlessly available to more users. The dramatic improvement in satellite orbits and clocks over the past decade has enabled automated processing of very large sets of repeated observations (e.g., SAR, optical, radar altimetry, and lidar) that was not possible just a few years ago. This advance is important because the data sets are too large for a human to be in the processing loop, and will require that the geodetic workforce work in close collaboration with the high performance computing community.

CONCLUDING REMARKS

The international geodetic infrastructure is the largely invisible foundation of Earth system science and applications. Most of the Decadal Survey science questions require maintenance of the geodetic infrastructure. However, key science questions—particularly those that need high-precision measurements from active remote sensing instruments—require enhancements to the geodetic infrastructure. Maintaining and in some cases enhancing the geodetic infrastructure will require collaboration among U.S. federal agencies and international partners as well as open data, accurate and open software, and a skilled geodetic workforce capable of developing and implementing improvements.

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1

Introduction

Approximately every 10 years the National Aeronautics and Space Administration (NASA) asks earth scientists to reach a community consensus on a science and observations strategy for the next decade. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (NASEM, 2018) lays out high priority science questions and associated space observational requirements for atmosphere and climate, weather, hydrology, ecosystems, and solid earth science for 2017–2027. Underpinning these space observations and their interpretation is the geodetic infrastructure and its data products, notably the International Terrestrial Reference Frame (ITRF).

The connections between the geodetic infrastructure and science applications are illustrated in Figure 1.1 and Box 1.1. The geodetic infrastructure (level 1 of Figure 1.1) comprises four measurement techniques used to accurately determine positions of reference points on the Earth, the Earth's orientation in space, its gravitational field, and the trajectories of satellites in orbit around the Earth. Data from these reference points are used to define the terrestrial reference frame (level 2). Other geodetic data products (level 3) are needed to generate and interpret high-precision data from Earth-orbiting missions (level 4). These missions provide the connection between the terrestrial reference frame and the geophysical observables (level 5), which, in turn, are needed to answer science questions (level 6).

The existing geodetic infrastructure can support many of the science questions discussed in NASEM (2018), as long as it is maintained. However, enhancements to the geodetic infrastructure are required to support other Decadal Survey science questions, such as those connected with sea-level change. For example, Morel and Willis (2005) showed that changing the position of the center of mass of the Earth results in a commensurate change in sea level (see Figure 1.2). The Decadal Survey calls for the accuracy of regional sea-level rise to be better than 0.5 mm/yr decade, which requires a highly accurate and stable terrestrial reference frame. Enhancements to the geodetic infrastructure are also needed to analyze high-precision data from a variety of satellite sensors. Understanding what improvements to the geodetic infrastructure and terrestrial reference frame are needed is a matter of some urgency because high-precision data needed for Decadal Survey science questions are already flowing from satellites in orbit (e.g., Gravity Recovery and Climate Experiment Follow-On [GRACE-FO] and Ice, Cloud and land Elevation Satellite 2 [ICESat-2]). Improving the geodetic infrastructure would also facilitate new discoveries in earth sciences.

COMMITTEE'S TASKS AND APPROACH

At the request of NASA managers, the National Academies of Sciences, Engineering, and Medicine established a committee to identify key connections between geodesy and priority earth science questions, and to explore how to improve the geodetic infrastructure to meet new science needs. The committee tasks are given in Box 1.2.

This report builds on two previous National Academies reports. *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* (NRC, 2010)

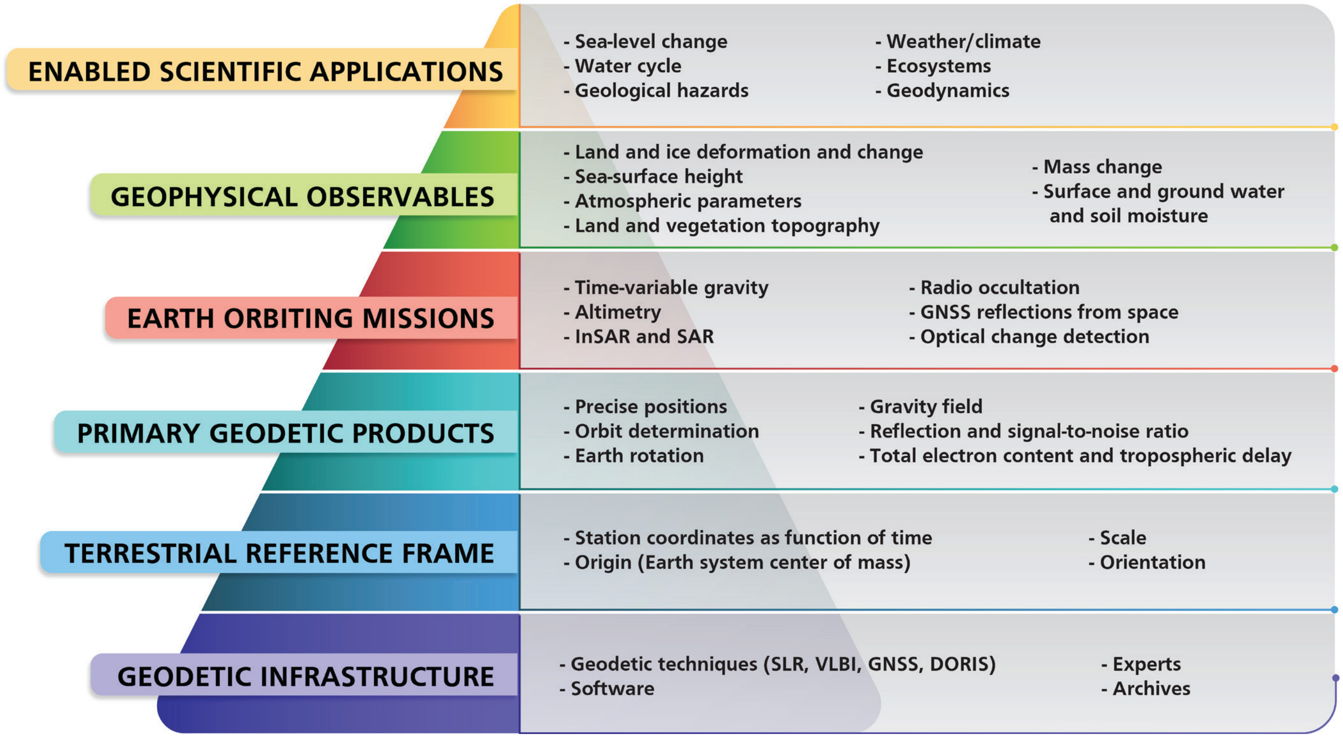

FIGURE 1.1 Illustration of how the geodetic infrastructure is connected to enabled scientific applications. NOTE: DORIS = Doppler Orbitography and Radiopositioning Integrated by Satellite; GNSS = Global Navigation Satellite System; InSAR = Interferometric Synthetic Aperture Radar; SLR = Satellite Laser Ranging; VLBI = Very Long Baseline Interferometry.

assessed the benefits of the geodetic infrastructure and recommended improvements to meet user demands for increasingly greater precision. To address Task 1, the committee invited U.S. federal agency managers responsible for the geodetic infrastructure to present their assessment of progress made in implementing the NRC (2010) recommendations and their aspirations for the future. The committee used material from the agency presentations, subsequent discussions with other experts, and its own expertise to address the task.

The second foundation report was *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (NASEM, 2018), which listed the science questions to be considered in this study. To address Task 2, the committee combed through the science questions in NASEM (2018) and selected the ones that depend either on maintaining the current geodetic infrastructure or improving its capabilities.

Those science questions were discussed at a 2-day workshop in February 2019 that brought together those who maintain and improve the geodetic infrastructure with scientists from multiple disciplines seeking to answer questions that require an accurate terrestrial reference frame. The workshop had two goals. The first goal was to identify what specific aspects of the geodetic infrastructure need to be maintained or improved to help answer the science questions being considered (Task 3). Workshop participants considered future needs for ground networks, data processing, on orbit requirements, space-based approaches, and tools, such as simulation capabilities to quantitatively assess the impact of reference frame improvements. The second goal was mutual education: the scientists would better understand how their research connects with the underlying terrestrial reference frame, and NASA and other federal agencies would better understand how terrestrial reference frame realizations need to evolve to answer priority science questions.

The results from the first meeting (Task 1) and the workshop (Tasks 2 and 3) were used to identify priority improvements to the geodetic infrastructure that would facilitate advances across the science questions (Task 4).

BOX 1.1
The Satellite Orbit Connects the Geophysical Measurement to the Terrestrial Reference Frame

There are two basic types of satellite remote sensing instruments: passive and active. A passive sensor, like a camera, uses reflected sunlight to measure the intensity of each pixel of the image. An active sensor, such as an altimeter, sends a pulse of light toward the Earth. The pulse reflects from the land, ocean, or atmosphere and the sensor measures the two-way travel time (see Figure 1.2a). Using the speed of light, the travel time is converted to a range. Thus, active sensors measure both range and intensity, whereas passive sensors measure just the intensity.

The range measured by an active remote sensing satellite is only one half of the geophysical measurement (e.g., sea-surface height); the other half is the satellite orbit. Thus, orbit error maps directly into the error in the geophysical measurement. The orbit accuracy depends on the accuracy of the tracking system as well as the accuracy of the terrestrial reference frame. Because accurate orbits are essential for several Decadal Survey satellite missions, combined Global Navigation Satellite System (GNSS) and Satellite Laser Ranging (SLR) tracking are used to reduce the orbit error as well as to provide backup should one tracking instrument fail. A classic example of such a failure occurred in 1991, when the European Space Agency's ERS-1 satellite lost its primary PRARE tracking system. (Global Positioning System [GPS] tracking was not fully developed at the time.) The backup SLR system saved the day, and ERS-1 became one of the most important Interferometric Synthetic Aperture Radar and altimeter missions to date.[a]

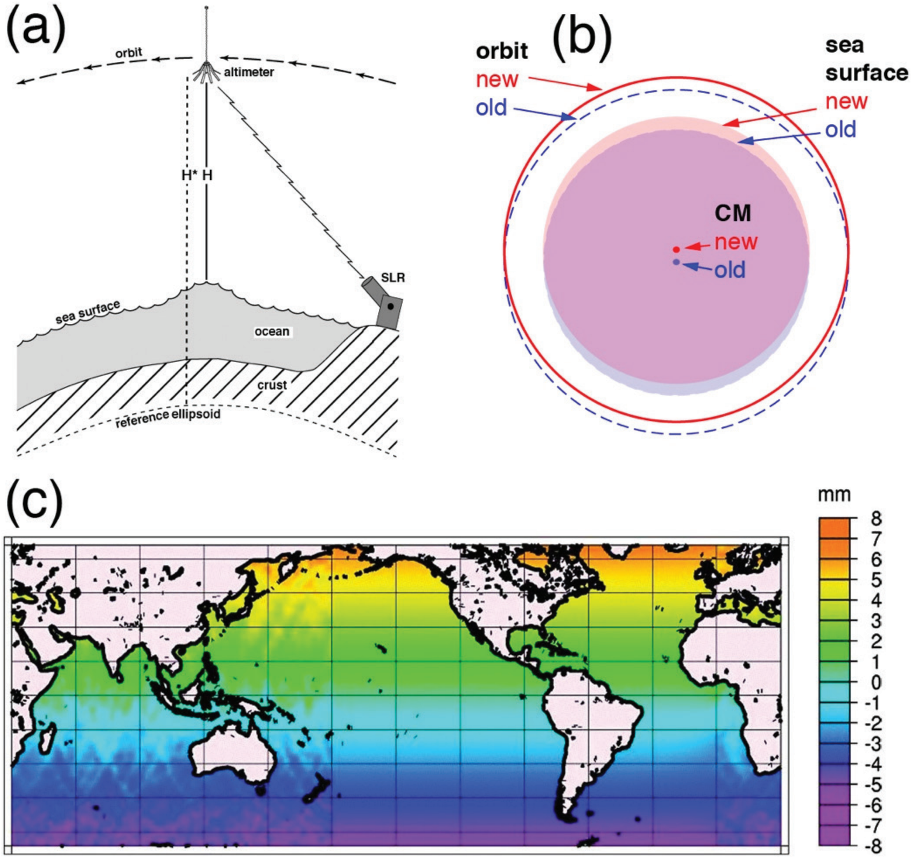

FIGURE 1.2 (a) The altimeter measures its height above the sea surface *H* by measuring the two-way travel time of a reflected radar pulse. The height of the satellite above the reference ellipsoid *H** is determined from the satellite orbit, which is measured by GNSS and SLR tracking. The sea-surface height is the difference between these two heights. SOURCE: Modified from Tapley et al., 1982. (b) The satellite orbits the center of mass (CM) of the Earth. A poleward shift in the CM causes a poleward shift in the orbit, which, in turn, results in a poleward shift in the sea-surface height. (c) Global change in sea-surface height caused by a 10 mm Z-translation of the center of mass of the terrestrial reference frame. While this is an extreme case based on the ITRF accuracy in 2005, the same direct connection between the terrestrial reference frame, orbit, and sea level holds today. SOURCE: Morel and Willis, 2005.

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[a] See https://ilrs.cddis.eosdis.nasa.gov/missions/satellite_missions/past_missions/ers1_general.html.

BOX 1.2
Committee's Charge

1. Summarize progress in maintaining and improving the geodetic infrastructure, as detailed in the recommendations in *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* (NRC, 2010), and aspirations for future improvements through, for example, new technology and analysis.
2. Identify science questions from the 2018 Decadal Survey on Earth Science and Applications from Space (NASEM, 2018) that depend on geodesy, and describe the connections between these questions, associated measurement requirements, and geodetic data.
3. Discuss the elements of these science questions that drive future requirements for the terrestrial reference frame, Earth-orientation parameters, and satellite orbits, and identify what geodetic infrastructure changes are needed to help answer the questions.
4. Identify priority improvements to the geodetic infrastructure that would facilitate advances across the science questions identified in Task 2.

GEODETIC INFRASTRUCTURE AND TERRESTRIAL REFERENCE FRAME

Terrestrial Reference Frame

A terrestrial reference system is a spatial reference system attached to the rotating Earth, and it includes the specification of its origin (usually at the center of mass of the Earth), its principal directions (connected with the equator or rotation axes and prime meridian), and a length scale. A terrestrial reference frame is the realization of the terrestrial reference system through a set of coordinates and velocities of stable reference points on the surface of the Earth whose positions are very accurately known as a function of time.[1] Such reference points are the locations of GNSS, SLR, Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) tracking stations. Use of satellite tracking data from these locations results in satellite orbit positions that are expressed in that particular realization of the terrestrial reference frame.

Adoption and use of common terrestrial reference systems and frames allow diverse geodetic measurements to be linked over space and time (see Figure 1.3). The reference points used to realize the terrestrial reference frame are selected so that they have steady and predictable motions on the Earth's surface at time scales ranging from months to decades. Consequently, the frame itself evolves slowly and predictably and thus can be used for several years without a major update.

The quality of positioning within the terrestrial reference frame is described in terms of precision, accuracy, stability, and drift (NRC, 2010; see Box 1.3). The accuracy of the terrestrial reference frame can be specified—by quantifying uncertainty or by comparing two reference frame realizations—using seven parameters and their time variations. These parameters are the origin (three translations), the orientation (three rotation angles), and the scale (scalar). The science requirements on the accuracy or stability of several of these reference frame parameters drive the future geodetic infrastructure needs.

An international terrestrial reference system has been adopted by the International Earth Rotation and Reference System Service (IERS). The IERS, in collaboration with multi-technique services of the International Association for Geodesy, is also responsible for obtaining ITRF realizations. The ITRF realizations are updated as new data are added and as new technologies or new analysis methods are incorporated. The latest such realization is the ITRF2014 (Altamimi et al., 2016), and preparations have begun for the ITRF2020. Although other global reference systems exist (e.g., WGS84), the ITRF is regarded as having the greatest quality and is the most widely disseminated. The international earth science community, including NASA space-mission data providers and data users, have long used the ITRF for consistent earth science data analyses and interpretation. Consequently, in this report, the ITRF is used as the reference frame realization relevant to the Decadal Survey science objectives, and the phrase "terrestrial reference frame" refers to the ITRF.

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[1] Presentation by Frank Lemoine, NASA, at the February 2019 workshop.

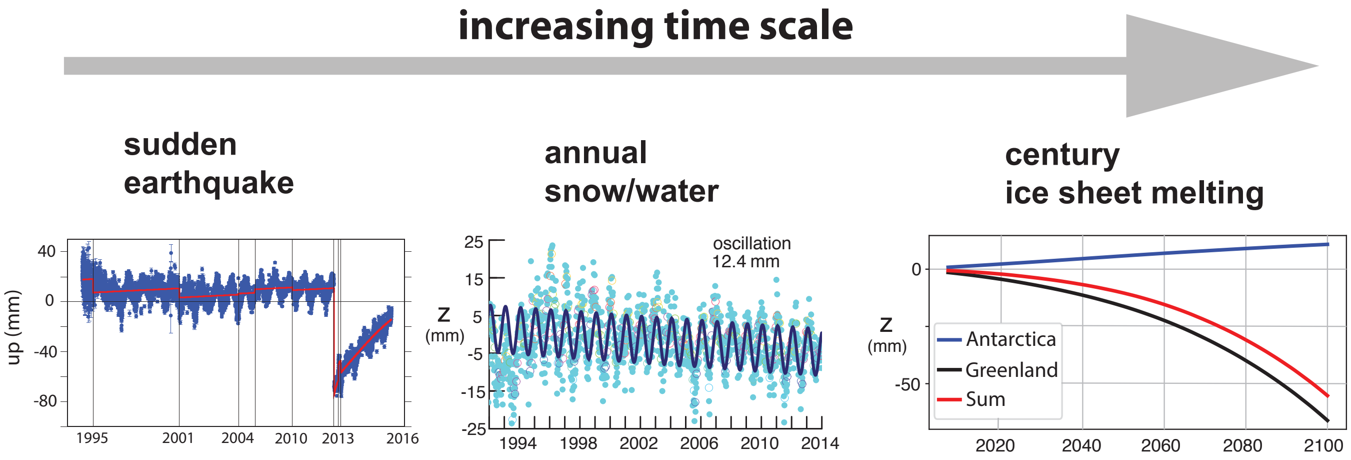

FIGURE 1.3 The Earth-fixed coordinates of the sites defining the terrestrial reference frame change on a wide range of time scales when mass is redistributed over the surface of the Earth. (Left) Sudden mass redistribution is caused by earthquakes and their postseismic response. SOURCE: Altamimi et al., 2016. (Middle) Annual variations in snow and water loading cause mainly Z-oscillations in the center of mass. SOURCES: Don Argus and colleagues, Jet Propulsion Laboratory, based on Altamimi et al., 2016. (Right) Melting of the ice sheets on century time scales causes nonlinear motions in the center of mass. The latter changes must be monitored for at least 100 years so sea level measured in 2100 can be compared with sea level measured in 2000. SOURCE: Modified from Adhikari et al., 2015.

BOX 1.3
Terms Used to Describe the Quality of Positioning Within a Reference Frame

Accuracy—how close a station position within a reference frame is to the truth. Precision contributes to accuracy, but accuracy also takes into account systematic biases arising from calibration errors or imperfect observation models.

Drift—the relative rotation, translation, and scale between different reference frames, which results in different velocities between stations given in each frame. Drift results from instability in one or both of the frames being compared, which in turn may result from systematic error in the measurement techniques, lack of precision in the measurements, or differences in the station motion models.

Precision—the ability to repeat the determination of position within a reference frame. Precision is necessary to resolve changes in position over time, and it is measured using statistical methods on samples of estimated positions. The precision of a reference frame itself refers to the variation in the reference frame parameters (origin, orientation, and scale) that arise from statistical variation in the data used to define the frame.

Stability—the predictability of the reference frame and the positions of the stations used to define the frame. In a stable reference frame, the defining parameters behave in a consistent manner, with no discontinuities over the time span of the geodetic observations. Furthermore, the ITRF should remain internally consistent, even as it is updated from time to time. Local site stability typically implies that all stations at that site do not move relative to each other, and that the site does not have nonlinear motions relative to the ITRF.

SOURCE: Abstracted from NRC, 2010.

Geodetic Infrastructure

The geodetic infrastructure includes the physical infrastructure (e.g., measurement systems and facilities) that allows continuous collection of data at the reference points that define the terrestrial reference frame, as well as geodetic services that play a role in the measurement systems or provide enabling data sets or models. Four complementary measurement techniques are used to define the time-dependent ITRF (see Figure 1.4), and their primary contributions include the following:

1. VLBI, which provides information on the three Earth orientation angles and scale.
2. SLR, which provides information on the location of the center of mass of the Earth and scale.
3. A network of GNSS stations, which enables densification of the reference frame, and provides supplementary information on all seven parameters of the terrestrial reference frame. The density of this network, compared with the relatively small number of VLBI and SLR sites, allows tens of thousands of GNSS receivers on spacecraft, aircraft, ships, and buoys and in local geodetic networks to access or connect to the ITRF (including in real-time). The GNSS network also makes a vital contribution to the measurement of polar motion.
4. DORIS, which is a ground-based beacon system mainly used for computing accurate orbits of altimetric spacecraft and for enhancing the global distribution of ITRF positions and velocities.

Each of these four measurement techniques makes several contributions to the terrestrial reference frame (see Table 1.1). These measurement techniques also underpin determination of satellite orbits and Earth orientation parameters.

Very Long Baseline Interferometry

The VLBI system comprises 47 radio telescopes that contribute to the measurements of the Earth's orientation and scale (Nothnagel et al., 2017; see

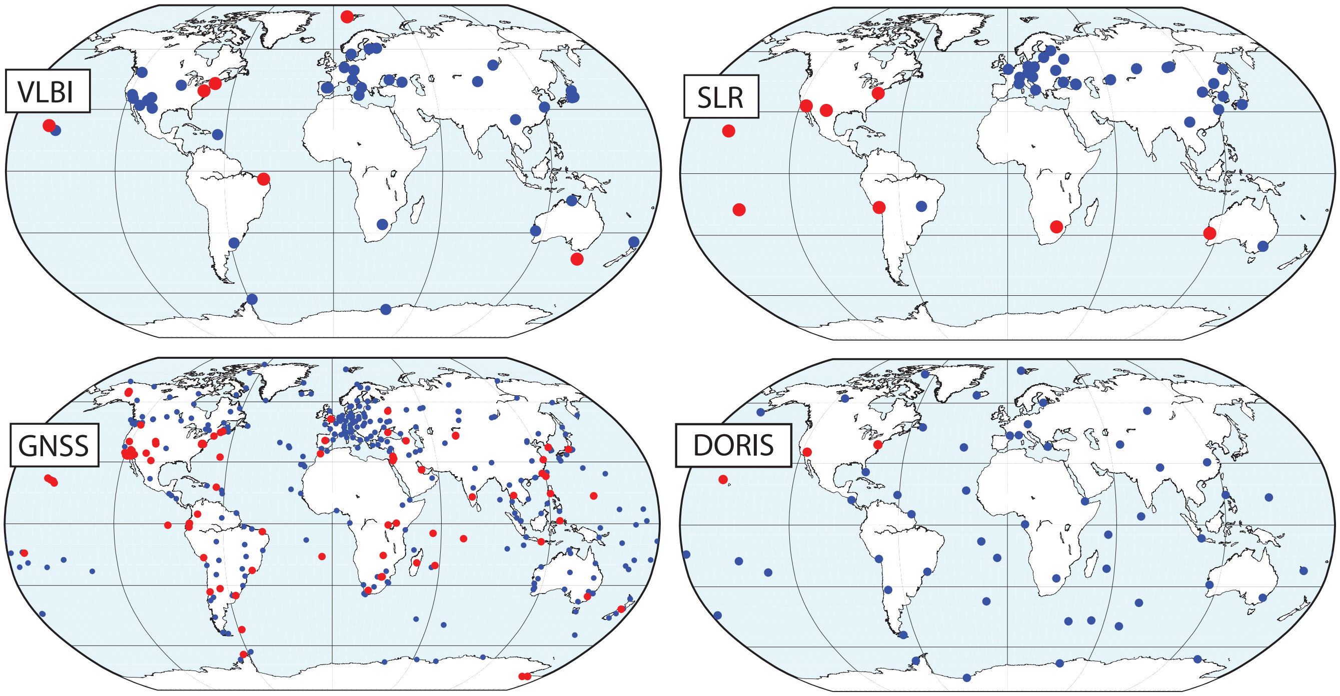

FIGURE 1.4 Positions of stations in the four measurement techniques that currently contribute to the ITRF. (Upper left) VLBI sites (47), including 6 sites (red) operated by NASA. (Upper right) SLR sites (39), including 8 sites (red) operated by NASA. (Lower left) GNSS sites (496) that form the core of the International GNSS Service. Of these, 122 sites (red) are operated by U.S. institutions, including NASA, the National Science Foundation, the National Geodetic Survey, the U.S. Geological Survey, and the National Geospatial-Intelligence Agency. (Lower right) DORIS sites (55), which are operated by the Centre National d'Etudes Spatiales. Three of these sites (red) are hosted by NASA. SOURCE: Data from Carey Noll, Secretary of the International Laser Ranging Service Central Bureau, 2019.

TABLE 1.1 Relative Contributions of Geodetic Measurement Techniques to the Terrestrial Reference Frame

Technique	VLBI	SLR	GPS	DORIS
Signal Target	Microwave quasars	Optical satellites	Microwave satellites	Microwave satellites
Observation type	Time difference	2-way range	Δ Range	Doppler
Celestial Frame (UT1)	**Strong**	Weak	Weak	Weak
Scale	**Strong**	**Strong**	Medium	Medium
Geocenter	Weak	**Strong**	Medium	Medium
Geographic Density	Weak	Weak	**Strong**	Medium

SOURCES: Don Argus, Jet Propulsion Laboratory, based on Altamimi et al., 2016, and Haines et al., 2015.

Figure 1.4). With this system, coordinated operation of two or more telescopes allows simultaneous recording of signals from the same extragalactic radio sources. The signal recordings are then pairwise cross-correlated between the telescopes to establish their changing positions with respect to the "fixed" celestial reference frame, as defined by the extragalactic radio sources. Ideally a large number of globally well-distributed VLBI stations should consistently participate in tracking sessions. Systematic errors in VLBI data and data products that can affect the stability of the terrestrial reference frame include the effects of gravitational deformation of VLBI antenna and tropospheric refraction errors.

VLBI is inherently a collaborative global activity, and the master schedule of observations is coordinated by the International VLBI Service for Geodesy and Astrometry (IVS; 41 institutions in 21 countries). This schedule is based on the availability of each station as well as the need for global and temporally dense sampling to measure daily changes in the rotation and orientation of the Earth. All VLBI observations are shared, and several centers of the IERS routinely produce Earth orientation parameters, such as the difference between Universal Time, which is defined by the Earth's rotation, and Coordinated Universal Time, which is defined by a network of precision atomic clocks. Predictions of this time difference are needed for many applications, such as satellite tracking and military operations.

NASA operates and maintains seven large radio telescopes at six sites around the Earth and is thus a major contributor to the ITRF. Moreover, NASA Goddard Space Flight Center currently hosts the IVS, which coordinates global operations up to 1 year in advance (Nothnagel et al., 2017). The NASA sites have been in operation since the 1980s and work is in progress to install the next-generation VLBI system (see Chapter 2).

Satellite Laser Ranging

The SLR system comprises 39 ground stations distributed around the Earth as well as 11 dedicated geodetic satellites (Pearlman et al., 2002, 2019; see Figure 1.4). The ground stations use short-pulse lasers, optical receivers, and accurate timing to measure the two-way travel time (and hence distance) to retroreflector arrays on the geodetic satellites. The geodetic satellites are mostly in high-altitude orbits where atmospheric drag and other nonconservative forces are minimal, ensuring a long lifetime in orbit. The SLR tracking data is sensitive both to the position of the center of mass of the Earth and to the large spatial scale variations in the gravity field. Such information is critical to the maintenance of the terrestrial reference frame. The biases in timing, range biases in tracking systems, and uncertainty in the knowledge of center of mass of the satellites carrying the retroreflectors can affect the quality of estimation of the reference frame parameters from SLR.

While several scientific satellite missions (e.g., ICESat-2, GRACE-FO, Jason-3, and NASA-ISRO Synthetic Aperture Radar) that support the Decadal Survey (NASEM, 2018) science questions normally use GNSS receivers for precise measurements of the orbital position, SLR provides independent validation of the centering and stability of the orbits for satellites orbits. SLR tracking also serves an important role as a backup tracking system in case of GNSS failure on Earth observation missions, and for determination of long-wavelength gravity field variations. As a result, the SLR ground stations routinely track more than 90 satellites, including much of the GNSS constellations, and thus provide an important link between the ITRF and satellite positions.

NASA currently operates 8 of the 39 global SLR stations. SLR operations, schedules, and products are coordinated by the International Laser Ranging Service (ILRS), which is currently located at NASA Goddard Space Flight Center. Weekly station coordinate solutions are developed at six ILRS analysis centers and combined as input to the ITRF.

Global Navigation Satellite System

The International GNSS Service (IGS) network comprises 496 globally distributed stations operated by a federation of more than 200 self-funded agencies, universities, and research institutions in more than 100 countries (see Figure 1.4). NASA's Jet Propulsion Laboratory operates 51 of the IGS stations and hosts the IGS Central Bureau. The IGS organizes the global GNSS network used to compute accurate GNSS orbits and clocks. Station coordinates from this network are an important contributor to the ITRF. The IGS orbits are available in real-time, rapidly (17-hour latency) and in post-analysis (13 days) time frames for GNSS orbits and Earth orientation parameters (polar motion). These frame products are used by continuously operating GNSS receivers (currently more than 10,000 receivers of geodetic quality) around the world, as well as by surveyors, aircraft, and NASA satellites. The IGS also provides other products, such as troposphere delays and maps of the variations in the Earth's ionosphere. All IGS products are provided without restriction.

In the committee's view, the GNSS infrastructure is not limited to the IGS stations, but also includes GNSS stations that have long duration and stability and are needed to meet the science objectives of this report.

Doppler Orbitography and Radiopositioning Integrated by Satellite

The DORIS system comprises approximately 55 autonomous and globally distributed stations that have been managed and deployed by the Centre National d'Etudes Spatiales and the Institut Géographique National since 1986 (Moreaux et al., 2016; see Figure 1.4). The third generation of antennae ("Starec C") is now being deployed. DORIS receivers are used primarily on altimeter satellites (Topography Experiment, Jason 1–3, Environmental Satellite, Cryosat-2, Sentinel-3A/B, and HY-2A) to provide real-time positions with ~30 mm radial orbit accuracy. Co-location of DORIS beacons with other satellite tracking techniques and cohosting other tracking instruments with DORIS onboard these altimetric satellites allows the altimetric sea-level measurements to be interpreted in the ITRF with confidence. Systematic errors in the solar radiation pressure modeling on spacecraft can affect the estimation of parameters of the ITRF.

The International DORIS Service (IDS) provides data and products to geodetic, geophysical, and other research and operational groups. Seven analysis centers contribute their time-dependent station positions and tracking data for the development of the ITRF.

Geodetic Services

Generation of the ITRF starts by distributing the raw data from the geodetic measurement systems discussed above to the analysis and combination centers (IVS, ILRS, IGS, and IDS), where it is analyzed and refined using computer models and statistical analyses (see Figure 1.5). These higher-level products are then distributed to the IERS to develop the ITRF. No single country or agency is responsible for generating these products. Instead, all parties involved work in an open international collaborative environment to provide the most accurate reference frame for science and applications. Several U.S. agencies, described in Chapter 2, contribute to and benefit from this global activity.

The geodetic services also play an important role in meeting the Decadal Survey (NASEM, 2018) science questions. All NASA missions that rely on accurate orbits for data collection and interpretation depend on the services providing GNSS satellite ephemerides and Earth orientation parameters (at various latencies) as key enabling or ancillary data sets. The services also test, establish, and disseminate the data processing models and standards to the community, which promotes harmonization across diverse space missions.

ORGANIZATION OF THIS REPORT

This report discusses the geodetic infrastructure needed to meet new science needs. Chapter 2

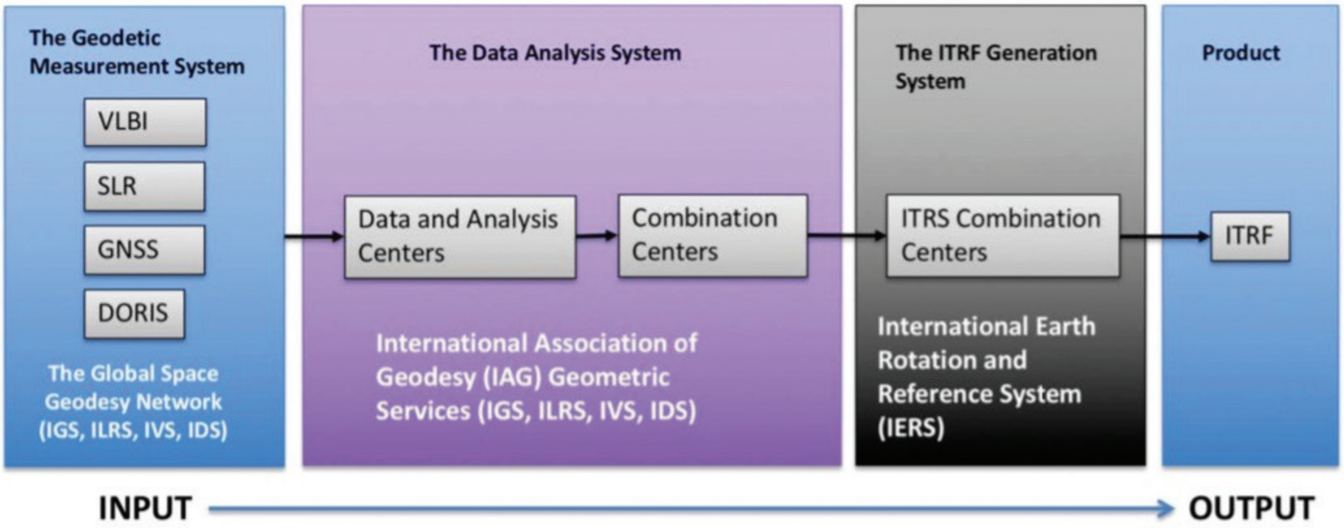

FIGURE 1.5 Schematic diagram of the production of the ITRF using geodetic measurements from VLBI, SLR, GNSS, and DORIS. All of the associated geodetic services are organized under the International Association of Geodesy. NOTE: IDS = International DORIS Service; IGS = International GNSS Service; ILRS = International Laser Ranging Service; IVS = International VLBI Service for Geodesy and Astrometry. SOURCE: Frank Lemoine, NASA.

summarizes agency progress in maintaining and improving the geodetic infrastructure since 2010, as well as aspirations for future improvements (Task 1). Chapters 3–7 discuss five categories of science questions (sea-level change, terrestrial water cycle, geological hazards, weather and climate, and ecosystems), the associated measurements that rely on an accurate terrestrial reference frame, and their geodetic needs (Tasks 2 and 3). Detailed connections between the scientific and geodetic needs are presented in Science and Applications Traceability matrixes in Appendix A. Chapter 8 sets priorities for improving the geodetic infrastructure to facilitate answers to the science questions (Task 4) and presents conclusions on all four tasks. The report ends with a list of meeting and workshop participants (see Appendix B), biographical sketches of committee members (see Appendix C), and acronyms and abbreviations used in this report (see Appendix D).

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2

Progress in Maintaining and Improving the Geodetic Infrastructure

The committee's first task was to summarize progress in maintaining and improving the geodetic infrastructure, as detailed in the recommendations in *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* (NRC, 2010), and aspirations for future improvements through, for example, new technology and analysis. A large number of U.S. federal agencies have a role in developing and maintaining the geodetic infrastructure, and the committee heard from six whose contributions are particularly relevant for achieving the Decadal Survey objectives laid out in *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (NASEM, 2018). These agencies were the National Oceanic and Atmospheric Administration's National Geodetic Survey (NOAA NGS), the National Geospatial-Intelligence Agency (NGA), the National Aeronautics and Space Administration's Goddard Space Flight Center (NASA Goddard) and Jet Propulsion Laboratory (NASA JPL), the National Science Foundation (NSF), the U.S. Geological Survey (USGS), and the U.S. Naval Observatory (USNO). The agency responses to the NRC (2010) recommendations and their aspirations for future improvements are summarized below.

MAINTAINING AND IMPROVING THE GEODETIC INFRASTRUCTURE

NRC (2010) Recommendation 1. The United States, to maintain leadership in industry and science, and as a matter of national security, should invest in maintaining and improving the geodetic infrastructure through upgrades in network design and construction, modernization of current observing systems, deployment of improved multi-technique observing capabilities, and funding opportunities for research, analysis, and education in global geodesy.

The progress in maintaining and improving the geodetic infrastructure reported by each agency is summarized below. Funding for research and education is discussed in the response to Recommendation 8 below.

Progress and Aspirations

Since 2010, several agencies have made upgrades to their networks (e.g., by replacing datums and upgrading Global Navigation Satellite Systems [GNSS] sites). Progress has been slower on modernizing observing systems (e.g., Very Long Baseline Interferometry [VLBI] and Satellite Laser Ranging [SLR]).

Upgrade of Networks

NOAA NGS is modernizing the current U.S. National Spatial Reference System (NSRS) in two key ways: (1) by replacing the horizontal datum (NAD 83) with a set of plate-fixed frames more closely tied to the International Terrestrial Reference Frame (ITRF), and (2) by updating the current vertical datum (NAVD 88) with a gravimetric geoid-based version. These changes will enable GNSS-based ellipsoidal heights to be related to orthometric heights used for local vertical control. Although widely used by surveyors, the NSRS is not sufficiently precise to meet the science requirements of the Decadal Survey. However, the GNSS tracking data from the Continuously Operating

Reference Stations (CORS) in the NSRS are used for scientific applications. Some of these data are processed by the International GNSS Service (IGS) and so are included in the ITRF.

With the end of the EarthScope Plate Boundary Observatory (PBO) project, NSF has combined PBO stations and GNSS networks built by NSF investigators in Central America and the Caribbean to form the Network of the Americas (NOTA). The receivers are gradually being upgraded to multi-GNSS tracking and real-time streaming. This network of almost 1,300 GNSS stations extends from the Aleutians to northern South America. However, NSF recently announced that this network will be reduced by 10 percent, to 1,100 stations.[1]

USGS has upgraded many of its GNSS sites to include real-time telemetry, and some sites have been upgraded to multi-GNSS receivers. The real-time data support the USGS shake-alert system, which uses instrumentation in the near-field of major earthquakes to send an accurate earthquake early warning to civilian populations (see the review by Allen and Melgar, 2019).

NASA JPL maintains a global GNSS network to support precise orbit determination and the ITRF. It has upgraded this network with multi-GNSS-capable receivers. In addition, its Global Positioning System (GPS) analysis software (GipsyX) has been modernized and is being extended to include multi-GNSS capability.

Modernization of Current Observing Systems

NGA has been working with NASA and the Department of Defense to deploy laser reflector arrays on the next-generation GPS-IIIF satellites, which will be launched after 2025. These arrays will allow SLR data to be used to evaluate the accuracy of GPS-III orbits.

NASA Goddard continues work on modernizing the SLR and VLBI systems with new VLBI Global Observing System (VGOS) hardware, a 12-meter dish with broadband tracking capabilities, and Space Geodesy Satellite Laser Ranging (SGSLR) hardware (see also NRC [2010] Recommendation 2). This work is proceeding in concert with USNO, which is supporting the operation and upgrade of U.S. VLBI stations (including NSF's Very Long Baseline Array) and international partners. USNO also collaborates with NASA Goddard to provide Earth orientation parameters and Celestial Reference Frame products to defense and civil communities.

Concerns

Long-standing efforts by NASA to design, build, and test the VGOS and SGSLR systems are not complete. The information provided to the committee was insufficient to assess the precision of these new prototype observing systems. Moreover, few peer-reviewed papers on VLBI and SLR error sources have been published by U.S. research groups in the past decade.

Modernization of the global VLBI network faces two challenges. The first is installing, testing, and commissioning the new telescopes and associated hardware and software. The second is the transitioning operations of the legacy systems to VGOS. This will involve new schedules and coordination, higher data rates and demand on correlators, and transition of the product base. For the global SLR network, only about a dozen global SLR stations (four supported by NASA) provide sufficient tracking data to contribute substantially to the ITRF, and those stations are geographically unbalanced, with too few in the southern hemisphere.

Although many U.S. agencies have supported the deployment of new equipment that is enabled to track multi-GNSS systems, the necessary software support for multi-GNSS users is not available. For example, multi-GNSS orbit and clock products are not currently provided by any of the U.S. analysis centers. Furthermore, none of the U.S. geodesy groups have an operational GNSS antenna calibration system, and some GNSS bias corrections are only provided by foreign partners.

ENHANCING SPECIFIC SLR AND VLBI SITES

NRC (2010) Recommendation 2. In the near term, the United States should construct and deploy the next generation of automated high-repetition-rate SLR tracking systems at the four current U.S. tracking sites: Haleakala, Hawaii; Monument Peak, California; Fort Davis, Texas; and Greenbelt, Maryland. It also should install the next-generation VLBI systems at the four U.S. VLBI sites: Greenbelt, Maryland; Fairbanks, Alaska; Kokee Park, Hawaii; and Fort Davis, Texas.

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[1] See https://www.nsf.gov/pubs/2019/nsf19072/nsf19072.jsp.

Progress and Aspirations

This recommendation was aimed at near-term enhancements of four SLR and four VLBI sites maintained by NASA (with USNO support at Kokee Park). In the decade since the NRC (2010) report, NASA has completed all of its site assessment studies. Next-generation VGOS systems have been operating in Greenbelt, Maryland, and NASA continues to operate the legacy broadband system at Westford, Massachusetts. One new VGOS system has been recently commissioned at Kokee Park (in concert with USNO and with a co-located legacy antenna there), and (as of this writing) the signal chain for a second VGOS system is being installed at the McDonald Observatory site. In addition, NASA supports the legacy station in Fortaleza, Brazil. The need for an Alaskan VLBI location is being reevaluated.

Achieving the full capabilities of the VGOS system will require equipping more stations with ultrawide bandwidth (multi-GHz) data acquisition backends and transporting up to 40 TB of data per station per day to central correlator facilities. There are now enough stations around the world to produce large-scale geodetic measurements.

The Goddard Geophysical and Astronomical Observatory hosts the prototype for the SGSLR. It will have a higher repetition rate, lower energy lasers, single photon detectors, additional laser wavelengths, shorter acquisition times and faster slewing, real-time data evaluation for quality control, and autonomous operations. NASA has stated its plan to deploy this new instrumentation at the four stations named above in 2019–2020 and at a new SLR station in Ny-Ålesund, Svalbard, in 2022. NASA also operates four legacy SLR stations (in Australia, Peru, South Africa, and Tahiti) and has begun discussions with local partners to upgrade or replace each of them (with the Peru station possibly moving to Brazil).

Concerns

NASA has upgraded VLBI instrumentation at three U.S. sites. None of these three sites have operating SGSLR systems. As noted in the previous section, the accuracy and long-term stability of the prototype SLR and VLBI systems have not been demonstrated.

INTERNATIONAL GEODETIC NETWORK

NRC (2010) Recommendation 3. In the long term, the United States should deploy additional stations to complement and increase the density of the international geodetic network, in a cooperative effort with its international partners, with a goal of reaching a global geodetic network of at least 24 fundamental stations.

Progress, Aspirations, and Concerns

Little progress has been made on implementing this recommendation. Only a handful of fundamental stations—defined as including the three techniques of VLBI, SLR, and GNSS—exist and they are poorly distributed globally. NASA Goddard has established one of these three-system fundamental stations and also operates a Doppler Orbitography and Radiopositioning Integrated by Satellite beacon.

NASA Goddard plans to deploy next-generation VLBI and SLR stations in Hawaii, Maryland, and Texas, and is currently in discussions with Australia, Brazil, South Africa, and Tahiti to replace NASA legacy stations. At current funding levels, subsequent deployments in Columbia, Kenya, and Nigeria would begin in 2028.

GNSS/GPS NATIONAL NETWORK

NRC (2010) Recommendation 4. The United States should establish and maintain a high-precision GNSS/GPS national network constructed to scientific specifications, capable of streaming high-rate data in real time.

Progress and Aspirations

The United States has not established a high-precision GNSS national network to scientific specifications. The PBO project (and now NOTA) installed many high-quality GNSS sites and many are currently being upgraded to track multi-GNSS and to stream high-rate data in real-time. However, because almost all PBO sites were installed to study plate boundary deformation, the sites are mostly concentrated along the west coast. More than 500 of these sites are in California and only a handful are east of the Rocky Mountains.

State departments of transportation have installed many GNSS sites in the eastern United States, but these sites were not built to scientific standards.

Although the data are sometimes freely available, their quality is highly variable and they are not archived according to scientific standards. For example, access to raw GNSS observations is generally not allowed and data streams are decimated to save disk space after 30 days.

NASA's Global GNSS Network provides high-rate, real-time data from more than 70 stations worldwide. NASA also works with NOAA NGS to align their efforts by augmenting the existing national GNSS array with foundation CORS to improve geometric coverage and linkage with the ITRF.

Concerns

Although GNSS data are available in the United States, the lack of coordination and disparate sources of funding mean that users, particularly real-time and scientific users, cannot rely on high-quality observations or support for their continued operation. This adversely affects both scientific and hazard applications. For example, despite the large number of continuously operating GNSS stations in the United States, observations of ground-based atmospheric water vapor for operational weather forecasting, for instance, lags far behind many other countries. In addition, the value of adding GNSS real-time positioning streams for tsunami warning has been demonstrated (Melgar et al., 2016), but it is unlikely that these data will be included unless the tsunami warning centers can rely on the continued support for GNSS networks in the United States. The recent decision by NSF to eliminate a large number of GNSS sites in North America is a further reminder that long-term support for this critical GNSS infrastructure is at risk.

INTERNATIONAL GEODETIC SERVICES AND THE ITRF

NRC (2010) Recommendation 5. The United States should continue to participate in and support the activities of the international geodetic services (IGS, ILRS, IVS, IDS, IGFS, and IERS).

NRC (2010) Recommendation 6. The United States, through the relevant federal agencies, should make a long-term commitment to maintain the International Terrestrial Reference Frame (ITRF) to ensure its continuity and stability.

Progress and Aspirations for Recommendations 5 and 6

An essential requirement for maintaining the global geodetic infrastructure is international collaboration, which is facilitated by the free and open exchange of raw data as well as synchronous observing schedules for VLBI and coordinated schedules for satellite tracking using SLR. This collaboration is achieved in part through the international geodetic services, which also enable the creation and maintenance of the ITRF. Both objectives were strongly endorsed by the NRC (2010) report.

All of the agencies that presented to the committee have firm commitments to the international geodetic services of the International Association of Geodesy (IAG), and many provide leadership and substantial institutional support. For example, all agencies with significant GNSS assets contribute raw GPS tracking data to public archives. Many also host web services and provide products. NASA JPL leads the IGS Central Bureau. NASA Goddard leads the Central Bureau of the International Laser Ranging Service (ILRS), contributes an analysis center, and operates eight legacy SLR stations (out of 39 ILRS stations). It also provides the coordinating center and an analysis center for the International VLBI Service for Geodesy and Astrometry (IVS), operates three legacy and two next-generation VLBI stations, and provides support for two partner legacy stations (out of 47 IVS stations). NOAA NGS provides the only current U.S. surveying team that measures high-accuracy local tie vectors at multi-technique co-location sites needed for ITRF.

U.S. agencies have been active participants and leaders in the Global Geodetic Observing System (GGOS) of the IAG. The primary role of GGOS is to promote the work of the IAG and the geodetic products generated by the IAG services.[2]

Concerns

None.

FEDERAL GEODETIC SERVICE

NRC (2010) Recommendation 7. The United States should establish a federal geodetic service to coordinate and

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[2] See http://www.ggos.org.

facilitate the modernization and long-term operation of the national and global precise geodetic infrastructure.

Progress and Aspirations

A federal geodetic service has not been established, and none of the presenting agencies identified it as a future objective.

Concerns

Research performed by one government agency (e.g., USGS) depends on networks funded by another agency (e.g., NSF or NASA), with no mechanism to guarantee continued operations. This poses risks to scientific and societal applications of geodesy (e.g., geologic hazards) because, for example, one agency may change or decommission a network that another agency relies on. The same holds true for software assets. In some cases, U.S. investigators are relying on software provided by international partners because no U.S. agency has agreed to support it. While NASA makes a strong commitment to the international GNSS geodetic infrastructure and the terrestrial reference frame, it relies on other agencies to densify it in the United States. In the absence of a federal geodetic service, an interagency forum would help identify and mitigate the risks.

GEODESY WORKFORCE

NRC (2010) Recommendation 8. A quantitative assessment of the workforce required to support precise geodesy in the United States and the research and education programs in place at U.S. universities should be undertaken as part of a follow-up study focused on the long-term prospects of geodesy and its applications.

Progress and Aspirations

A formal labor analysis of the geodetic workforce was commissioned by NGA and carried out in 2012 (see Box 2.1). However, data on the number of graduates from geodesy programs or the number of people working in geodesy-related occupations are not tracked by the federal government, and so quantitative estimates of the current and future geodetic workforce cannot be made. Anecdotal evidence points to a current and growing shortage of experts in geodetic techniques. Several agencies noted that their geodesists are aging. Because they are unable to find replacements with the needed skills, they need to provide on-the-job training in geodesy. NGA used to send some employees to universities for advanced training in geodesy, but is now training staff in house (NRC, 2013). NASA has a student fellowship program, but it primarily funds students who study science applications of geodesy, rather than those who improve geodetic techniques or models.

Concerns

The small and declining number of geodesists in the workforce poses risks for data analysis. For example, there are currently only two GPS data analysis software systems of the highest geodetic caliber in the United States: GipsyX (NASA JPL) and GAMIT

BOX 2.1
Labor Analysis of the Geodesy Workforce

In 2012, a National Research Council committee performed a formal labor analysis for geodesy and 9 other areas of interest to NGA (NRC, 2013). The analysis used Department of Education statistics on the number and level of graduates in more than a thousand instructional programs. Geodesy is not tracked, but it appears in the descriptions of five instructional programs: (1) aerospace, aeronautical, and astronautical engineering; (2) engineering physics; (3) engineering science; (4) surveying engineering; and (5) geophysics and seismology. The committee estimated that these five programs produced on the order of hundreds of geodesy graduates in 2009, the latest year statistics were available. The report noted that federal agencies were already concerned about a growing deficit of highly skilled geodesists and projected that competition and the small number of graduates would likely result in shortages long before 2030.

The report shows that because geodesy is taught in a variety of programs, many of which focus on other topics (e.g., geophysics), a labor analysis can provide only an estimate of the number of graduates with geodesy training. It cannot quantify the number of highly-skilled graduates capable of developing and maintaining the geodetic infrastructure.

(Massachusetts Institute of Technology). Although GipsyX was designed to enable full GNSS data processing, the lack of multi-GNSS orbit and clock production by NASA JPL limits the value of this software for many scientific investigators. While research is ongoing, GAMIT is not currently capable of simultaneous multi-GNSS data processing, and ongoing support for its maintenance is unclear. Similar risks exist for VLBI and SLR, with too few software systems to assure robust data analysis.

SUMMARY

The United States continues to make a strong contribution to the international geodetic infrastructure with significant participation and leadership in international geodetic services. However, there are three areas of concern. First, the accuracy of the next-generation VLBI and SLR systems developed with NASA funding have not been validated with long-term, data-driven studies (as opposed to simulation) in the refereed literature. Second, few core or SLR stations have been added to complement and increase the density of the international geodetic network, especially in the southern hemisphere. Third, a unified, highly accurate, national GNSS observing system has not been developed that could both serve as the U.S. realization of and connection to the ITRF and support the scientific studies described in the next chapters. Although most of the networks operated by U.S. geodetic agencies have upgraded their GPS systems with multi-GNSS capabilities (or have clear plans to do so), plans for the software and associated products (orbits and clocks) and models (e.g., phase centers) needed for multi-GNSS data streams are not in place.

With an aging workforce and declining number of graduates trained in geodetic techniques and models, the United States is at risk of not being able to maintain a leadership role in geodesy or even to meet the needs of U.S. geodesy programs. It is also at risk of losing redundancy (and hence validation capability) in the highest-grade geodetic data analysis software, independently written and maintained by more than one research group.

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3

Sea-Level Change

Sea level is a leading indicator of climate change because its long-term change is driven mainly by the amount of heat being absorbed by the oceans and the amount of land ice being melted by a warmer atmosphere and oceans. Monitoring sea-level changes at global to regional scales, understanding why it is changing, and projecting how sea level might change in the future are critical for mitigating adverse impacts on coastal infrastructure, ecosystems, and human society. A broad array of satellite observational systems, whose accuracy depends heavily on precise geodetic infrastructure, is required to observe and understand these changes and impacts.

Studies of sea level focus on (a) absolute sea-level change (sea level measured with respect to the Earth's center of mass or other suitable reference surface), which is important for understanding climate change; and (b) relative sea level (sea level measured with respect to the land surface, which may itself be moving), which is important for assessing impacts along the coasts. The Decadal Survey (NASEM, 2018) describes the scientific needs for understanding both absolute and relative sea-level rise. This chapter examines what is needed from the geodetic infrastructure to help answer the important Decadal Survey science questions:

C-1. How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?

S-3. How will local sea level change along coastlines around the world in the next decade to century?

C-6. Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?

H-1. How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?

The geodetic infrastructure needs associated with these questions appear in the Sea-Level Change Science and Applications Traceability Matrix (see Appendix A, Table A.1).

SCIENCE OVERVIEW

Sea-level science has been revolutionized by satellite observations because of their precision and near global coverage. Sea level has been monitored continuously over the past 27 years by a series of high-precision satellite altimetry missions (see Figure 3.1), which have been validated with tide gauge data. These records show that climate-driven global mean sea level has risen by 3.1 ± 0.3 mm/yr since 1993 and that the rate has accelerated by 0.084 ± 0.025 mm/yr^2 (Dieng et al., 2017; Nerem et al., 2018; WCRP Global Sea Level Budget Group, 2018).

An important goal of sea-level science is to determine not only how much sea level is changing, but why it is changing and the relative contributions of thermal expansion, melting of ice sheets and glaciers, and other factors. With this knowledge, we can better forecast how sea level will change in the future. Satellite gravity measurements from missions such as the Gravity

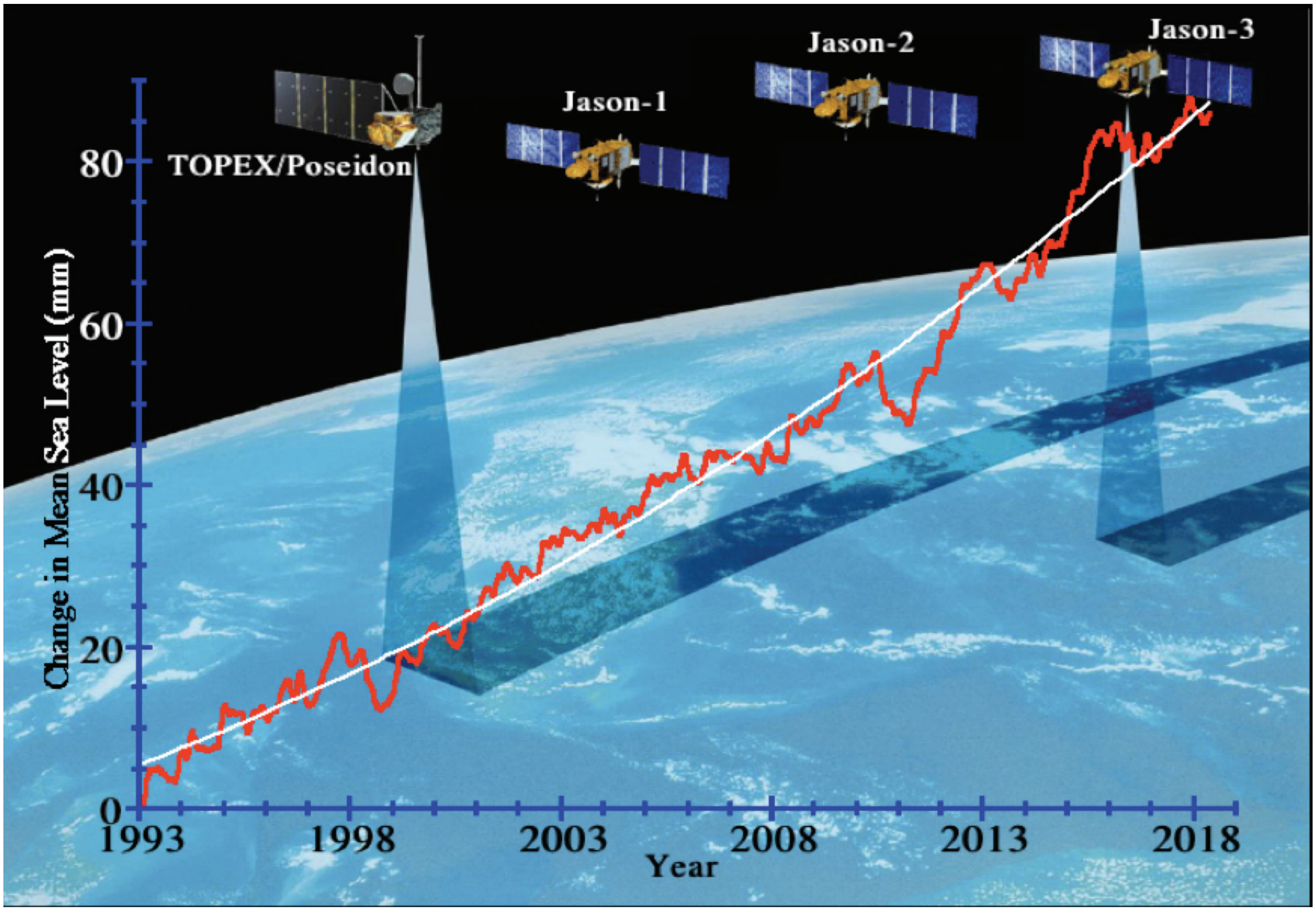

FIGURE 3.1 Altimetry record of global mean sea level from 1993 to present. The mean rate of rise is 3.1 ± 0.3 mm/yr. The climate-driven acceleration, estimated after correcting for short-term natural variability (effects of volcanic eruptions and the El Niño–Southern Oscillation), is 0.084 ± 0.025 mm/yr^2. SOURCES: Modified from Beckley et al., 2017, and Nerem et al., 2018.

Recovery Climate Experiment (GRACE) have proven valuable in this regard, because they provide information on how much melting ice is contributing to sea-level change, as well as variability caused by land-ocean hydrologic exchanges. Melting of land ice is currently the largest contributor to sea-level rise (44 percent for 1993–2015 and 55 percent for 2005–2015; see WCRP Global Sea Level Budget group, 2018), followed by thermal expansion of the ocean due to ocean warming (see Figure 3.2). Changes in ocean heat content can be measured by differencing altimetric sea-level measurements with satellite gravity measurements of ocean mass. Ocean heat content change can also be measured with the Argo network of profiling floats, which have minimal dependence on the geodetic infrastructure.

Changes in land water storage cause considerable interannual variability in global mean sea-level change. Much of this variability is driven by precipitation changes associated with climate oscillations such as the El Niño–Southern Oscillation. While climate-driven changes in total land water storage are currently small, it is important to understand the interannual variations so that they can be separated from the forced response (ice melt and ocean expansion) due to climate change.

Satellite altimetry has revealed that the rates of sea-level change vary regionally (see Figure 3.3), driven primarily by ocean circulation and winds, which redistribute heat and fresh water, as well as by gravitationally driven patterns caused by melting ice. The latter also causes relative sea-level change due to vertical land motion in response to the deformation of the Earth from ancient and modern land ice melt. Recent research suggests the 26-year regional sea-level trends are dominated by the forced response due to climate

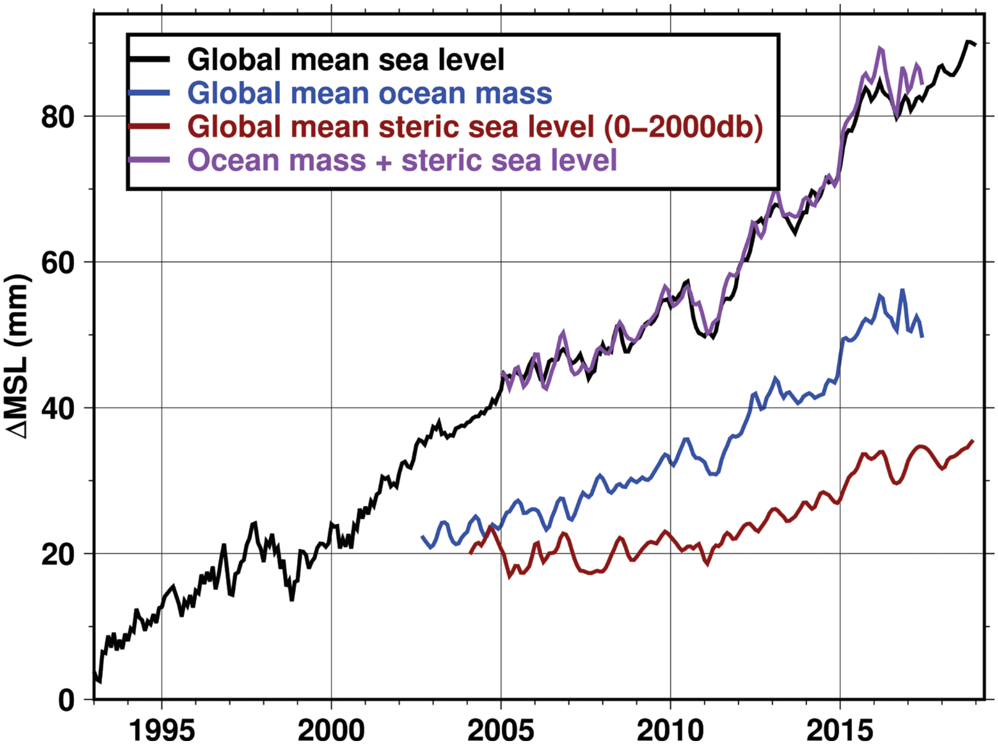

FIGURE 3.2 Global mean sea-level variations from satellite altimetry (black), global ocean mass from GRACE (blue), thermal expansion from Argo (red), and the sum of ocean mass and thermal expansion (purple). SOURCE: Updated from Leuliette and Nerem, 2016.

change, and that these patterns will continue into the future (Fasullo and Nerem, 2018). Therefore, the regional trends shown in Figure 3.3 provide insights on regional variations in future sea-level change.

Coastal sea level relative to the land surface is the quantity of most practical interest for understanding the societal impacts of sea-level change. Relative sea level depends on global mean sea-level rise and its regional variations, vertical land motion, and other local processes, such as small-scale currents, wind, waves, fresh water input from river estuaries, shelf bathymetry, and along-shore and cross-shore sediment transport (e.g., Woodworth et al., 2019).

Along many coasts, land subsidence amplifies the impacts of climate-related sea-level rise. Consequently, measuring vertical land motion is important for assessing the societal impacts of sea-level change. Vertical land motions are caused by a variety of phenomena, including tectonic and volcanic deformations, ground subsidence due to natural processes (e.g., sediment loading in river deltas) or human activities (e.g., groundwater pumping in coastal megacities and oil and gas extraction on continental shelves (Woppelmann and Marcos, 2016). Figure 3.4 shows relative sea-level time series measured by tide gauges, before and after correcting for vertical land motions. The case of Galveston in the Gulf of Mexico is particularly interesting. The uncorrected tide gauge record indicates that relative sea level rose by 6.4 mm/yr since 1900, mostly due to ground subsidence caused by sediment compaction due to groundwater withdrawal.[1] After correcting for vertical land motion, the rate of sea-level rise in that area is reduced to 1.8 mm/yr.

The solid Earth response to melting land ice also gives rise to vertical land motion by two other mechanisms: (1) the viscoelastic response associated with the last deglaciation, called glacial isostatic adjustment (GIA), and (2) the elastic response associated with present-day land ice changes. These responses, mostly known from modeling, create complex re-

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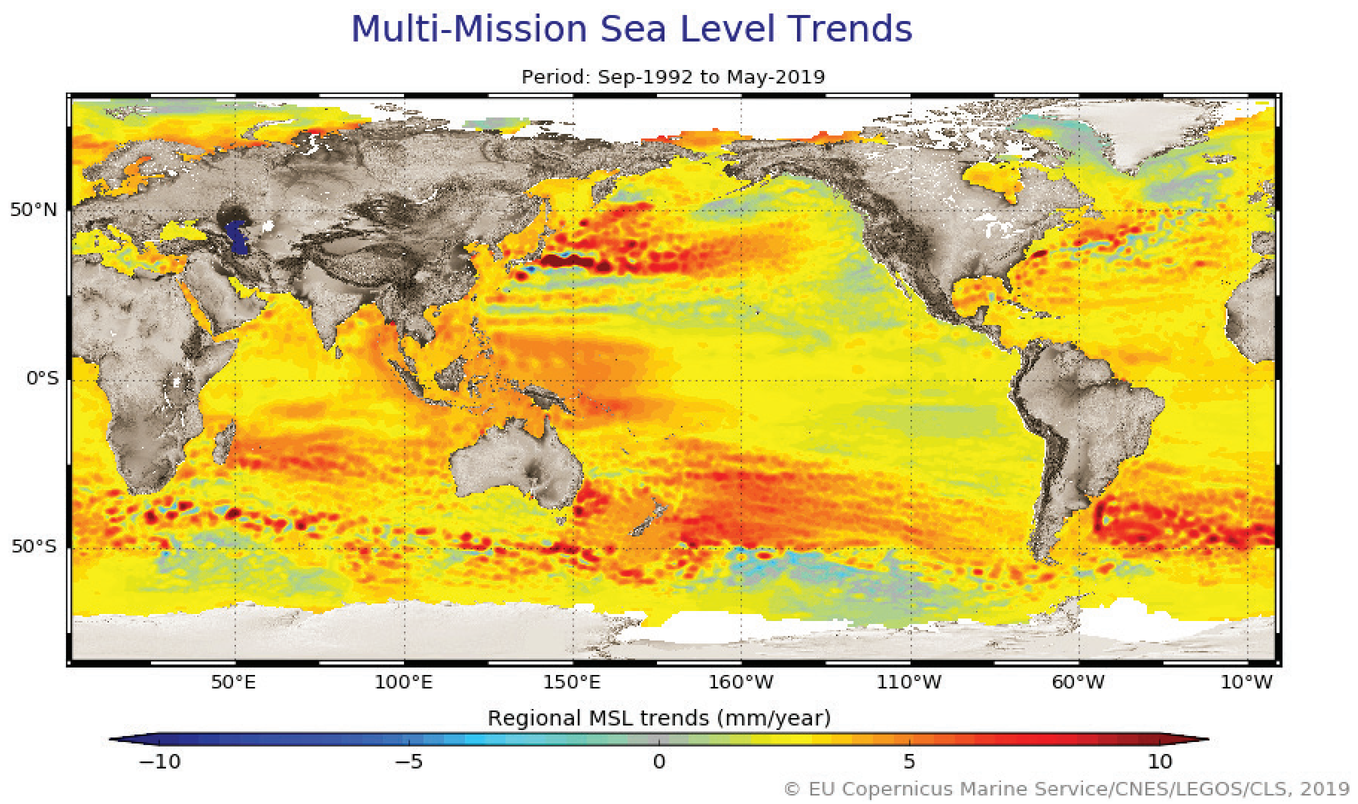
[1] See https://txpub.usgs.gov/houston_subsidence/home.



Multi-Mission Sea Level Trends

Period: Sep-1992 to May-2019

© EU Copernicus Marine Service/CNES/LEGOS/CLS, 2019

FIGURE 3.3 Regional sea-level trends (September 1992–May 2019) from multi-mission satellite altimetry. SOURCE: Copernicus Marine Environment Monitoring Service.

gional patterns in both absolute and relative sea-level change (Peltier, 2004; Tamisiea, 2011): sea level drops in the immediate vicinity of the melting land ice and rises in areas that were not covered by high volumes of ice during the last glacial maximum. GIA depends on the Earth's mantle viscosity and deglaciation history (Peltier, 2004; Lambeck et al., 2010), whereas the response of the solid Earth to modern land ice melt depends on lithosphere elasticity and the amount and location of ice mass loss. The latter deforms the ocean floor and changes the Earth's gravity field, resulting in a nonuniform pattern of sea-level rise, generally known as "sea-level fingerprints" (Mitrovica et al., 2009). Although decades of sea-level observations may be needed to routinely detect sea-level fingerprints, some fingerprints have already been detected (Hsu and Velicogna, 2017). As ice melt contributions from Greenland and Antarctica grow, regional sea-level trends will be dominated by the gravitational fingerprints of ice sheet mass loss.

GIA increases the volume of the ocean basins, producing a linear effect of ~–0.3 mm/yr on the altimetry-based record of global mean sea-level rise (Peltier, 2004; Tamisiea, 2011). GIA is usually considered a correction that needs to be subtracted from the global mean sea-level rise time series to estimate changes in water volume. Its uncertainty is estimated to be of the order of 0.15 mm/yr (Tamisiea, 2011). The effect of GIA on GRACE-based global mean ocean mass estimates is much more important (and must be corrected for), because it is on the same order of magnitude as the ocean mass change signal itself.

The response of the solid Earth to ancient and present-day ice loading needs to be better understood, because it is a leading source of error in GRACE estimates of ice mass loss from the ice sheets. Global Navigation Satellite System (GNSS) measurements of vertical and horizontal crustal motion are an important tool for improving GIA models, but they depend on an accurate terrestrial reference frame (TRF) so that the measurements are not biased or regionally distorted. GNSS measurements are also important for accurately measuring vertical land motions due to earthquakes (coseismic and postseismic) and local subsidence due

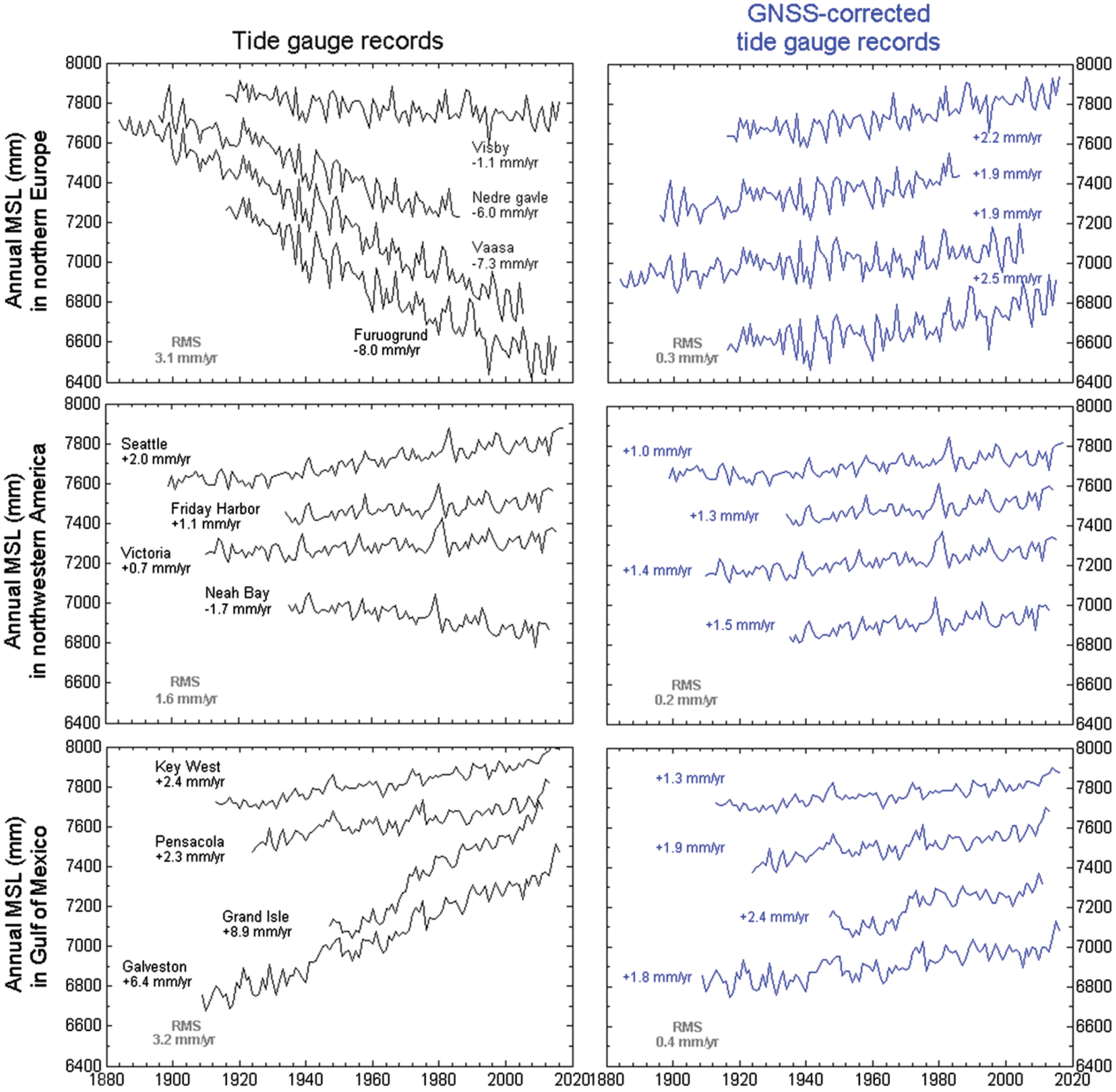


FIGURE 3.4 Relative sea-level rise at different sites measured by tide gauges. Left panels: uncorrected records. Right panels: records corrected for vertical land motions. SOURCE: Woodworth et al., 2019.

to hydrologic pumping, for example, so tide gauge measurements can be properly defined in the TRF.

SEA-LEVEL CHANGE

Sea level is measured by a constellation of altimeter satellites that enable near-global coverage. The height of the satellite above the ocean surface is converted to a sea-surface height (or sea level) above a reference surface determined from precise orbit determination. The estimated sea-surface height is then corrected for atmospheric (ionospheric and tropospheric) delays, biases between successive altimetry missions, and geophysical effects such as the sea state bias, solid Earth tides, and pole and ocean tides. With these corrections, satellite altimeter measurements have a point-to-point accuracy of a few centimeters. The Topography Experiment (TOPEX)/Poseidon and Jason-1, -2, and -3 missions have provided a continuous record of sea-level change over ±66° latitude with a 10-day repeat period. The precision of global mean sea level for each 10-day average is about 4–5 mm.

Measurements

The Decadal Survey (NASEM, 2018) called for determining global mean sea-level rise to within 0.5 mm/year over the course of a decade (Objective C-1a) and regional sea-level change to within 1.5–2.5 mm/yr over the course of a decade (Objectives C-1d and S-3a). For the latter objective, 1.5 mm/yr corresponds to a ~6,000 km^2 region and 2.5 mm/yr corresponds to a ~4,000 km^2 region. Achieving these objectives will require measurements of sea-surface height with a sampling of 7 km along-track, every 10 days, and a precision of 30 mm at 7 km and 1 mm/yr globally. This requires satellite radar altimeter measurements (including water vapor radiometer measurements) and precise orbit determination of the satellites relative to a well-defined terrestrial reference frame.

Observations of relative sea-level variations along the coast are essential for understanding the processes at work and for evaluating the impacts of sea-level rise on coastal environments and infrastructure. The world's coastal zones are severely undersampled by tide gauges and, until recently, were unsurveyed by conventional satellite altimeters within 15 km of the coast. Dedicated reprocessing of conventional nadir altimetry and use of innovative new observations from synthetic aperture radar technology (e.g., on Sentinel-3A/B) and wide swath altimetry would help fill some of these data gaps.

Tide gauge measurements provide one of the few records of sea-level change prior to the era of satellite altimetry. As such, they provide one of the only methods for placing the satellite record of sea-level change into a longer term context, although they can be influenced by vertical land motion. In addition, tide gauges are used to validate satellite altimetry and detect drifts in the satellite instruments (Mitchum, 2000). The error in the altimeter tide gauge validation is the leading error source for monitoring sea-level change with satellite altimetry. Thus, for both sea-level science and altimeter validation, it is important that the geodetic infrastructure include the means for monitoring vertical land motion at as many tide gauges as possible (Woodworth et al., 2017). The use of GNSS to validate altimetry measurements at tide gauge sites is described in Box 3.1.

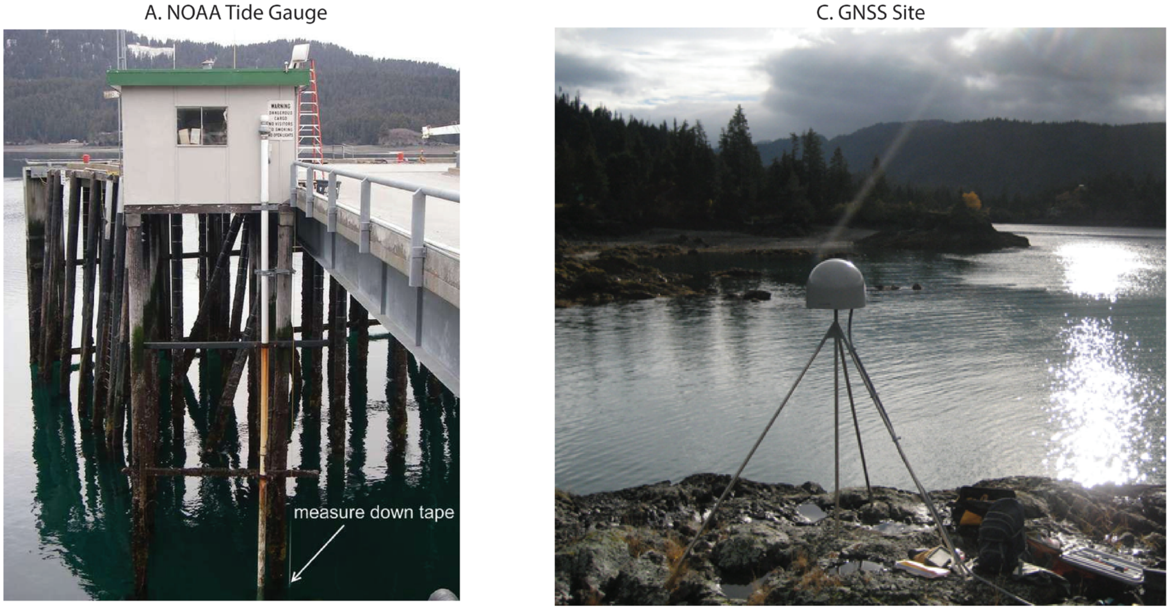
Geodetic Needs

An accurate TRF and precision orbit are fundamental science requirements for satellite altimetry applications, such as sea-level change (Blewitt et al., 2010). The orbit accuracy is directly linked to the accuracy and stability of the TRF in which the orbit is computed. The performance of the tracking systems (Satellite Laser Ranging [SLR], Doppler Orbitography and Radiopositioning Integrated by Satellite, and GNSS) in terms of network coverage and atmospheric propagation corrections, the accuracy of the tracking station positions versus time, and the accuracy of the reference frame origin (geocenter motion) and Earth orientation parameters are all important. The radial orbit accuracy for satellites such as Jason-3 now approaches 10 mm RMS. Errors in the TRF map into the orbit, and through the orbit directly to the altimeter-based, sea-level measurement. Errors in the Z component of the geocenter are the most problematic, because they map directly into the orbit. The X/Y geocenter errors, which are modulated by the Earth's rotation once per day relative to the satellite orbit, do not map directly into the orbit errors, and thus have minimal impact on the orbit. Orbit error remains the largest source of error in the altimetry system, although its amplitude has decreased over time due to improved Earth gravity models (from GRACE and Gravity field and steady-state Ocean Circulation Explorer observations). Despite this improvement, temporal changes in the gravity field, largely due to the melting ice sheets, can introduce biases into regional sea-level change measurement if not properly accounted for in the orbit determination process.

Satellite altimetry is potentially subject to instrument drifts that could masquerade as climate signals. For this reason, tide gauge measurements have been used to validate altimeter measurements (e.g., Mitchum, 2000). For estimates of the rate of sea-level rise from satellite altimetry, the error estimate derived from the tide gauge validation is driven by errors in the amount of vertical land motion at the tide gauge sites. Therefore, improved estimates of vertical land motion can reduce the error estimate for the rate of sea-level rise from satellite altimetry.

BOX 3.1
Measuring Sea Level in the International Terrestrial Reference Frame (ITRF) Using GNSS

Globally distributed tide gauges are needed to calibrate satellite altimetry measurements of the ocean. Because tide gauges only measure water level with respect to the tide gauge's anchor point (usually a pier), all tide gauge records are inherently biased due to any vertical motion of the pier (see Figure 3.5A). This vertical land motion can be caused by many factors, including local subsidence, glacial isostatic adjustment, and earthquakes. Figure 3.5B shows vertical land motion at a GNSS site in Kachemak Bay, Alaska. The uplift rate at this site is almost 15 mm/year. If uncorrected, this land motion would bias the National Oceanic and Atmospheric Administration (NOAA) tide gauge record and hence the global sea level record. Ideally GNSS instruments would be installed at all tide gauges being used for altimetry validation (Woodworth et al., 2017). Another solution is to use a GNSS instrument (see Figure 3.5C) to simultaneously measure vertical land motion and the water level. This technique uses the interference between the direct and water-reflected GNSS signals to back out the water level with respect to the GNSS antenna's phase center. Combined with the GNSS vertical coordinates (see Figure 3.5B), the technique can produce a water-level measurement defined in the ITRF (see Figure 3.5D). Studies have shown that GNSS-based water level results are consistent with existing tide gauge instrumentation and produce unbiased results that can be used for both short- and long-term ocean studies (Larson et al., 2013, 2017). Similar principles can be used to measure snow accumulation on ice sheets (Larson et al., 2015).


A. NOAA Tide Gauge

C. GNSS Site

B. GNSS Vertical Coordinates

D. Tides measured by NOAA and GPS Reflections

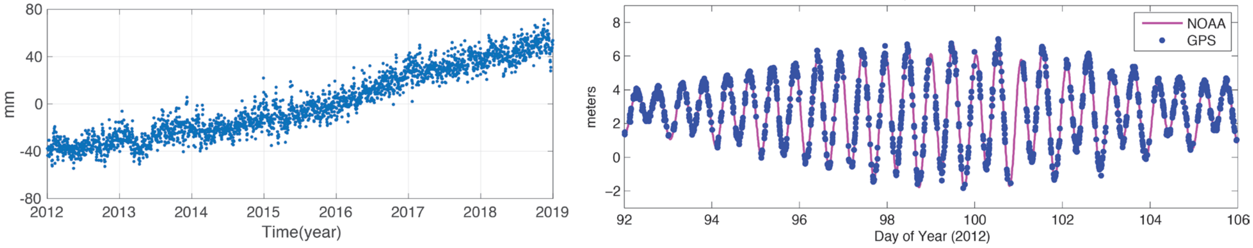


FIGURE 3.5 Tide gauge and GNSS measurements in Kachemak Bay, Alaska. A. NOAA tide gauge. SOURCE: https://tidesandcurrents.noaa.gov/stationphotos.html?id=9455500. B. GNSS vertical coordinates. SOURCE: Data from the Nevada Geodetic Laboratory, http://geodesy.unr.edu/NGLStationPages/stations/PBAY.sta. C. GNSS antenna. SOURCE: Max Kaufman, University of Alaska, Fairbanks. D. Comparison of GNSS reflections and NOAA water level measurements. SOURCE: Republished with permission of Annual Reviews Inc., from Larson, 2019; permission conveyed through Copyright Clearance Center, Inc.

The geodetic needs associated with obtaining satellite measurements with an accuracy of 20 mm (after correction for tides and wave effects) and long-term measurement drift errors of less than 0.5 mm/yr over a decade are as follows:

- The tracking systems used for precision orbit determination need to support a radial orbit accuracy of at least 20 mm and tracking station position accuracy of 1 mm in the TRF.
- TRF accuracy of less than 1 mm at all times (i.e., the TRF must be maintained). It should always be possible to relate the reference frame in one year to the reference frame in another year so that sea-level changes from year to year can be accurately computed.
- Drifts in the TRF origin to an accuracy of less than 0.1 mm/yr.
- The TRF should be free of deformations that might cause errors in regional patterns of sea-level change.
- Vertical land motion accuracy at tide gauges of less than 0.5 mm/yr to minimize errors in validating satellite altimeter observations of sea-surface height.

THERMAL EXPANSION—OCEAN HEAT STORAGE

More than 90 percent of the heat trapped by greenhouse gas emissions since the Industrial Revolution is stored in the ocean (Cheng et al., 2017). Determining the ocean heat storage change is important for assessing the current state of climate and how it may change in the future. The difference between altimeter measurements of sea-level change and satellite gravity measurements of changes in ocean mass (due to land-ocean water/ice exchanges) provides an estimate of the global mean steric sea level associated with thermal expansion, from which the full-depth ocean heat content can be estimated (Levitus et al., 2005; Melet and Meyssignac, 2015).

Thermosteric sea level and ocean heat storage can also be estimated from the Argo array of profiling floats. The present array measures heat storage only in the upper 2,000 m of the global oceans, creating uncertainty in estimates of the total ocean heat storage (Purkey and Johnson, 2010; Johnson et al., 2015). Expanding the Argo array to sample the deep ocean would improve understanding of total ocean heat storage and the heat exchange between the upper and deeper ocean, and improve forecasts of oceanic heat uptake and expansion. It would also improve validation of altimetry and GRACE systems.

Measurements

Measurements of the change in the global oceanic heat uptake are needed to within 0.1 W/m^2 over the course of a decade (Objective C1-b). Achieving this objective will require measurements of sea-surface height, ocean mass distribution, and in situ measurements of temperature and salinity (Argo floats that employ satellite links for data transmission and data localization). Altimetry measurements need to be acquired with a sampling of 7 km along-track, every 10 days, precision of 30 mm at 7 km 1 mm/yr globally. These requirements can be met with a radar altimeter, a microwave radiometer, and precision orbit determination of the satellite carrying these instruments.

For ocean mass distribution, monthly gravity measurements with 300 km × 300 km spatial resolution, a stability of 15 mm water equivalent at 300 km × 300 km, and precision in ocean mass change of 0.1 mm/decade. Globally averaged ocean mass from satellite gravity measurements is very sensitive to errors in the GIA model employed (Tamisiea, 2011). Ocean temperature and salinity measurements are needed for every 3 degree × 3 degree grid, every 10 days, with an accuracy of 0.01 degrees and 0.01 practical salinity units. These measurement requirements can be met by maintaining the core Argo float program and developing the deep Argo float program.

Geodetic Needs

Same as "Sea-Level Change."

ICE SHEETS AND GLACIER MASS CHANGES

Glaciers and ice sheets represent the largest uncertainty in sea-level projections and will soon dominate the pattern of regional sea-level change. Three main approaches for measuring ice sheet mass changes are based on satellite observations that depend on the geodetic infrastructure. First, time series of time-variable gravity measured by GRACE have proven invaluable for measuring the total changes in the mass of ice sheets (see Figure 3.6), glaciers, and ice caps at coarse spatial

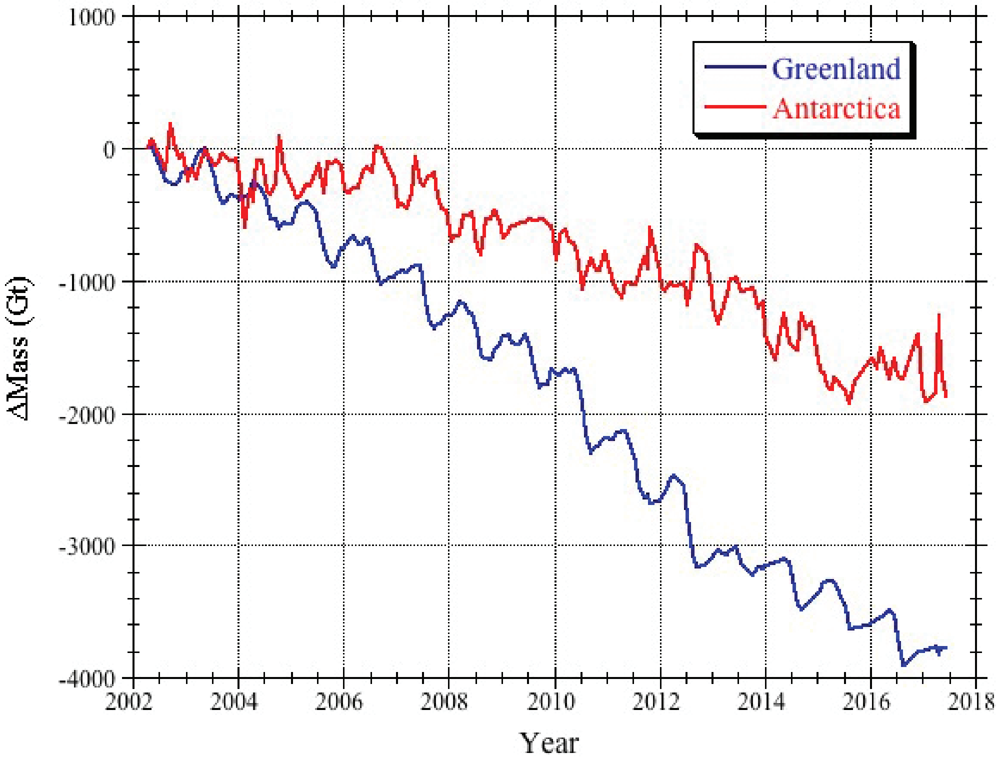


FIGURE 3.6 Change in mass of the Greenland and Antarctica ice sheets over time, measured from GRACE. SOURCE: Created using data from sealevel.nasa.gov.

resolution. Limitations of GRACE include its short temporal record and the need to correct the measurements for land hydrology and GIA to isolate the ice mass change signal. In addition, GRACE cannot measure the mass change signal associated with spherical harmonic degree 1 (the geocenter motion), and some degree 2 and 3 terms have large errors. These must be estimated from other techniques, such as SLR.

The second approach involves measurements of ice motion and grounding line positions from Interferometric Synthetic Aperture Radar (InSAR). Ice motion measurements are essential for documenting changes in ice dynamics and for understanding processes, such as how glaciers react to climate forcing, which parts of the ice sheets are changing and how rapidly, and what fraction of the mass loss is controlled by glacier speed. Precise geocoding and knowledge of satellite orbits, which are essential for making quality observations, require a precise geodetic framework, but does not require the same accuracy as other techniques.

The third approach involves estimating ice mass changes from radar and laser altimetry measurements of elevation changes. The instrument requirements are similar to those for ocean applications and so are the constraints placed on the quality of the geodetic infrastructure. The laser and radar altimeters rely on precise determination of the satellite orbits (20 mm radially) to maintain a high precision determination of the height of the snow or ice surface. The measurements are sensitive to surface slope, and so multiple beams and precise georeferencing of the laser pointing or interferometric processing of the radar altimeter data are required in coastal areas with steep slopes. The results must be corrected for the GIA. Uncertainties remain in the interpretability of the mass change signal since the density of the ice/snow must be known to determine mass changes from elevation changes.

Measurements

Objective C-1c is to determine the changes in total ice-sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over all of the ice sheets, continuously, for decades to come. The relevant measurements are ice sheet mass, velocity, surface and bed elevation, and thickness, as well as ice shelf (floating land ice) thickness and cavity shapes.

Determining ice sheet mass balance requires monthly gravity measurements at the basin scale and a precision of 10 mm water equivalent or better on spatial scales of a few hundred km. These measurements are already provided by GRACE and will be improved and extended with GRACE-FO and with supplemental geodetic measurements for GIA corrections.

Ice sheet velocity needs to be measured with weekly to daily samples every 100 m pole to pole, a precision of 1 m/yr in fast flow areas and 0.1 m/yr in the interior. The necessary precision can be achieved with InSAR for fast flow and interior regions and with high-resolution optical sensors for fast flow areas only. The same measurements should provide information on grounding line position with a sampling of 100 m pole to pole, and a vertical motion precision of 5 mm, which can be achieved with InSAR.

Measurements of ice sheet elevation are needed with weekly to daily sampling, vertical resolution of 0.1–0.2 m, along-track resolution of 100 m, and across-track resolution better than 1 km. These requirements can be met with a multi-beam laser altimeter. At present, Ice, Cloud, and land Elevation Satellite-2 provides better than 0.1 m vertical resolution, 70 m along-track resolution, and 3 km across-track resolution (Kwok et al., 2019).

Measurements of ice sheet thickness and ice shelf thickness are needed with a vertical precision of 10 m, horizontal spacing of 100 m pole to pole, and yearly sampling. These requirements can be met with sub-orbital radar sounders, laser altimetry (ice shelf only), high resolution optical sensors with stereo capability, and algorithms (mass conservation) that require information on ice velocity, surface velocity, and changes in surface height to interpolate in between radar sounding tracks on land ice.

Geodetic Needs

The GRACE mass change measurements strongly depend on the geodetic infrastructure. The determination of the geocenter is directly linked to the realization of the TRF origin. At present, degree-one spherical harmonic contributions (geocenter motion, due to the motion of the Earth's center of mass with respect to the TRF) are calculated using GRACE-based gravity field variations and model-based assumptions on water mass redistribution in the global ocean (Swenson et al., 2008). However, geodetic techniques used to realize the TRF, particularly SLR (GNSS is also showing promise in this area), can be used to determine the geocenter motion independently. Given that the geocenter motion is one of the largest sources of uncertainty in GRACE-based surface mass change estimates (e.g., Blazquez et al., 2018), it is important to maintain the geodetic infrastructure to improve these parameters (also involved in the orbit precision; see above).

The geodetic requirements for ice sheet altimetry are the same as those discussed in "Sea-Level Change." For interferometry, the tracking systems used for precision orbit determination should support a three-dimensional orbit precision of less than 0.1 m, and the tracking station positions should be known to 1 mm in the TRF. In addition, the TRF should be known to <1 mm at all times (i.e., maintain the TRF). The geodetic infrastructure should also support determination of ionosphere and water vapor delays so that InSAR measurements can be corrected for atmospheric effects.

LAND WATER HYDROLOGY

Water on land is stored in different reservoirs, including rivers, lakes, wetlands, upper soil, and aquifers. Because of water mass conservation, changes in terrestrial water storage have an impact on the global mean sea level, but mainly at interannual frequencies. These changes have two main causes: (1) natural climate variability, in particular El Niño–Southern Oscillation events, and (2) human activities, such as dam construction, groundwater extraction, deforestation, and wetland conversion. GRACE observations of net land water storage are available since 2002 (Llovel et al., 2010; Reager et al., 2016; Scanlon et al., 2018). However, uncertainties are relatively high due to the coarse resolution of GRACE (~300 km) and the associated leakage of unrelated signals (e.g., nearby glaciers). The land water contribution to sea-level change can also be estimated using global hydrological models, but these models are also uncertain due to errors in the meteorological forcing and imperfect representation of human activities. Improvement is expected from assimilating GRACE data into the models (Döll et al., 2017). As with the other contributions based on GRACE, GIA and geocenter motion issues are central and rely on a precise TRF.

In the near future, wide swath interferometric altimeters such as Surface Water Ocean Topography will provide novel constraints on lake levels, river discharge, and temporal changes in water storage. In addition, InSAR will observe land water withdrawal (subsidence), a major hazard caused by human activities, landslides, volcanoes, and earthquakes. These interferometric techniques impose significant requirements on the geodetic infrastructure.

Measurements and Geodetic Needs

Same as "Ice Sheets and Glacier Mass Changes."

VERTICAL LAND MOTION

Measuring vertical land motions along the coasts using GNSS and InSAR is of primary importance. Land motions have different origins, including tectonics, which may uplift coastal areas and so reduce relative sea-level rise (e.g., Oregon and Washington; NRC, 2012), or sediment compaction or extraction of groundwater or hydrocarbons, which may cause significant ground subsidence, and so amplify climate-related sea-level rise. GIA also causes vertical land movements, particularly in high-latitude regions. GNSS near tide gauges can be used to estimate vertical land motions, but less than 14 percent of Global Sea Level Observing System tide gauge stations are equipped with a permanent GNSS station (e.g., Ponte et al., 2019). Several studies have shown the benefit of using InSAR in different coastal environments (e.g., Brooks et al., 2007). Measuring vertical land motions at the coast strongly relies on the geodetic infrastructure.

Measurements

Objective S-3b calls for measurements of vertical land motion along the coast with an uncertainty of <1 mm/yr. In addition, Objective C-1c specifies measurements of vertical land motion within 100 m of the coast around the globe, with monthly temporal resolution, and an accuracy of 1 mm/yr.

Geodetic Needs

Ideally, vertical land motion near tide gauges would be measured using GNSS receivers co-located with the tide gauges. In addition, GNSS reflection techniques should be investigated as an alternative means for measuring sea level and vertical crustal motion simultaneously. GNSS and InSAR are needed to map vertical crustal motion along the coasts.

SUMMARY

Satellite altimetry and satellite gravity are the main tools used by sea-level scientists that depend most strongly on the geodetic infrastructure. These measurements require a TRF that is precisely defined as a function of time. The TRF needs to have a precisely defined origin and be free of drifts and deformations, lest they create errors in the satellite measurements that could be misinterpreted as climate signals. Deformation of the TRF occurs when a fiducial site (or a regional group of fiducial sites) behaves in a nonlinear manner (caused by, for example, a melting ice sheet, earthquakes, or other nonlinear phenomena) that is not represented by the linear TRF models currently in use. This will become particularly challenging as the Earth's shape and gravity field change due to climate change. Of particular concern is the movement of the Earth's center of mass relative to its center of figure as the ice sheets melt, which could amount to several cm over a century. In addition, geodetic sites near areas of ice mass loss may show anomalous motion and should be treated carefully if used to define the reference frame. It is also important to always be able to reconstruct the TRF back in time, so that sea-level measurements made a century from now can be compared to sea-level measurements made today and to sea-level measurements made 25 years ago. This is generally referred to as maintaining the TRF.

Both satellite altimetry and satellite gravity require precision orbit determination. Onboard GNSS receivers can provide sufficient accuracy, but SLR is useful as a backup technique in case of failure of the GNSS receiver as well as for validating the orbit accuracy. The positions of GNSS and SLR tracking stations must be known precisely in the TRF.

The ITRF may not have sufficient accuracy for sea-level science in the future. As the Earth responds to climate change, the motion of the fiducial sites that comprise the TRF may depart significantly from the linear behavior currently assumed in the TRF definition. In addition, the geocenter will also respond to

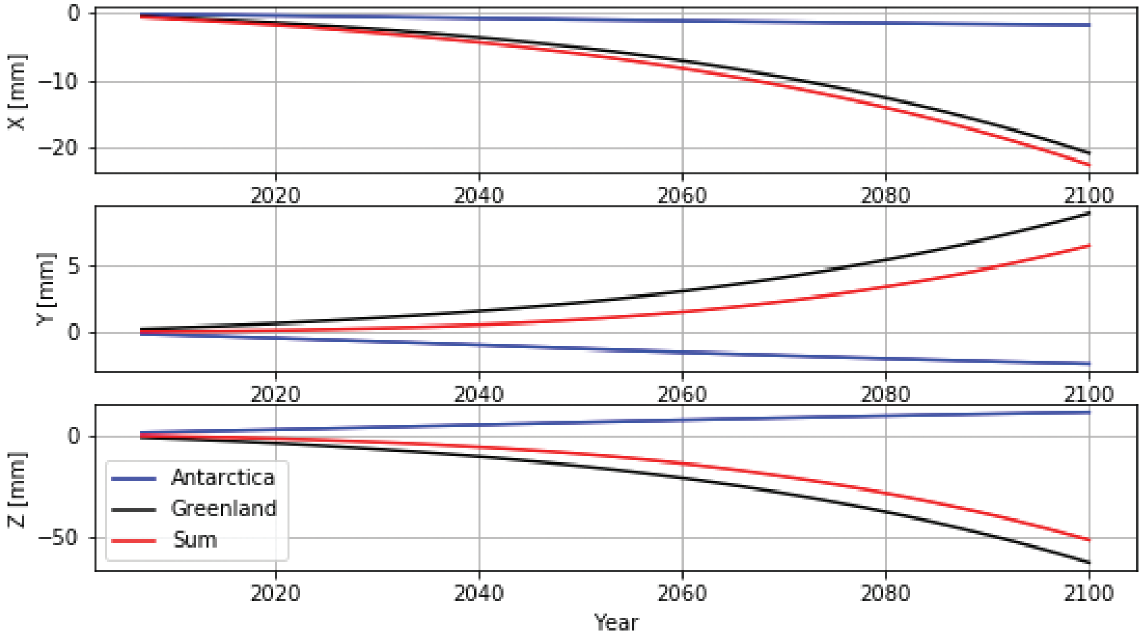


FIGURE 3.7 Motion of the geocenter due to projected melting of Greenland and Antarctica. SOURCE: Modified from Adhikari et al., 2015.

climate change, especially the melting of the ice sheets (see Figure 3.7). Research is needed on how to maintain the accuracy of the TRF in an era when the Earth is experiencing profound changes. This could include, for example, site characterization and modeling nonlinear motions of the TRF or locations of fiducial sites. It has also been proposed that a space-based collocation experiment could provide further improvements.

One area where the geodetic infrastructure could be improved is the monitoring of tide gauge positions using GNSS. Reducing the errors in vertical land motion for the tide gauge calibration of satellite altimeter measurements could significantly improve the error estimates for sea-level change from satellite altimetry. The following summarizes the needs for maintaining or enhancing the geodetic infrastructure, and related improvements to enhance scientific returns.

Maintenance of the Geodetic Infrastructure

- Maintain and enhance the geodetic infrastructure to achieve the TRF requirements as described below.
- Maintain the tide gauge record to validate the satellite altimetry data in order to achieve 0.1 mm/yr in the altimeter measurements averaged over a decade.
- The orbit determination requirements for altimetric satellites are 10–20 mm radial position. Three-dimensional orbit accuracy of better than 0.1 m is required for ice-sheet flow-rate measurements using InSAR.
- Maintain the current accuracy of the low degree and order geopotential field.
- Maintain and enhance the ancillary models and corrections for the altimetric satellites, including time-variable gravity, time-variable surface deformation, and atmospheric and ionospheric propagation models.

Enhancements to the Geodetic Infrastructure

- The sea-level science questions require a TRF accuracy of 1 mm and drift in the origin of the TRF of less than 0.1 mm/yr (or less than 0.02 ppb/yr in scale rate equivalent). Meeting these requirements would allow global sea-level rise to be determined to an accuracy of better than 0.5 mm/yr over the course of a decade and regional sea-level rise to within 1.5–2.5 mm/yr over the course of a decade. The definition of the Earth's center of mass, especially in the Z-component, is especially dependent on successful tracking of SLR in the southern hemisphere.
- The signals in the motion of the Earth center of mass are expected to vary by as much as 50 mm in the next 100 years. There must be commensurate stability of

the reference points for metrology at the fundamental sites, such as the invariant points of SLR telescopes or Very Long Baseline Interferometry dishes, or the GNSS monumentation. This may require studies on the stability and longevity of monumentation and drifts or stability of the tracking equipment.

- Install GNSS stations at tide gauges to achieve the absolute vertical land motion requirement of better than 0.5 mm/yr to minimize errors in validating satellite altimeter observations of sea-surface height. Encourage use of GNSS reflectometry methods to expand the number of worldwide tide gauges defined in the ITRF.

Related Improvements to the Geodetic Infrastructure to Enhance Scientific Returns

- Enhance the shallow water tide models to better connect the offshore altimetric heights with the coastal tide gauges.
- Develop software tools and automated handling for processing and integrating the diverse geodetic data sets used to investigate sea level.

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4

Terrestrial Water Cycle

Observing and understanding the water cycle and changes in the water cycle are essential to protect this life-enabling resource both now and in the future. In the past decades, high-precision geodesy has become an important source of information for hydrologists, climate scientists, and water managers. This chapter examines the components of the geodetic infrastructure that are required to meet scientific needs related to the water cycle, as laid out in the Decadal Survey (NASEM, 2018). The Decadal Survey science questions used to focus this discussion are:

H-2. How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally and what are the short- and long-term consequences?

H-4. How does the water cycle interact with other Earth System processes to change the predictability and impacts of hazardous events and hazard chains (e.g., floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?

S-6. How much water is traveling deep underground and how does it affect geological processes and water supplies?

The geodetic infrastructure needs associated with these questions appear in the Water Cycle Science and Applications Traceability Matrix (see Appendix A, Table A.2). Some water cycle components such as soil moisture and snow depth/water equivalent are discussed in Chapter 7 (Ecosystems).

SCIENCE OVERVIEW

The water cycle interacts with all near-surface Earth system processes. Surface topography and surface and subsurface structure largely control the location and movement of water. Surface topography is dynamic—resulting from surface loading and unloading, land subsidence, erosion and deposition, sea-level rise, tectonics, and volcanoes—and thus requires repeated geodetic measurements to quantify that change in three dimensions. The location, quantity, and flow direction of surface water is often determined using knowledge of channel and floodplain morphology or lake bathymetry and gradients, all of which rely on geodetic observations in three dimensions.

Subsurface aquifer-system structure and groundwater levels are generally mapped relative to the land surface, and so require an accurate understanding of land-surface elevations and changes in elevations through time. To understand flood risk, accurate geodetic data describing the land surface is critical for forecasting flood location, frequency, depth, and duration. Land subsidence induced by dropping groundwater levels permanently reduces the storage capacity of aquifer systems, damages near-surface or surface infrastructure, shifts migration of river courses and wetlands, and alters surface water. Subsidence also can exacerbate flood frequency, depth, and duration, as well as alter (or reverse) gravity-driven flow or drainage of storm water or sewage. Land subsidence alone or exacerbated by sea-level rise causes coastal retreat, including marshes and wetlands, which serve as protective barriers against wave action or storm surge.

Repeated geodetic observations of dynamic land surfaces enable these hazardous areas to be mapped.

Some of the recent and novel applications of geodesy to hydrologic science are highlighted below. These include (1) elastic loading caused by changes in terrestrial water storage; (2) aquifer-system compaction and land subsidence caused by groundwater overdraft; (3) surface-water monitoring by satellite altimetry to support science, water management, and flood forecasting; and (4) water cycle monitoring by satellite gravimetry to track changes in total water storage. These new applications require high accuracy in the vertical and gravity components of deformation that rely on maintaining, and in some cases enhancing, the geodetic infrastructure.

ELASTIC LOADING

The hydrological cycle and associated water availability vary both on longer time scales according to wet and drought periods, and on shorter time scales from intense precipitation events (Anderson et al., 2005). Increases and decreases of surface and near-surface water mass cause elastic deformation, inducing vertical and horizontal displacements (Farrell, 1972). In the western United States, seasonal changes in crustal loading are linked to precipitation changes. Increased precipitation in the cool seasons increases terrestrial water storage (surface water, snowpack, soil moisture, and groundwater) and decreased precipitation in the warm seasons decreases the terrestrial water storage. Precipitation and surface-water levels are well-sampled in the western United States, but snowpack, soil moisture, and groundwater are monitored at a small number of locations. For example, the U.S. Climate Reference Network[1] has only seven soil moisture stations in California. The number of Snow Telemetry[2] stations (snow pillows for measuring snow water equivalent) in the Sierra Nevada is limited, and so repeated, labor-intensive measurements at snow courses are required.

Measurements

The sensitivity of methods that can directly monitor changes in terrestrial water vary at different temporal and spatial scales. Gravimeters can detect highly local (a few hundred meters) mass changes, but they are not deployed in sufficient numbers to be useful for water cycle research (Van Camp et al., 2014). The Gravity Recovery Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) can detect changing mass distributions over the entire Earth, but the spatial resolution is several hundred kilometers and the measurements are made monthly (Frappart et al., 2014; Thomas et al., 2014). The load-induced signals measured with the Global Navigation Satellite System (GNSS) or Interferometric Synthetic Aperture Radar (InSAR) reflect both local and regional changes, which can be inverted to estimate mass loss at basin to regional scales (Argus et al., 2014; Borsa et al., 2014; Chew and Small, 2014). Combining GNSS loading estimates and GRACE mass distribution estimates is a promising approach for monitoring terrestrial water storage at higher temporal and spatial scales (Milliner et al., 2018).

The availability of large and dense GNSS networks and improved GNSS analysis software has enabled new studies of hydrologic signals in GNSS time series, particularly in the western United States, where high-quality receivers, antennas, and monuments were installed at the 1,100 sites of the Plate Boundary Observatory. Argus et al. (2014) used GNSS data from the stations in California and Nevada and inverted the seasonal vertical coordinates to infer changes in equivalent water thickness. Their map of seasonal water mass (see Figure 4.1) has a spatial resolution of ~50 km, four times higher than that provided by GRACE. Borsa et al. (2014) used GNSS data from Plate Boundary Observatory stations throughout the western United States (see Figure 4.2). Although details of the analysis differ from Argus et al. (2014), the same general principles for elastic loading were used to estimate terrestrial water changes, in this case over several years. Their maps show the response of the solid Earth, as observed by almost 1,000 GNSS receivers, to a sustained drought in the western United States. The results indicate uplift caused by decreased loading and correlate with measured decreases in precipitation and streamflow. Water maps, such as those developed by

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[1] See https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/us-climate-reference-network-uscrn.

[2] See https://www.wcc.nrcs.usda.gov/snow.

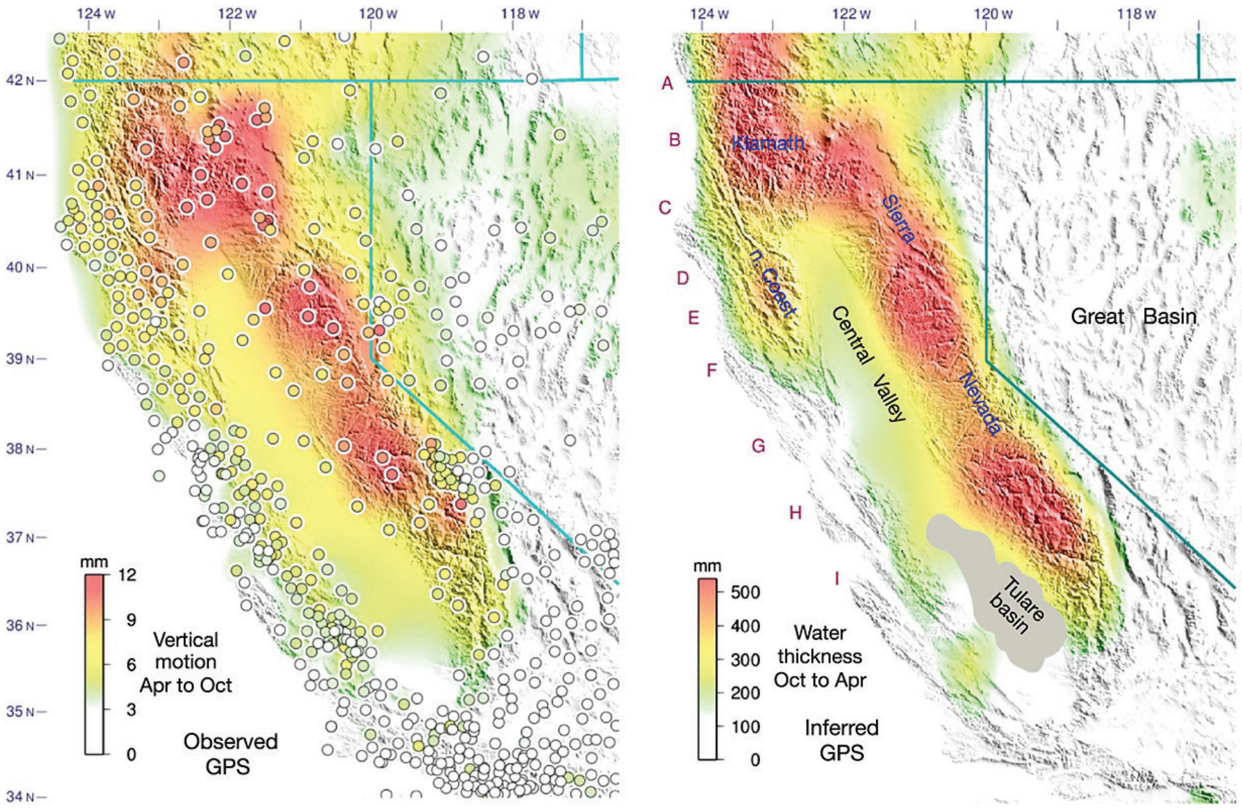

FIGURE 4.1 Vertical land displacement observed with the Global Positioning System (GPS) in the spring and summer (left) and the inferred change in total water storage, which increases in the fall and winter (right). Warm colors indicate higher amounts of uplift and greater amounts of water storage. Circles (left) indicate GPS sites. SOURCE: Argus et al., 2014.

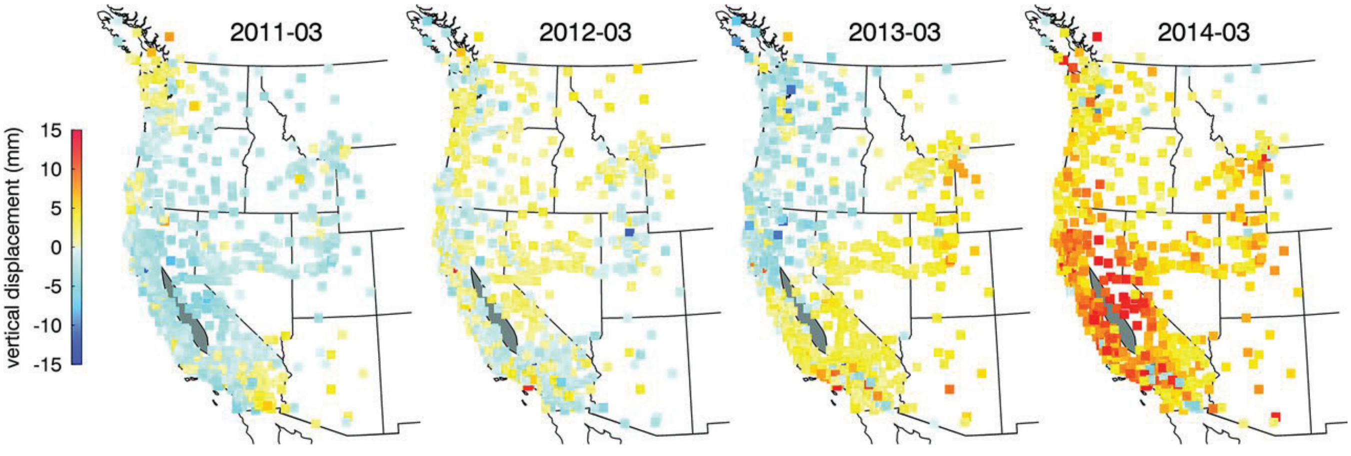

FIGURE 4.2 Vertical land displacements observed by GPS in the western United States from March 2011 through March 2014. The shift from land subsidence (blue) to land uplift (yellow and red) shows the effects of severe drought over the 4-year period. Stations in the gray region (Central Valley of California) were excluded because groundwater-pumping induced land subsidence (see Box 4.2). SOURCE: Borsa et al., 2014. Reprinted with permission from AAAS.

Borsa et al. (2014) and Argus et al. (2014), can be used for climate studies and they also provide independent constraints on annual snowpack estimates needed by water managers in California and Nevada.

Although hydrologic studies using GNSS data have focused almost entirely on seasonal and long-term land-surface deformation, studies of deformation on much shorter time periods are emerging. An example is heavy precipitation loading associated with Hurricane Harvey (see Box 4.1).

Geodetic Needs

In the western United States, the existing network of continuous GNSS stations and the underlying terrestrial reference frame (TRF) measures vertical crustal motion at sufficient precision (3–5 mm), sampling frequency (daily), and sampling density (40 km) to estimate interannual changes in water loads (Argus et al., 2014). The exceptional stability of the GNSS monumentation at Plate Boundary Observatory sites (Langbein et al., 1995; Herring et al., 2016) means that the GNSS network can be used to monitor the long-term effects of drought and regional climate change in this area (Borsa et al., 2014; Chew and Small, 2014). However, its value as a hydrological network assumes that this GNSS network will be maintained in the future. On the order of a few hundred of these stable, long-duration GNSS stations are now considered part of the geodetic infrastructure. At the time of this writing, the instruments are nearly 15 years old and need to be replaced or upgraded to track modern GNSS signals. Surface displacement observations from GNSS networks in other parts of the world could make an enormous contribution to the global hydrological observing network, which supports understanding current and future hydrological changes and provides clear social and economic benefits. However, a sustained commitment is required to install and operate these international GNSS networks over decadal time scales.

GNSS loading applications for hydrology require center of mass velocity and scale rate stability of 0.2 mm/yr. This requirement is equivalent to 10 mm/yr of water. In addition, a stable TRF over seasonal time scales is needed for hydrological studies. More study is needed to assure that this requirement is being met.

AQUIFER-SYSTEM COMPACTION (LAND SUBSIDENCE)

Land subsidence is inextricably linked to the development of groundwater. The compaction of aquifer systems that are partly composed of unconsolidated to semi-consolidated silt and clay and have been heavily pumped is the primary cause of subsidence in the United States (Galloway et al., 1999). Aquifer-system compaction has lowered the elevation of nearly 125,000 km^2 of land and waterways, an area larger than Pennsylvania (Sneed, 2018; see Figure 4.4).

Groundwater-level changes cause aquifer systems to deform elastically (reversibly) or inelastically (permanently) as pore spaces expand or contract. Groundwater levels that vary with the seasons can cause a few centimeters of elastic land subsidence and uplift. However, sustained groundwater declines can result in a one-time discharge of water from the pore spaces of fine-grained sediments and a permanent reduction in the pore volume. The result is a decrease in the volume of the aquifer system, which is manifested as subsidence at the land surface (Galloway et al., 1999). An example of aquifer compaction in the Central Valley of California appears in Box 4.2.

Subsidence from aquifer compaction damages engineered structures, such as dams, roads, bridges, and pipelines. It can also adversely affect natural systems, for example by altering stream gradients or causing wetlands to migrate toward subsiding areas. Finally, subsidence in coastal basins can amplify relative sea-level rise (see Chapter 3).

Measurements

Geodetic surveying (spirit leveling and campaign GNSS), continuous GNSS, InSAR, and altimetry are needed to determine the location and extent of land subsidence. The ground measurements capture temporal (monthly, seasonal, or interannual) variations in subsidence rates at specific locations, and the InSAR data delineate the spatial extent of subsidence. Together, these techniques yield the spatially and temporally dense data needed to understand the causes of the observed spatial subsidence patterns and to improve subsidence models.

Repeated geodetic measurements are needed to track the changing topography to operate surface

BOX 4.1
Heavy Precipitation Loading Detected Using GNSS: Hurricane Harvey

A category four cyclone, Hurricane Harvey, deposited almost 100 km^3 of water along the Gulf Coast over several days (Milliner et al., 2018). Analysis of the daily GNSS positions found that both the vertical and horizontal components (maximum of 21 mm and 4 mm, respectively) from the Gulf Coast sensed the initial water load, followed by a gradual uplift in the following month (see Figure 4.3). Further modeling made it possible to distinguish whether the water was removed as runoff or through evapotranspiration. Coupled with improved floodplain models, the Hurricane Harvey GNSS study demonstrates the power of continuous GNSS networks to improve flood forecasting by quantifying the spatial extent and evolution (drainage) of terrestrial water storage associated with extreme precipitation events.

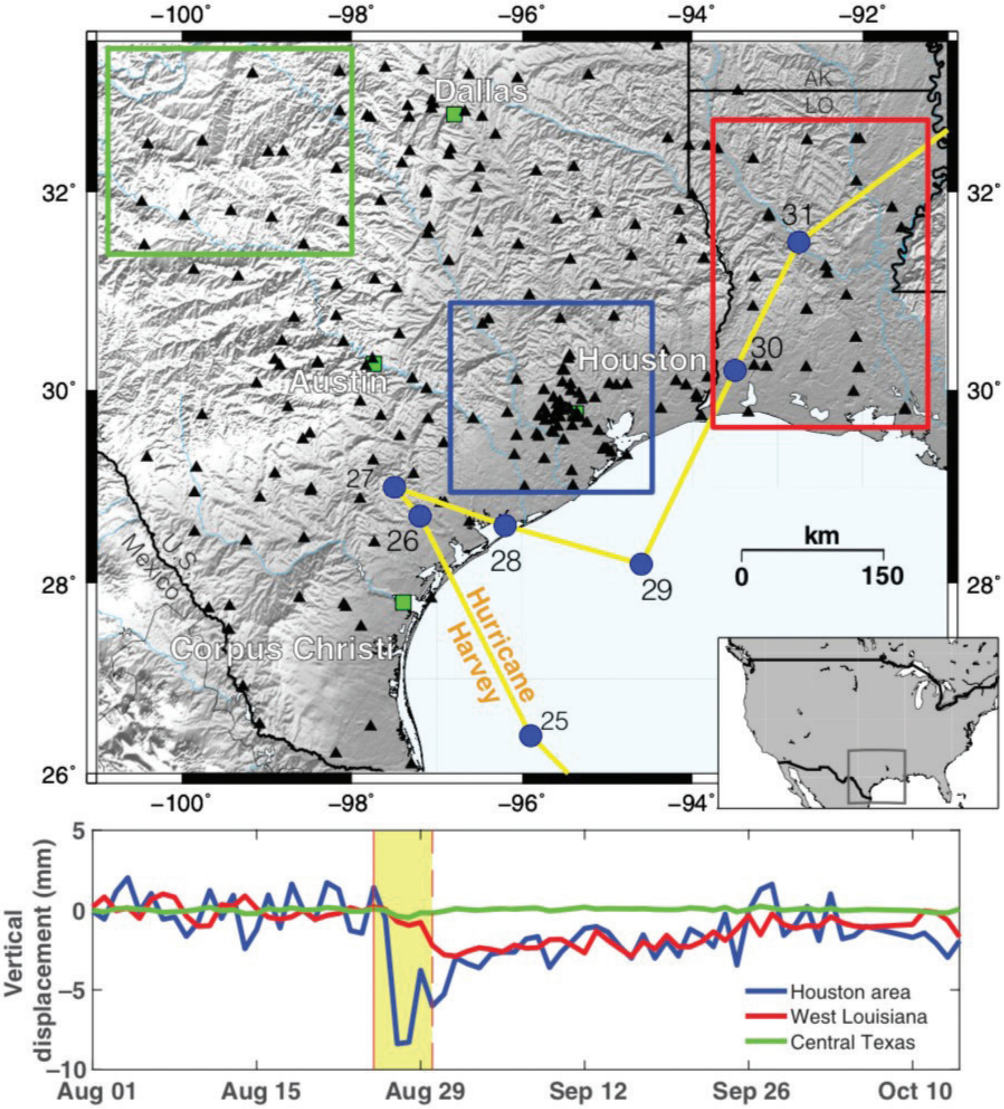

FIGURE 4.3 (Top) The path of Hurricane Harvey (yellow line) and its eye at noon (UTC), August 25–31, 2017 (blue dots), as it migrated across Texas and Louisiana. Black triangles are GPS stations. (Bottom) GPS motions from time series in Houston (blue), western Louisiana (red), and central Texas (green). The yellow shaded region marks the hurricane landings, with the first landing causing 8 mm of subsidence in Houston, followed by a 5-week period of uplift, and the second landing in Louisiana having smaller loading effects. SOURCE: Reprinted with permission of AAAS from Milliner et al., 2018. © The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC) http://creativecommons.org/licenses/by-nc/4.0.

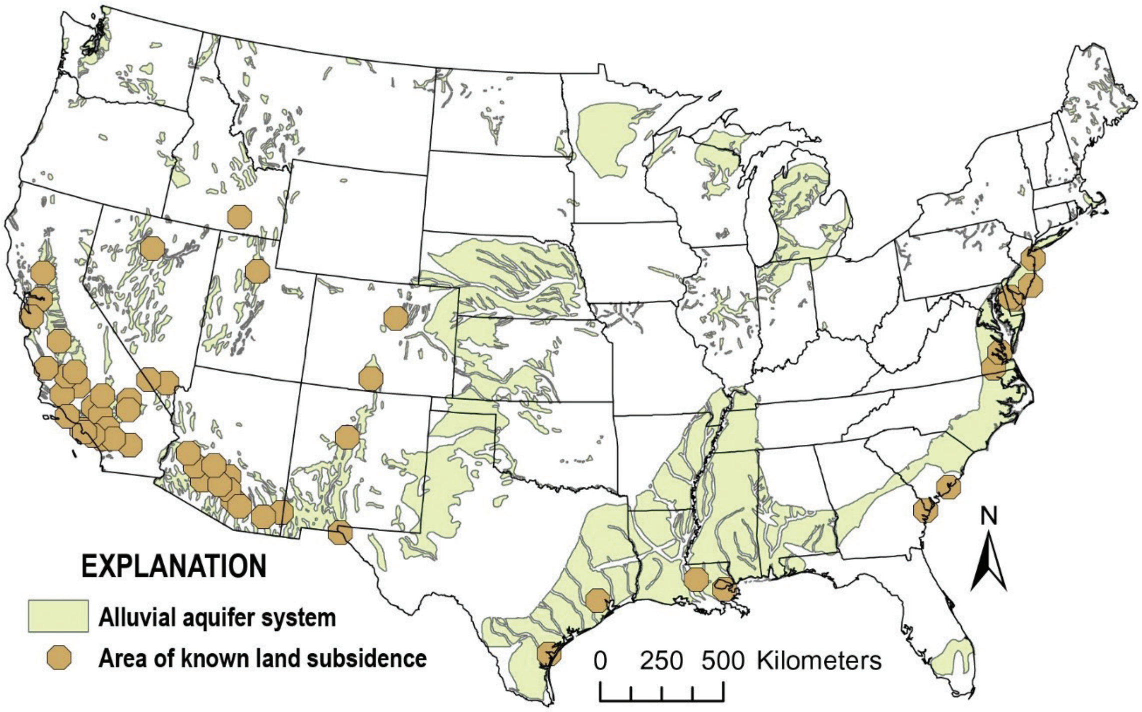

FIGURE 4.4 Areas where subsurface fluid withdrawal has caused land subsidence (brown) in the conterminous United States. SOURCES: Sneed, 2018, as modified from Clawges and Price, 1999, and Galloway et al., 1999.

water conveyance infrastructure, and to evaluate flood risk and stream (ecosystem) health. InSAR analyses yield spatially detailed subsidence maps that in some instances can reveal subsurface geologic structure controlling groundwater-flow fluxes (Sneed et al., 2014). InSAR is also used as a reconnaissance tool, guiding the spatial design of ground-based networks and the temporal frequency of surveying those networks (Sneed et al., 2014). Altimetry analyses provide strips of subsidence maps along tracks (Hwang et al., 2016).

Geodetic Needs

Weekly InSAR and daily GNSS verticals in the current program of record are precise enough (~5 mm) for most current water science and management applications. The program of record specifies 40 km spacing of GNSS stations, with increased spatial deployment in watersheds. Although InSAR has superior spatial sampling compared with GNSS, decorrelation, atmospheric, and ionospheric errors continue to limit its use in many areas. For this reason, a combined InSAR-GNSS product would be preferred for many land subsidence studies. Deployment of GNSS instruments augmented with nearby corner reflectors or radar transponders to amplify the synthetic aperture radar (SAR) signal, particularly in landscapes with high-frequency dynamics (agriculture), is also a possibility. While this strategy could improve InSAR retrievals, such deployments should be carefully assessed for their negative impact on nearby GNSS infrastructure.

As was discussed for loading studies, continuously operating GNSS sites are more valuable for water cycle studies if they are located in watersheds and in geographic regions that lack traditional hydrological measurement networks (e.g., Africa, South America, and some parts of Asia). Support for GNSS software in general, and for precise positioning station coordinates in particular, is needed. Automated processing of InSAR data would make the data far more accessible to more users and could serve as reconnaissance for targeted ground-based investigations, which is especially critical for those with scarce resources, such as local water districts.

Measurements of elevation changes must be tied to the TRF. Hydrological applications also need a high-quality digital elevation model (DEM), preferably a bare-earth DEM. This DEM needs to be consistent

BOX 4.2
Land Subsidence in the Central Valley, California

The San Joaquin Valley is a highly productive agricultural region. Both surface and groundwater are used in the valley, but the contributions of each can vary substantially from year to year. Two recent droughts (2007–2009 and 2012–2016), coupled with recent land-use changes and surface-water restrictions, put the valley's groundwater system under considerable strain (Thomas et al., 2017). Extensive pumpage of groundwater systems has caused the land to subside at rates up to 0.3 m/yr. Monitoring can result in early detection of subsidence, provides a measure of water resources sustainability within relevant planning horizons, and produces data and information needed for subsidence management.

The magnitude and extent of land subsidence since the 1920s have been studied using data from geodetic surveys (initially spirit-leveling and later GPS surveys), extensometers, continuous GNSS, and InSAR (Sneed et al., 2013, 2018; Farr et al., 2015, 2016). An example of GNSS and InSAR data for 2008–2010 is shown in Figure 4.5. Spirit-leveling surveys indicate that more than half the valley subsided at least 0.3 m and locally exceeded 8 m from the 1920s to 1970. Surface-water delivery systems were mostly in place by 1970, and extensometer and other data indicate that subsequent subsidence occurred largely during droughts. However, recent data from the full suite of instruments shows that subsidence patterns have changed, and now subsidence is sometimes tied to land-use change (Sneed and Faunt, 2018).

The Central Valley subsidence study demonstrates the interconnection between surface-water availability, groundwater, and land use. When surface-water availability falls short of demand, groundwater is pumped to close the deficit. In the Central Valley, pumping has caused land subsidence which has damaged natural and engineered structures, including a reduction of aquifer-system storage capacity and impaired conveyance capacities of both local and statewide surface-water delivery systems. The ability to continuously measure land subsidence in space and time are critical for tracking hazards to both natural and engineered systems.

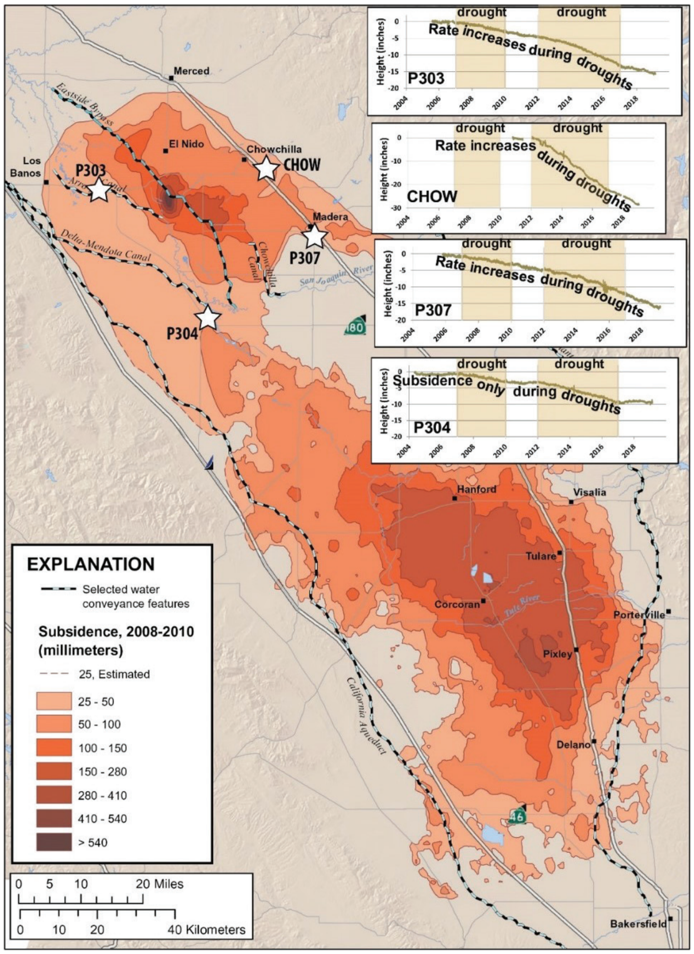

FIGURE 4.5 Spatial extent and magnitude of subsidence in the San Joaquin Valley for 2008–2010 as interpreted from InSAR data, and time series from four GNSS stations showing varying heights during drought and nondrought periods (inset). The complimentary data sets are needed to track subsidence spatially and temporally. SOURCE: Modified from Sneed et al., 2018.

across entire basins for local ground control or to support suborbital navigation. Radar or lidar can be used to develop accurate land-surface topography data sets, but they require GNSS (and positioning software) and the geodetic infrastructure to define the DEM in the TRF. In locations where subsidence is fairly rapid, repeat DEMs are required, or high-quality InSAR data could be used to periodically adjust an initial high-quality DEM. A high-quality DEM also could be used to improve water level measurements in wells (which are referenced to a point on or near ground surface). In places where the flow gradient is small, even small errors in water level measurements can lead to mischaracterization of the flow direction.

SURFACE WATER MONITORING BY SATELLITE ALTIMETRY

Although optimized to study ocean dynamics, satellite altimetry has been used for more than two decades to monitor water-level changes over rivers, lakes, human-made reservoirs, and floodplains (e.g., Birkett, 1998). The number of water gauges has been declining in many regions of the world (Milliman and Farnsworth, 2013), and some river basins are ungauged. Consequently, satellite altimetry plays an important and unique role in providing homogeneous and long-term monitoring of surface water levels and volumes (if combined with optical or radar imagery) over the continents (Alsdorf and Lettenmaier, 2003; Alsdorf et al., 2007). Water-level time series based on altimetry (e.g., Topography Experiment/Poseidon, Jason) extend more than 25 years, are routinely computed over thousands of surface water bodies, and are freely available.[3]

Measurements

The Surface Water Ocean Topography (SWOT) mission will support a range of applications in land hydrology science, surface water management, and flood forecasting (e.g., Biancamaria et al., 2010; Bates et al., 2014). SWOT will produce water elevation images for two 50 km swaths on either side of the satellite, globally (Desai, 2018). The mission will allow water height and lake extent to be measured at a resolution of 250 m or better (the goal is 100 m resolution) every 10 days. The water level of lakes, reservoirs, and floodplains will be measured with 0.1 m accuracy over 1 km^2 areas. On rivers, the river slope will be measured over successive 10 km-long segments on rivers wider than 100 m to within 17 mm/km, allowing direct estimation of river discharge.

Geodetic Needs

As with other applications of satellite altimetry (see Chapter 3), the geodetic infrastructure is fundamental for estimating accurate water heights of surface waters on land. For SWOT and other altimetry missions, precise orbit determination relies on well distributed GNSS stations at the surface of the Earth, as well as a stable and accurate TRF. As with any satellite mission, SWOT also requires calibration and validation data. Accurate water level measurements can be provided with existing tide gauges only if they are tied to TRF using GNSS (Santamaria-Gomez et al., 2012).

WATER CYCLE MONITORING WITH SATELLITE GRAVITY

The 2018 launch of the GRACE-FO mission ensures the continuation of land water cycle change measurements that began in 2002. Gravity change measurements from these missions are being interpreted as change in the total water storage at spatial scales greater than 300 km and time scales longer than subseasonal. Results from these missions have been used to study total water storage variations as well as the associated meteorological and climate processes or societal influences in nearly every major river basin around the world (Rodell et al., 2018). For example, these data have been used to study drought conditions (Zhu et al., 2018) and flood potential (Geoweleeuw et al., 2018). Gridded total water storage data sets are now routinely assimilated with other data into land surface models, leading to disaggregation and downscaling of satellite geodetic observations to the catchment scales (Khaki et al., 2019).

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[3] See http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir for lakes and http://ctoh.legos.obs-mip.fr/data/hydroweb for lakes, rivers, floodplains, and man-made reservoirs.

Measurements

The GRACE-FO mission has a design lifetime of 5 years and is expected to continue to provide measurements compatible with the GRACE mission. This application would benefit from improved measurement of all fluxes in and out of groundwater systems (Objective S-6c) at target 100-km gravity field resolution with a precision of 10 mm water layer equivalent thickness.

Geodetic Needs

Results from GRACE and GRACE-FO need to be supplemented with information from other components of the geodetic infrastructure before the results can be used in water cycle applications. First, the geodetic infrastructure is needed to determine the geocenter. Geocenter motion is one of the largest sources of uncertainty in GRACE-based surface mass change estimates (e.g., Blazquez et al., 2018), and it is typically determined using GRACE-based gravity field variations and model-based assumptions on water mass redistribution in the global ocean (Swenson et al., 2008; see also Chapter 3). Satellite laser ranging (SLR) can be used to determine the geocenter motion independently. Second, SLR is needed to independently determine the low-degree harmonics of the geopotential to mitigate the nongeophysical spaceflight environmental effects on the low-degree harmonics measured from satellites (Landerer et al., 2019). Independent estimates of low-degree harmonics are also essential to support continuity between space missions. As a practical matter, gaps are inevitable between space gravity missions, and SLR and tracking to other geodetic satellites can help test measurement continuity across these gaps.

CALIBRATION/VALIDATION AND GNSS-IR

The sections above emphasize the role of GNSS infrastructure in measuring terrestrial water storage variations, land subsidence, and surface-water heights. This same ground-based infrastructure also plays a key role in hydrologic research by providing calibration and validation data for water-related satellite missions. For example, GNSS Interferometric Reflectometry (GNSS-IR) measurements from ~120 sites in the western United States were used to validate results from the Soil Moisture Active Passive (SMAP) mission (Al-Yaari et al., 2017). GNSS-IR measurements of the ice sheet surface in Greenland and Antarctica are being used to constrain surface mass balance (Larson et al., 2015) and thus provide validation data sets for Ice, Cloud, and land Elevation Satellite 2. GNSS sites installed in the cryosphere to measure effects of glacial isostatic adjustment can also be used to provide tide gauge data in a region with limited in situ sensors (Larson et al., 2013). The SWOT mission will also need validation data sets on lakes and rivers, which can be provided by opportunistic GNSS-IR data sets or by targeted deployments of GNSS receivers. Unlike any other tide gauge technology, GNSS-IR directly provides water measurements defined in the International Terrestrial Reference Frame (ITRF).

Measurements

The measurements used in GNSS-IR are the signal-to-noise ratio computed by any high-precision GNSS receiver. Thus, they are already provided in existing GNSS data streams. Initially these data streams included only GPS but are increasingly including signals from the other constellations. This expansion provides a spatially and temporally dense data set. The spatial footprint of GNSS-IR depends on the height of the antenna above the reflecting surface, about 1,000 m^2 for most GNSS sites. For a tower site (such as the 30-m Alexander tower on the Ross Ice Shelf used for meteorological measurements), the GNSS-IR footprint is nearly 1 km^2 (Roesler and Larson, 2018). The temporal sensing mostly depends on whether only GPS or all GNSS satellites are tracked and varies from ~15–60 minutes.

Geodetic Needs

The main geodetic needs for GNSS-IR are orbits and software to retrieve the reflection parameters. The needed orbit accuracy is low, several meters radially. In some cases, resolving the reflection parameters requires a higher sampling rate than the standard geodetic sampling interval of 30 seconds.

SUMMARY

Water cycle research using the geodetic infrastructure requires the maintenance of at least the current stability of the ITRF. All of the geodetic products described in this chapter depend on the frame for traceability of measurement precision. The following summarizes needs for maintaining or enhancing the geodetic infrastructure, and related improvements to enhance scientific returns.

Maintenance of the Geodetic Infrastructure

- Maintain the current stability of the ITRF. All geodetic products described herein depend on an accurate global frame scale for absolute measurement precision traceability.
- Maintain InSAR orbit accuracy to 20 mm radially and 60 mm along-track. The onboard GNSS precise orbit determination measurements should be International GNSS Service (IGS) quality (i.e., mm-level phases and dm-level pseudoranges at two or more frequencies for all four global GNSSs and with accurately calibrated antennas).
- Maintain a robust global distribution of high-quality GNSS stations, analysis products, and software. This includes high-quality GNSS satellite orbits and clocks for near-real-time and long-term scientific studies, currently provided by the IGS.
- Continue support for high-accuracy GNSS analysis software.
- Support antenna phase calibrations (for GNSS transmitters and ground antennas), currently provided by the IGS.
- Support automated GNSS processing services that can be accessed by the hydrologic community (e.g., Nevada Reno positioning products), including high-rate positions.
- Maintain geodetic expertise to maintain institutional knowledge and technical capabilities. Training is required for GNSS, InSAR, GRACE, and lidar software. Stable and predictable funding is needed to support an educated technical workforce, software development, and infrastructure.

Enhancements to the Geodetic Infrastructure

- Additional GNSS stations in the western United States to be made part of the geodetic infrastructure. These stations would have ~40 km spacing, with additional stations in watersheds or areas that lack traditional hydrological measurement networks. They may be selected largely from the existing National Science Foundation Plate Boundary Observatory. They must meet the highest standards for data quality, site design, stable monumentation, and metadata definition and dissemination. In addition to the water cycle needs, they would improve the accuracy of local surveys (e.g., aircraft lidar).

Related Improvements to the Geodetic Infrastructure to Enhance Scientific Returns

- Automated estimates of daily soil moisture, snow depth/snow water estimate, vegetation water content, and subdaily water level variations.
- Improved spatial resolution in time-variable gravity from GRACE-type missions.
- Automated InSAR processing and improvements in removing atmospheric errors.
- Improvements in GNSS vertical accuracy and precision.
- Combined GNSS-InSAR products.
- Enhance GNSS stations with corner reflectors or radar transponders for coherent InSAR signal.
- Support for GNSS reflection software for hydrological, cryosphere, and water level applications.
- Lidar for defining an initial bare-earth DEM, which could be updated regularly using InSAR for flood and wetland/riparian ecosystems applications.
- Free and open SAR data, analysis software, and products such as time series.
- Free and open GRACE data and ancillary products.

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5

Geological Hazards: Earthquakes and Volcanoes

The Decadal Survey identified several Earth surface and interior questions that require maintenance or enhancement of the geodetic infrastructure. The most stringent geodetic demands are associated with geological hazards. Earthquakes and volcanic eruptions provide a window on processes operating within the Earth. They are also capable of great destruction, which has led to substantial efforts to forecast their occurrence and mitigate their impacts (e.g., reinforcing buildings to withstand expected shaking). This chapter describes the geodetic infrastructure needed to understand the causes and impacts of geological hazards, primarily earthquakes and volcanic eruptions, but also landslides and tsunamis. The guiding Decadal Survey (NASEM, 2018) science questions for this chapter are:

S-1. How can large-scale geological hazards be accurately forecast in a socially relevant time frame?

S-2. How do geological disasters directly impact the Earth system and society following an event?

The geodetic infrastructure needs associated with these questions are summarized in the Geological Hazards Science and Applications Traceability Matrix (see Appendix A, Table A.3).

SCIENCE OVERVIEW

Over the past quarter century, earthquakes, tsunamis, and, to a lesser extent, volcanic eruptions and landslides have caused heavy economic losses and deaths, and they will continue to be major threats to lives and economies in the future. For example, the 2004 magnitude (M) 9.2 megathrust earthquake in Sumatra generated a tsunami that propagated across the Indian Ocean Basin, killing more than 230,000 people in coastal areas.[1] The 2011 M9.0 Tohoku earthquake in Japan was the most costly natural disaster in history at up to $235 billion (World Bank, 2011). In addition to the massive destruction of the Sendai region, the complete shutdown of nuclear energy generation in Japan for more than 1 year and permanent closures of many nuclear plants in other countries raised questions about the safety of coastal nuclear power plants (NRC, 2014). The 2010 eruption of the Eyjafjallajökull volcano in Iceland halted air traffic in northern Europe, causing a significant disruption to the European population and economy (Gill, 2010). Similar threats to the U.S. population and economy are associated with the Cascadia subduction zone (last major event in 1700; see Figure 5.1), the San Andreas Fault System (last major earthquakes in 1856 and 1906), and the volcanoes in the Aleutians and Pacific Northwest (last major eruption at Mount St. Helens in 1980).

Although these events cannot be prevented, steps can be taken to lessen the adverse impacts on life and property. The first step is to monitor the earthquake, volcano, or landslide areas before the event. For example, in the case of an earthquake, the surface deformation rate surrounding the fault can be inverted for the seismic moment accumulation rate (Maurer et al., 2018). Then, knowing the time since the last major event, one can

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[1] See https://web.archive.org/web/20130507101448 and http://earthquake.usgs.gov/earthquakes/world/most_destructive.php.

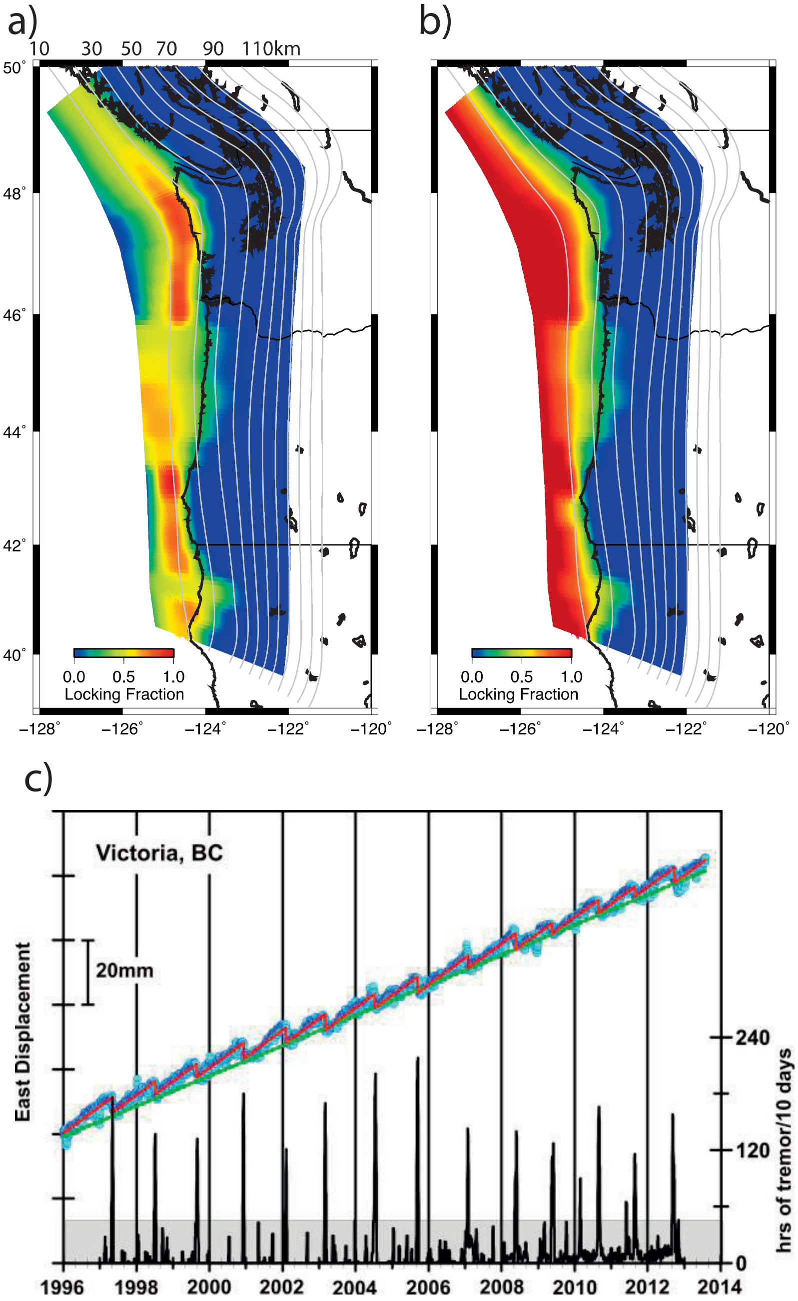

FIGURE 5.1 Two models (a) and (b) of interseismic locking of the Cascadia subduction zone fit the land-based geodetic data equally well. The models agree for areas landward of the shoreline, where geodetic coverage is good, but have major differences offshore, where coverage is poor. Tsunamis are generated by shallow slip (<10 km) during megathrust earthquakes, so these models yield very different tsunami hazard forecasts. (c) The transition from locked to partially locked between depths of 15 and 30 km is well resolved by land data. The downdip transition zone undergoes episodic tremor and slip events at approximately 14 month intervals, as seen in Global Positioning System time series (c) and tremor activity. This megathrust zone last ruptured in 1700 and generated tsunami waves that propagated across the Pacific Ocean and caused damage along the coast of Japan. Coastal communities in Washington and Oregon would have less than 20 minutes to retreat to high ground following a major tsunamigenic event on the megathrust. SOURCES: (a) and (b) Modified from Schmalzle et al., 2014; (c) updated from Dragert et al., 2004, and Herb Dragert, National Resources Canada, personal communication on March 21, 2017.

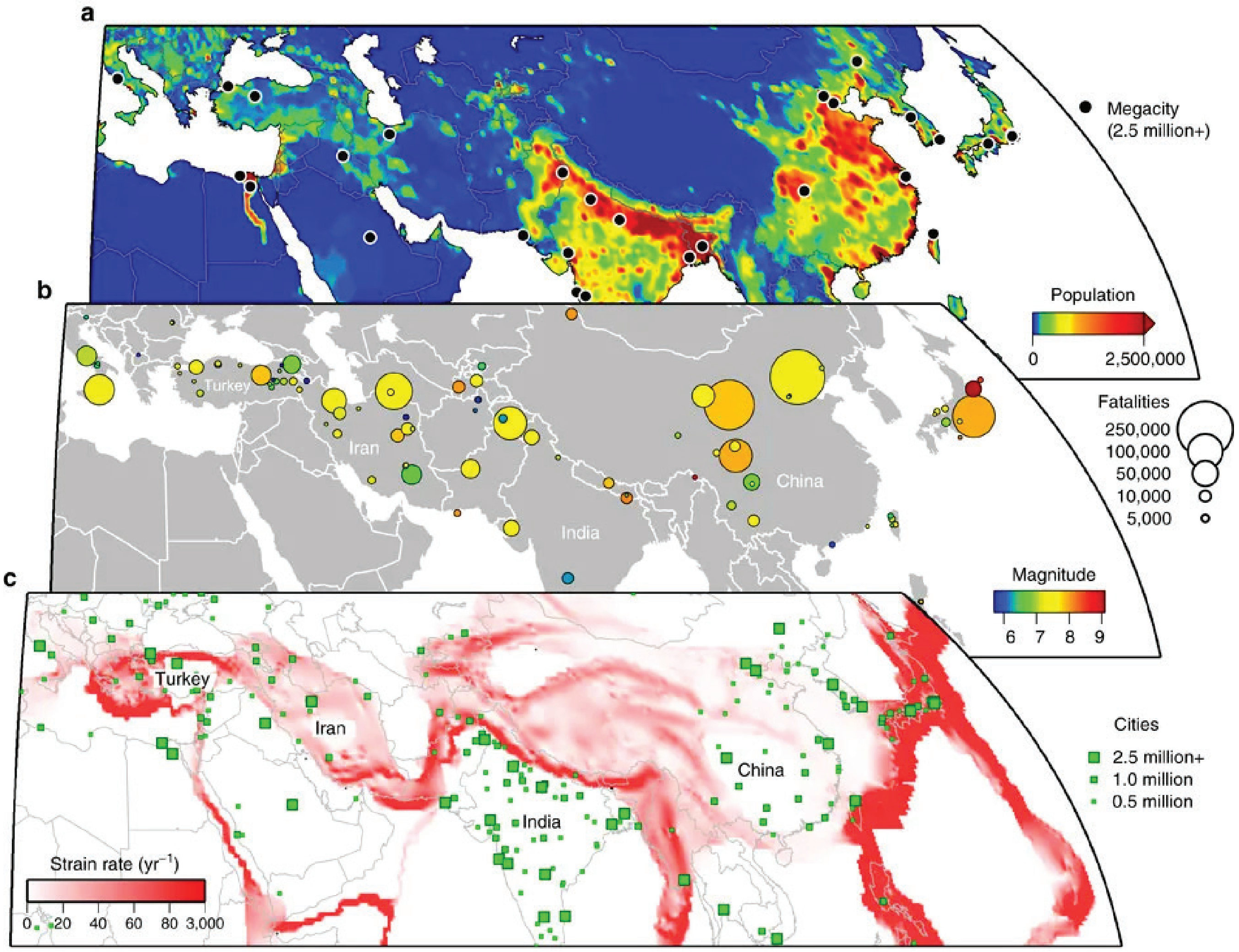

FIGURE 5.2 Population density, destructive earthquakes (>1,000 fatalities), and crustal strain rate for Eurasia. Most large continental earthquakes occur in areas where the strain rate exceeds 50 nanostrain per year. Many of these areas are heavily populated and have had major destructive earthquakes in the past. The deformation of this large area is best monitored by a combination of Global Navigation Satellite System (GNSS) and Interferometric Synthetic Aperture Radar (InSAR). High-resolution topography would also reveal the paleoseismic activity on the many faults in the region. SOURCE: Elliott et al., 2016.

place bounds on the size of the next major rupture. Most destructive earthquakes occur in regions where the strain rate exceeds ~50 nanostrain per year (Elliott et al., 2016; see Figure 5.2). For strike-slip faults, which typically have a locking depth of about 12 km, this strain rate corresponds to an average velocity accuracy of 0.5 mm/yr over the 10 km averaging distance. For volcanic eruptions and landslides, a period of accelerated activity often occurs prior to the event, and so the event timing can be estimated with an accuracy useful for effective evacuation measures (Sigmundsson et al., 2010).

Understanding the seismic moment accumulation rate in the shallow parts of subduction zones is particularly challenging because onshore geodetic measurement techniques such as GNSS, InSAR, tide gauges, and strain gauges are too remote to resolve the degree of shallow coupling (see Figure 5.1). The tools of seafloor geodesy (i.e., GNSS acoustics,[2] bottom pressure gauges, seafloor strain gauges, and repeated sonar surveys) can directly measure displacements accumulating offshore in subduction zones. Consequently, their

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[2] GNSS acoustics is a method to precisely measure the horizontal displacement of the seafloor. The technique uses a combination of GNSS for accurately positioning a platform on the sea surface (e.g., ship or wave glider) and acoustics for ranging to transponders on the seafloor.

use can greatly improve the spatial and temporal resolution of megathrust coupling and earthquake/slow-slip source characterization with signals ranging from episodic slip, interseismic strain, coseismic motion, and postseismic afterslip and relaxation (Burgmann and Chadwell, 2014). GNSS acoustics and repeated sonar surveys rely on cm-level accuracy GNSS positioning of moving platforms (ship, wave glider, or buoy), which, in turn, depends on the GNSS infrastructure to provide a reference land station and high accuracy GNSS orbit information.

The second step is to map the displacement and surface destruction of the event. In the case of an earthquake, for example, a rapidly determined rupture model can be used to estimate the size of the tsunami (if any) as well as to forecast the size and location of large, potentially damaging aftershocks (Bock and Melgar, 2016). Similarly, the duration of a volcanic event can be forecast through careful geodetic monitoring and modeling (Segall, 2013).

The third step is to use a suite of ground- and space-based measurements to map the areas of greatest destruction to optimally deploy emergency services and other relief efforts.

REQUIRED MEASUREMENTS AND LINKS TO THE TERRESTRIAL REFERENCE FRAME

Because earthquake and volcanic cycles occur on hundred- to thousand-year time scales, global and long-duration observations are needed to capture enough partial cycles to understand and model the underlying physical processes and so advance forecasting. The required measurements include surface deformation, time-variable gravity, surface topography, sea surface tsunami waves, and surface cover and atmospheric changes.

Surface Deformation

Ground-based Global Navigation Satellite System (GNSS) measurements, defined in the International Terrestrial Reference Frame (ITRF; Altamimi et al., 2016), are used to measure the seismic moment rate that is accumulating in the elastic crust surrounding the land portions of subduction zones (e.g., Cascadia; see Figure 5.1) and continental transform faults (e.g., San Andreas). GNSS stations deployed with other ground-based instrumentation also provide important information to forecast the onset and duration of hazardous volcanic eruptions (see Box 5.1). The temporal sampling for an individual GNSS site varies from 1 second to daily, depending on the application. Repeat-pass interferometry has matured as a reliable observational system that provides 6-day snapshots of scalar surface deformation over tectonically active land areas. Requirements for spatial resolution and precision vary with the application. Plate motions and vertical deformations related to hydrologic loading and postglacial rebound need to be measured to an accuracy of better than 1 mm/yr over spatial scales of several thousand km. The spacing of the continuous GNSS stations is as small as 10 km in western North America (Wei et al., 2010) and Japan, but is much greater (50–100 km) along other active continental plate boundaries. Consequently, Interferometric Synthetic Aperture Radar (InSAR) deformation measurements are needed to fill the gaps. Currently the orbits of the InSAR satellites are better than 50 mm in all three components. However, with the new TOPS-mode data from the Sentinel-1 satellites, an emerging requirement is to connect interferograms over the 20-year lifetime of the satellite series to better than 20 mm radially and 60 mm along-track accuracy.[3] This accuracy can be achieved only if the global GNSS tracking network has a similar accuracy over the 20-year period through an accurate link to the terrestrial reference frame (TRF).

Time-Variable Gravity

Time-variable gravity measurements can reveal vertical deformation and mass change associated with seismic events having rupture lengths greater than the spatial resolution of Gravity Recovery Climate Experiment-type satellites (~200 km). They also provide the only means for measuring co- and postseismic deformation of offshore major subduction zones globally (Han et al., 2014). The postseismic gravity changes from the largest earthquakes are about 1 microgal at a spatial resolution of 500 km in 2 years after the rupture (Han et al., 2014, 2016). Time-variable gravity can also be measured on the surface of the Earth, and the approach is becoming common because of

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[3] Andy Hooper, University of Leeds, personal communication, 2019.

BOX 5.1
2018 Kilauea Eruption

The Kilauea eruption began on April 30, 2018, and continued for approximately 3 months. During that time, Kilauea's summit crater and the East Rift Zone underwent continuous deflation, and a M6.9 earthquake struck the south flank on May 4. This was the largest eruption of the lower East Rift Zone in at least 200 years (Neal et al., 2019). Approximately 0.8 cubic kilometers of lava flowed toward the ocean in three areas and destroyed 718 dwellings in the Leilani Estates and Lanipuna Gardens. Lava flowed into Kapoho Bay and created new land nearly 1 mile into the sea.

The surface deformation associated with this event was well documented by a combination of GNSS and InSAR (see Figure 5.3). The GNSS stations provided frequent (1 second) vector displacement measurements at ~35 sites. The Sentinel-1A and -1B Synthetic Aperture Radar (SAR) satellites provided 6-day interferograms from two look directions at ~100 m spatial resolution to fill gaps in Global Positioning System (GPS) coverage. Both GNSS and InSAR were used in near-real-time to inform emergency responders and the affected population.

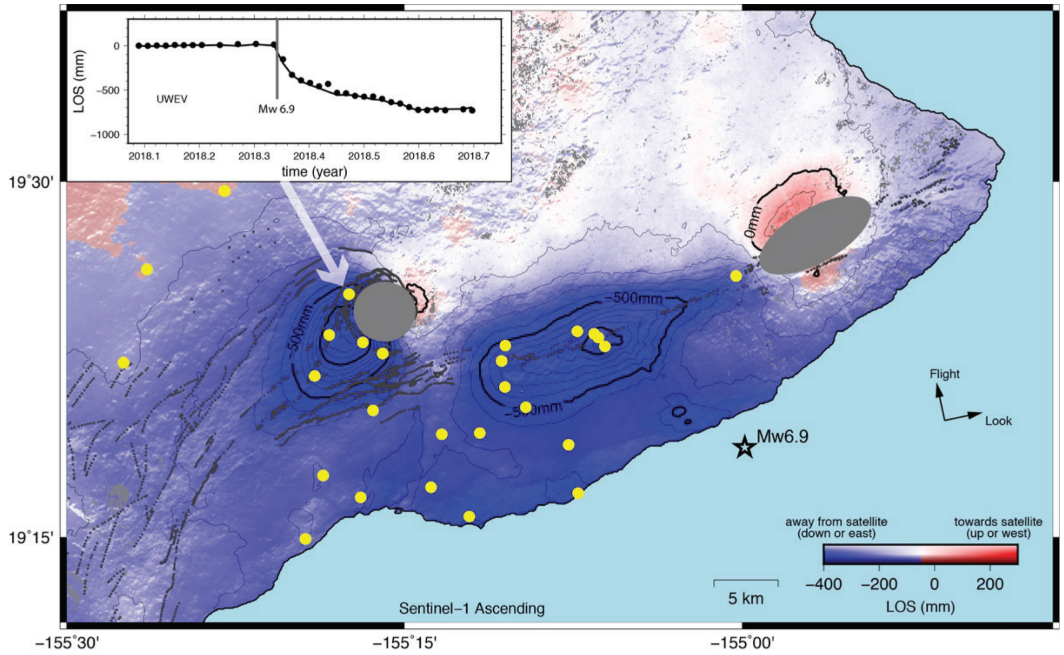

FIGURE 5.3 Cumulative surface deformation from the Kilauea eruption between April and September 2018. Yellow circles indicate GPS locations. Deformation was not recovered in the gray areas, including the caldera crater and an area along the lower east rift zone. SOURCE: Modified from http://pgf.soest.hawaii.edu/Kilauea_insar.

low-cost microelectromechanical systems (Middlemiss et al., 2016).

Global Maps of Bare-Earth Topography

Global maps of bare-earth topography are needed to provide the pre-event (e.g., earthquake, volcanic eruption, and landslide) reference surface as well as to assess areas of potential landslides and volcanic lahars. Bistatic radar interferometry (e.g., Shuttle Radar Topography Mission and TerraSAR-Tandem-X) has provided global topographic reference data at 10–30 m resolution. These methods require TRF accuracies of 0.1 m to achieve accuracy of 1 m vertical topography. The interferometric baselines for the bistatic radar measurements have much more stringent requirements (1 mm).

Tsunami Waves

Real-time measurement of tsunami waves and communication to emergency response officials are vital for warning coastal populations. Direct wave height measurements can be made using ocean bottom pressure sensors and GNSS receivers mounted on buoys or ships of opportunity (Foster et al., 2012; see Figure 5.4). The vertical precision of these measurements should be better than 0.1 m at 1-minute sampling. Because the

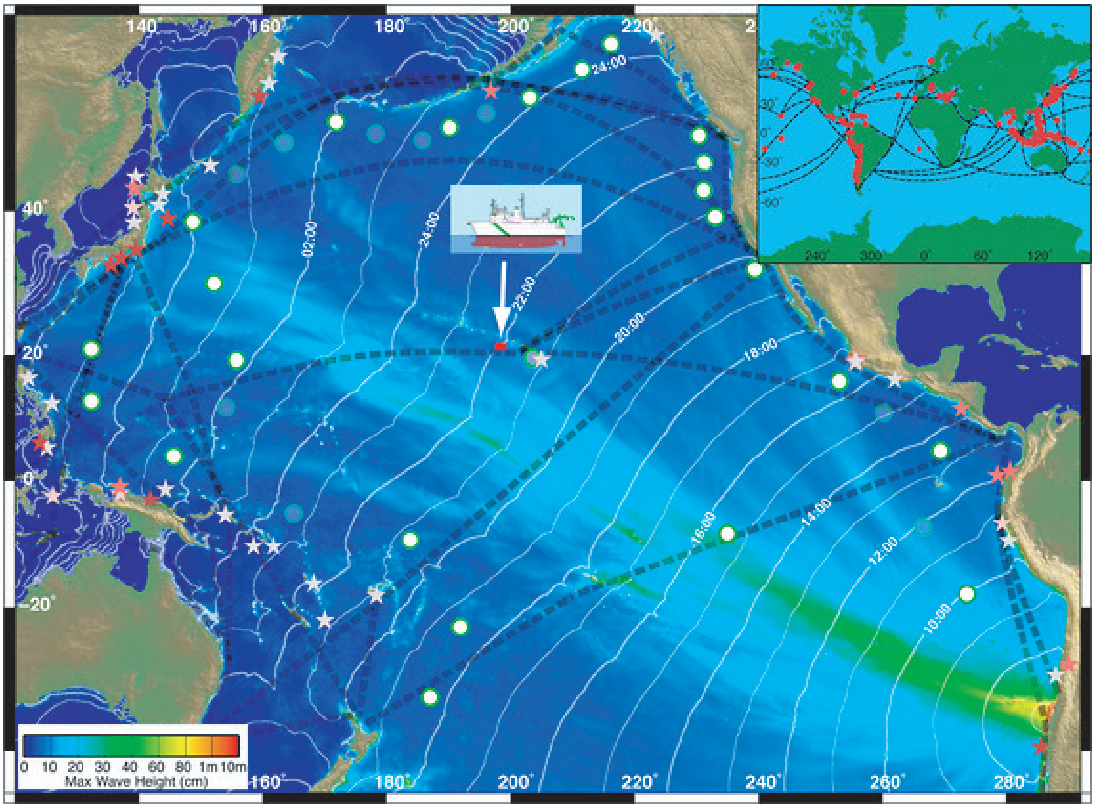

FIGURE 5.4 Maximum wave height from the 2010 M8.8 Maule Chile earthquake. The arrival time contours are shown in white. The R/V Kilo Moana measured the wave train at its remote position near Hawaii using high-precision GNSS. The circles show the location of Deep-ocean Assessment and Reporting of Tsunamis (DART) bottom pressure sensors. The red stars indicate where the source events for fatal 20th century tsunamis occurred. Colors represent the number of fatalities: white ≤50; pink ≤100; red ≤1,000; dark red >1,000. Dashed lines are the primary shipping lanes in the Pacific where precise GNSS receivers could be deployed to augment the DART buoys. SOURCE: Foster et al., 2012.

receivers are usually thousands of kilometers from a land-based reference station, the measurement accuracy relies on the International GNSS Service (IGS) to do processing by precise point positioning.

Big Data, Software, and Workforce

Addressing the geological hazards questions framing this chapter will involve the analysis of larger geodetic data sets (InSAR, GNSS, and dense GNSS arrays), higher geodetic accuracy, and lower latency (real-time) delivery than are available today. For example, the National Aeronautics and Space Administration-Indian Space Research Organisation Synthetic Aperture Radar (NISAR) mission will provide systematic global observations and more imagery per day than is available from all of the previous satellite missions (Rosen et al., 2016). Some networks along plate boundaries are now telemetering high-rate GNSS data in real-time for earthquake and tsunami early warning, but lack of computing and telemetry resources has limited this application in many regions of the world (e.g., Asia). Accurate processing of these new data streams will require benchmarking of software and processing methods from two or more groups. Of course, these improvements will rely on a well-trained geodetic workforce working in close collaboration with the high performance computing community (Davis et al., 2016).

SUMMARY

Observing, mitigating, and forecasting the hazards associated with major earthquakes and volcanic eruptions require very accurate geodetic measurement of surface deformation and time-variable gravity. The new generation of InSAR satellites employs a new type of image alignment that requires a geolocation accuracy of better than 70 mm, which translates to an along-track orbit accuracy of better than 70 mm (Xu et al., 2017). This accuracy must be maintained over the 20-year lifetime of the Sentinel-1 satellite series. Strain-rate mapping over continental scales requires vector GNSS deformation time series having velocities better than 0.5 mm/yr. Monitoring postseismic deformation from megathrust earthquakes requires gravity change accuracy of better than 1 microgal at a 1-month sampling rate or better. Finally, monitoring the propagation of tsunami waves across the oceans requires vertical GNSS accuracy of better than 0.1 m at 1-minute sampling in remote locations. All of these applications need steady improvements in the accuracy of the TRF as well as extremely accurate satellite orbits. The following summarizes needs for maintaining or enhancing the geodetic infrastructure, and related improvements to enhance scientific returns.

Maintenance of the Geodetic Infrastructure

- Maintain the current stability of the TRF for monitoring surface deformation at high accuracy (0.5 mm/yr) globally.
- Track the InSAR satellites at an accuracy of 20 mm radially and 60 mm along-track. The onboard GNSS precise orbit determination measurements should be of IGS quality (i.e., mm-level phases and dm-level pseudoranges at two or more frequencies for all four global GNSSs and with accurately calibrated antennas).
- Similar orbital requirements are needed for global lidar surveys (Abshire et al., 2005) of land motion as well as for spacecraft pointing accuracy of better than 2 microradians.
- Maintain the geodetic infrastructure to support gravity change measurements of 1 microgal accuracy at spatial resolution of 300 km or better, and sampling better than monthly to monitor large subduction zone earthquakes offshore.
- Maintain GNSS station density in areas of high strain rate, such as plate boundaries. GNSS Station spacing of 20 km or better is needed to bring the InSAR measurements into an absolute frame at 0.5 mm/yr accuracy at better than 10 km spatial resolution.
- Maintain free and open access to all data used in the formulation of the TRF.

Enhancements to the Geodetic Infrastructure

- Improve the reference frame formulation to quickly accommodate global-scale motions associated with the very large subduction zone earthquakes that affect GNSS stations over much of the Earth's surface (e.g., 2004 Sumatra). The specific requirements are 1–10 mm accuracy maintained over 10 years.
- Maintain and enhance a globally distributed set of GNSS sites over a long period to measure large-scale, plate-boundary deformation and plate motions at an accuracy of 0.5 mm/yr. These sites are also needed to correct InSAR displacement time series.
- Develop a GNSS-based, time-dependent TRF, fully aligned to the ITRF, and with frequent updates to accommodate sudden changes in the locations of the fundamental stations.
- Ensure there are at least two open software development efforts for each geodetic method, including GNSS processing, InSAR processing, and lidar processing.
- Transition processing of all geodetic data from human-intensive analysis to automated analysis.
- Develop a geodetic workforce versed in the fundamentals of geodetic methods as well as in advanced automated processing approaches.
- Encourage free and open access to all GNSS and InSAR data.

Related Improvements to the Geodetic Infrastructure to Enhance Scientific Returns

- Improve GNSS station density in selected areas to address relevant science and applications. This may include GNSS buoys and wave gliders in ocean areas.
- The requirement for bare-earth topography at 0.1 m vertical accuracy over selected tectonic areas drives the need for local GNSS ground station positioning of better than 50 mm for differential GNSS aircraft.

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6

Weather and Climate

The atmosphere is a complex thermodynamic system that varies across length scales ranging from meters to the circumference of the Earth and time scales ranging from minutes and weeks (weather) to years and longer (climate). Understanding and predicting weather and climate requires high spatial and temporal sampling using a wide variety of terrestrial and space-based sensors, combined with complex numerical modeling systems that can properly assimilate these data. The Decadal Survey (NASEM, 2018) includes a range of science questions aimed at advancing our understanding of weather and climate, both in terms of natural processes and anthropogenic forcing. Among the science questions supported by observations that rely on maintenance or enhancement of the geodetic infrastructure are:

W-2. How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?

C-2. How can we reduce the uncertainty in the amount of future warming of the Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?

The geodetic infrastructure needs associated with these questions are summarized in the Weather and Climate Science and Applications Traceability Matrix (see Appendix A, Table A.4).

GNSS FOR ATMOSPHERIC REMOTE SENSING

Atmospheric effects have long been an important error source in geodetic measurements. In particular, mismodeled atmospheric delay is a significant contributor to the overall error budget of geodetic measurement techniques. The current positioning precision achieved by the Global Positioning System (and now the Global Navigation Satellite System [GNSS]) is possible only because of the development of advanced models to remove tropospheric effects on GNSS signals. On the other hand, the atmospheric effects on GNSS signals can be used to provide critical data to the atmospheric community (Bevis et al., 1992; Anthes et al., 2011; Ho et al., 2019). The linkage between geodesy and the atmosphere is through refractivity. The index of refraction is a function of pressure, temperature, and water vapor pressure. Refractivity creates delays in the GNSS observations along the path of the signal from the transmitting satellite to the receiving system.

Ground-based GNSS receivers have been used since the 1990s beginning with the Global Positioning System Meteorology (GPS-Met) proof of concept mission (Rocken et al., 1997). These measurements, now made at thousands of sites, are considered an important component of the Global Observing System, and their value to operational numerical weather prediction at the short and medium range is well established. These integrated water vapor products can be used to monitor climate (Wang and Zhang, 2009; Ning and Elgered, 2012), to understand atmospheric circulation features such as the

North American monsoon (Serra et al., 2016), and to improve numerical weather prediction (e.g., Vedel et al., 2004; Bennitt and Jupp, 2012). Ground-based integrated water vapor is also used to calibrate satellite-derived water vapor retrievals (Chen et al., 2008; Mears et al., 2015).

When GNSS receivers are deployed on a low-Earth orbiting satellite with an antenna pointed at the Earth's limb, GNSS signals are measurably delayed and bent by the Earth's atmosphere as the satellite either rises or sets behind the Earth with respect to a transmitting GNSS satellite. These signals can be used to retrieve atmospheric refractivity in the sounding region (see Box 6.1). GNSS radio occultation (GNSS-RO) systems depend critically on the International GNSS Service (IGS) geodetic infrastructure to specify the GNSS orbits and clocks.[1]

GNSS-RO measurements have been used to study large-scale atmospheric dynamics, such as the El Niño Southern Oscillation and sudden stratospheric warming, and to understand atmospheric gravity waves so they can be parameterized in global climate models (Alexander et al., 2008). Because GNSS-RO measurements are traceable to the International System of Units, they do not require bias correction (Ho et al., 2010, 2019). In this regard, they can be used as "anchor" measurements for microwave and infrared observations (Aparicio and Laroche, 2015) and improve bias corrections applied to satellite radiance measurements (Auligné et al., 2007). When GNSS-RO data are assimilated into global weather reanalyses systems, this anchoring ability has been demonstrated to provide a continuous record of upper air temperature since 2006 (Dee et al., 2011). This long-term accuracy is due to the timing stability of GNSS, which itself is based on the timing stability of the geodetic infrastructure.

The importance of GNSS-RO for climate monitoring and climate model testing is still an emerging field, primarily because of the relatively short length of the GNSS-RO time series. Nevertheless, the Intergovernmental Panel on Climate Change (IPCC) intends to include GNSS-RO results in its Sixth Assessment Report, and recent work has shown how GNSS-RO improves the consistency of climate reanalyses in the stratosphere (e.g., Ho et al., 2019).

IMPROVEMENTS IN WEATHER MODELS

Question W-2 touches on the societal need to extend the accuracy of numerical weather prediction forecasts for 2 months. Accurate and detailed specification of the environmental state and analysis is a key precondition for any forecast. GNSS-RO offers the ability to sound the atmosphere over land and water in all weather conditions, and to provide observations with high vertical resolution, making it an essential component of the Global Observing System. The direct assimilation of GNSS-RO observations into the analysis fields improves the initial conditions used for forecasting. Multiple studies have demonstrated the value of GNSS-RO to improve analysis fields for numerical weather prediction (Healy, 2008, 2013; Aparicicio and Deblonde, 2009; Cucurull, 2010; Nie et al., 2019). This improvement is evident even though the number of GNSS radio occultations is low compared with the number of satellite radiances that are assimilated (e.g., Healy and Thepaut, 2006; Aparicio and Deblonde, 2008; Poli et al., 2008; Cucurull, 2010; Rennie, 2010). The impact of this relatively small amount of data has led the International Radio Occultation Working Group to recommend establishment of an observing system that provides a minimum of 20,000 occultations per day for numerical weather prediction and other applications.[2] One application of RO with significant society benefit is predicting heavy precipitation events associated with atmospheric rivers (see Box 6.2).

Using GNSS-RO data within a model verification system is an additional way to extend the accuracy of numerical weather prediction forecasts. Understanding how errors in numerical weather prediction systems grow over time is a key aspect of extending forecast accuracy. High-quality observations of the atmosphere are critical for this task. Using GNSS-RO data as a diagnostic tool to identify errors in numerical weather prediction systems will have a significant impact in improving model forecasting skill.

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[1] The International Radio Occultation Working Group—a permanent Working Group of the Coordination Group for Meteorological Satellites (CGMS)—recommends that CGMS works with responsible entities, including IGS, to assure that GNSS ground station infrastructure is sufficiently supported so that they can provide the necessary orbit and geodetic data.

[2] See http://www.wmo.int/pages/prog/sat/meetings/documents/IPET-SUP-3_INF_02-01_IROWG5-Minutes-Summary-Feb16-2017VApr2017.pdf.

BOX 6.1
Profiling the Atmosphere Using GNSS-RO

Radio occultation is a measurement technique dating back to the dawn of the space age when scientists at the National Aeronautics and Space Administration and Stanford University profiled the atmosphere of Mars during the Mariner IV mission in 1965. It took 30 years and the development of constellations of GNSS satellite systems to demonstrate the concept of GNSS radio occultation as part of the GPS-Met mission in 1995. GNSS-RO is an active limb sounding technique that relies on well-defined GNSS signals being tracked by receiving systems in low-Earth orbit (see Figure 6.1). As GNSS signals are tracked by a receiving instrument in low-Earth orbit, the geometry of the transmitter and receiver can be occulted by the Earth's limb. In these cases, the GNSS signal is bent as a function of the refractive index of the atmosphere that the signal passes through. The excess delay (in comparison to a signal traveling through a vacuum) caused by this bending can be computed when precise knowledge of the GNSS transmitter and low-Earth orbit receiver are known.

Data and derived products from the IGS facilitate the computation of excess delay from radio occultation missions through the accurate and reliable production of GNSS orbits and clocks. When dual-frequency GNSS occultation measurements are made, the data can provide vertical profiles of atmospheric pressure, temperature, water vapor, and total electron content from the atmospheric boundary layer through the troposphere, stratosphere, and ionosphere. The demonstrated precision of the technique (see Figure 6.2), along with its International System of Units traceability and stability, make it the most accurate measurement of atmospheric temperature from space (Anthes, 2008; Ho et al., 2010; Fong et al., 2019).

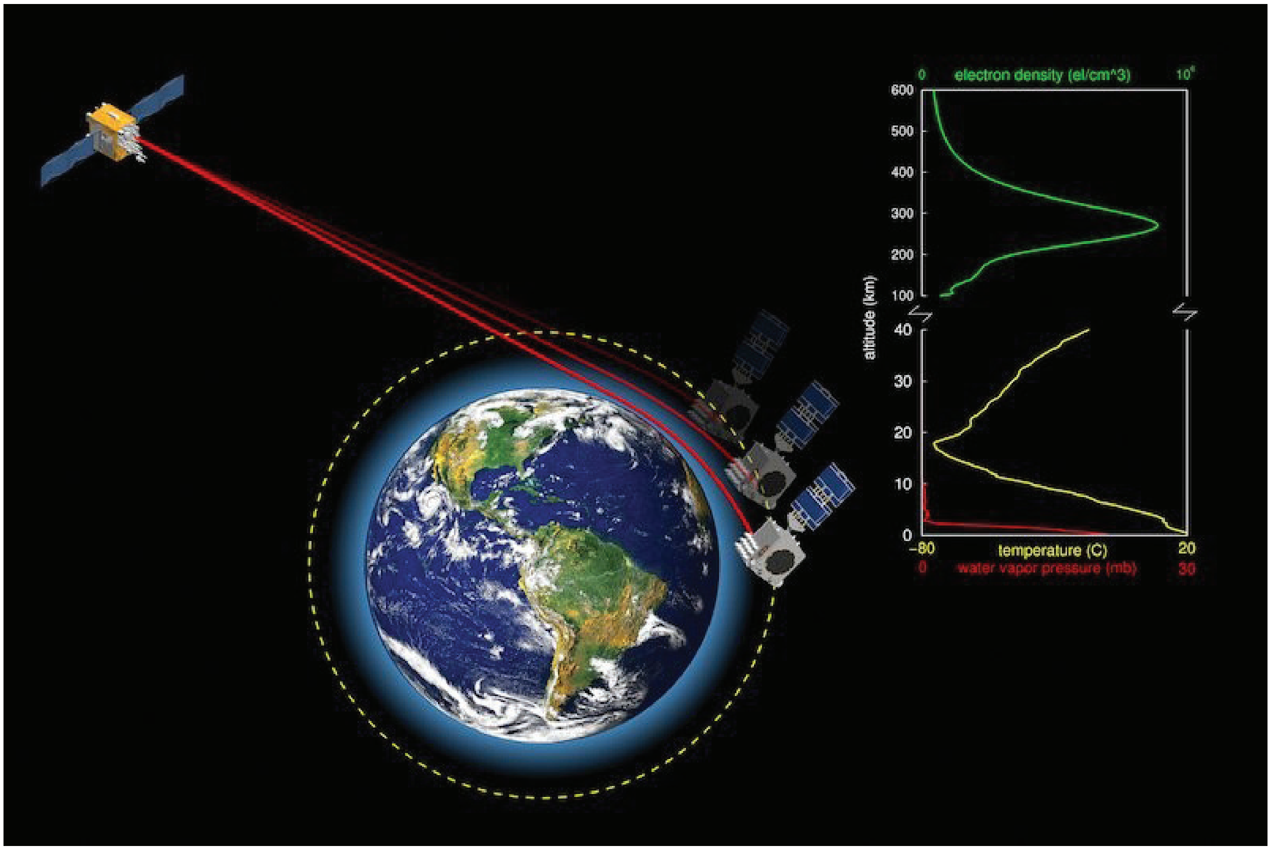

FIGURE 6.1 Geometry of limb sounding GNSS-RO measurements to measure atmospheric profiles of temperature (yellow), water vapor pressure (red), and electron density (green). SOURCE: https://www.cosmic.ucar.edu/what-we-do/cosmic-2.

continued

BOX 6.1 Continued

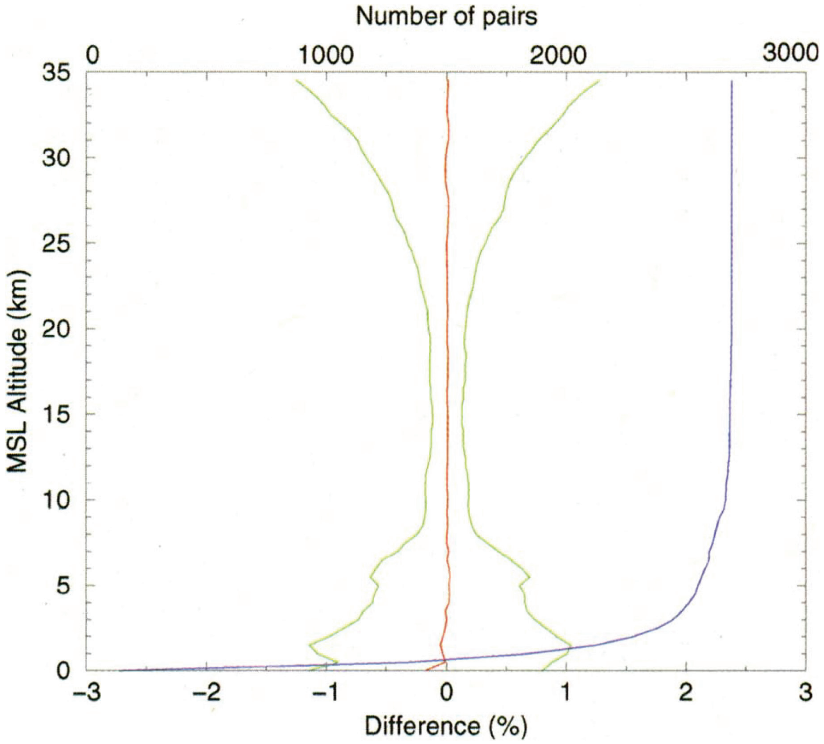

FIGURE 6.2 The precision of the index of refraction based on near-repeat occultations from two of the Constellation Observing System for Meteorology Ionosphere and Climate (COSMIC)-1 satellites. The red line shows the mean difference and the green lines show the standard deviation in percentage of difference. The number of paired occultations decreases at altitudes less than 5 km because of GNSS tracking errors, super refraction of the atmosphere, and low signal-to-noise of attenuation of the GNSS signal in the lower atmosphere. SOURCE: Anthes et al., 2008.

As the number of GNSS transmitters increases, so does the potential for GNSS-RO. Figure 6.3 illustrates the expected daily distribution of occultations from the COSMIC-2 mission, launched in June 2019. The quasi-random distribution of these measurements over the Earth means that remote ocean areas that are largely inaccessible by in situ measurements are sampled. The latitudinal distribution of the occultations in Figure 6.3 is a function of the 24° inclination of the COSMIC-2 satellites.

BOX 6.1 Continued

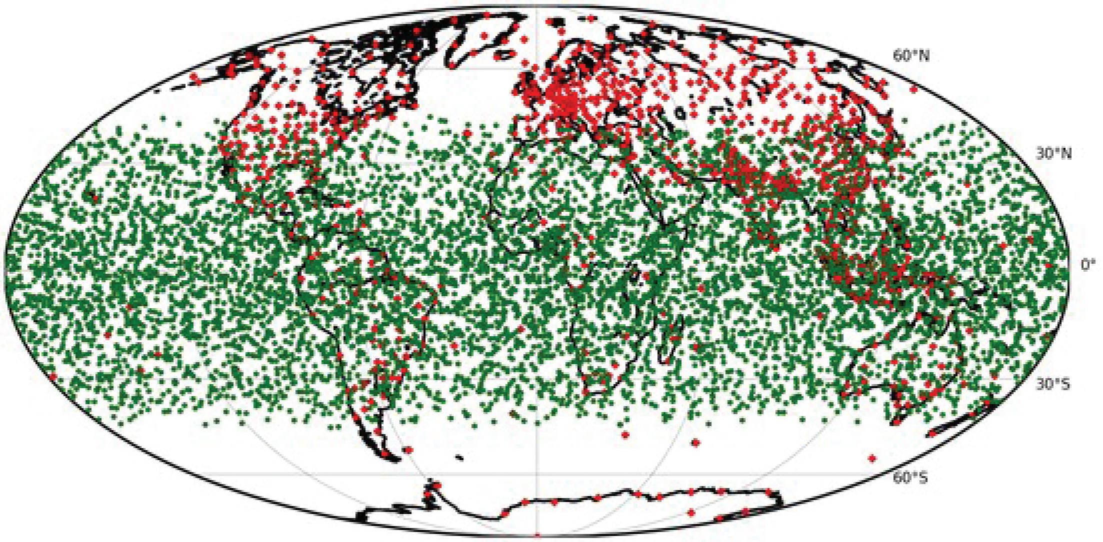

FIGURE 6.3 Locations of 4,000 occultations (green) for the COSMIC-2 constellation of 6 GNSS receivers orbiting at an altitude of 500 km and an inclination of 24°. Ground-based radiosonde locations (red) only sample the atmosphere above land. SOURCE: https://www.cosmic.ucar.edu/what-we-do/cosmic-2.

Measurements

The basic geometry of the RO measurement is described in Box 6.1. Once the ray path reaches the top of the atmosphere any error in the clocks or positions of the satellites maps directly into an error in the total path delay, which becomes an error in the retrieval of the vertical profiles of temperature, water vapor pressure, and, to a lesser extent, the total electron content of the ionosphere (Kuo et al., 2004). Determining clock error estimates at intervals of 1 second enables single differencing to remove receiver errors, resulting in a significant reduction in random noise. This is particularly important for refractivity retrievals above 30 km (Schreiner et al., 2010).

Geodetic Needs

As discussed in the section "GNSS For Atmospheric Sounding," a significant advantage of GNSS-RO with respect to other satellite and ground based measurements is that it is not necessary to cross-calibrate sensors over time because GNSS-RO depends on accurate measurements of travel time and satellite orbits. Therefore, RO is critically dependent on the geodetic infrastructure through its ability to provide precise and accurate GNSS satellite orbits and clocks. These geodetic products are used to estimate the low-Earth orbit satellite orbit and clocks, and to remove the geometric portion of delay from the RO signals. Maintaining the climate record also depends on the maintenance and long-term stability of the terrestrial reference frame (TRF) and enhancements in the GNSS satellite and processing systems. Other needs include

- Upgrading the global IGS sites (hardware and products) to achieve GPS-like accuracies in the other constellations (e.g., Galileo, Glonass, and Beidou; Steigenberger et al., 2015). This upgrade is important because it would result in an increase in the number of GNSS satellites used for making occultation measurements.

BOX 6.2
Predicting Precipitation Events in Western North America: Atmospheric Rivers

Atmospheric rivers are narrow corridors of water vapor transport typically associated with a low-level jet stream ahead of a cold front. In the Eastern Pacific, they make landfall along the west coast of North America (Neiman et al., 2008; Wang et al., 2019; see Figure 6.4), and deliver long-duration heavy precipitation. The heavy precipitation produces beneficial increases in the snowpack and water supply in California, but can also cause damage from extreme winds and flooding. Predicting the onset, duration, and amount of precipitation of these events is therefore critical for water resource management and emergency preparedness. Microwave satellite sensors such as the Special Sensor Microwave Imager (SSM/I) can resolve the filamentary structure of atmospheric rivers and their extent and motion, but not their vertical structure. However, GNSS-RO soundings from COSMIC-1 provide high-resolution vertical profile information not available in the numerical weather models based mostly on the SSM/I data (Neiman et al., 2008; see Figure 6.4). In particular, GNSS-RO soundings provide enhanced vertical resolution for intense events, especially in the lower atmosphere, where atmospheric rivers have the highest concentration of water vapor and satellite water vapor measurements have lower accuracy.

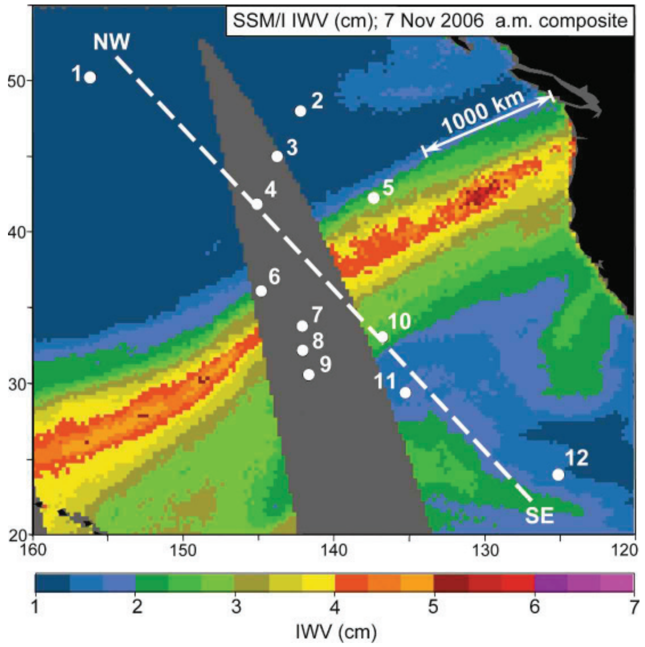

FIGURE 6.4 Color image of integrated water vapor (IWV) from SSM/I shows an atmospheric river flowing across the Eastern Pacific Ocean and making landfall along the west coast of North America. Axes are latitude and longitude. This sensor recovers the vertically integrated total water vapor but does not recover the vertical structure. White dots are the locations of 12 COSMIC-1 soundings. These were used to assemble the water vapor cross-section shown in Figure 6.5. SOURCES: Republished with permission of American Meteorological Society, from Neiman et al., 2008; permission conveyed through Copyright Clearance Center, Inc.

BOX 6.2 Continued

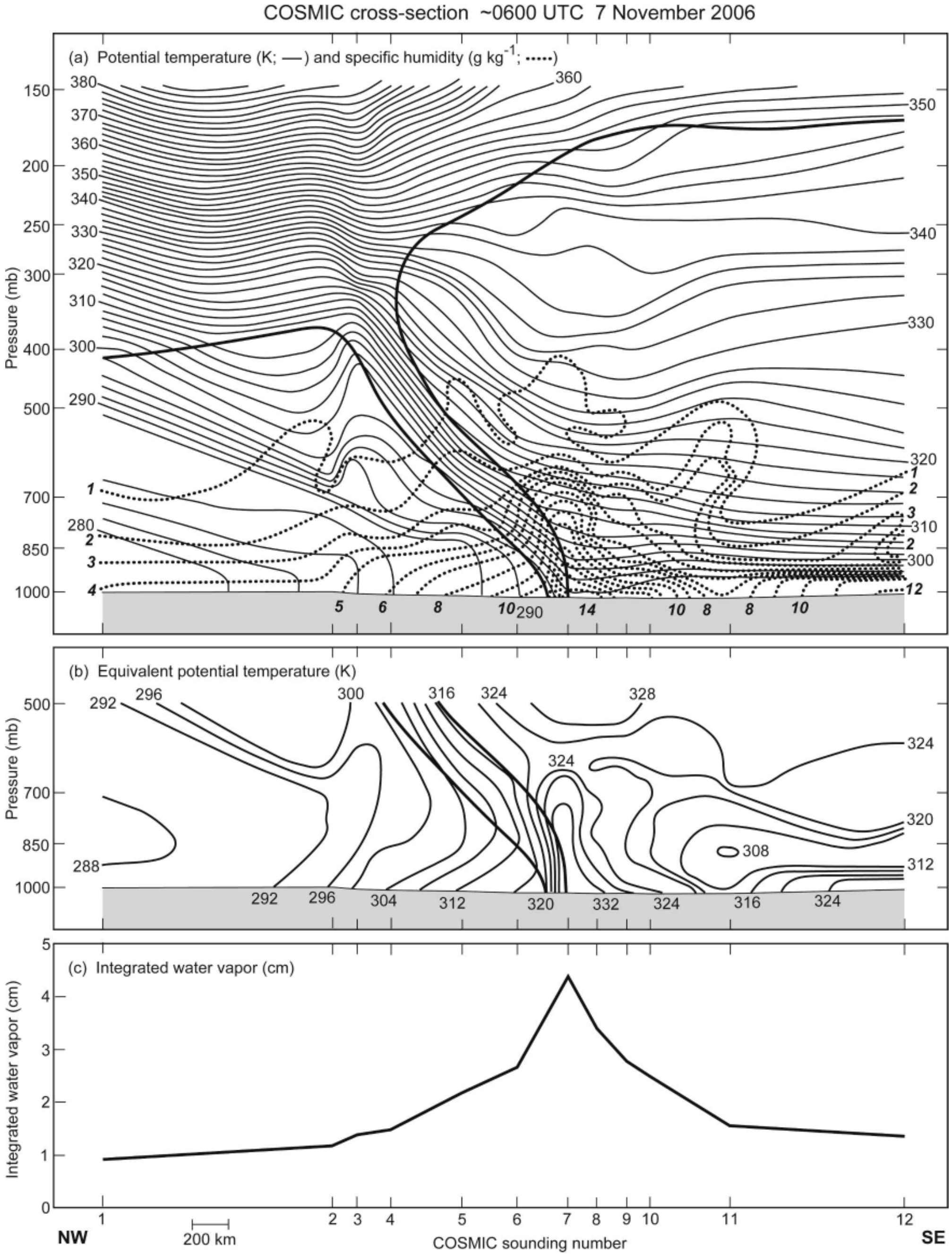

FIGURE 6.5 Cross-section of atmospheric parameters of potential temperature and specific humidity derived from 12 COSMIC-1 soundings reveals the vertical structure of the water vapor associated with the low level jet. The integrated water vapor (lower) has a maximum roughly matching the location of the peak in the SSM/I image. SOURCES: Republished with permission of American Meteorological Society, from Neiman et al., 2008; permission conveyed through Copyright Clearance Center, Inc.

- Improve the modeling of non-GPS GNSS observables within geodetic analysis systems, including transmitter attitude information, satellite metadata, and radiation force models.
- Improving GNSS clock accuracies over the 0.5–30 sec time span to improve temperature and water vapor profiles (Schreiner et al., 2010).
- Increasing GNSS sampling rate to 2 Hz from the standard 1 Hz at IGS sites to minimize clock interpolation errors.
- Encouraging multi-GNSS (e.g., GPS, Galileo, Glonass, and Beidou) analysis of orbits and clocks by U.S. groups.
- Improving global GNSS coverage by adding ~10 GNSS sites on remote islands, ocean mooring sites, and ice sheets. These additional sites will improve estimates of integrated water vapor, especially at high latitudes.
- Collocating the Global Climate Observing System Reference Upper-Air Network (GRUAN) and space geodetic infrastructure sites (GNSS, Very Long Baseline Interferometry, Satellite Laser Ranging) for mutual calibration and validation.

REDUCING UNCERTAINTY IN CLIMATE PROJECTIONS

Question C-2 concerns reducing uncertainty in projections of global warming to better understand future economic impacts and to devise appropriate adaptation and mitigation strategies. Surface air temperature is not a robust measurement for monitoring global warming because the spatial pattern of temperature variations is highly variable and is not well resolved by the current distribution of ground stations (Leroy et al., 2006). Because of its high accuracy, lack of observational drift, and bias-free nature (Anthes et al., 2011), GNSS-RO has been colloquially termed the most accurate thermometer in space. GNSS-RO can provide critical measurements of atmospheric temperature and pressure in the 5–20 km altitude range where there are less spatial and temporal variations to obscure the longer-term climate signal (NASEM, 2018). In the lower troposphere, GNSS-RO can be used to retrieve atmospheric water vapor profiles, including boundary layer water vapor, providing essential water vapor information throughout the globe. It is also complementary to other satellite sensors, such as infrared and microwave sensors.

Figure 6.6 illustrates the sensitivity of the change in atmospheric pressure versus time for each of the 12 climate models used in the IPCC Fourth Assessment. The models are all similar in the troposphere (<10 km) but are very different at the 20 km altitude range where GNSS-RO has its highest sensitivity. Leroy et al. (2006) showed that GPS-RO measurements could discriminate among the 12 models at 95 percent confidence in 7 to 13 years. They also found that the strongest indicator of atmospheric climate change in the data is the poleward migration of the midlatitude jet. The ability to use GNSS-RO to assess the accuracy of climate models and to track changes in features such as the midlatitude jet are just two examples of the contribution of GNSS-RO for monitoring climate change.

Measurements

Same as for "Improvements in Weather Models."

Geodetic Needs

Same as for "Improvements in Weather Models."

SUMMARY

A robust and resilient geodetic infrastructure has underpinned the rapid GNSS-RO progress in both numerical weather prediction and climate applications since the 1990s. It is essential that this infrastructure is maintained and developed, in order to continue to exploit this observation type and take advantage of new opportunities, such as the availability of more GNSS systems. GNSS-RO measurements rely on accurate clocks and orbits of the GNSS constellations, which in turn rely on the geodetic infrastructure. The sheer number of RO per day requires a fully automated system with frequent updates of clocks and orbital information. Maintaining absolute accuracy over perhaps hundreds of years will require a stable TRF, precise orbits for the GNSS satellites as well as the low-Earth orbiting satellites, and a consistent approach to antenna models and data processing. In addition, a workforce with the appropriate technical capacity and institutional knowledge needs to be trained and maintained. The following summarizes needs for maintaining or enhancing the geodetic infrastructure, and related improvements to enhance scientific returns.

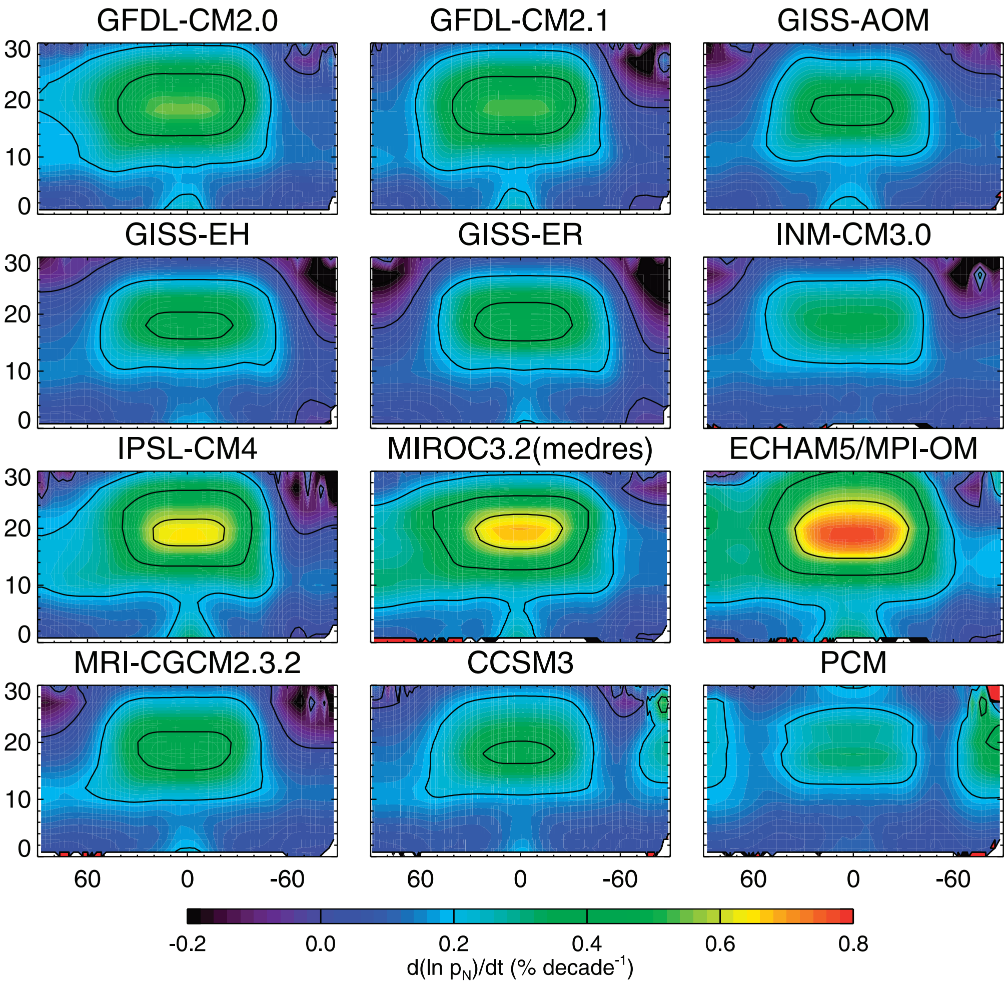

FIGURE 6.6 Yearly change in dry atmospheric pressure based on the 12 climate models used in the IPCC Fourth Assessment. The horizontal axis is latitude and the vertical axis is geopotential height. Contours are percent per decade. Model projections are similar in the troposphere (<10 km) but have large differences in the upper atmosphere where GNSS-RO has its highest measurement accuracy. SOURCE: Leroy et al., 2006.

Maintenance of the Geodetic Infrastructure

- Maintain robust global distribution of GNSS stations providing free, open, and near-real-time raw observational data.
- Continued support of IGS analysis products, including accurate orbits and clocks.
- Maintain geodetic expertise for institutional knowledge and availability of trained personnel. This will require stable and predictable funding.

Enhancements to the Geodetic Infrastructure

- Upgrade the global IGS sites (at least the National Aeronautics and Space Administration sites) to achieve GPS-like accuracies for the other constellations (e.g., Galileo, Glonass, and Beidou). In addition, improve the modeling of GNSS observables within geodetic analysis systems, including attitude information, satellite metadata and radiation force models. A significant upgrade would result in an increase in the number of radio occultations for weather and climate applications.

Related Improvements to the Geodetic Infrastructure to Enhance Scientific Returns

- Improve the GNSS instrumentation on the low-Earth orbiting satellites and IGS sites to include Navigation Data Message data collection (for RO open-loop processing).
- Deploy surface meteorology (pressure/temperature) sensors at core sites.

- Provide an integrity check for near-real-time clocks.
- Improve GNSS clock estimation from 0.5–30 sec time scales.
- Co-locate some IGS core sites with the GRUAN sites for mutual calibration and validation.
- Install GNSS on ocean platforms (~10) to calibrate satellite observations of integrated water vapor as well as to support studies of air-sea fluxes.
- Use the global GNSS constellation and low-Earth orbiting satellites to improve ionospheric models.
- Use ionosphere models developed by the space weather community to develop geodetic products. These products could be better than IGS Global Ionospheric Total Electron Content Map products and thus could be used for ionospheric corrections to single frequency Interferometric Synthetic Aperture Radar measurements.

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7

Ecosystems

Ecosystems supply the services on which all life depends. Understanding how ecosystems are changing and how these changes influence the Earth system are important for sustaining life on the Earth. Observing and understanding ecosystems and their change is both a major theme in the Decadal Survey (NASEM, 2018) and a key component of a broad range of science and application questions in the report. This chapter describes the geodetic infrastructure required to meet new scientific needs related to ecosystem science. The ecosystems-related science questions which use active remote sensing and thus rely on the geodetic infrastructure are:

E-1. What are the structure, function, and biodiversity of the Earth's ecosystems, and how and why are they changing in time and space?
E-2. What are the fluxes (of carbon, water, nutrients, and energy) between ecosystems and the atmosphere, the ocean and the solid Earth, and how and why are they changing?
E-3. What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing?
E-4. How is carbon accounted for through carbon storage, turnover, and accumulated biomass? Have all of the major carbon sinks been quantified and how are they changing in time?
S-4. What processes and interactions determine the rates of landscape change?

The geodetic needs associated with each question appear in the Ecosystems Science and Applications Traceability Matrix (see Appendix A, Table A.5). In this chapter, the discussion of geodetic needs is organized around four themes: vegetation dynamics; lateral transport of carbon, nutrients, soil and water; global soil moisture; and permafrost and changes in the Arctic.

VEGETATION DYNAMICS

Understanding vegetation dynamics, including structure and function, requires a knowledge of the three-dimensional structure of terrestrial and aquatic vegetation over space and time (e.g., Pugh et al., 2019). Previous studies have demonstrated the efficacy of lidar and radar for quantifying forest and aquatic biomass (Liu et al., 2015; Du et al., 2017), characterizing rangeland (Streutker and Glenn, 2006), estimating vegetation height (Hopkinson et al., 2005), monitoring (Rosso et al., 2006), and assessing biodiversity and habitats (Bergen et al., 2009). In addition, optical, lidar, and radar (active and passive) are important for monitoring essential biodiversity variables (Vihervaara et al., 2017; see Box 7.1). Interferometric Synthetic Aperture Radar (InSAR) and Polarimetric SAR Interferometry (Pol-InSAR) are the primary radar techniques used to obtain vegetation structure as well as to understand change over time (Ghasemi et al., 2011; Berninger et al., 2018).

In addition to active radar techniques, passive microwave satellite (using vegetation optical depth) and Global Navigation Satellite System Interferometric Reflectometry (GNSS-IR) data have been found useful for understanding changes in land surface phenology (Jones et al., 2013; Chaparro et al., 2018). GNSS-IR uses ground GNSS receivers to measure the reflection amplitude, which is used for vegetation studies. However,

BOX 7.1
Forest Height

Forest above-ground biomass is recognized as an essential climate variable because it controls land uptake of CO_2. Quantifying biomass loss from deforestation and degradation at a global scale requires satellite-based lidar or Synthetic Aperture Radar (SAR). New radar satellite missions, such as the National Aeronautics and Space Administration-Indian Space Research Organisation Synthetic Aperture Radar (NISAR) and the European Space Agency Biomass mission, are aimed at determining the global distribution of forest biomass. A range of SAR techniques can be used to characterize forests, including P-band Polarimetric SAR, Pol-InSAR, and SAR Tomography. For example, forest height can be derived from Pol-InSAR by inversion, as illustrated in Figure 7.1. In this map, much of the area is covered by mangrove forests.

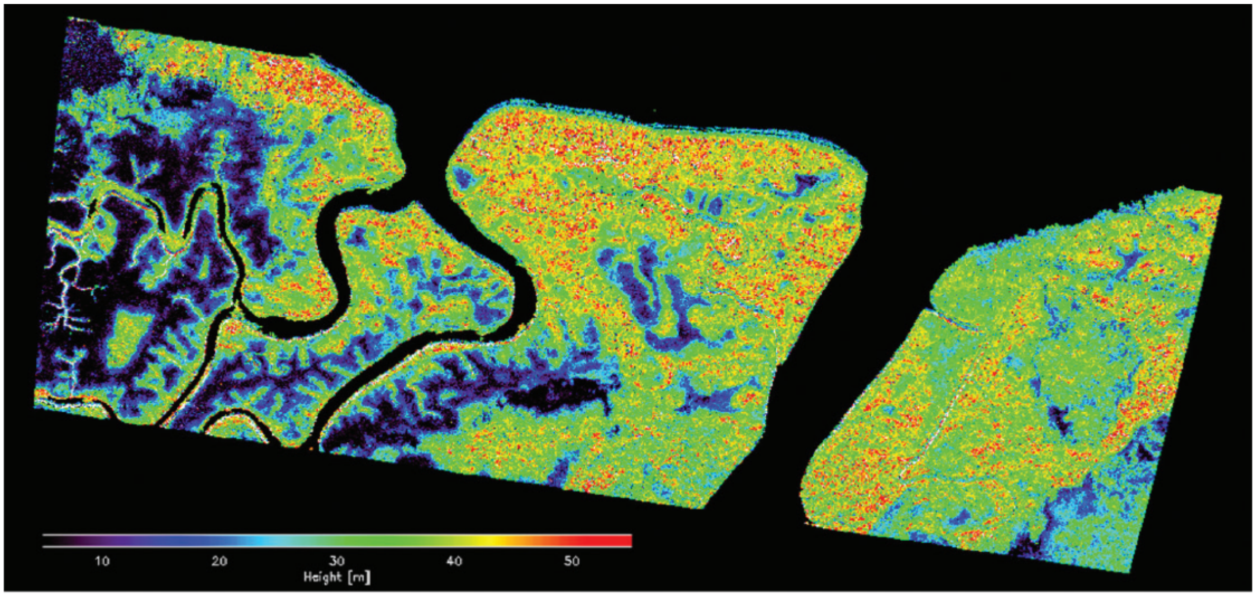

FIGURE 7.1 Forest height map obtained by inverting P-band Pol-InSAR data from Pongara National Park, Gabon. Color ramp represents forest height with much of the area covered by mangroves. SOURCE: Reprinted from Quegan et al., 2019, with permission from Elsevier.

the utility of GNSS-IR signals for estimating vegetation water content changes (Small et al., 2014) and for studying drought (Small et al., 2018) is an emerging area of study. Amplitude reflections from GNSS Reflectometry (GNSS-R) are sensitive to changes in soil moisture and inundation and thus can be used for mapping wetland ecosystem dynamics (Jensen et al., 2018). While global lidar is not yet available, tropical and temperate forest structure will be measured at roughly 1 km by the Global Ecosystem Dynamic Investigation (GEDI) on the International Space Station (Qi et al., 2019).

Measurements

The vertical accuracy of data from the technologies mentioned previously is a distinguishing characteristic that dictates the horizontal and vertical scales at which vegetation structure and function can be studied (see Figure 7.2). For example, to obtain vertical vegetation structure and derivatives, scientists require lidar (or SAR) with <1 m vertical resolution in forested ecosystems and <0.30 m vertical resolution in dryland ecosystems. For these studies, accuracy and scale depend strongly on land cover and microtopography (e.g., Glenn et al., 2011). For most ecosystems, a 0.1 m or better lidar bare-earth model is needed to derive many of the products necessary for understanding vegetation dynamics. Horizontal precision of lidar is required at roughly 1 m for bare-earth topography for canopy structure use. Annual repeats of airborne lidar surveys are needed, especially in areas with dynamic landscapes.

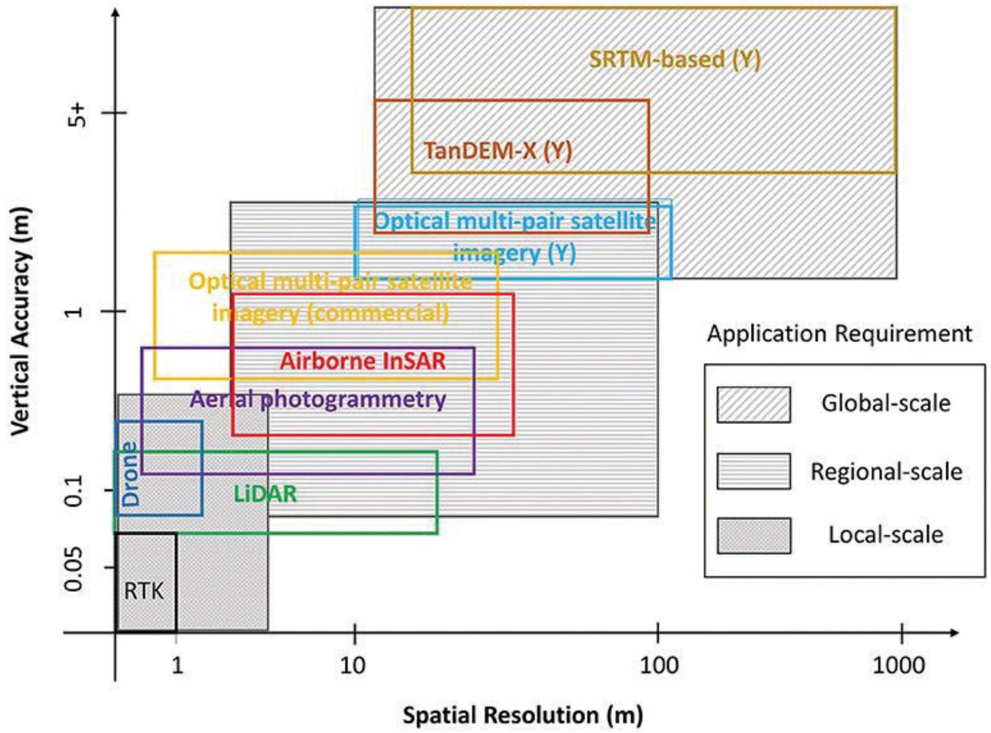

FIGURE 7.2 Sensors that provide digital elevation model data at varying spatial resolutions and vertical accuracies. NOTE: InSAR = Interferometric Synthetic-Aperture Radar; LiDAR = Light Detection and Ranging; RTK = Real-time Kinematic; SRTM = Shuttle Radar Topography Mission; TanDEM-X = TerraSAR-X's twin satellite. SOURCE: Schumann and Bates, 2018.

For regional studies that use SAR (L- and P-band), a 10-m global digital elevation model (DEM) is necessary to understand vegetation dynamics. A bare-earth DEM is used as a reference for SAR methods, but is less critical for Pol-InSAR methods. Necessary repeat periods for SAR data range from every 6 days to daily in high latitudes (for freeze-thaw applications, see "Permafrost and Changes in the Arctic" below). SAR data are also needed to augment the coarser sampling of GEDI for forest heights (see Figure 7.3).

Geodetic Needs

The measurements discussed above require maintenance of the current terrestrial reference frame (TRF) for precision positioning with lidar. In remote areas such as Alaska and the Arctic, more base stations (approximately every 30 km without L5 frequency or 50 km with L5 frequency) are needed to develop the 0.1 m lidar bare-earth topography model. L5 frequency is a GNSS frequency with improved signal strength. Tracking L5 in addition to L1 and L2 frequencies provides greater accuracy in these ionospherically active regions.

Determining water vapor from GNSS-derived total column water vapor and additional radio occultation (RO) measurements is needed for SAR correction. Recent simulations indicate that at least 20,000 occultations per day are needed (IROWG, 2017). For example, errors in water vapor will cause errors in biomass estimates. To derive vertical biomass structure using InSAR, the long-wavelength errors need to be reduced by staying within the critical baseline.

For ecosystem studies using GNSS-IR, it is important to configure the ground stations to remove elevation angle masks and to archive the required signal-to-noise ratio (SNR). The low elevation angle GNSS data provide the largest ecosystem footprints. GNSS networks installed by most geoscientists already store SNR data and track low elevation angle signals, and this needs to become standard practice. The GNSS-IR data will need to be augmented with soil moisture sensors distributed across environmental gradients to obtain more comprehensive information on ecosystems and soil moisture. These new products are also useful for calibration and validation of satellite missions.

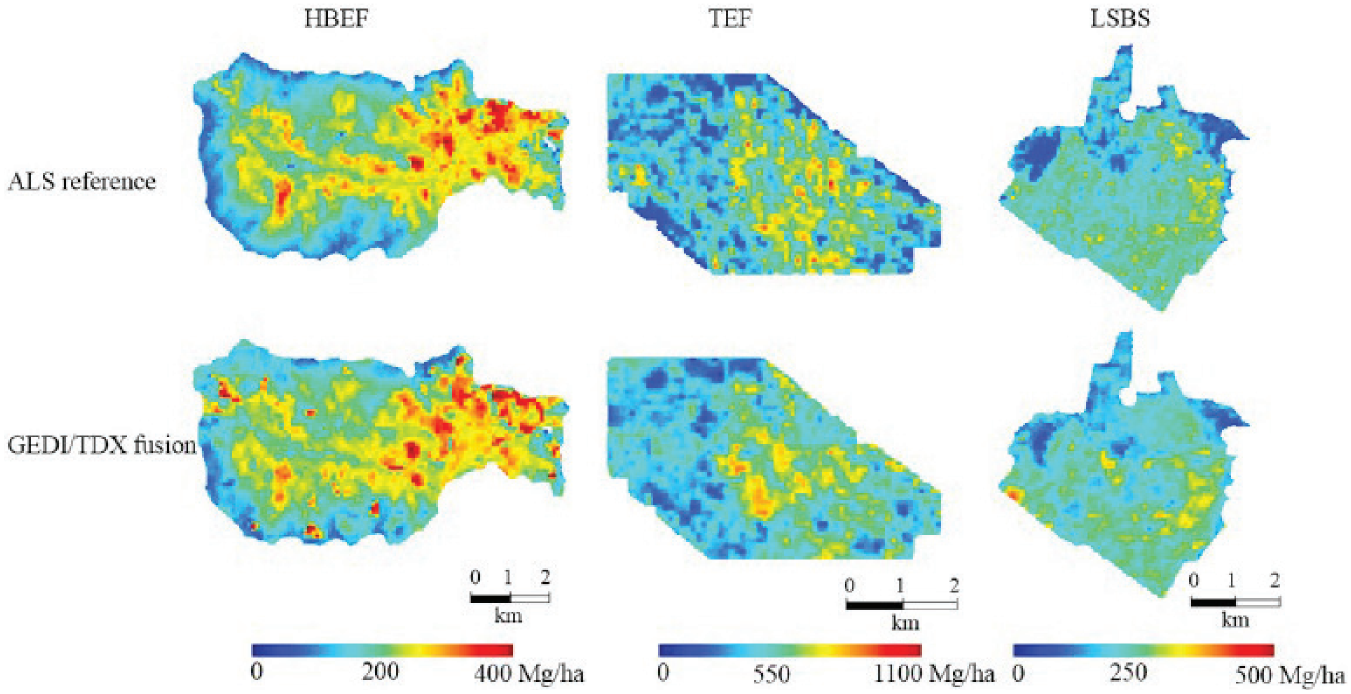

FIGURE 7.3 Airborne lidar (ALS) is used as a reference for biomass estimates from GEDI and InSAR data from TerraSAR-X (2007) and TanDEM-X (2010) (abbreviated as TDX). Simulated GEDI and TDX data were fused to estimate biomass at 1 km scales, with uncertainties ranging from 7 percent to 12 percent. The three areas shown above are the Hubbard Brook Experimental Forest (HBEF, New Hampshire), Teakettle Experimental Forest (TEF, California), and the La Selva Biological Station (LSBS, Costa Rica). SOURCE: Reprinted from Qi et al., 2019, with permission from Elsevier.

LATERAL TRANSPORT OF CARBON, NUTRIENTS, SOIL, AND WATER

Lateral transport of carbon, nutrients, soil, and water is a key process in the terrestrial carbon cycle. For example, mangroves are highly productive ecosystems that provide carbon storage as well as discharge terrestrial carbon to the ocean (Alongi, 2014). In terrestrial ecosystems, a recent satellite-based study showed that nutrients originating in the Sahara can travel thousands of kilometers and feed the Amazonian forest (Yu et al., 2015). Hillslopes and coastal erosion can transport substantial amounts of carbon (e.g., Naipal et al., 2018; Braun et al., 2019). Landslides, often triggered by weather events, transport rock and alter the Earth's surface (Hilley et al., 2004). An example is the Oso landslide (see Figure 7.4).

The lateral transport of carbon, nutrients, soil, and water can be quantified with geodetic techniques when the surface displacements are coherent. Particularly relevant are surface displacements associated with landscape change, including subsidence or uplift from volcanic or tectonic processes, and geomorphic (e.g., landslides, channel incision), hydrologic (precipitation, freeze/thaw, and snow accumulation and melt), cryosphere (e.g., ice streams and permafrost thaw), or ecological (e.g., vegetation structure) change. Measuring rates of landscape change and lateral processes, as well as the processes that drive changes, require mm- to m-level vertical and horizontal accuracies, depending on the process being measured (Lambin et al., 2003; Jorgenson and Grosse, 2016). The use of space based reflections (GNSS-R) is emerging as a critical measurement for studying lateral transport from landslides (Carlà et al., 2019) and wetlands (Jensen et al., 2018). For example, GNSS-R was used to understand inundation dynamics of wetlands in the Peruvian Amazon (see Figure 7.5). The variability of wetland extent and inundation plays an important role in ecosystem dynamics and ecosystem services. In addition, wetlands are the largest natural source of methane, contributing roughly 30 percent of global methane emissions (Kirschke et al., 2013), with substantial uncertainty associated with wetland extent (Saunois et al., 2016).

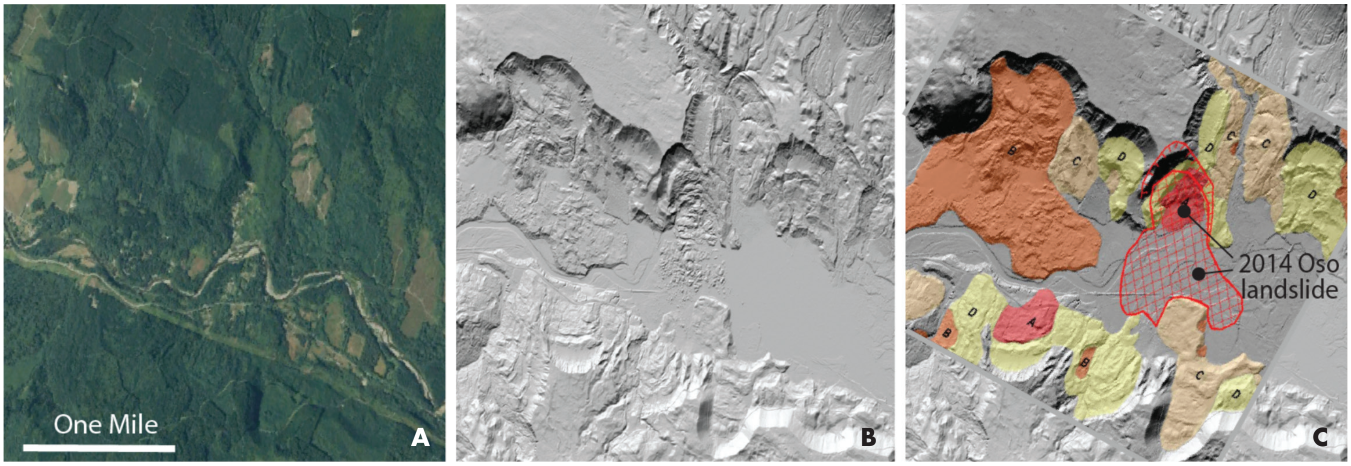

FIGURE 7.4 In the rain-soaked forests of Washington state (A), the density, extent, and frequency of destructive landslides were largely unrecognized until airborne lidar (B) was acquired after the 2014 Oso landslide, which killed 43 people. With vegetation removed, multiple generations of large landslides are obvious (C), and their relative ages are revealed both by cross-cutting relationships among them and by the relative roughness of their current topography. Older landslides become smoother over time. SOURCE: Haugerud, 2014.

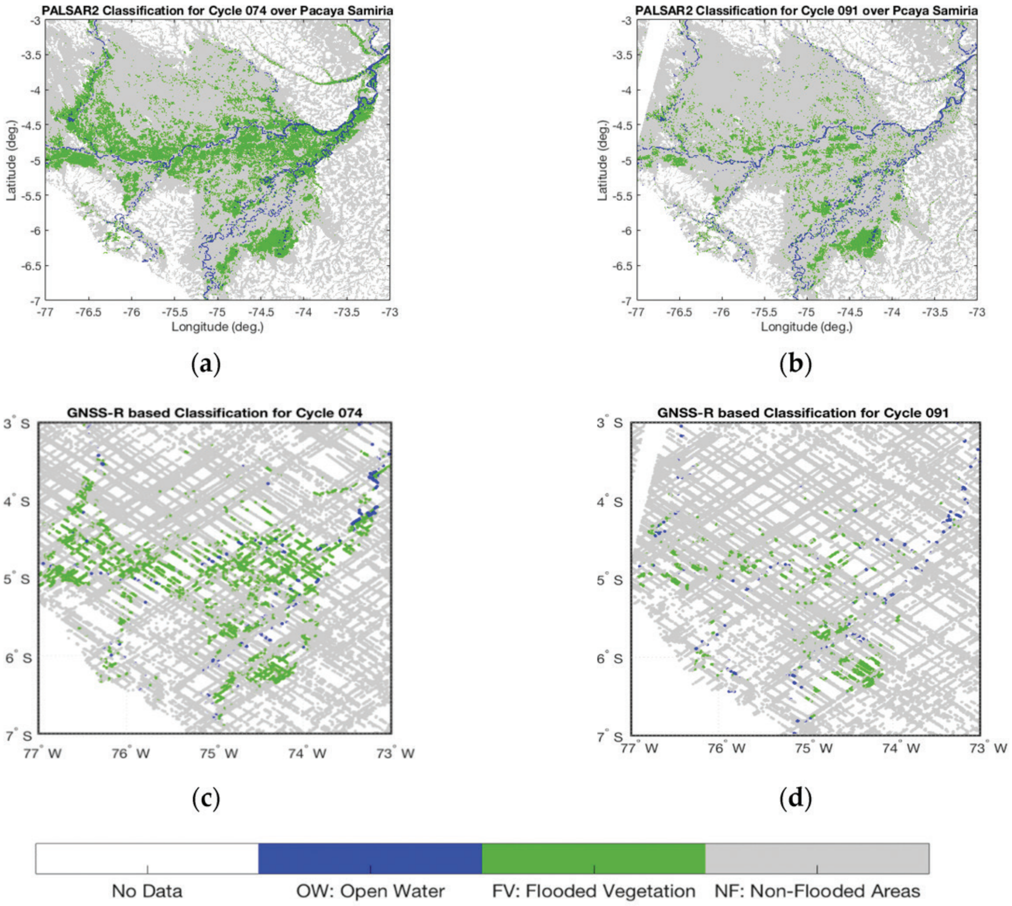

FIGURE 7.5 Inundation classification of tropical wetlands in the Pacaya-Samiria National Reserve in the Peruvian Amazon. PALSAR-2 (L-band SAR) cycles are compared to the Cyclone Global Navigation Satellite System (CYGNSS). In the top row are PALSAR-2 inundation reference maps for the end of the high-flood season (cycle 74, panel a) and the end of the low-flood season (cycle 91, panel b). In the bottom row are GNSS-R inundation classification results for cycle 74 (panel c) and cycle 91 (panel d). The CYGNSS results are shown at approximately 3 km for display purposes. SOURCE: Rodriguez-Alvarez et al., 2019.

Measurements

A key geophysical observable for understanding landscape processes is the change in bare-earth topography, that is, the change in the Earth's surface devoid of above-ground biomass. Recent studies have demonstrated the need for high resolution (<0.1 m) bare-earth topographic models for modeling mass transport across landscapes (Passalacqua et al., 2015), and for supporting sustained gravity measurements for assessing changes in water storage across space and time (Pail et al., 2015).

Vertical and horizontal measurements of landscape change depend on whether surface motions are uniform over a relatively broad area (e.g., earthquakes, volcanic inflation, and large landslides) or are highly localized (e.g., displacement of soil, rock, or vegetation on the surface). For broad areas where the surface remains coherent, GNSS-IR and repeat-pass InSAR are optimal techniques for measuring mm changes (see Chapter 5). However, InSAR cannot measure landscape change where the rock or soil is locally deformed because the reference and repeat images are decorrelated. Measuring this surface change is best done using repeat lidar measurements from spacecraft or aircraft.

Numerous studies have shown that repeat topographic surveys with spatial resolution of 1 m and vertical precision of 0.1 m can resolve most of the important landscape changes. The best global space-based topography grids are from the TanDEM-X mission, and they have a spatial resolution of ~10 m and measure the top of the canopy, rather than bare earth. The Ice, Cloud, and land Elevation Satellite (ICESat-2) laser altimeter would take more than 600 years to map the Earth at 1 m spatial resolution.[1] Development of a multibeam lidar (~1,000 beams) would reduce the mapping time to about 4 years, which is still inadequate to resolve many landscape processes. Given these constraints, the best way to obtain the necessary time series may be to acquire a global, baseline high-resolution topographic data set and revisit select areas using an airborne lidar having a 1 m resolution and 0.1 m vertical precision.

In coastal areas, the vertical measurement needs to have an accuracy of 0.1 m or better with respect to the TRF to provide a connection with absolute sea level. This accuracy requirement also covers coastal areas where permafrost soil has retreated. Achieving this accuracy using aircraft lidar will require deployment of several GNSS base stations within 30–50 km of the survey area, depending on whether the aircraft is tracking multi-GNSS.

Spatial and temporal requirements for lateral transport from a water budget perspective include improved measurements of evapotranspiration, snow, and water storage (Lettenmaier et al., 2015). Finer temporal and spatial scale gravity measurements are needed to capture basin geometry as well as to capture basins at high latitudes. Accurate fine-scale DEMs (<10 m) and GNSS every 100 km (or <50 km without Gravity Recovery Climate Experiment gravity measurements) are needed to help calculate better estimates of water storage change, especially in small- to mid-size basins, and thus to track lateral carbon exchanges (e.g., Knappe et al., 2018). Similarly, surface water measurements need to capture high temporal dynamics associated with processes such as flooding and wetland inundation. For these dynamic processes, Surface Water Ocean Topography measurements of 250 m × 250 m-sized water bodies (the science objective) can be spatially complemented with measurements from ICESat-2, GNSS-R, GNSS-IR, and the upcoming NISAR mission. Multiple pairs of satellites or reflections from closely-spaced GNSS stations are required to fully capture spatial and temporal dynamics. Estimates of lateral relocation of sediment, carbon, and nutrients from storm surges and other coastal processes could be improved by using GNSS-IR to measure water levels (Larson et al., 2017).

Geodetic Needs

Lateral transport studies require maintenance of the current geodetic infrastructure. The geodetic needs for both airborne lidar and GNSS are the same as for vegetation dynamics. Collocating GNSS and tide gauges at coastal sites, installing additional geodetic monuments, and using GNSS-IR to measure tides will support measurements of subsidence and coastal erosion for carbon storage changes. The geodetic needs for

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[1] Mapping the circumference of the Earth in meters requires 40,000,000 orbits. There are 14 orbits per day, so that is 7,600 years. ICESat-2 has 6 beams and there are ascending and descending tracks, so divide by 12 for 638 years.

InSAR are also similar to those discussed for vegetation dynamics, with the addition of daily observations in high latitudes (for freeze-thaw dynamics). The InSAR measurements of coherent surface motion will require orbits with precision of 20–40 mm across-track and 40–70 mm along-track, and additional RO measurements and total column water vapor from GNSS for water vapor determination. The geodetic needs for total and surface water storage require an increased number of closely-spaced GNSS stations (100 km or less).

GLOBAL SOIL MOISTURE

Soil moisture is an essential climate variable that modulates vegetation activity (Ali et al., 2015; Karthikeyan et al., 2017). Measurements of soil moisture are necessary to understand ecosystem function and critical zone processes, and they can be made using passive and active microwave. The radiometer on the Soil Moisture Active Passive (SMAP) mission enables global soil moisture measurements to be downscaled (Abbaszadeh et al., 2019) with up to 4 percent volumetric error in soil moisture. Recently, GNSS-IR signals have been used to estimate soil moisture (Chew et al., 2015). On space platforms, Carreno-Luengo et al. (2018) used CYGNSS, GNSS-R, and SMAP microwave radiometry brightness temperature to estimate soil moisture and distinguish land cover types across the globe.

Measurements

The footprint of each GNSS-IR soil moisture instrument is ~1,000 m^2. Thus, GNSS-IR is essentially a point measurement, similar to measurements from other continental-scale soil moisture networks, such as the U.S. Climate Reference Network. Nearly all GNSS-based studies of soil moisture have been made using instruments deployed for other purposes. For example, GNSS data from the Plate Boundary Observatory (PBO) were used in the PBO H2O project to create water cycle products (Larson, 2016). Because it met the 4 percent volumetric error accuracy requirement of the SMAP and Soil Moisture Ocean Salinity missions (Small et al., 2016), data from the PBO H2O project were also used for satellite validation (Al-Yaari et al., 2017).

A benefit of PBO H2O was that the GNSS sites were located in more diverse land cover than traditional soil moisture satellite validation sites, which are concentrated in agricultural areas. PBO H2O produced a 7-year record of volumetric soil moisture measurements at more than 125 GNSS sites in the western United States (Larson, 2016). An example of variations in soil moisture and its relationship to precipitation from spring to fall 2015 is shown in Figure 7.6. This project took advantage of the high-quality instrumentation and the coordinated archiving system used by the PBO project, which are not always available from other GNSS networks.

Geodetic Needs

Geodetic needs for global soil moisture measurements are similar to those described above for SAR and GNSS (see the section "Lateral Transport of Carbon, Nutrients, Soil, and Water"). SAR requires the current geodetic infrastructure to be able to precisely geolocate with GNSS/Galileo. GNSS-IR requires access to the raw GNSS observation files, SNR archive, and elimination of elevation angle masks. Current positioning initiatives indicate that more than 15,000 such sites are available on a daily basis worldwide. However, a global effort is currently limited by the lack of standardized community software for soil moisture retrievals. An increase in the number of GNSS sites in vegetated areas and in a range of biomes (e.g., savannahs and grasslands) are needed. The number of GNSS sites could be potentially increased by coordinating with the geological hazards community.

PERMAFROST AND CHANGES IN THE ARCTIC

The geodetic infrastructure plays an important role in understanding a wide variety of processes that operate at high latitudes (see Figure 7.7). A number of different remote sensing observations can be used to understand Arctic processes. For example, satellite gravity is used to measure rock-, soil-, water-, and ice-mass change in high latitudes (Talpe et al., 2017). Lidar and InSAR have been used to track subsidence in the Arctic (Stettner et al., 2017; Whitley et al., 2018). Understanding permafrost dynamics is essential for

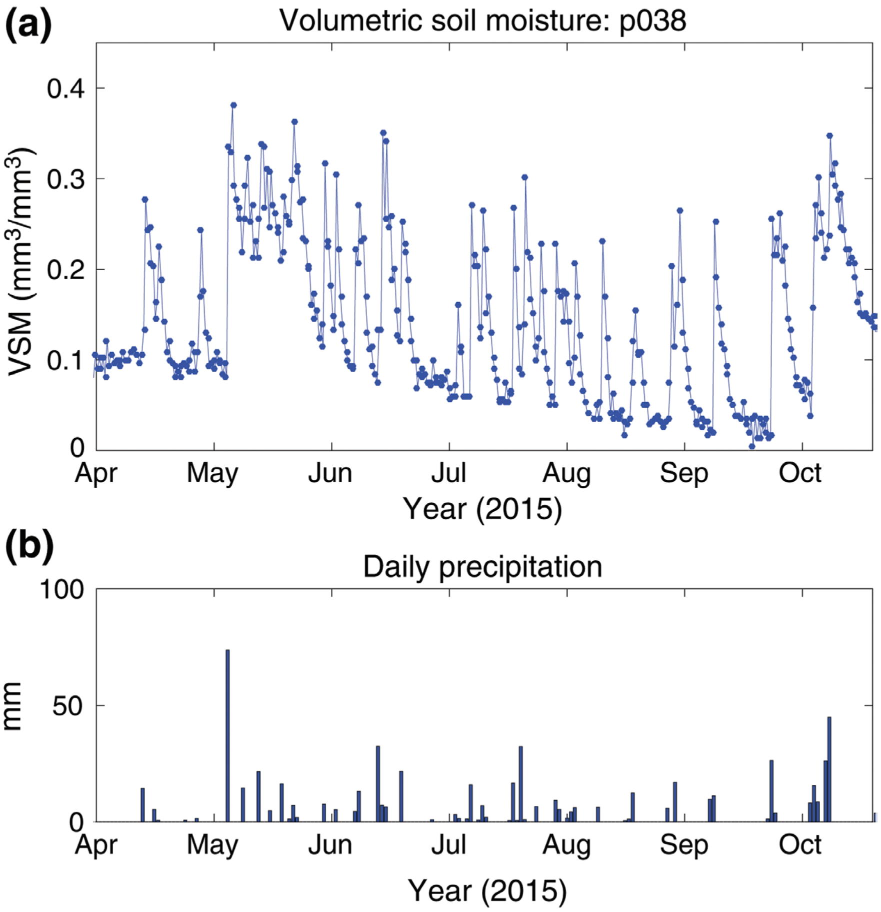

FIGURE 7.6 Volumetric soil moisture from GNSS-IR (a) and daily precipitation (b) for a PBO site in eastern New Mexico. SOURCE: Larson, 2016.

understanding carbon dynamics in the Arctic, including the vegetation growth period and soil respiration (Bloom et al., 2016; Nitze et al., 2018). Monitoring temperature transitions when large surges of melt water occur is important for Arctic marine communities (Frainer et al., 2017). In addition to gravity and InSAR, L-band radar backscatter is used to study freeze/thaw (Du et al., 2015); P-band is better for ice penetration (Gusmeroli et al., 2013). L-band and C-band coherence maps from NISAR and Sentinel-1, respectively, will be useful for studies of permafrost and freeze/thaw dynamics, such as noted in Rowland (2010). Compared with InSAR, GNSS-R and GNSS-IR offer enhanced temporal (daily) sensitivity for permafrost studies. The use of ground-based GNSS-IR for this application has been demonstrated for a site in Barrow, Alaska (Liu and Larson, 2018).

Measurements

SAR measurements with at least a 30 m spatial resolution are ideal, because of heterogeneity in the microclimate of the Arctic. Daily measurements are necessary to capture the temporal dynamics. Measuring finer-scale terrain deformation (e.g., ~10 mm-scale variations) using InSAR and airborne lidar is important for understanding some of the variability in the freeze-thaw zones. Repeat lidar surveys with precise relocation over time are necessary to capture permafrost thaw and the resulting mobilization of materials (Rowland, 2010). High-resolution DEMs are needed for vertical resolutions of frozen ground (Westermann et al., 2015). The timing of these measurements is critical because the transition from winter to spring to summer is when most of the dynamics can be accounted for. GNSS-IR requirements are the same as for soil moisture. Recent

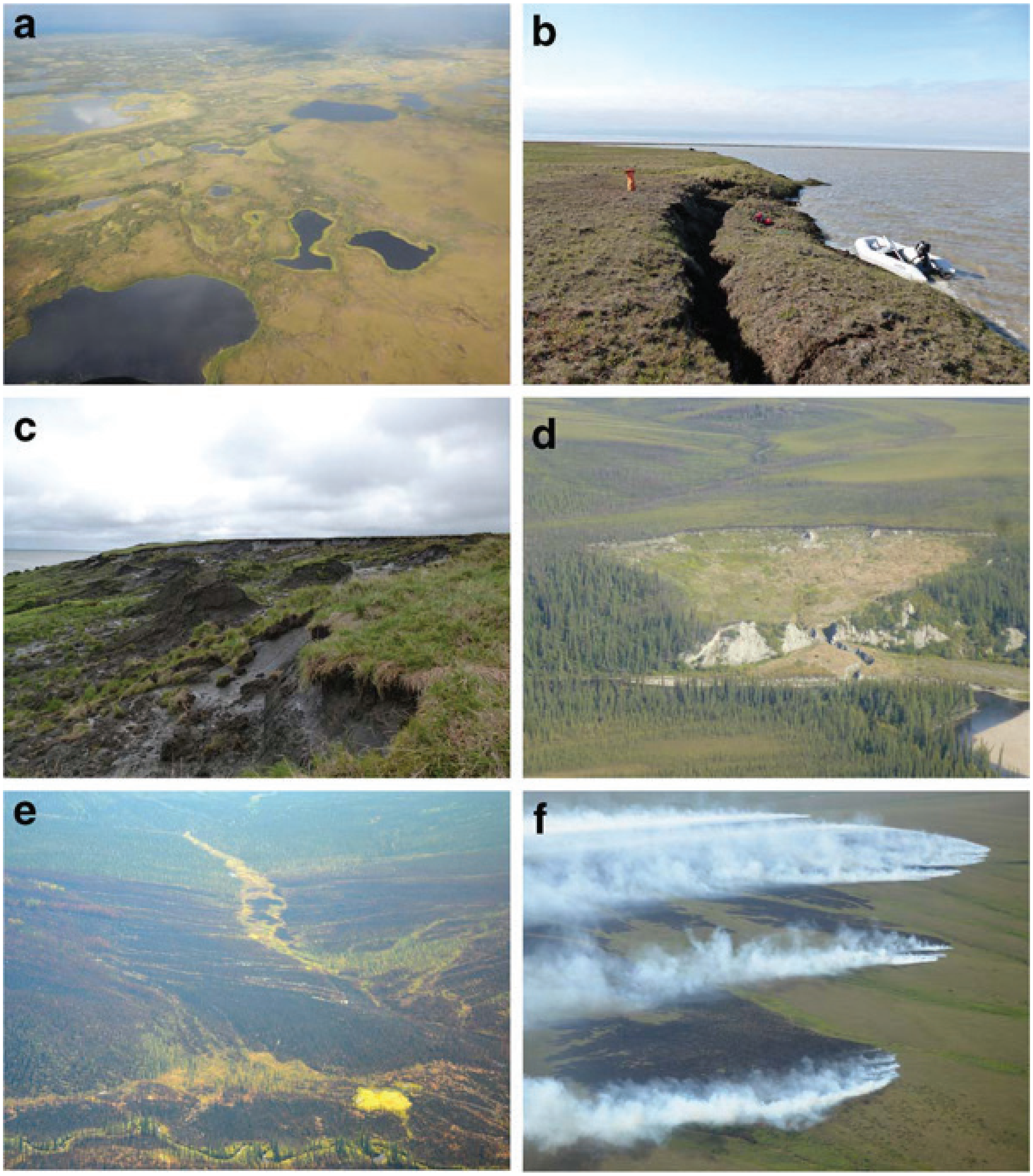

FIGURE 7.7 Examples of key disturbances causing degradation of permafrost. The top two rows show indicators of disturbance, including lake changes and mass wasting processes: (a) frequent lake drainage in western Alaska; (b) expanding Thermokarst Lake in northern Alaska; (c) thaw slump on Bykovsky Peninsula in northeastern Siberia; and (d) thaw slump in western Alaska. The bottom row shows triggers of permafrost degradation: (e) wildfire burn scar in boreal Alaska; and (f) burning tundra fire in northern Alaska. SOURCES: Nitze et al., 2018, with photos taken by M. Fuchs (a), I. Nitze (b–d), and B.M. Jones (e, f).

InSAR measurements of the freeze-thaw cycles in Tibet require relative orbital accuracies of better than 20–40 mm to recover the 10 mm annual signals (Daout et al., 2017).

Geodetic Needs

Airborne lidar, InSAR, and GNSS-IR measurements are needed for tracking permafrost and changes in the Arctic. The geodetic infrastructure requirements to support these measurements are the same as those for lateral transport of carbon, nutrients, soil, and water, and vegetation dynamics.

SUMMARY

Maintaining the current TRF is important for ecosystem science. Many measurements in ecosystem science require that the current precision of orbit determination be maintained. The application of GNSS to ecosystem science is emerging, and so the SNR from GNSS should continue to be archived. Sustained gravity measurements are also a priority.

New geodetic needs to help answer the ecosystem science questions in the Decadal Survey include increasing the number of GNSS stations across environmental gradients and placing these stations at locations with tide gauges and soil moisture sensors. These stations should also complement the scale at which gravity measurements are made (e.g., more stations are needed if gravity observations continue to be relatively coarse). In addition, many more RO measurements are needed to support water vapor observations. Land and vegetation topography at 1 m spatial and 0.1 m vertical resolution are needed, both weekly in areas dominated by change, and yearly for most other areas. Finally, cyberinfrastructure, analytical software, and tools, as well as the training to utilize them, need to be made widely accessible to the community, especially to early-career scientists. For example, while lidar and InSAR processing have become more user friendly in the past decade, training and processing software for GNSS reflections are not widely available. Additional support is needed to combine disparate data types (e.g., GNSS, InSAR, PolSAR, and lidar) to augment data gaps. Finally, cyberinfrastructure that allows easy access to pull or push data for processing (e.g., through application programming interfaces) is needed.

The following summarizes needs for maintaining or enhancing the geodetic infrastructure, and related improvements to enhance scientific returns.

Maintenance of the Geodetic Infrastructure

- Maintain the current TRF.
- Maintain orbit determination, with 10–20 mm orbit accuracy, 40–70 mm along-track accuracy, and mm/yr orbit stability.
- Sustained gravity measurements for an accurate geocenter.

Enhancements to the Geodetic Infrastructure

- Additional base stations in remote areas (every 30 km without L5 frequency or 50 km with L5), and more GNSS frequencies (e.g., L5 frequency and the receivers to support additional frequencies).
- Training and cyberinfrastructure to support adoption of above technologies.

Related Improvements to the Geodetic Infrastructure to Enhance Scientific Returns

- Additional GNSS stations (or in situ GNSS-IR) co-located with soil moisture sensors in diverse ecosystems and with tide gauges along coastlines in northern latitudes.
- Gravity every 100 km and GNSS every 50 km. GNSS needs include a regional network in northern latitudes (e.g., Alaska, which has synergies with tectonics applications), and increased temporal resolution (weekly to every 10 days) for monitoring water storage fluxes.
- Increased number of RO measurements and GNSS-derived total column water vapor for SAR and InSAR.

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8

Priorities for Maintaining and Enhancing the Geodetic Infrastructure

The previous chapters discussed the role of the geodetic infrastructure, its current state, and future requirements for answering selected science questions from the Decadal Survey (NASEM, 2018). The geodetic infrastructure required to help answer each of these science questions is given in Appendix A. This chapter identifies priority improvements to the geodetic infrastructure that would facilitate advances across those science questions (Task 4). These improvements are organized into five themes: (1) accuracy and stability of the terrestrial reference frame (TRF), (2) accuracy and stability of satellite orbits, (3) accuracy of the low-degree geopotential harmonics, (4) augmentation of the Global Navigation Satellite System (GNSS) station network, and (5) analytical support for an enhanced geodetic infrastructure.

ACCURACY AND STABILITY OF THE TRF

Questions on sea-level rise, terrestrial water cycle, and geological hazards require improvements in the accuracy and stability of the TRF. The most stringent science requirements are driven by sea-level science needs, which are quantified in terms of allowable errors in the rates of sea-level rise. We thus describe these limits in terms of reference frame accuracy and drift (see definitions in Box 1.2).

The sea-level science questions require a TRF accuracy of 1 mm and drift in the origin of the TRF of less than 0.1 mm/yr (or less than 0.02 ppb/yr in scale-rate equivalent). Meeting these requirements would allow global sea-level rise to be determined to an accuracy of better than 0.5 mm/yr over the course of a decade (Objective C-1a) and regional sea-level rise to within 1.5–2.5 mm/yr over the course of a decade (Objectives C-1d and S-3a). The TRF should be free of deformations due to ancient and modern ice melt that might cause errors in the regional patterns of sea-level change. The signals in the motion of the Earth's center of mass are expected to vary by as much as 50 mm in the next 100 years. There must be commensurate stability of the reference points for metrology at the fundamental sites, such as the invariant points of Satellite Laser Ranging (SLR) telescopes or Very Long Baseline Interferometry (VLBI) dishes, or the GNSS monumentation. This may require studies on the stability and longevity of monumentation and drifts or stability of the tracking equipment. Finally, the tide gauge record must be maintained to validate the satellite altimetry data in order to achieve 0.1 mm/yr accuracy in the altimeter measurements averaged over a decade (Objective C-1a).

The TRF accuracy and drift requirements are somewhat less stringent for the terrestrial water cycle and geological hazards questions. The water cycle questions require that the center of mass drift rate be maintained to better than 0.2 mm/yr (Objectives H-2b and H-2c). Monitoring surface deformation associated with geological hazards requires that the TRF be maintained at an accuracy of 0.5 mm/yr globally (Objectives S-1a, S-1b, S-2a, and S-2b). The current accuracy of the TRF is sufficient for the Decadal Survey weather and climate and ecosystems science questions.

Three areas of improvement in the geodetic infrastructure are needed to meet the above requirements.

First, despite long-standing efforts, the next-generation VLBI and SLR systems have either not been installed or have not been fully tested (see Chapter 2). Deployment of the new systems, particularly in the southern hemisphere, is critical for maintaining the highest accuracy of the TRF. The definition of the Earth's center of mass, especially in the Z-component, is especially dependent on successful tracking of SLR in the southern hemisphere. The National Aeronautics and Space Administration (NASA) will need to continue coordinating with international partners to improve the balance of fundamental stations with VLBI, SLR, and GNSS between the northern and southern hemispheres. Second, modeling of the center of mass motions expected over the next 100 years, due to the melting of the Greenland and Antarctic ice sheets, produces a large drift that can be monitored only if the monumentation of the fundamental sites remains stable over that time period (see Chapter 3). An assessment of the long-term stability of the monumentation may be required. Third, moving toward a fully time-dependent TRF would accommodate long-term (10–100 years) variations in the center of mass due to ice sheet melting, seasonal variations in the center of mass due to redistribution of water over the Earth, and short-term variations in the center of mass caused by large earthquakes and their postseismic deformation (Altamimi et al., 2019).

ACCURACY AND STABILITY OF SATELLITE ORBITS

The Decadal Survey science questions place different requirements on the accuracy and stability of satellite orbits. The highest accuracy of orbit determination is needed for low-Earth orbiting radar and laser altimetric satellites used to measure and interpret sea-level change and ice-sheet elevation changes (Objectives C-1a, C1-b, and C1-d). The requirements for their precision orbit determination act in concert with the requirements for TRF stability, particularly for measuring the rate of sea-level rise. Altimetric measurements with an accuracy of 20 mm or better and a stability of less than 0.5 mm/yr over a decade are required (Objectives C-1a and S-3a). The associated orbit determination requirements are 10–20 mm radial position accuracy. Three-dimensional orbit accuracy of better than 0.1 m is required for ice-sheet flow-rate measurements using Interferometric Synthetic Aperture Radar (InSAR; Objective S-3a).

The orbit determination and clock requirements for the weather and climate questions (Objectives C-2b, W-1a, and W-1b) are less stringent. For integrated water vapor, the GNSS orbits need a three-dimensional root mean square (RMS) accuracy of better than 50 mm in near-real-time and better than 25 mm post processing. For radio occultation, the low-Earth orbiting satellites need clock estimates every 30 seconds, with a velocity accuracy better than 0.5 mm/s RMS in near-real-time and better than 0.07 mm/s RMS post processing. Orbital accuracies need to be better than 0.21 m in real-time and better than 0.12 m post processing.

Orbit determination requirements for InSAR satellites are driven by terrestrial water cycle (Objectives H-2c, S-6a, and S-6b) and geological hazards (Objectives S-1a and S-1b) questions. Answering these questions requires sub-cm deformation measurements with high spatial density (<100 m), which can be achieved through a combination of GNSS stations having a spacing of better than 40 km and weekly InSAR coverage being provided by Sentinel-1 and soon NASA-ISRO Synthetic Aperture Radar (NISAR). The orbit accuracy requirements are similar to the requirements for satellite altimetry, with an accuracy of 20 mm radially and 60 mm along-track.

Enhancements to the geodetic infrastructure will be needed to meet the related requirement of bare-earth topography for geological hazards, vegetation structure, and carbon and water fluxes (Objectives E-1a, E-1b, E-2a, E-3a, S-1b, S-1c, S-2c, and S-4a), with 0.1 m vertical accuracy over selected tectonic areas and the attendant need for local GNSS ground stations for differential GNSS aircraft positioning better than 50 mm. For ecosystems science questions, maintenance of the current geodetic infrastructure is essential for delivering the current capability of 20 mm orbit accuracy and 40–70 mm along-track orbit position of lidar imaging (Objectives E-1a, E-1b, E-1c, E-1d, E-2a, E-3a, and S-4a).

ACCURACY OF THE LOW-DEGREE GEOPOTENTIAL HARMONICS

The same geodetic infrastructure and data (GNSS and SLR tracking) that provide the orbits for GNSS and altimeter satellites also enable determination of the long-wavelength components of the Earth's time-variable gravity field. The long-wavelength gravity field is needed for Decadal Survey questions related to determination of ocean mass (Objective C-1a), changes in ice sheets (Objective C-1c), temporal variations in total water storage of midsize basins (>200 km; Objective S-4a), and gravity change for large subduction zone earthquakes (Objectives S-1a and S-1b). The geodetic infrastructure enables a unique determination of the geocenter or degree-1 harmonics, provides validation for other long-wavelength components of the gravity field from dedicated gravity missions, and helps fill the gaps when no dedicated gravity missions are flying. Maintenance of the current geodetic infrastructure is essential for the continued availability of measurements of large-scale mass exchange in the Earth system.

AUGMENTATION OF THE GNSS STATION NETWORK

The stations of the GNSS network that define the global terrestrial reference frame must meet the highest standards for data quality, site design, stable monumentation, and metadata definition and dissemination. Global, national, and regional reference frame needs require a high-density network of such stations operating continuously, with a free and open dissemination of data with low latencies.

For the Decadal Survey science questions, the geographic coverage and density of the GNSS network are driven by the need to characterize large-scale plate boundary deformation and plate motions with an accuracy of 0.5 mm/yr (Objectives S-1a and S-1b). Tide gauges need to have co-located GNSS receivers that are part of this network. Reflectometric GNSS receiver installations can augment traditional tide gauges by simultaneously measuring sea level and vertical land motion (Objective C-1a). At regional and smaller scales, increased GNSS density is needed to calibrate InSAR and lidar techniques for terrestrial water cycle and geological hazards science questions (Objectives H-2a, H-2c, H-4a, S-1a, S-1b, S-1c, S-6a, and S-6b).

The terrestrial water cycle, geological hazards, and ecosystems chapters discuss the need for an increase in the density of core GNSS stations in the United States with good monument stability, long-duration time series (>10 years), and high data rate (~1 Hz). These stations would improve measurements of the elastic response of the Earth to changes in water loading (Objectives H-2b), provide measurements for correcting the long-wavelength errors in InSAR due to unmodeled atmospheric and ionospheric errors (Objectives E-1a, H-2b, S-1a, and S-1b), and allow estimation of soil moisture, snow water equivalent, and vegetation water content using reflectometry (Objectives E-1d and W-2a). In coordination with the International GNSS Service (IGS), these stations could become a permanent U.S. contribution to the global geodetic infrastructure.

In addition, having additional core GNSS receivers on remote islands or GNSS buoys would support climate change questions (Objective C-2b), and having them on ocean platforms would support seafloor geodesy and tsunami forecasting (Objective S-1d).

SUPPORTING SOFTWARE, MODELS, DATA, AND EXPERTISE

To gain the full benefit of enhancements to the geodetic infrastructure discussed above, software, models, open data archived to scientific specifications, and a skilled workforce have to be maintained.

Open Data, Cyberinfrastructure, and Workforce

Geophysical data analyses supporting Decadal Survey science questions must be able to utilize the International Terrestrial Reference Frame, which requires free, open, and timely access not only to the source geodetic data but also to high-quality software tools and automated processing. For example, GNSS applications connected to the terrestrial water cycle, geological hazards, atmospheric monitoring, and ecosystems require access to software for modeling or utilizing high-quality GNSS clocks and orbits, antenna phase center calibrations, software for GNSS reflections, and, in some cases, access to automated processing services. All software systems used by geodesists require high-quality metadata standards, which allow users to properly model changes at a site caused by changes in the equipment, firmware, or in some cases, the site itself (e.g., an earthquake). Similarly, InSAR applications connected to geological hazards, terrestrial water cycle, and ecosystems require open access to raw Synthetic Aperture Radar (SAR) data, accurate orbital information, and two or more open software developments to continue advancing InSAR as a geodetic tool similar to GNSS. An important component of both the GNSS and InSAR infrastructure is the development of new software delivery tools to make these data available seamlessly to more users. The dramatic improvement in satellite orbits and clocks has enabled automated processing of very large sets of repeated observations (e.g., SAR, optical, radar altimetry, and lidar) that was not possible just a few years ago. This advance is important because the data sets are too large for a human to be in the processing loop. A continued linkage between accurate orbits, models, and automated software will enable the improvement of climate models in the coming decades. Developments in cyberinfrastructure will require an evolving workforce that can maintain institutional knowledge and technical capabilities of the geodetic infrastructure and also work in close collaboration with the high-performance computing community.

Ancillary Corrections and Models

A significant component of the geodetic infrastructure is the ancillary corrections and models used to achieve cm-level accuracy for all the geodetic methods. These models need to be maintained for the continued accuracy of the TRF, but they also need to evolve as the time series are extended and the measurements improve. Three types of models are important: time-variable gravity, time-variable surface deformation, and atmospheric and ionospheric propagation models. A time-variable gravity model is needed to maintain the TRF as well as achieve the cm-level accuracies of the low-Earth orbiting geodetic satellites. Continuation of Gravity Recovery Climate Experiment (GRACE)-type missions is needed to augment the low-degree gravity variations that are determined from SLR analysis. Maintenance of time-variable gravity models is needed for sea-level change (Objectives C-1a, C-1c, C-1d, and S-3a), terrestrial water cycle (Objectives H-2b, H-2c, and S-6b), geological hazards (Objectives S-1b, S-1c, and S-2c), and ecosystems (Objective E-2c).

Time-variable surface deformation models are associated with numerous processes, including plate motions, large earthquakes, elastic loading from ocean tides, ice loss, redistribution of surface water, atmospheric pressure variations, and viscous rebound associated with glacial cycles. As discussed in Altamimi et al. (2019), these models are used to constantly update the TRF, so there is a close connection between TRF accuracy and model accuracy. Improving these models requires collaboration between the scientists who develop the models to understand Earth processes, and the geodesists who maintain the TRF.

Atmospheric and ionospheric propagation models are needed to correct path delays of all of the main components of the geodetic infrastructure: VLBI, SLR, GNSS, and Doppler Orbitography and Radiopositioning Integrated by Satellite. As discussed in Chapter 6 (weather and climate), the GNSS geodetic infrastructure is used directly to measure path-delay variables, such as integrated water vapor and total electron content of the ionosphere. Accurate atmospheric models (for altimeters, GNSS, and InSAR) are needed to maintain the accuracy of the TRF, which again requires close collaboration between the scientists and TRF geodesists.

Finally, an important enhancement to the GNSS infrastructure is to upgrade the global IGS sites (hardware and products) to achieve Global Positioning System (GPS)-like accuracies for the other constellations (e.g., Galileo, Glonass, and Beidou). A significant upgrade would result in a dramatic increase in the number of radio occultations for weather and climate applications. This requires the support of multiple GNSS analysis software systems within the United States and moving from current GPS-only orbit and clock production.

SUMMARY

All of the active satellite systems recommended by the Decadal Survey (e.g., SAR, radar altimetry, lidar, and radio occultation) rely on very accurate three-dimensional orbital information to obtain the required measurement of range change; the accuracy of the range-change measurement is directly related to the accuracy of the orbit. While some passive satellite systems do not need decimeter or better orbital accuracies to achieve their imaging requirements, the availability of accurate orbits has enabled fully automated processing and accurate geolocation, which increases the exploitation of the large data sets being collected by Decadal Survey missions.

The accuracy and stability of satellite orbits relies on the accuracy and stability of the TRF, which is derived from the geodetic infrastructure. The committee identified three areas of improvement in the geodetic infrastructure needed to help answer the Decadal Survey science questions:

1. **Finalize deployment and testing of next-generation VLBI and SLR systems and complete deployment of multi-GNSS to achieve a balance of geodetic measurement techniques between the northern and southern hemispheres, document the errors in the systems, and improve our ability to estimate their positions accurately and automatically.**
2. **Increase the capabilities for measuring the center of mass motions expected over the next 100 years, due to the melting of the Greenland and Antarctic ice sheets.**
3. **Work with the international community to implement a fully time-dependent TRF that will accommodate annual as well as sudden changes in the locations of the fundamental stations.**

The most stringent requirements for enhancements to the accuracy and stability of the TRF are driven by science questions related to sea-level change, ice-mass loss, and land-surface deformation associated with (a) the movement of water over the surface of the land, cryosphere, and oceans; and (b) the elastic and viscoelastic response of the solid Earth to water loading, earthquakes, and volcanic eruptions. If any of the associated flagship missions of the current NASA program of record (e.g., NISAR; Ice, Cloud, and land Elevation Satellite 2; GRACE-Follow On; and Surface Water Ocean Topography) had a failure of its on-board GNSS systems, it is not clear that the ground-based SLR tracking network (mostly international) would have sufficient capacity to handle the increased load.

Ground-based GNSS is essential for achieving the Decadal Survey science objectives related to sea level, cryosphere, terrestrial water cycle, weather, climate, geological hazards, and ecosystems. The density of core GNSS stations needs to be increased in high priority regions, including plate boundary zones to capture the earthquake cycle, coastlines to capture land motion that could affect sea-level impacts and coastal ecosystems, and regions with substantial terrestrial water storage. In addition, the United States will need to work with the International GNSS Service to deploy additional GNSS sites in remote, rapidly deforming areas, such as the perimeters of the ice sheets that deform by changes in mass loading. Such sites need good monument stability, long duration, and high data rate and availability. The U.S. stations should be considered part of the U.S. geodetic infrastructure, open to everyone, and thus have long-term financial support. Many of these stations already exist, but they are supported mainly through the National Science Foundation and thus long-term funding is not guaranteed.

Maintaining and enhancing the geodetic infrastructure to compute the TRF, satellite orbits, and other products requires complex software systems developed over decades by teams of scientists and engineers. The software systems ingest both the raw measurements from the geodetic infrastructure and models for the steady and tidal deformation of the Earth and for propagation of the electromagnetic waves through the ionosphere and atmosphere. The most important aspects of this activity are that all of the raw data are completely open and that there is cross-checking by at least two independent groups using largely independent and open software. Needless to say, this relies on a skilled geodetic workforce. Unfortunately, several federal agencies noted the difficulty of finding scientists and engineers with the skills needed to replace the pool of aging geodesists. On-the-job training of graduate students is becoming increasingly important for agencies involved with the geodetic infrastructure.

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Appendix A

Science and Applications Traceability Matrixes

A key element of the Decadal Survey (NASEM, 2018) was the science and applications traceability matrixes (SATMs), which trace the priority science questions in five thematic areas to the measurements and observing systems needed to answer them. The matrixes do not systematically connect the measurements with the underlying geodetic infrastructure. Consequently, this committee modified the Decadal Survey matrixes to emphasize the geodetic infrastructure by (a) adding a geodetic needs column, (b) removing rows of measurements that do not depend on the geodetic infrastructure, and (c) removing columns that are not important for understanding the connections between the science and the geodetic infrastructure. The geodetic needs column includes the measurement specifications in the Decadal Survey matrix as well as geodetic needs identified by the committee. The committee did not modify the Decadal Survey text or numbers.

The geodetic needs were drafted by the working groups at the February 2019 workshop and subsequently refined by the committee. This appendix presents the SATMs for the science questions discussed in Chapters 3–7.

TABLE A.1 Sea-Level Rise Reduced SATM

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION C-1. How much will sea-level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?	**C-1a.** Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade.	Sea-surface height	Coverage: Global or near global Spatial: 7 km along-track Temporal: Every 10 days Accuracy/Stability: 30 mm at 7 km, 1 mm/yr global *Geodetic needs:* • *POD: 10 mm RMS/0.1 mm/yr stability in height.* • *Altimeter drift: calibration via tide gauge network: requires 0.1 mm/yr (averaged over a decade) in TRF scale.* • *Wet troposphere: GNSS in complement of radiometers.*
		Terrestrial reference frame	Temporal: Monthly Coverage: Global every year Accuracy/Stability: 1 mm, 0.1 mm/yr/decade *Geodetic needs:* • *Maintain core multi-technique sites over long term (20+ years) to ensure continuity over very long term (full altimeter record), improve stability of TRF to 0.1 mm/yr in origin and scale.* • *Monitor and quantify gravitational deformation of VLBI antennas.* • *Monitor and quantify SLR timing biases, range biases and center of mass offsets (e.g., T2/L2).* • *Calibrate GNSS spacecraft antennas independent of frame.* • *Multi-technique POD to tie frame at the observation level.* • *Measurement and modeling of time-dependent earthquake-related deformation.* • *Explore multi-technique tropospheric parameter estimation.* • *To avoid degradation of TRF, consider experimenting with more frequent updates (e.g., Kalman filtering, monthly updates).* • *Develop inclusion of GNSS into geocenter and scale determination to provide independent uncertainty assessment.*
		Ocean mass distribution	Spatial: 300 km^2 Temporal: Monthly Coverage: Global every month Accuracy/Stability: 15 mm/0.1 mm/yr/decade *Geodetic needs:* • *Augment GRACE-type missions with degree-1 (intercompare different approaches).* • *C20 (and other low degree if needed) from SLR.* • *GIA model required at same level of accuracy as sea-level measurement.*
	C-1b. Determine the change in the global oceanic heat uptake to within 0.1 W/m^2 over the course of a decade.	Sea-surface height	See C-1a.
		Ocean mass distribution	See C-1a.
		Ocean temperature and salinity profile	Spatial: 3° × 3° Temporal: 10 days Coverage: Global every 10 days Accuracy/Stability: 0.01 deg/0.01 psu *Geodetic needs:* • *Maintain Core Argo and develop Deep Argo.* • *Solve coverage issues in the Arctic and Indonesian seas.*

TABLE A.1 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
	C-1c. Determine the changes in total ice-sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over the entire ice sheets, continuously, for decades to come.	Ice-sheet mass	Spatial: 100 km Temporal: Monthly Coverage: Global Precision: 10 mm water equivalent on scale of 200 km *Geodetic needs:* • *See C-1a requirements except localized GIA for cryosphere with supplement from geodetic infrastructure.* • *SAR (e.g., NISAR) Orbit accuracy <0.1 m RMS total position.*
		Ice-sheet velocity	Spatial: 100 m Coverage: Global Temporal: Weekly to daily Precision: 1 m/yr in fast flow areas, 10 mm/yr near ice divides *Geodetic needs: Orbit accuracy: <0.1 m RMS total position (NISAR requirement).*
		Ice-sheet elevation	Spatial: 100 m Coverage: Global Temporal: Weekly to Daily Precision: 0.1–0.2 m *Geodetic needs:* • *See C-1a.* • *Orbit stability: 4 mm/yr (ICESat-2 requirement).*
		Ice-sheet bed elevation, ice-shelf cavity shape	Spatial: 100 m Coverage: Global Temporal: Once Precision: 30 m *Geodetic needs:* • *Improved resolution required at ice-shelf pinning points.* • *Maintain and improve software and computation methods to continue analysis of bed elevations.*
		Ice-sheet surface mass balance	Spatial: 5 km Coverage: Global Temporal: Monthly Precision: 1 mm/yr *Geodetic needs: Improve surface mass balance models with assimilation methods.*
	C-1d. Determine regional sea-level change to within 1.5–2.5 mm/yr over the course of a decade (1.5 corresponds to a ~6,000 km^2 region, 2.5 corresponds to a ~4,000 km^2 region).	Sea-surface height	Spatial: 250 m Coverage: Global every 20 days Temporal: Weekly Precision: 0.1 m *Geodetic needs:* • *See C-1a.* • *High latitude coverage needed.* • *GNSS RO as an independent observation.*
		Land vertical motions	Spatial: 100 m along coasts Coverage: Global Temporal: Monthly Precision: 1 mm, 1 mm/yr *Geodetic needs: Capture fingerprints in general (not just at coastlines): loading by water and ice plus that caused by GIA.*
		Ocean mass distribution	See C-1a.

continued

TABLE A.1 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION S-3. How will local sea-level change along coastlines around the world in the next decade to century?	**S-3a.** Quantify the rates of sea-level change and its driving processes at global, regional, and local scales, with uncertainty <0.1 mm/yr for global mean sea-level equivalent and <0.5 mm/yr sea-level equivalent at resolution of 10 km.	Ice topography	Spatial: 100 km^2 Temporal: Monthly or less Precision: >0.1 m for mean, 0.25 m/yr for change *Geodetic needs: Orbit stability required 4 mm/yr.*
		Gravity	Spatial: 200 km at equator Coverage: Global Temporal: Monthly Precision: 10 mm water equivalent *Geodetic needs: Desire methods that would mitigate the problem of leakage in the solutions between ocean and land at their mutual boundaries.*
		3D surface deformation vectors on ice sheets	Spatial: 100 m Coverage: Ice sheets Temporal: Monthly Precision: cm/yr *Geodetic needs: Orbit accuracy: <0.1 m RMS total position.*
		Sea-surface height	Spatial: 100 km Coverage: Global Temporal: Monthly Precision: 20 mm *Geodetic needs:* • *30 mm radially RMS; <0.2 m RSS cross-track + along-track.* • *Need improved geophysical corrections: wet troposphere, ocean tide, geoid.* • *GNSS reflectometry (high-rate observations).* • *Denser tide gauge coverage, with support from the communities that use them.* • *Consider an array of altimeters to provide enough track coverage.*
		Terrestrial reference frame	See C-1a.
		In situ temperature/salinity	Spatial: 300 km Comparable to Argo *Geodetic needs: Stable continuous measurements with greater spatial density. Connect and integrate these with other coastal observing systems.*
		Ice velocity	Spatial: 100 km^2 Temporal: Monthly Precision: <0.1 m/yr *Geodetic needs: <0.1 m RSS total position.*
		High-resolution topography	Spatial: 1 m Precision: Vertical accuracy 0.1 m *Geodetic needs: <30 mm radially RMS; <0.2 m RSS cross-track + along-track.*

TABLE A.1 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
	S-3b. Determine vertical motion of land along coastlines at uncertainty <1 mm/yr.	Bare-earth topography	Spatial: 1 m Coverage: Global Precision: 0.1 m vertical *Geodetic needs:* • *See C-1a.* • *Maintaining/develop 50 km spacing high-quality GNSS stations. These are key tie-ins to whatever airborne/space-borne measurement system is used to produce differential DEMs and/or point scattering interferometry.*
		Land-surface deformation	Spatial: 50 m Coverage: Global Temporal: Weekly Precision: 5–10 mm vertical *Geodetic needs: Orbit accuracy: <0.1 m RMS total position.*
QUESTION C-6. Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?	**C-6a.** Decrease uncertainty, by a factor of 2, in quantification of surface and subsurface ocean states for initialization of seasonal-to-decadal forecasts.	Sea-surface height	Spatial: 1–3 km Coverage: Global Temporal: Weekly *Geodetic needs: See sea-surface height (C-1a).*
		Sea-ice thickness	Spatial: Few km Coverage: Global Temporal: 10 days Precision: <30 mm *Geodetic needs: Radial orbit accuracy better than 30 mm for ICESat-2 and CryoSat-2.*[a] *Desire improved ocean tides in sea-ice cover conditions. Computational infrastructure issue.*
		Surface currents	Spatial: 5–10 km Temporal: 1–2 days Precision: ≤1 m/s *Geodetic needs: Knowledge of orbital velocity <1 m/s.*
		Ocean mass	Spatial: 100 km Precision: 20 mm *Geodetic needs: Ocean bottom pressure changes.*
	C-6b. Decrease uncertainty, by a factor of 2, in quantification of land surface states for initialization of seasonal forecasts.	Total water storage	Spatial: 100 km Temporal: Weekly Precision: 0.04 volumetric percent *Geodetic needs: Maintain interdisciplinary connection to hydrology community.*

[a] The instrument specifications in this cell were added after release of the prepublication version to clarify the geodetic needs for the sea-ice thickness observable.

TABLE A.2 Terrestrial Water Cycle Reduced SATM

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION H-2. How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally and what are the short- and long-term consequences?	**H-2b.** Quantify the magnitude of anthropogenic processes that cause changes in radiative forcing, temperature, snowmelt, and ice melt as they alter downstream water quantity and quality.	Snow and ice albedo, contaminant type (dust, soot) and concentration, land cover. Surface temperature. Glacier, river, and lake mapping and characterization	Spectral snow and ice albedo, optical properties and concentrations of contaminants (dust and soot), surface temperature to ±1 K. *Geodetic needs for all questions: Support for TRF at current level of stability (international network of VLBI, SLR, GNSS stations), regional GNSS networks at 40 km spacing, GRACE, and current/future InSAR missions. Notably, GNSS loading applications for hydrology require center of mass velocity and scale rate stability of 0.2 mm/yr. This requirement is equivalent to 10 mm/yr of water. In addition, stability of the terrestrial reference frame on seasonal time scales is needed for hydrological studies. More study is needed to assure that this requirement is being met.* *Specific geodetic needs:* • *Distribution of both GNSS and GNSS-IR sites would be more valuable for water cycle studies if located in watersheds and in geographic regions that lack traditional hydrological measurement networks.* • *Current hydrologic water loading studies require daily GNSS positioning precision of ~3–5 mm, which can be achieved at scientific quality sites (i.e., good monumentation and maintenance).* • *For GNSS-IR, current soil moisture accuracy of <4% volumetric (Small et al., 2016), snow depth (accuracy of 0.04–0.06 m) and SWE (0.02 m; McCreight et al., 2014). Footprint 1,000* m^2*. Support is needed for open GNSS-IR software.* • *Lidar applications (e.g., the NASA Airborne Snow Observatory) need a good bare-earth DEM. Ground control (GNSS regional networks) is needed for precise navigation solutions of the aircraft. Better DEMs are needed for mountains and valleys, which would help improve runoff models.*
	H-2c. Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies.	Recharge rates (i.e., space-time rates of change in groundwater storage and availability) at 1 km (desired) up to 10 km (useful) scale globally at 10-day intervals with accuracy of better than ±1 mm/day	Soil moisture profile to 4% volumetric accuracy in top 1 m of the soil column. *Geodetic needs: Daily GNSS positions can be used to quantify changes in total water storage (soil moisture, SWE, ground water). These types of studies require continued support for GNSS networks, high-precision GNSS analysis software, and the underlying TRF. InSAR and GRACE provide complimentary measurements of total water storage at different temporal and spatial scales.* Changes in vadose zone moisture and in groundwater storage. Changes in groundwater levels. Changes in snow water equivalent. *Geodetic needs: See H-2b.* Land-surface deflection to 10 mm accuracy, 100 m spatial resolution. *Geodetic needs: Program of record supports this application using both InSAR and GNSS (daily positioning precision is ~5 mm). See H-2b.*

TABLE A.2 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION H-4. How does the water cycle interact with other Earth system processes to change the predictability and impacts of hazardous events and hazard-chains (e.g., floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?	**H-4a.** Monitor and understand hazard response in rugged terrain and land margins to heavy rainfall, temperature and evaporation extremes, and strong winds at multiple temporal and spatial scales. This socioeconomic priority depends on success of addressing H-1b, H-1c, H-2a, and H-2c.	Magnitude and frequency of severe storms. Depth and extent of floods	Precipitation, snowmelt, water depth, and water flow in soil at time and space scales consistent with events. *Geodetic needs:* • *InSAR and lidar can improve floodplain knowledge, leading to better runoff models and landslide warnings. SAR can also measure flood extent using existing and future missions.* • *Ecosystem health can be related to water loss estimates based on subsidence studies using GNSS positioning and InSAR (Argus et al., 2017).*
	H-4b. Quantify key meteorological, glaciological, and solid Earth dynamical and state variables and processes controlling flash floods, and rapid hazard chains to improve detection, prediction, and preparedness. (This is a critical socioeconomic priority that depends on success of addressing H-1b, H-1c, and H-4a.)	Rainfall intensity and volume for storms in the 95th percentile of values specific to areas, especially estimates in mountainous terrain where other measurement sources are not available, soil moisture, SWE, and glacier changes	Precipitation, snowmelt, and flow in soil and glaciers at time and space scales consistent with events. *Geodetic needs:* • *See H-2b for soil moisture, SWE.* • *The loading effect of large precipitation events can be sensed on a daily basis with the existing GNSS program of record. This allows estimates of how much water is stored in the ground and for how long.*
QUESTION S-6. How much water is traveling deep underground, and how does it affect geological processes and water supplies?	**S-6a.** Determine the fluid pressures, storage, and flow in confined aquifers at spatial resolution of 100 m and pressure of 1 kPa (0.1 m head).	Topography	Topography at 10 m resolution. *Geodetic needs: Groundwater levels measured in wells are reported to 3 mm precision and referenced to land surface. Accurate elevations are required to determine gradients of groundwater flow, particularly where gradients are small.*
		Land-surface deformation	For seasonal variations: 10 mm/yr measured weekly at 10 m spatial sampling (which allows stacking for sub-10 mm secular trends). *Geodetic needs: See H-2c. Note: GNSS can measure daily vertical coordinates ~5 mm. InSAR can measure land surface deformation with very high precision in many regions.*
		Surface water distribution	100 m spatial (e.g., SWOT), stream gauge network, seasonally. *Geodetic needs: Measurement of surface water distribution from space (i.e., SWOT) requires stable reference including POD of the satellite. GNSS-IR can provide cal/val data for SWOT, which would require GNSS sites near lakes and rivers.*

continued

TABLE A.2 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
	S-6b. Measure all significant fluxes in and out of the groundwater system across the recharge area.	Soil moisture, snow/SWE, rainfall	1–5 km spatial, from SMAP, other radar, thermal inertia using TIR and VNIR data, and GPS reflections, weekly. *Geodetic needs:* • *See H-2b for discussion of GNSS-IR measurements, which measures soil moisture and snow/SWE at 1,000 m^2 scale.* • *Daily GNSS positions and can sense large precipitation events and the distribution of that water.*
		Gravity	Monthly, uncertainty 10 mm water-equivalent thickness at resolution of 100 km. *Geodetic needs: Support for GRACE Follow On and analysis products (mascons).*
		Topography	Vertical accuracy of 0.1 m, resolution of 1 m. *Geodetic needs: Requires local ground control (GNSS networks) to support suborbital navigation.*
		Deformation from fluid fluxes (uses several above measurements)	Spatiotemporal distribution of subsidence/uplift at 3 mm vertical per year, 5 m horizontal, weekly. Coverage over active reservoirs. *Geodetic needs: InSAR and daily GNSS verticals using the current program of record are precise enough for current water management applications.*
		Land-surface deformation	Spatiotemporal distribution of subsidence/uplift at 10 mm vertical, 5 m horizontal, weekly. Coverage over managed watersheds, other watersheds of interest. *Geodetic needs: Program of record suggests 40 km spacing of GNSS stations, with increased spatial deployment in watersheds. Combination of InSAR and GNSS data products can provide improved spatial and temporal sensitivity.*
	S-6c. Determine the transport and storage properties in situ within a factor of 3 for shallow aquifers and an order of magnitude for deeper systems.	Deformation from fluid fluxes (uses several above measurements)	Spatiotemporal distribution of subsidence/uplift at 3 mm/yr vertical, 5 m horizontal, weekly. Coverage over active reservoirs. *Geodetic needs: See S-6b.*
	S-6d. Determine the impact of water-related human activities and natural water flow on earthquakes.	Vertical surface deformation	Spatiotemporal distribution of subsidence/uplift at 3 mm/yr vertical, 5 m horizontal, weekly. *Geodetic needs: See S-6b.*

TABLE A.3 Geological Hazards Reduced SATM

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION S-1. How can large-scale geological hazards be accurately forecast in a socially relevant time frame?	**S-1a.** Measure the pre-, syn-, and post eruption surface deformation and products of Earth's entire active land volcano inventory at a time scale of days to weeks.	Land-surface deformation	At least two components of land-surface deformation over length scales ranging from 10 m to 1,000 km and a precision of 1 mm at a sampling frequency related to the earthquake or volcanic activity. L- or S-band InSAR with ionospheric correction, GPS/GNSS. *Geodetic needs:* • *InSAR satellite orbit accuracy of 20 mm radially and 60 mm along-track. For interseismic strain recovery. (Note the 60 mm along-track accuracy comes from the azimuth alignment needs of Sentinel-1 to eliminate phase jumps at burst boundaries [Xu et al., 2017].)* • *The onboard GNSS POD measurements should be of IGS quality (i.e., mm-level phases and dm-level pseudoranges at two or more frequencies for all four global GNSS constellations and with accurately calibrated antennas).* • *Maintenance of at least the IGS GNSS core sites is needed to bring the InSAR measurement into an absolute frame at 0.5 mm/yr accuracy.* • *Maintain or enhance GNSS station density in areas of high strain rate such as the San Andreas Fault system. Station spacing of 20 km or better is needed to bring the InSAR measurement into an absolute frame at 0.5 mm/yr accuracy.*
		Topography	High spatial resolution (5 m) bare-earth topography at 1 m vertical accuracy over all volcanoes. Spacecraft swath lidar or radar. *Geodetic needs: Orbit accuracy better than 0.1 m radial. Requires lidar pointing accuracy of better than 2 microradian (Abshire et al., 2015). Conduct lidar survey before an event to enable a repeat-lidar survey after the event. Requires local/regional ground calibration/validation.*
	S-1b. Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas on time scales ranging from hours to decades.	Land-surface deformation	InSAR and GNSS same as S-1a. *Geodetic needs: For very large subduction zone earthquakes that affect GNSS stations over much of the Earth's surface (e.g., 2004 Sumatra), the 1–10 mm accuracy maintained over 10 years will require time-dependent corrections to the reference frame as in ITRF2014 (Altamimi et al., 2016).*
		Large spatial scale gravity change	Gravity change for large events (GRACE and follow-on missions). *Geodetic needs: 1 microgal accuracy at spatial resolution of 300 km or better and sampling better than monthly.*
		Topography	High spatial resolution (1 m), bare-earth topography at 0.1 m vertical accuracy over selected tectonic areas (aircraft/UAV lidar). *Geodetic needs: Requires local GNSS ground station for differential GNSS aircraft positioning of better than 50 mm.*
		Land cover change	High spatial resolution (1 m) stereo optical imagery (commercial optical). *Geodetic needs: Same as S-1a.*

continued

TABLE A.3 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
	S-1c. Forecast and monitor landslides, especially those near population centers.	Land-surface deformation	At least two components of land-surface deformation at <50 m spatial resolution and 1 mm/yr at a temporal frequency < seasonal (e.g., InSAR and GPS/GNSS). L- or S-band InSAR, GPS/GNSS (complements ground-based seismic data). *Geodetic needs: Same as S-1a.*
		High-resolution topography	Spatial resolution 1–5 m, vertical 0.5 m (aircraft/UAV lidar). *Geodetic needs: Same as S-1b.*
		High spatial resolution time series of distribution of vegetation and rock/soil composition	Hyperspectral VNIR/SWIR and TIR data at 30–45 m spatial resolution and ~weekly temporal resolution. Moderate-resolution imaging/spectometry (e.g., ASTER, Landsat, Hyperion but at slightly improved spatial resolution and much improved temporal resolution). *Geodetic needs: Same as S-1a.*
	S-1d. Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events.	Topography and shallow bathymetry	High spatial resolution (1 m), bare-earth topography at 0.1 m vertical accuracy over selected tectonic areas. *Geodetic needs:* • *Orbital geodetic needs: Same as S-1b.* • *Need improved local reference system to tie ship bathymetry to land topography at ~0.1 m accuracy.*
		Sea-surface tsunami waves	Tsunami wave height (0.1 m at 1 min sampling). Swath altimetry (e.g., SWOT), GPS/GNSS ships, buoys, ocean altimetry, complements seafloor pressure changes. *Geodetic needs:* • *Altimetry satellite orbit accuracy <20 mm radial.* • *GNSS vertical moving platform position <20 mm (Foster et al., 2012).*
		Global bathymetry and seamless nearshore bathymetry	Global marine gravity from swath radar altimetry (SWOT). Swath altimetry. *Geodetic needs: Altimetry satellite orbit accuracy <20 mm radial.*
		Optical, radar, and InSAR change detection on demand with low latency processing and distribution	Enable high spatial resolution space-borne or aircraft asset that can provide timely information to relief efforts (commercial 1 m optical, GPS/GNSS). *Geodetic needs: Same as S-1a.*
		Rapid characterization of the magnitude of earthquakes	1 Hz deformation time series. Terrestrial seismic and GPS/GNSS networks. *Geodetic needs: Need for real-time, high-rate GPS/GNSS data at 1 Hz together with near real-time data processing to final station displacements.*

TABLE A.3 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION S-2. How do geological disasters directly impact the Earth system and society following an event?	**S-2a.** Rapidly capture the transient processes following disasters for improved predictive modeling as well as response and mitigation through optimal retasking and analysis of space data.	Provide rapid deformation map acquisitions and interconnectivity to other sensors	At least two components of land-surface deformation over 10 m to 1,000 km length scales at 10 mm precision and as soon as possible after the event. Adequate resolution of 10 mm/week for afterslip applications. InSAR. *Geodetic needs: Same as S-1.*
	S-2b. Assess surface deformation (<10 mm), extent of surface change (<100 m spatial resolution) and atmospheric contamination, and the composition and temperature of volcanic products following a volcanic eruption (hourly to daily temporal sampling).	Land-surface deformation	At least two components of land-surface deformation and surface fracturing over length scales ranging from 10 m to 1,000 km and temporal resolution of 1 mm/yr at a sampling frequency related to the volcanic activity (InSAR and GPS/GNSS) everywhere. L- or S-band InSAR with ionospheric correction (e.g., from GPS/GNSS global ionosphere maps). *Geodetic needs: Same as S-1.*
	S-2c. Assess co- and postseismic ground deformation (spatial resolution of 100 m and an accuracy of 10 mm) and damage to infrastructure following an earthquake.	Land-surface deformation	At least two components of land-surface deformation at 100 m spatial resolution and 1 mm/yr at a temporal frequency related to the tectonic activity (InSAR and GPS/GNSS). Need more than 10 years of interseismic observations and 5 years of postseismic observations. L- or S-band InSAR with ionospheric correction (e.g., from GPS/GNSS global ionosphere maps). *Geodetic needs: Same as S-1.*
		Large spatial scale gravity change	Gravity change for large events. Gravity (e.g., GRACE-FO). *Geodetic needs: Same as S-1.*
		Topography	High spatial resolution (1 m), bare-earth topography at 0.1 m vertical accuracy over selected tectonic areas (aircraft/UAV lidar). *Geodetic needs: Same as S-1.*
		Optical imaging	Map surface rupture, liquefaction features and damage at spatial scales better than 5 m (Worldview, aircraft/drone imaging). *Geodetic needs: No new geodetic components except routine POD of satellite instruments.*

TABLE A.4 Weather and Climate Reduced SATM

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION C-2. How can we reduce the uncertainty in the amount of future warming of Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?	**C-2b.** Reduce uncertainty in water vapor feedback by a factor of 2.	Atmospheric water vapor and temperature profiles	Vertical resolution/coverage: 2 km from 0–15 km altitude Space/time sampling: 100 km horizontal resolution/monthly average Time/space coverage: decadal trends/global Accuracy/stability: 0.03 K (1σ) *Geodetic needs:* • *Improve GNSS clock accuracies over the 0.5–30 sec time span to improve temperature/water vapor profiles.* • *Increase GNSS sampling rate to 2 Hz from the standard 1 Hz at IGS sites to minimize clock interpolation errors for RO applications.* • *Encourage multi-GNSS analysis of orbits and clocks by U.S. groups.* • *Collocation of the Global Climate Observing System Reference Upper-Air Network and space geodetic infrastructure sites (GNSS, VLBI, SLR). There is an opportunity for mutual cal/val benefit.*
	C-2c. Reduce uncertainty in temperature lapse rate feedback by a factor of 2.	Atmospheric temperature profile	Vertical resolution/coverage: 2 km from 0 to 15 km altitude Space/time sampling: 2 km vertical resolution, 100 km horizontal resolution/monthly Time/space coverage: decadal trends/global Accuracy/stability: 0.03 K (1σ) *Geodetic needs: Same as C-2b.*
QUESTION W-2. How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?	**W-2a.** Improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability (e.g., MJO, ENSO), including upscale interactions between the large-scale circulation and organization of convection and slowly varying boundary processes to extend the lead time of useful prediction skills by 50% for forecast times of 1 week to 2 months. Advances require improved: (1) process understanding and assimilation/modeling capabilities of atmospheric convection, mesoscale organization, and atmosphere and ocean boundary layers, (2) global initial conditions relevant to these quantities/processes. Observations needed for boundary layer, surface conditions, and convection are described in W-1, W-3, and W-4, respectively.	Vertical temperature profile	Boundary layer through middle atmosphere Threshold horizontal resolution 5 km, objective horizontal resolution 3 km, both at 1 km vertical resolution Threshold refresh 3 hr, objective refresh global 90 min and CONUS 60 min Measured with 1 K RMS. *Geodetic needs: Same as C-2b.*
		Vertical water vapor profile	Boundary layer through middle atmosphere Threshold horizontal resolution 5 km, objective horizontal resolution 3 km, both at 1 km vertical resolution Threshold refresh 3 hr, objective refresh global 90 min and CONUS 60 min Measured with 10% LTH RMS and 20% UTH RMS. *Geodetic needs: Same as C-2b.*
		Surface pressure	To within 1 mb. *Geodetic needs: Maintain pressure, temperature, and humidity at SLR and VLBI stations.*

TABLE A.5 Ecosystem Reduced SATM

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION E-1. What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space?	**E-1a.** Quantify the distribution of the functional traits, functional types, and composition of vegetation and marine biomass, spatially and over time. **E-1b**. Quantify the three-dimensional (3D) structure of terrestrial vegetation and 3D distribution of marine biomass within the euphotic zone, spatially and over time. **E-1c.** Quantify the physiological dynamics of terrestrial and aquatic primary producers. **E-1d.** Quantify moisture status of soils.	3D physical structure of vegetation and aquatic biomass	Airborne lidar: 0.1 m bare-earth topography; 1–10 m spatial resolution; 1 year repeat observations. *Geodetic needs for lidar: Maintain reference frame; more base stations (need base stations every 30 km without L5 frequency or 50 km with L5) in remote areas; overall need more GNSS frequencies (e.g., L5 and receivers need to support this).* C-, L-, and P-band SAR: 10 m spatial resolution; daily in high latitudes (for freeze-thaw), 6-day in other regions; not necessarily near-real-time needs. SAR imagery benefits from maintaining the current geodetic infrastructure for orbit determination; water vapor determination from radio occultation is needed for InSAR correction. GNSS: For GNSS-IR stations in diverse ecosystems with good returns; increased number of stations and dense network in regions with water storage and coastlines (erosion, e.g., Alaska); co-location with tide gauges, soil moisture sensors. *Geodetic needs for GNSS: Need SNR from GNSS; for GNSS-IR need increased number of stations in diverse ecosystems and along coastlines in northern latitudes; co-location with soil moisture sensors distributed across environmental gradients; GNSS-R can benefit from investigating increasing ways for space-based reflectometry and enhance monitoring GNSS transmit power for reflections.*
QUESTION E-2. What are the fluxes (of carbon, water, nutrients, and energy) between ecosystems and the atmosphere, the ocean and the solid Earth, and how and why are they changing?	**E-2a.** Quantify the fluxes of CO$_2$ and CH$_4$ globally at spatial scales of 100 to 500 km and monthly temporal resolution with uncertainty <25% between land ecosystems and atmosphere and between ocean ecosystems and atmosphere. **E-2b.** Quantify the fluxes from land ecosystems between aquatic ecosystems. **E-2c.** Assess ecosystem subsidies from solid Earth.	GPP, respiration, and decomposition and biomass burning Riverine transport of nutrients, organic matter and other constituents to oceans and inland waters Dust inputs, soil erosion, landslides, black carbon	Airborne lidar: 0.1 cm bare-earth topography; 1–10 m spatial resolution; 1 year repeat observations. *Geodetic needs for lidar: Same as E-2a.* C-, L-, and P-band SAR: 10 m spatial resolution; daily in high latitudes (for freeze-thaw), 6-day in other regions; not necessarily near-real-time needs. Ka-band Radar Interferometer (SWOT): 250 m spatial resolution supported by ICESat-2, NISAR, and GNSS-IR to increase temporal and spatial coverage for high temporal dynamics (flooding, wetland inundation). Ultimately need 3–10 m spatial resolution and 0.1 m vertical. SAR imagery benefits from maintaining the current geodetic infrastructure for orbit determination; water vapor determination from radio occultation is needed for InSAR correction. Humidity and temperature profiles, and water fluxes from radio occultation can also be leveraged to place constraints on evapotranspiration. *Geodetic needs for InSAR: orbits with precision of 20–40 mm across track and 40–70 mm along-track.* GNSS: For GNSS-IR stations in diverse ecosystems with good returns; increased number of stations and dense network in regions with water storage and coastlines (erosion, e.g., Alaska); co-location with tide gauges, soil moisture sensors. *Geodetic needs for GNSS: Same as E-2a.* Gravimetry: Sustained gravimetry measurements (gravimetry 300 km and GNSS-IR every 100 km [or <50 km without GRACE], in addition to 1–10 m bare-earth DEMs) for total water storage. *Geodetic needs: Same as E-2a for InSAR and GNSS; need multiple pairs of satellites and/or closely spaced GNSS.*

continued

TABLE A.5 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
QUESTION E-3. What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing?	**E-3a.** Quantify the flows of energy, carbon, water, nutrients, etc. sustaining the life cycle of terrestrial and marine ecosystems and partitioning into functional types. **E-3b.** Understand how ecosystems support higher trophic levels of food webs.	GPP, respiration, litterfall and decomposition, nonPS vegetation, functional types CO$_2$, CO, CH$_4$, etc. fluxes from biomass burning ET and root zone moisture Aquatic NPP, PhytoC and Chl, NCP, export from the euphotic zone, N$_2$ fixation and calcification, partitioned into functional types Rates of herbivory on terrestrial vegetation Zooplankton population dynamics and secondary production	Airborne lidar: 0.1 m bare-earth topography; 1-10 m spatial resolution; 1 year repeat observations. *Geodetic needs for lidar: Same as E-2a.* C-, L-, and P-band SAR: 10 m spatial resolution; daily in high latitudes (for freeze-thaw), 6-day in other regions; not necessarily near-real-time needs. Ka-band radarinterferometer (SWOT): 250 m spatial resolution supported by ICESat-2, NISAR, Sentinel-1 and/or GNSS-IR to increase temporal and spatial coverage for high temporal dynamics (flooding, wetland inundation). Ultimately need 3–10 m spatial resolution and 0.1 m vertical. SAR imagery benefits from maintaining the current geodetic infrastructure for orbit determination; water vapor determination from radio occultation is needed for SAR correction. Humidity and temperature profiles, and water fluxes from radio occultation can also be leveraged to place constraints on ET. *Geodetic needs for InSAR: Same as E-2a and GNSS needs.* Daily fluxes: For GNSS-IR stations in diverse ecosystems and along gradients with good returns for daily fluxes; increased number of stations and dense network in regions with water storage and coastlines (erosion, e.g., Alaska); co-location with tide gauges, soil moisture sensors. *Geodetic needs for GNSS: Same as E-2a.* Gravimetry: Similar to E-2a but important to have total water storage of small to mid-sized basins, need gravimetry every 100 km and GNSS-IR 50 km; for the latter needs include a regional network in northern latitudes (e.g., Alaska, which has synergies with solid earth/tectonics); for monitoring water storage fluxes need increased temporal resolution (weekly to every 10 days, not monthly). *Geodetic needs: Same as E-2a for SAR and GNSS; need multiple pairs of satellites and/or closely spaced GNSS.*
QUESTION E-4. How is carbon accounted for through carbon storage, turnover, and accumulated biomass? Have all of the major carbon sinks been quantified and how are they changing in time?	**E-4a.** Improve assessments of the global inventory of terrestrial C pools and their rate of turnover.	Aboveground carbon density (biomass)	See E-1.
		Terrestrial GPP, respiration, decomposition and biomass burning	See E-3 above (daily fluxes, GNSS).
QUESTION S-4. What processes and interactions determine the rates of landscape change?	**S-4a.** Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface from surface processes, tectonics, and societal activity.	Bare-earth topography	Airborne lidar: 0.1 m bare-earth topography; 1 m spatial resolution; 1 year repeat observations. Also need top of canopy: surface roughness at 1 m spatial resolution (this is also useful for imaging spectroscopy for vegetation health). *Geodetic needs for lidar: Maintain reference frame; more base stations (need base stations every 30 km without L5 frequency or 50 km with L5) in remote areas; overall need more GNSS frequencies (e.g., L5 and receivers need to support this).*
		Land-surface deformation	L-, C-band SAR: 10 m spatial resolution, 0.1 m vertical; weekly repeat cycles. *Geodetic needs for InSAR: 20–40 mm orbit precision; 40–70 mm along-track precision; increased number of radio occultation measurements. Because it is important to develop long-time series, orbit stability and reference frame stability are of similar importance as for measurement of sea surface height from satellite altimetry.*

TABLE A.5 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
		High spatial resolution time series of changes in optical surface characteristics	See above, land-surface deformation.
		Measurement of rock-, soil-, water-, and ice-mass change	Surface water: L-, P-band SAR: 10 m spatial resolution; daily in high latitudes (for freeze-thaw), 6-day in other regions; not necessarily near-real-time needs. Ka-band radar interferometer (SWOT): 250 m spatial resolution supported by ICESat-2, NISAR, Sentinel-1 and GNSS-IR to increase temporal and spatial coverage for high temporal dynamics (flooding, wetland inundation). Ultimately need 3–10 m spatial resolution and 0.1 m vertical. SAR imagery benefits from maintaining the current geodetic infrastructure for orbit determination; water vapor determination from radio occultation is needed for SAR correction. Humidity and temperature profiles, and water fluxes from radio occultation can also be leveraged to place constraints on evapotranspiration. *Geodetic needs for InSAR: Same as E-2a and GNSS needs.* GNSS: For GNSS-IR stations in diverse ecosystems with good returns; increased number of stations and dense network in regions with water storage and coastlines (erosion, e.g., Alaska); co-location with tide gauges, soil moisture sensors. *Geodetic needs for GNSS: Same as E-2a.* Total water storage: Gravimetry: similar to above but important to have total water storage of small to mid-sized basins, need gravimetry every 100 km and GNSS-IR 50 km; for the latter needs include a regional network in northern latitudes (e.g., Alaska, which has synergies with solid earth/tectonics); for monitoring water storage fluxes need increased temporal resolution (weekly to every 10 days, not monthly). *Geodetic needs: Same as E-2a for InSAR and GNSS; need multiple pairs of satellites and/or closely spaced GNSS.*
		Measurement of rainfall and snowfall rates	See Water Cycle, H-4. For snow: Airborne lidar: 0.1 m bare-earth topography; 1 m spatial resolution; weekly repeat observations for snow depth. Also need top of canopy: surface roughness at 1 m spatial resolution (this is also useful for imaging spectroscopy for vegetation health). *Geodetic needs for lidar: Maintain reference frame; more base stations (need base stations every 30 km without L5 frequency or 50 km with L5) in remote areas; overall need more GNSS frequencies (e.g., L5 and receivers need to support this).*
		Reflectance for freeze/thaw spatial and temporal distribution	C-, L-, and P-band SAR; 10 m spatial resolution; benefits from maintaining current geod. infrastructure for orbit determination; water vapor determination with radio occultation (require new observations); daily in high latitudes (for freeze-thaw), 6-day in other regions; not near-real-time needs. *Geodetic needs:* • *See E-1, E-2, E-3, E-4, and S-4a.* • *Increased radio occultation; 20–40 mm orbit precision; 40–70 mm along-track precision.*

continued

TABLE A.5 Continued

Question	Objective	Geophysical Observable	Measurement Parameters and *Geodetic Needs*
	S-4b. Quantify weather events, surface hydrology, and changes in ice/water content of near-surface materials that produce landscape change.	Measurement of rainfall and snowfall rates	See S-4a.
		Reflectance for freeze/thaw spatial and temporal distribution	See S-4a.
		Optical characterization of spatial and temporal distribution of freeze/thaw	
		Reflectance for snow depth/snow water equivalent	
		Soil/root zone moisture content	
	S-4c. Quantify ecosystem response to and causes of landscape change.	High spatial resolution time series of distribution of vegetation in VIS/NIR	See E-1, E-2, E-3, E-4, and S-4a.
		Observations of canopy structure and carbon inventory	
		Bare-earth topography	
		Observations of ecosystem status and near-surface material composition	

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Appendix B

Speakers and Workshop Participants

Don Argus, National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory
Srinivas Bettadpur, The University of Texas at Austin
Geoff Blewitt, University of Nevada, Reno
Adrian Borsa, Scripps Institution of Oceanography
John Braun, University Corporation for Atmospheric Research
Walter Brisken, Long Baseline Observatory
Ben Brooks, U.S. Geological Survey
Anny Cazenave, Centre National d'Etudes Spatiales
Theresa Damiani, National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey
Pedro Elosegui, Massachusetts Institute of Technology Haystack Observatory
Richard Forster, The University of Utah
Jeff Freymueller, Michigan State University
Sarah Gille, Scripps Institution of Oceanography
John Gipson, NASA Goddard Space Flight Center
Nancy Glenn, Boise State University
Craig Glennie, University of Houston
Jake Griffiths, U.S. Naval Research Laboratory
Richard Gross, NASA Jet Propulsion Laboratory
Bruce Haines, NASA Jet Propulsion Laboratory
Michael Heflin, NASA Jet Propulsion Laboratory
Patrick Heimbach, The University of Texas at Austin
Erik Ivins, NASA Jet Propulsion Laboratory
Jack Kaye, NASA Headquarters
Russ Kelz, National Science Foundation
John Kimball, University of Montana
Kristine Larson, University of Colorado (emeritus)
Frank Lemoine, NASA Goddard Space Flight Center
Dennis Lettenmaier, University of California, Los Angeles
Steve Malys, National Geospatial-Intelligence Agency
Carl Mears, Remote Sensing Systems
Stephen Merkowitz, NASA Goddard Space Flight Center
Mark Merrifield, Scripps Institution of Oceanography
Gary Mitchum, University of South Florida
Steve Nerem, University of Colorado
Susan Owen, NASA Jet Propulsion Laboratory
Ben Phillips, NASA Headquarters
Erika Podest, NASA Jet Propulsion Laboratory
Jim Ray, NOAA National Geodetic Survey (retired)
John Ries, The University of Texas at Austin
David Sandwell, Scripps Institution of Oceanography
Bill Schreiner, University Corporation for Atmospheric Research
Yolande Serra, University of Washington
Michelle Sneed, U.S. Geological Survey
Mark Tamisiea, The University of Texas at Austin
Isabella Velicogna, University of California, Irvine
Frank Webb, NASA Jet Propulsion Laboratory
Mike Willis, University of Colorado
Guy Woppelmann, University of La Rochelle

Appendix C

Biographical Sketches of Committee Members

David T. Sandwell (NAS), *Chair*, is a professor of geophysics at the Scripps Institution of Oceanography at the University of California, San Diego. Dr. Sandwell's research interests are focused on mapping large-scale topographic features beneath the ocean using data collected by remote-sensing instruments on satellites orbiting the Earth and sonars on research vessels. He co-chaired the National Academies 2017 Decadal Survey Panel on Earth Surface and Interior and was a member of the Committee on National Requirements for Precise Geodetic Infrastructure. Dr. Sandwell is a fellow of the American Academy of Arts & Sciences, the American Geophysical Union, and the Geological Society of America, and is a member of the National Academy of Sciences. He earned a B.S. in physics from the University of Connecticut, and an M.S. and a Ph.D. in geophysics and space physics from the University of California, Los Angeles.

Srinivas Bettadpur is an associate professor in the Department of Aerospace Engineering and Engineering Mechanics and director of the Center for Space Research at The University of Texas at Austin. Dr. Bettadpur's areas of expertise are orbital mechanics, perturbations, and orbit determination; space geodesy, including multi-technique space-geodetic methods for precision global reference frames; and determination and interpretation of the Earth's gravity field. He is a recipient of the Vening Meinesz Medal from the European Geosciences Union and several National Aeronautics and Space Administration awards for his work determining the time-variable gravity field from space. Dr. Bettadpur is a fellow of the International Association of Geodesy. He received a B.E. in mechanical engineering from Punjab University, India, an M.Tech. in aeronautical engineering from IIT-Kanpur, India, an M.S. in aerospace engineering from the University of Oklahoma, and a Ph.D. in aerospace engineering from The University of Texas at Austin.

Geoffrey Blewitt is a professor with joint appointments in the Department of Physics and the Nevada Bureau of Mines and Geology at the University of Nevada, Reno. Dr. Blewitt's research focuses on geodesy, global reference frames, and the application of very high precision Global Positioning System to earth science including geodynamics, plate tectonics, earthquake cycle, surface mass loading, glacial isostatic adjustment, sea-level change, and atmospheric science. His contributions in these areas earned him the Vening Meinesz Medal from the European Geosciences Union. He is also a fellow of the American Geophysical Union and the International Association of Geodesy. Dr. Blewitt served on the National Academies Committee on National Requirements for Precise Geodetic Infrastructure. He received a B.Sc. in physics from Queen Mary's College of the University of London and a Ph.D. in physics from the California Institute of Technology.

John J. Braun is the project scientist for the Constellation Observing System for Meteorology Ionosphere and Climate Program at the University Corporation for Atmospheric Research. Dr. Braun's research interests are focused on using Global Navigation Satellite

System (GNSS) signals to remotely sense the atmosphere and land surface to support water cycle research. He holds a patent on a high-resolution ionospheric technique for regional area high-accuracy Global Positioning System applications. Dr. Braun is a member of the International GNSS Service Tropospheric Working Group. He received a B.A. in physics and mathematics and an M.S. and a Ph.D. in aerospace engineering, all from the University of Colorado Boulder.

Anny Cazenave (NAS) is a senior scientist at the Laboratoire d'Etudes en Géophysique et Océanographie Spatiale at the Centre National d'Etudes Spatiales in Toulouse, France. She is also the director for Earth Science at the International Space Science Institute in Bern, Switzerland. Dr. Cazenave's research deals with the applications of space techniques to geosciences, including geodesy, gravity, and solid Earth geophysics; sea-level variations and study of climatic causes; global water cycle and land hydrology from space; and climate research. She has served on several National Academies committees, including the Committee on National Requirements for Precise Geodetic Infrastructure. Dr. Cazenave is a fellow of the American Geophysical Union and the American Association for the Advancement of Science, a member of the French Academy of Sciences, and a foreign member of the American, Indian, and Belgian academies of sciences. She earned a Ph.D. in geophysics from the University of Toulouse.

Nancy Glenn is a professor in the Department of Geosciences and the director of the Boise Center Aerospace Laboratory at Boise State University. She is an expert in imaging spectroscopy and lidar of terrestrial ecosystems and is particularly interested in the structure and function of dryland ecosystems and understanding how these ecosystems respond to changes in climate and disturbance. Dr. Glenn serves on several advisory committees related to remote sensing, including an advisory board member of the National Science Foundation's OpenTopography, a chair and a committee member of UNAVCO's Terrestrial Imaging Geodesy Working Group, and a member of the National Aeronautics and Space Administration's Remote Sensing of Invasive Plants group. She received a B.S. in geological engineering from the University of Nevada, Reno; an M.S. in civil engineering from the University of California, Berkeley; and a Ph.D. in geoengineering from the University of Nevada, Reno.

Kristine M. Larson is a professor emerita in the Department of Aerospace Engineering Sciences at the University of Colorado Boulder. Dr. Larson's research interests are focused on developing new applications for Global Positioning System instruments, including measuring seismic displacement, ice sheet speed, firn density, soil moisture, vegetation water content, snow depth, volcanic ash, and water levels. She served on both the 2017 Decadal Survey Panel on Earth Surface and Interior and the Committee on National Requirements for Precise Geodetic Infrastructure of the National Academies. Dr. Larson is a fellow of the American Geophysical Union and a recipient of the Christiaan Huygens Medal from the European Geosciences Union. She earned a B.A. in engineering sciences from Harvard University and a Ph.D. in geophysics from the Scripps Institution of Oceanography at the University of California, San Diego.

R. Steven Nerem is a professor in the Department of Aerospace Engineering Sciences and the associate director of the Colorado Center for Astrodynamics Research at the University of Colorado Boulder. Dr. Nerem's research interests include sea-level change, satellite altimetry, the Earth's gravity field, planetary geodesy, precision orbit determination, and astrodynamics. He is a former member of the National Academies Committee on Earth Science and Applications from Space and the UNAVCO study on grand challenges in geodesy. Dr. Nerem is the recipient of numerous awards, including the American Astronautical Society's Earth Science and Applications Award and the American Geophysical Union's (AGU's) Geodesy Section Award. He is a fellow of the AGU. Dr. Nerem earned a B.S. in geology from Colorado State University and an M.S. and a Ph.D. in aerospace engineering from The University of Texas at Austin.

Michelle Sneed is a hydrologist at the U.S. Geological Survey. Her research focuses on land subsidence related to fluid-pressure changes in the western United States, using measurements of land-surface elevation and elevation change, including spirit leveling, Global

Positioning System, extensometry, and Interferometric Synthetic Aperture Radar. Ms. Sneed is a member of the UNESCO Land Subsidence International Initiative and was a participant in a recent National Science Foundation–sponsored workshop on hydrological applications of geodetic techniques. She received a B.S. and an M.S. in geology from California State University, Sacramento, where she also periodically teaches geology classes.

Isabella Velicogna is a professor in the Department of Earth System Sciences at the University of California, Irvine. She is also a part-time scientist faculty at the California Institute of Technology/Jet Propulsion Laboratory. Dr. Velicogna uses novel geophysical methods and satellite remote sensing techniques to understand the physical processes governing ice sheet and high mountain mass balance and the hydrologic cycle of high latitude regions. She uses data from a variety of sensors, especially time-variable gravity and altimetry, but also passive microwave, Global Positioning System, and in situ data. Dr. Velicogna is a recipient of the European Geosciences Union's Vening Meinesz Medal for distinguished research in geodesy and is a Kavli Fellow of the National Academies of Sciences, Engineering, and Medicine. She earned a B.S. and an M.S. in physics and a Ph.D. in engineering (geodynamics) all from the University of Trieste, Italy.

Appendix D

Acronyms and Abbreviations

CORS	Continuously Operating Reference Stations
COSMIC	Constellation Observing System for Meteorology Ionosphere and Climate
CYGNSS	Cyclone Global Navigation Satellite System
DART	Deep-ocean Assessment and Reporting of Tsunamis
DEM	digital elevation model
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
GEDI	Global Ecosystem Dynamics Investigation
GGOS	Global Geodetic Observing System
GIA	glacial isostatic adjustment
GNSS	Global Navigation Satellite System
GNSS-IR	GNSS Interferometric Reflectometry
GNSS-R	GNSS Reflectometry
GNSS-RO	GNSS Radio Occultation
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	GRACE Follow On
GRUAN	Global Climate Observing System Reference Upper-Air Network
IAG	International Association of Geodesy
ICESat	Ice, Cloud, and land Elevation Satellite
IDS	International DORIS Service
IERS	International Earth Rotation and Reference Systems Service
IGS	International GNSS Service
ILRS	International Laser Ranging Service
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
ITRF	International Terrestrial Reference Frame
IVS	International VLBI Service for Geodesy and Astrometry
JPL	Jet Propulsion Laboratory
M	magnitude
NASA	National Aeronautics and Space Administration
NGA	National Geospatial-Intelligence Agency
NGS	National Geodetic Survey
NISAR	NASA-Indian Space Research Organisation Synthetic Aperture Radar
NOAA	National Oceanic and Atmospheric Administration
NOTA	Network of the Americas
NSF	National Science Foundation
NSRS	National Spatial Reference System
PBO	Plate Boundary Observatory
Pol-InSAR	Polarimetric SAR Interferometry

RO	radio occultation
SAR	Synthetic Aperture Radar
SATM	science and applications traceability matrix
SGSLR	Space Geodesy Satellite Laser Ranging
SLR	Satellite Laser Ranging
SMAP	Soil Moisture Active Passive
SNR	signal-to-noise ratio
SSM/I	Special Sensor Microwave Imager
SWOT	Surface Water Ocean Topography
TDX	TanDEM-X
TOPEX	Topography Experiment
TRF	terrestrial reference frame
USGS	U.S. Geological Survey
USNO	U.S. Naval Observatory
VGOS	VLBI Global Observing System
VLBI	Very Long Baseline Interferometry