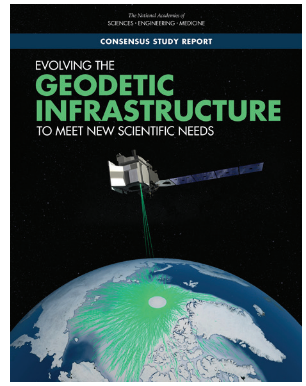
Consensus Study Report

HIGHLIGHTS

January 2020

Evolving the Geodetic Infrastructure to Meet New Scientific Needs



Space observations from the international geodetic infrastructure provide data needed to answer many high-priority scientific questions. However, answering some key questions, such as those connected with sea-level change, require improvements to the existing infrastructure. This report identifies specific improvements needed.

Approximately every ten 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 to support Earth system science and applications for 2017–2027. Underpinning these space observations and their interpretation is the geodetic infrastructure (see Box 1) 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. The existing geodetic infrastructure can support many of the science questions identified in the Decadal Survey, as long as it is maintained. However, enhancements to the geodetic infrastructure are required to support other Decadal Survey science questions. For example, a change in the position of the center of mass of the Earth, caused by melting of the ice sheets, results in a commensurate change in sea level. The geodetic infrastructure is needed to accurately determine the Earth's center of mass, and an accurate and stable terrestrial reference frame is needed to achieve the science objective of measuring sea-level rise to better than 0.5 mm/yr over a decade.

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, for example, the Gravity Recovery and Climate Experiment Follow-On [GRACE-FO] and Ice, Cloud and land Elevation Satellite 2 [ICESAT-2]).

BOX 1
Four Measurement Techniques of the Geodetic Infrastructure

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.

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 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.

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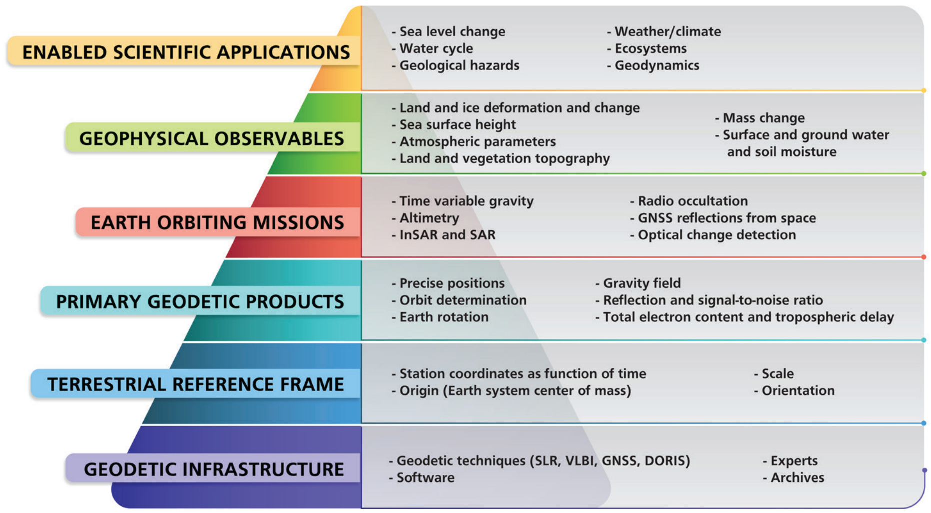

FIGURE 1. How the geodetic infrastructure is connected to enabled scientific applications. The geodetic infrastructure (level 1) comprises four measurement techniques used to accurately determine Earth's orientation in space, its gravitational field, the trajectories of satellites in orbit around the 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).

MAINTENANCE AND IMPROVEMENTS NEEDED IN KEY AREAS

In a two-day workshop in February 2019 those working to maintain and improve the geodetic infrastructure came together with scientists seeking to answer questions that require an accurate terrestrial reference frame. Together, they examined five areas 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).

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. 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 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. 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 monitoring absolute vertical deformation at local, regional, and continental scales. In the United States, this monitoring ability requires improvements to 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., Surface Water Ocean Topography [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.

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 both for long-term monitoring and for 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.

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 an 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 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.

NEEDED IMPROVEMENTS 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.

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 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. Three areas of improvement in the geodetic infrastructure are needed to help answer the Decadal Survey science questions:

1. Finalize 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.

In addition, 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.

COMMITTEE ON EVOLVING THE GEODETIC INFRASTRUCTURE TO MEET NEW SCIENTIFIC NEEDS

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For More Information . . . This Consensus Study Report Highlights was prepared by the National Academies of Sciences, Engineering, and Medicine based on the Consensus Study Report *Evolving the Geodetic Infrastructure to Meet New Scientific Needs* (2020). The study was sponsored by the National Aeronautics and Space Administration and the National Academies of Sciences' Arthur L. Day Fund. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project. Copies of the Consensus Study Report are available from the National Academies Press, (800) 624-6242; http://www.nap.edu or via the Board on Earth Sciences and Resources web page at http://www.nationalacademies.org/besr.

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