NATIONAL ACADEMY OF SCIENCES
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NATIONAL RESEARCH COUNCIL

REPORT IN BRIEF

Precise Geodetic Infrastructure

National Requirements for a Shared Resource

The geodetic infrastructure provides accurate information about fundamental properties of the Earth as they change over time and has led to many scientific, civil, military, and commercial applications. Numerous agencies and organizations have made valuable contributions to the geodetic infrastructure over the past half century; however, this critical infrastructure is now degrading from age and lack of support. Renewed investment in the geodetic infrastructure is needed to maintain and modernize existing systems and to enable the development of sophisticated new applications with significant economic, national security, and scientific benefits.

A middle-aged rocky planet, Earth offers a wondrous combination of interconnected systems. From its molten core below to the ionosphere above, planetary layers interact dynamically, moving constantly, affecting climate and environment, and impacting life of all forms on the planet. Quantifying these changes is essential for understanding the underlying processes well enough to identify their root causes and to anticipate and respond to future changes.

Geodesy is the science of accurately measuring the Earth's shape, orientation in space, and gravity field, and the changes in these properties over time. The precision of geodetic measurements has increased by several orders of magnitude over the past half century; in that time span, geodesy has proven immensely valuable for both scientific and commercial applications. Techniques and instrumentation developed for geodesy have enabled scientists to determine the changing position of any point on the Earth with centimeter accuracy or better. They also provide the technological underpinnings for surveying and navigation, determining flood maps, measuring sea level rise, coastal wetland monitoring, assessing groundwater resources, and monitoring earthquakes and other natural hazards. Even more precise and reliable geodetic measurements could enable an enormous array of advanced applications in autonomous navigation, precision agriculture, space exploration, hazard prediction, and other areas. Geodetic measurements are made using a variety of satellites, ground-based sensors and receivers, laser ranging devices, radio beacons, radio telescopes, and data-integration methods—a set of tools collectively known as the precise geodetic infrastructure.

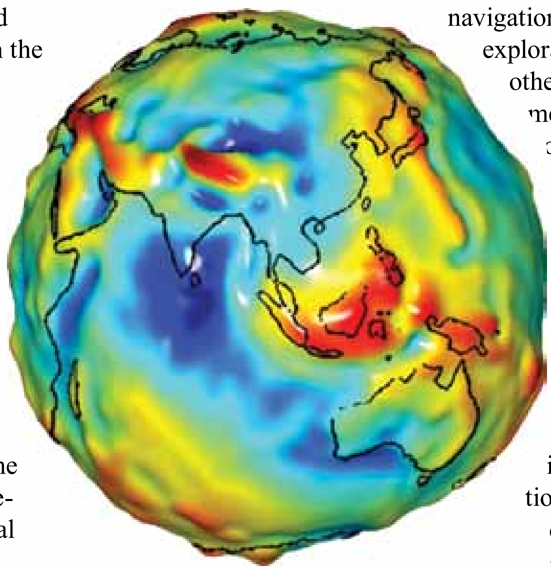


Figure 1 Gravity Model of Asia created by the Gravity Recovery and Climate Experiment (GRACE).
SOURCE: The University of Texas Center for Space Research, as part of a collaborative data analysis effort with the NASA Jet Propulsion Laboratory and the GeoForschungsZentrum Potsdam

U.S. federal agencies, in collaboration with international partners, led the development of much of the geodetic infrastructure that exists today. Recognizing this infrastructure as a shared national resource, the National Aeronautics and Space Administration, the U.S. Naval Observatory, the National Geospatial-Intelligence Agency of the Department of Defense, the National Science Foundation, the National Geodetic Survey of the National Oceanic and Atmospheric Administration, and the U.S. Geological Survey requested the

National Research Council to establish a committee to assess the state of the U.S. geodetic infrastructure, to define the need for and role played by this infrastructure, and to make recommendations on how to maintain its viability in the future. In response to this charge, the committee reviewed prior studies and the scientific literature and interviewed members of stakeholder communities to assess the scientific and societal benefits of precise geodesy, explore opportunities for innovation, and suggest ways to improve national coordination to support the geodetic infrastructure.

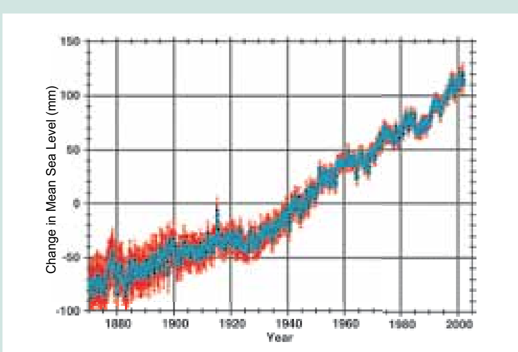
The Need for Precise Geodesy

The ground beneath your feet may seem solid, but it is not. Rather than being a solid ball spinning like a perfectly-balanced top, the Earth is constantly moving and changing. Even in the middle of continents, the ground moves up and down in response to lunar and solar tides; tectonic plates beneath the Earth's surface shift and collide; earthquakes and volcanoes change familiar landscapes; and storms redefine shorelines. In addition, the Earth wobbles on its axis, causing its spin rate (and, as a result, the length of day) to change over time scales as short as hours. Some of the movements of the Earth's surface and the planet as a whole are subtle and occur over long periods of time; others are sudden and catastrophic. All of these shifts can have significant impacts on human life.

The Earth's constant movements also mean that determining the location or height of a specific point on the Earth—for example, to predict where water may flow in a flood—is not as simple as it may seem. Precision geodesy, which uses techniques both on the ground and in space, offers the opportunity to accurately measure and understand the changes on the Earth's surface over time. Accurate measurements of the Earth are essential to improving our understanding of—and enhancing our ability to respond to or even predict—the processes behind many natural disasters, as well as climate change, sea level rise, and landscape changes at the local scale. High-precision measurements also enhance the many commercial, civil, and military applications of geodesy.

Why Precision Matters: Sea Level Rise

The rising global sea level provides a compelling example of the importance of precision measurements for science and decision making. Over the past decade, global sea level has increased by an average of 3.3 millimeters per year; some models predict that it will rise by as much as one meter by the end of the 21st century. Given the potentially devastating effects sea-level rise could have in low-lying inhabited areas, monitoring sea level rise is a high priority for many scientists and leaders. Because local sea levels fluctuate as a result of tides and other forces, scientists depend on geodetic measurements that span the entire planet to track changes in global and regional sea level. However, scientists must always consider the level of possible error, or uncertainty, in their measurements. That uncertainty is currently comparable to the annual contribution of Greenland's melting ice sheet to global sea level rise; this makes it more difficult to accurately predict sea level 100 years from now. Increased precision of the geodetic infrastructure is critical to accurately assessing and planning for the potential impact of sea level rise and other global changes on the ecology and human activities.[See figure below from Church and White, 2006. A 20th century acceleration in global sea-level rise. *GeophysicalResearch Letters* 33(1).]



Applications of Geodesy

The science of geodesy has significantly improved our understanding of the Earth system and has led to a

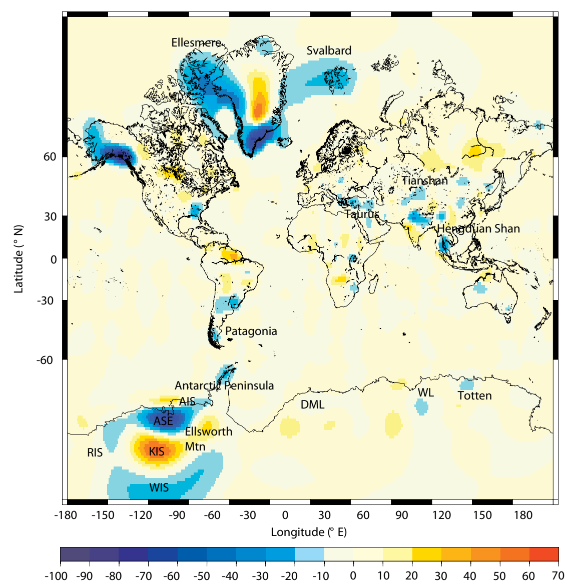
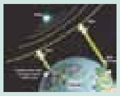


Figure 2 Average global transport of mass in the Earth's system, including estimates of the atmospheric mass in thickness of water equivalent.

SOURCE: Wu et al., 2010. Simultaneous estimation of global present-day water transport and glacial isostatic adjustment. *Nature Geoscience Online* (August 15), DOI: 10.1038/NGEO938.

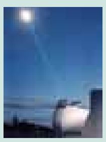
Critical Geodetic Infrastructure

The geodetic infrastructure comprises a vast collection of ground and space-based equipment and data processing tools. This infrastructure is organized into networks focused on particular scientific needs; the following are the critical geodetic networks that operate at the global scale, and support the International Terrestrial Reference Frame.

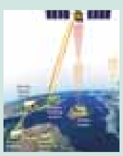


VLBI (Very Long Baseline Interferometry) uses radio telescopes to determine the position of the Earth in space.

GNSS (Global Navigational Satellite Systems, a generic term for systems like the U.S. Global Positioning System, GPS) use ground-based receivers and satellites to determine the locations of points on the Earth's surface.



SLR/LLR (Satellite Laser Ranging and Lunar Laser Ranging) reflects laser signals off satellites or the moon to provide information about the Earth's surface and gravity field, and the moon's orbit.



DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) uses satellites and ground beacons to track the precise positions of satellites and measure the height of water in the Earth's oceans.

host of applications. The following is a sampling of the current benefits of geodesy and potential future applications.

Elevation maps. High-accuracy surveys using geodetic instruments have increased our ability to map the height of land and water features. Accurate maps are important for navigation, floodplain mapping, and many other needs. For example, the depletion of an underground aquifer can cause the land above to sink, disrupting underground utility lines. Precise measurements of land height help to identify when sinking is occurring and can inform response and mitigation efforts.

Navigation systems. Geodesy is critical to maintaining the accuracy of GPS and other navigation systems. Scientists use geodetic techniques to monitor the precise locations of a set of reference points around the world and their change over time. Together, these points form a reference frame that can be used to determine the position of other points on the Earth. The agreed upon global reference frame is the International Terrestrial Reference Frame; regional reference frames also contribute to navigation systems. Providing the infrastructure to maintain these reference frames is one way geodesy underpins the navigation devices that are

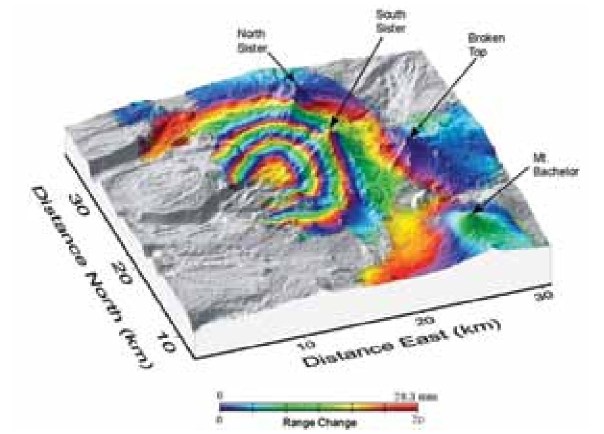


Figure 3 An area of uplift near the Three Sisters cluster of volcanoes in central Oregon, mapped using satellite interferometric synthetic aperture radar (InSAR). Each concentric circle of red corresponds to approximately 28 millimeters in deformation.

SOURCE: Courtesy of the American Geophysical Union. Wicks et al., 2002. Magmatic activity beneath the quiescent Three Sisters volcanic center, central Oregon Cascade Range, USA.*Geophysical Research Letters* 29(7):1122.

ubiquitous in our society today. Continuing to maintain the reference frames and improving the accuracy of positioning systems would enable even more precise navigation—for example, to support autonomous navigation for vehicles, planes, and ships.

Precision agriculture. Geodetic instruments provide high-accuracy positioning information farmers can use to plant crops in innovative patterns—such as interlacing two compatible crops on the same field—for higher efficiency and environmental benefit. In addition, the geodetic infrastructure improves the accuracy of satellite and ground-based environmental sensors that monitor soil moisture and enhance weather predictions. The combination of precise positioning and accurate environmental monitoring has made possible comprehensive new farming systems that reduce waste and environmental impact.

Early warning for hazards. Geodesy enhances our understanding of the mechanisms behind earthquakes, tsunamis, landslides, and volcanic eruptions, because all of these phenomena are related to changes in the shape of the Earth's crust. Using geodetic techniques, scientists can measure subtle changes in the surface of the Earth that are associated with these phenomena, such as a slight uplift in the ground around a volcano before it erupts. High-precision, real-time geodetic observation systems placed in areas at risk of these natural disasters could help provide early warning for—and perhaps even someday help predict—such hazards. Such warning systems, however, are in the early stages of development and require greater geodetic capability than is available today.

Optimizing Investments in the Geodetic Infrastructure

U.S. federal agencies have made considerable contributions to the geodetic infrastructure on the global scale. These past investments, however, are degrading as the infrastructure ages. Unless the infrastructure is maintained, the existing applications that depend on accurate information about the Earth will degrade in quality, and progress toward more sophisticated applications will stall. To capitalize on past investments and optimize future ones, the report recommends the following actions.

Make the most of existing instruments. In the near term, the United States should construct and deploy next-generation automated SLR tracking systems at its four current SLR tracking sites (which are in Hawaii, Texas, Maryland, and California). It also should install next-generation VLBI systems at its four VLBI sites (which are in Hawaii, Texas, Maryland, and Alaska). Maintaining and upgrading these existing sites will leverage past investments and enhance the continuity of global reference frames as new geodetic technologies are deployed.

Augment the current infrastructure. 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 multi-technique ("fundamental") stations.

Maintain a high-precision GPS network. The United States should establish and maintain a high-precision GPS national network constructed to scientific specifications that can work with other GNSS networks around the world and stream high volumes of data in real time.

Collaborate on the global stage. The United States should continue to participate in the activities of the Global Geodetic Observing System (GGOS) by providing long-term support for the operation of geodetic stations around the world and by supporting the participation of U.S. investigators in the activities of these services.

Maintain the International Terrestrial Reference Frame. A long-term U.S. commitment to maintain the International Terrestrial Reference Frame would provide a foundation for Earth system science, studies of global change, and a variety of societal and commercial applications.

Investigate workforce and education challenges. An assessment of the geodesy workforce and the research and education programs in place at U.S. universities is needed to evaluate the long-term prospects of geodesy and its applications.

Establish a federal geodetic service. A federal geodetic service charged with coordinatingthe modernization and operation of the geodetic infrastructure would ensure convenient, rapid, and reliable access to accurate geodetic data and products by government, academic, commercial, and public users. This service would not need to replace the geodetic activities currently carried out in a number of federal agencies; rather, it would build from the expertise and resources across these agencies to unify and bolster the national geodetic infrastructure and ensure that this shared resource meets the nation's evolving economic, scientific, and national security needs.

Committee on National Requirements for Precise Geodetic Infrastrucure: J. Bernard Minster (*Chair*), Scripps Institution of Oceanography; **Zuheir Altamimi,** Institut Géographique National; **Geoffrey Blewitt**, University of Nevada; **William E. Carter**, University of Florida; **Anny Cazenave**, Centre National d'Études Spatiales; **Herb Dragert**, Natural Resources Canada; **Thomas A. Herring**, Massachusetts Institute of Technology; **Kristine M. Larson**, University of Colorado; **John C. Ries**, University of Texas at Austin; **David T. Sandwell**, Scripps Institution of Oceanography; **John M. Wahr**, University of Colorado; **James L. Davis**, Lamont-Doherty Earth Observatory at Columbia University (*Liaison from Committee on Seismology and Geodynamics*); **David A. Feary** (*Study Director*), **Lea A. Shanley** (*Postdoctoral Fellow*), **Nicholas D. Rogers** (*Financial and Research Associate*), **Courtney R. Gibbs** (*Program Associate*), **Eric J. Edkin** (*Senior Program Assistant*), **National Research Council.**

The National Academies appointed the above committee of experts to address the specific task requested by the National Aeronautics and Space Administration, the National Science Foundation, the Department of Interior – U.S. Geological Survey, the Department of Defense – National Geospatial-Intelligence Agency, the Department of Defense – United States Naval Observatory, and the Department of Commerce – National Oceanic and Atmospheric Administration's National Geodetic Survey. The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.

EXPERT CONSENSUS REPORT

For more information, contact the Board on Earth Sciences and Resources at (202) 334-2744 or visit http://dels.nas.edu/besr. Copies of *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; http://www.nap.edu.