

A Foundation for Innovation:



Grand Challenges in Geodesy



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Preface

Over two decades, rapid advances in new and maturing geodetic technologies have supported the interrogation of the kinematics, structure, and dynamics of the solid Earth and its fluid envelopes. The quickening pace of technological change has fueled major new interdisciplinary research opportunities, even in the last few years. With the continued development of advanced terrestrial and space geodetic methods, geodesy has grown rapidly and there are now crucial geodetic applications in a wide range of scientific fields, from ground water systems and fault dynamics to mapping the speed of ice flows and the amount of water vapor in the atmosphere.

Widespread recognition that technology-driven science is a national asset in a global economy has further strengthened public investment in exploring these phenomena and their relevance to society. During October 2009, seventy-six scientists met to articulate new and emerging research opportunities in geodesy and its interdisciplinary applications. The meeting was followed by community comment on the results of the workshop. This report summarizes that work and identifies the key areas where additional research is needed to further our understanding of dynamic systems within the solid Earth, atmosphere, cryosphere, and hydrosphere.

Front Matter

A Foundation for Innovation: Grand Challenges in Geodesy

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Executive Summary

A Foundation for Innovation: Grand Challenges in Geodesy

Geodesy is the science of observing and understanding Earth’s time-varying shape, gravity field, and rotation. Over the last three decades, emerging observing technologies have revolutionized geodesy. The creation of new and often satellite-based data acquisition systems has generated large, diverse, and rich data sets that must be set in a coordinated framework for analysis. The development and improvement of mathematical models and data analysis techniques required for extracting information from the geodetic observables in turn supports investigation, quantification, and refinement of accuracy. Geodetic observations are used then to investigate the Earth’s structure and surface mass distribution, its response to internal and external forcing, and the interaction among its various systems. Over several decades, the unprecedented accuracy, spatial and temporal coverage, and integration achieved by geodetic observing systems has led to an explosion in the number and scope of Earth science fields that are advanced through geodesy. Throughout this document are many examples of the ways in which geodesy is utilized to achieve these advances.

This report uses the terms “geodetic science” and “geodetic applications” to distinguish the science behind geodetic techniques from the geophysical investigations that benefit from that science. The distinction enables us to discuss a large number of such applications and their great value to Earth science, without neglecting the underlying geodetic science that is the central activity of many researchers in the field and which makes possible the continued development of new geodetic observing systems and new applications for the resulting data.

CHALLENGES FOR GEODESY

In October 2009, seventy-six scientists met near Salt Lake City to discuss the future of geodesy. That workshop, *Long-Range Science Goals for Geodesy*, brought together geodesists and other geoscientists to identify the following grand scientific challenges that will determine the direction of geodesy over the next decade:

- Will humanity have enough water to sustain itself?
- How will Earth change as sea level rises?
- How do Earth's glaciers and ice sheets change on timescales of months to decades to centuries?
- How do tectonic plates deform?
- What physical processes control earthquakes?
- How does Earth's surface evolve?
- What are the mechanics of magmatic systems?

Workshop participants also made clear the importance of emphasizing the core geodetic science activities needed to address these grand challenges. Thus, the organization of this report reflects the distinction between “geodetic science” and “geodetic application,” while acknowledging the importance of both.

The main “grand challenge” sections of the report, Sections O1 and O2, review the great Earth science questions that can be addressed by geodetic applications. Section O1 (*Where is the Water?*) focuses on the distribution of water in the Earth system, in oceans, glaciers and great ice sheets, in the atmosphere, and on continents. Section O2 (*Earth the Machine*) is concerned with the dynamics of solid-Earth systems. Within these sections are a number of spotlights focusing on various geodetic observing systems, specific applications of geodetic technology, or sample activities within geodetic science.

Section O3 (*In the Public Interest: Societal Benefits*) discusses the application of geodesy and other Earth sciences toward the benefit of society as a whole. One subsection focuses on early warning for natural hazards, while the other reveals how the improvement of geodetic methods and accuracy led to a host of benefits to society in non-scientific realms such as commercial and civic planning.

Section O4 (*The Global View*) argues that modern geodesy requires multiple global observing networks, and that the infrastructure that geodesists have established for global coordination of geodetic data acquisition and analysis has been crucial for achieving the accuracy required for many applications. The declining state of the global geodetic infrastructure is reviewed in the Appendix.

Section O5 (*Teaching our Children*) argues that geodesy provides unique insights into changes in the Earth system, and that new understanding of global systems should inform science education. This section poses a central challenge for Geodesy:

- To nurture a deeper public understanding of geodesy and its benefits, and engage the children who will become the next generation of talent for advancing science and informing policy and planning.

Challenges confronting geodesy for maintaining a professional workforce are addressed in Section O6 (*The Next Generation: The Geodesy Workforce*). The concerns expressed by the recent NRC report on geodetic infrastructure (*Precise Geodetic Infrastructure: National Requirements for a Shared Resource, 2010*) regarding the lack of long-term U.S. support for research and education in geodetic science are echoed here. The authors hope to stimulate discussion regarding current U.S. funding structures for fundamental geodetic science in light of future needs of the U.S. Earth science community, science education, and of broader society.

KEY RECOMMENDATIONS

Geodesy has been stunningly successful in achieving increasingly higher accuracies over the last few decades, leading directly to the explosion of geodetic applications within Earth science documented in this report. At the present time, the focus of geodesy has begun to shift to improvements in temporal resolution, spatial resolution, geographic coverage, data latency, speed of data analysis, and distribution of data products. Geodesists boldly imagine an era of “geodetic imaging” to serve the needs of science and society, in which we observe Earth’s solid surface and glaciers, the height of the sea, and the gravity field, in near-real time. Continuous observations at high spatial and temporal resolution are needed to fully understand the changing Earth and the variation of its changes with time.

The recommendations presented in Section 07 (Summary and Recommendations) set realistic goals for U.S. geodesy for the next decade. This report refrains from presenting specific geodetic accuracy goals, deferring instead to the “integrated scientific and societal user requirements” detailed thoroughly in Chapter 7 of *Global Geodetic Observing System (2009)*.

The seven recommendations presented here derive directly from challenges posed in Sections 01–07:

1. Undertake geodetic missions recommended by the Decadal Survey.
2. Obtain continuous observations of the dynamic Earth and its environment.
3. Advance open, real-time access to data and data products.
4. Improve the robustness of the global geodetic reference frame.
5. Enable seafloor geodesy.
6. Emphasize system integration and interdisciplinary cooperation.
7. Use geodesy for Earth science education and public outreach.

The record of geodetic innovation chronicled in this report results from the work of geodesists developing novel technologies and creative modeling approaches, and through cooperation with multidisciplinary teams of scientists to devise original applications for geodetic science. Implementation of these recommendations will expand on the innovation that has become the hallmark of geodesy.

"... 'down' is not any chance direction but where what has weight and what is made of Earth are carried..."

Aristotle, Physics (ca. 350 BCE)

Introduction: The Science of Geodesy

A Foundation for Innovation: Grand Challenges in Geodesy

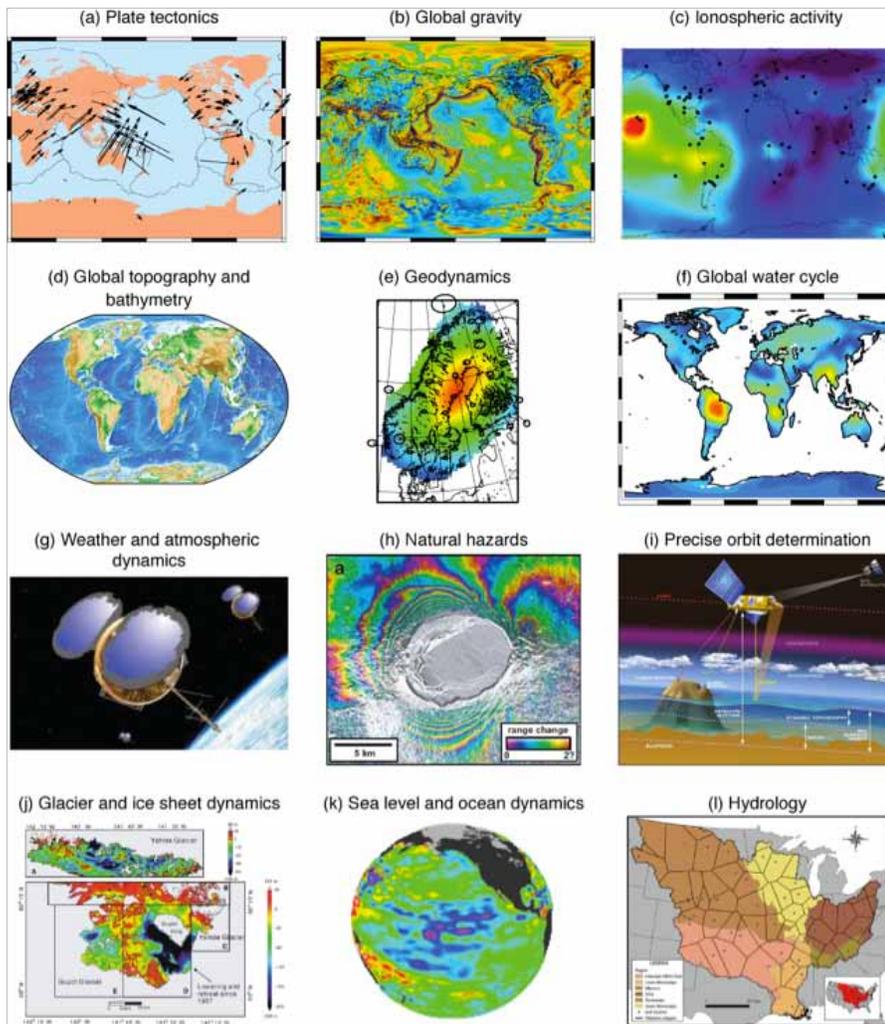


Figure 01

Geodetic observing systems have advanced an extremely broad range of applications within Earth sciences. This figure illustrates a few of these applications. These and others are discussed in this document.

The earliest geodetic measurements were obtained over two thousand years ago, when Eratosthenes established that our planet has a spheroidal shape and described Earth in terms of a single number: its size.

Since the time of Eratosthenes, geodesy has grown into the science of observing and understanding Earth's time-varying shape, gravity field, and rotation. What makes this science so powerful is the immense range of phenomena that can be studied using these observations. Modern geodesy targets the study of processes as diverse as deformation of Earth's surface, redistribution of mass within and on the surface of the solid Earth, oceanic and atmospheric circulation, changes in sea level; and variations in the flow and mass balance of glaciers. In addition, since geodetic techniques often use electromagnetic signals propagating through the atmosphere of Earth, modern geodesy provides information on atmospheric temperature and water vapor, and on ionospheric electron density. Recent studies suggest that geodesy might be used to study snow accumulation, vegetation structure, biomass and carbon sequestration, and soil moisture. Thus, in the early twenty-first century, the goal of geodesy has

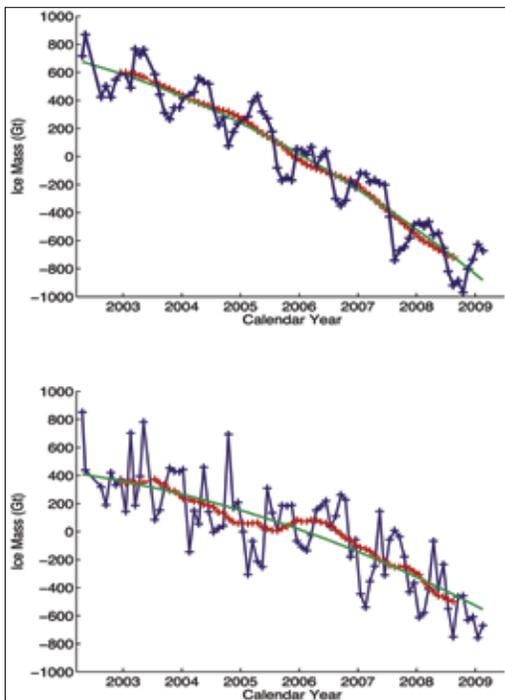


Figure 02

Extremely accurate intersatellite range-rate measurements by the Gravity Recovery and Climate Experiment (GRACE) tandem satellites have produced the first ever maps of global time-variable gravity. Some of the most important targets for GRACE are the major ice-mass complexes in Greenland and Antarctica. This figure shows that ice-mass loss from Greenland (top) and Antarctica (bottom) has been accelerating.

evolved to include the study of the kinematics and dynamics of, and interaction among, the solid Earth, cryosphere, hydrosphere, atmosphere, and biosphere (Figure 01).

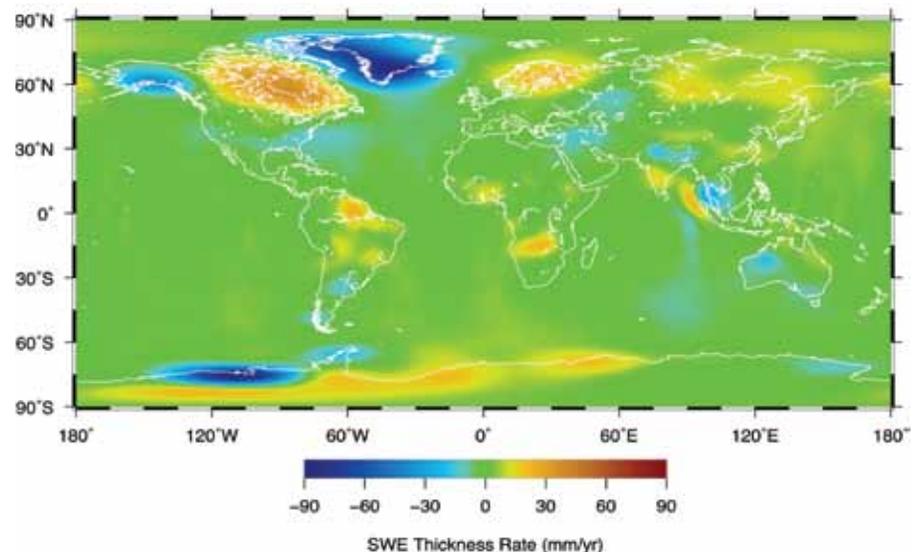
To achieve these broad goals, geodesy uses a rich assortment of high-accuracy measurement techniques that reveal the dynamic Earth system at a wide range of spatial and temporal scales. Current applications of these techniques include:

- Reflecting laser light from mirrored, orbiting satellites to reveal changes in the geocenter and the orientation of Earth in space.
- Using superconducting magnets to levitate a metal sphere in a nearly perfect vacuum to measure the acceleration due to gravity.
- Reflecting microwave signals off Earth's surface from a spaceborne or airborne radar to detect motions of Earth's crust and ice sheets, measure sea-surface height and ocean currents, and characterize biomass.

- Measuring the distance between twin satellites with micron accuracy to track the movement of mass within the interior of Earth and water and ice on the surface of Earth (Figures 02, 03).
- Surveying glaciers with spaceborne lasers to track ice motions and monitor loss of ice mass due to climate change.
- Observing quasars at the edge of the universe with giant radio telescopes to reveal the dynamics and shape of Earth's core.
- Combining optical and radar images from satellites and aircraft to track horizontal motions over days to decades.
- Scanning the local environment with ground-based lasers and illuminating the ground with airborne lasers to create images that reveal the dynamic forces that shape Earth's surface (Figure 04).
- Using global and regional networks of GNSS¹ instruments for an increasing variety of high-precision Earth science applications, a short list of which includes detailed measurement of tectonic plate motion and deformation, volcano monitoring, and glacier flow.

Figure 03

Geodetic observing systems such as GRACE enable us to observe the movement of mass near the surface of Earth for the first time. This is a map of the mean rate of change of mass near Earth's surface, expressed as the rate of equivalent water depth, based on GRACE data. The GRACE data in this map, for example, reveal ongoing mass changes (mostly mass loss) to ice sheets in Greenland, Antarctica, and Alaska; GIA in North America and northern Europe; groundwater changes in South America and Africa; and other mass motions. 101 monthly gravity fields from the period 2002–10 were combined to make this map.



These measurements would not be useful without the mathematical techniques necessary to analyze the data, the computational capacity of modern cyberinfrastructure, and the contributions of engineers and computer scientists. The information that is sought must often be obtained from the observations using intricate inversion methods. In fact, the famous mathematician and physicist Gauss invented the least-squares method in the eighteenth century in part to invert data from triangulation networks, which were the state-of-the-art geodetic system of his time. Since Gauss's era, the method of least squares has become the basis for a wide variety of inversion techniques that are used in many different fields.

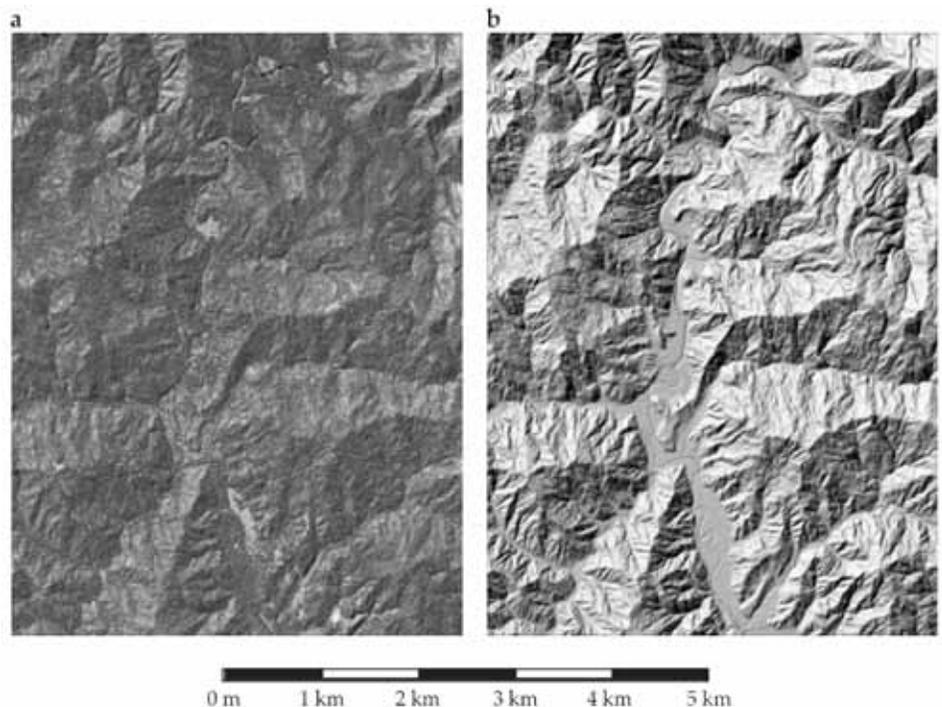
Theoretical models that express geodetic observations in terms of physical parameters are often quite complex, even more so when observations have been made from platforms that are themselves in motion with respect to the Earth, or

when long-term changes may affect the observing system itself.

Geodesy provides a rich toolbox of applications for cutting-edge research in other scientific fields, such as earthquake physics, volcanology, geodynamics oceanography, atmospheric and climate science, hydrology, glaciology, geomorphology, ecosystem science, as well as physics and astronomy. In addition to these research applications, geodesy may be used to study natural hazards and, potentially, to provide early warning of earthquakes, tsunamis, landslides, and volcanic eruptions; and to study how the coasts respond to sea-level change and to storms. Given the current trend of innovation within geodesy, the range of geodetic applications will continue to increase.² The relationships between geodesy and these disparate fields attest to the strength of geodesy as a discipline.

Figure 04

Airborne Laser Swath Mapping (ALSM) produces images of the terrain with unprecedented resolution. In (a), an unfiltered ALSM image of the South Fork Eel River in northern California shows heavily forested terrain. In (b), a filtering process has been used to extract a "bare-Earth" image from the ALSM data set, revealing subtle landslide features that are hidden beneath the forested terrain.



¹ Throughout this document, the more general term "Global Navigational Satellite System" (GNSS), which includes all satellite navigation systems such as GPS. In some instances, the more specific "Global Positioning System" (GPS) is used where it is more appropriate.

² In the context of this document "geodetic science" involves research relevant to geodetic theory or observation, including: satellite orbit determination; rotational dynamics; electromagnetic wave propagation; signal detection; causes and modes of crustal deformation; inversion theory and error analysis; gravity and potential theory; and reference systems. The term "geodetic application" refers to application of geodetic science to other fields of research, such as those listed above.

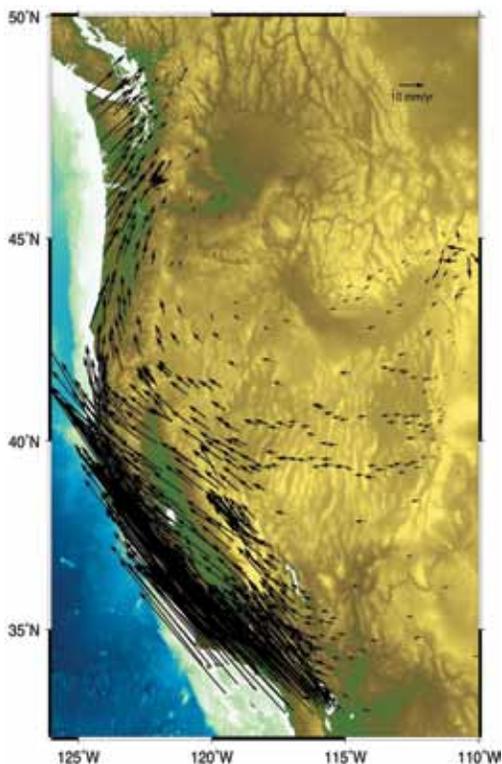


Figure 05

One of the targets for the EarthScope Plate Boundary Observatory (PBO) is the integrated velocity fields (and their temporal variability) for North America. This figure shows the mean horizontal crustal velocity field from PBO GNSS solutions through November 2009. For clarity, error ellipses are not shown, but all velocity estimates with formal uncertainties greater than 1 mm/yr are omitted. Data from PBO sites in Alaska and CONUS east of 100° W are not shown.

Within these fields, geodesy enables transformative observations and discoveries. Recent examples include:

- Measurement of present-day instantaneous velocities of Earth's tectonic plates.
- First global determination of the mass balance of Earth's great ice sheets, and the observation that the mass loss in Greenland and Antarctica may be rapidly accelerating.
- Discovery of periodic, slow aseismic slip in subduction zones in Japan, Cascadia, Mexico, and around the world.
- Precise measurements of secular and transient deformation due to active seismogenic faults (in particular, major plate boundary faults such as the San Andreas fault in California), with direct relevance to seismic hazard estimates.
- Accurate determination of present-day global sea-level rise, which is a sensitive indication of climate change caused by melting of glaciers and ice sheets as well as changes to the thermal and salinity conditions of the ocean.³
- Unexpected, sudden and dramatic accelerations and decelerations of deep outlet glaciers in Greenland and elsewhere.
- Determination of the crustal deformation field of North America with unprecedented accuracy, and spatial and temporal resolution (Figure 05).
- Extraordinary images obtained from LiDAR (Light Detection and Ranging) mapping of active faults, which has enabled new insights into the slip distribution of recent earthquakes that are not possible with any other approach.
- Detection of magmatic activity at dozens of volcanoes worldwide that were previously thought to be dormant.
- Establishment of international geodetic services for the development of standards, models, and documentation, including the International DORIS Service (IDS), International GNSS Service (IGS), the International Laser Ranging Service (ILRS), and the International VLBI Service (IVS). These services coordinate data analysis of global networks and make data and data products freely available.
- Development of the Global Geodetic Observing System (GGOS), recently adopted as a permanent component of the International Association of Geodesy (IAG).
- Establishment of UNAVCO for focused support of geodetic applications by providing state-of-the-art geodetic equipment, facilities, engineering, and data services for projects located all over the world.

³ Geodetic determination of sea level change featured prominently in the Fourth Assessment Report of the Inter-governmental Panel on Climate Change (IPCC).

- Inferences of the mechanical properties of damage zones around major crustal faults from measurements of small strain or seismic shaking induced by nearby earthquakes (Figure 06).
- Establishment of NCAALM for the acquisition of airborne LiDAR data and the Open Topography portal to integrate and distribute high-resolution topography data and tools.

This document addresses two different perspectives of “geodetic science” and “geodetic applications” by embracing both and recognizing their power in combination. It is organized around Earth science applications that might emerge and evolve over the next 5–10 years. To that end, this document identifies seven “Grand Challenges” for Earth science. These challenges were chosen because they are fundamental to understanding Earth, they are important to a global society that increasingly depends on this understanding for its safety and prosperity, and they can be significantly transformed by the application of geodetic observations. The recommendations that follow the Grand Challenges are intended to position the field of geodesy for a decade of innovation, collaboration, and scientific achievement.

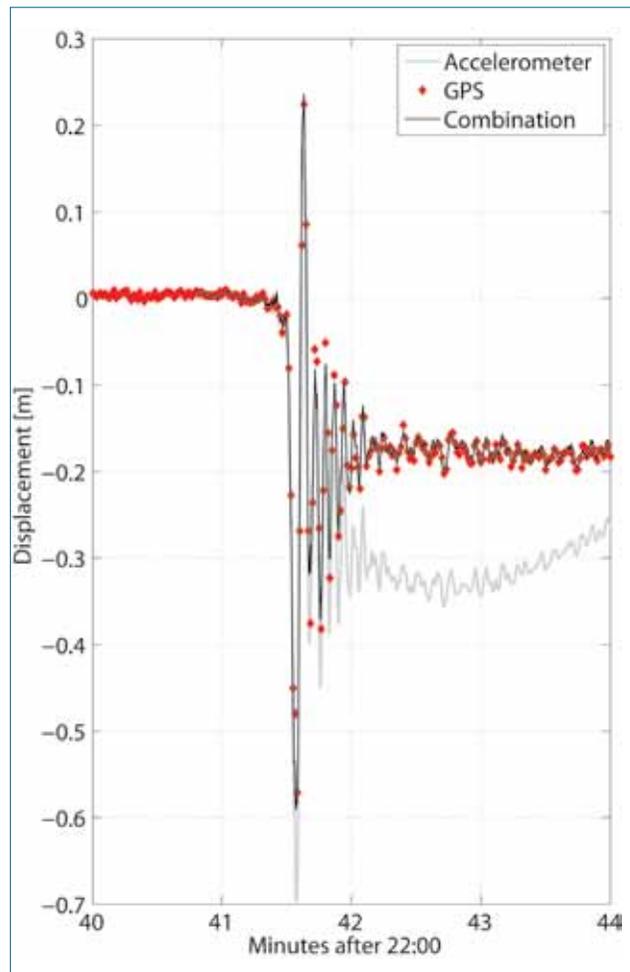


Figure 06

The recent occurrence of moderate and great earthquakes within high-rate GNSS networks drives new capabilities for understanding their impact, with implications for early detection and warning. A new approach for deriving displacements relies on a joint stochastic filtering of a high-rate GNSS displacement time series (the determination of which is itself a recent geodetic advance) and very-high-rate accelerometer data. This approach has the advantages inherent to GNSS, namely accurate determination of the static offset during an earthquake with no clipping for large displacements, and takes advantage of the higher observation rate provided by accelerometers. Above is a detail from the April 4, 2010 M_w 7.2 El Mayor-Cucapah earthquake vertical displacement record.

"If there is magic on this planet, it is contained in water."

Loren Eiseley, *The Immense Journey* (1957)

SECTION

01

Where is the Water?

A Foundation for Innovation: Grand Challenges in Geodesy

Water is arguably *the* fundamental component of the Earth system. It enables life, moves energy through the Earth system, and reshapes our planet. Water is exchanged on a variety of timescales among the oceans, atmosphere, cryosphere, and lithosphere. As Earth responds to climate change, water in the Earth system responds and redistributes itself in a variety of ways. Water formerly locked up in the ice sheets melts and joins the oceans or is stored on the continents. Precipitation patterns continue to change. Rainfall is reduced in some areas, causing drought, while formerly arid regions may have abundant rainfall. Sea levels rise and ocean circulation changes. Thus, the monitoring of the temporal changes in Earth's water reservoirs is fundamental to understanding the planet-scale impact of climate change.

Various impacts of the redistribution of water on Earth can be monitored by geodetic observational systems. The redistribution of water can be determined directly by estimating changes in Earth's gravitational field as it responds to the moving water mass and to the deformation of the solid Earth caused by moving water (Figure 07). We can measure the height of the oceans and the ice sheets using laser and radar altimetry, the velocity of glaciers using Interferometric Synthetic Aperture Radar (InSAR), sub-pixel optical and SAR pixel tracking and GNSS, and the response of the solid Earth due to the weight of the redistributed water using GNSS. Changes in the amount of water contained in the atmosphere can be measured by the delays they cause to electromagnetic signals used by geodetic measurement systems.

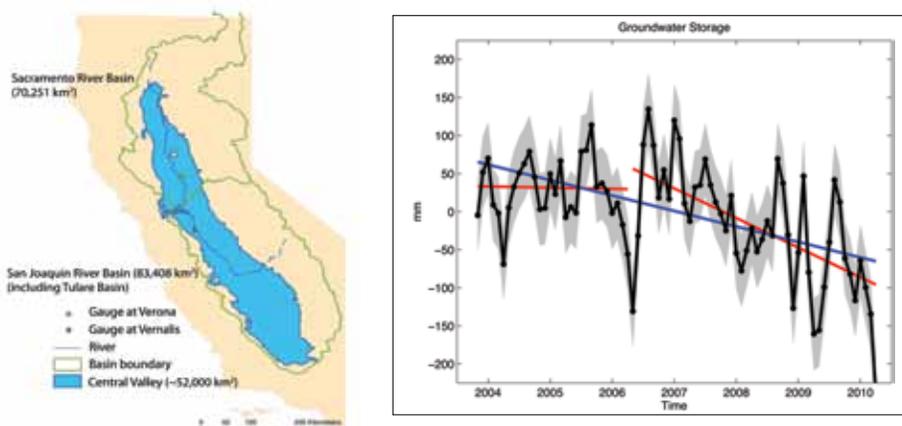


Figure 07

Data from GRACE satellite gravity observations indicate that California's Central Valley (left) is losing groundwater (right) at a rate of 31 ± 3 mm/yr from 2004 -10. This amount of water is nearly the capacity of Lake Mead, the largest reservoir in the United States. The Central Valley is a major agricultural producer, and depends to a great extent on groundwater for irrigation. Geodetic measurements such as these raise questions regarding the sustainability of groundwater depletion on this scale.

Reflections of electromagnetic signals off of Earth's surface can inform us even about the amount of water contained on and within the ground. Geodesy thus provides the precise tools to monitor the small, but very important, changes we see in the water reservoirs of Earth as it responds to climate change.

In this section, we present three Grand Challenges focused on issues relating to water and climate. The title of this section is "Where is the Water?" because that is an aspect of this problem that geodesy, through its sensitivity to mass redistribution and accurate distance measurements, is uniquely positioned to answer.

GRAND CHALLENGE 1

Will the global population have enough water to sustain itself?

Fresh water is the fundamental building block of terrestrial ecosystems and, ultimately, civilization. With the world's population expected to reach 9 billion by 2050, the demand for potable water will continue to grow, as will the need for water for the production of energy. Power generation is the single largest user of water in the United States, where steam-driven power plants account for 49% of the total U.S. water use in 2005 and 41% of the total freshwater withdrawals. Global climate change and human activity will continue to influence the redistribution and storage of water, emphasizing the need to understand the fundamental mechanisms that drive global hydrology.

Geodetic observations are enabling us, for the first time, to follow the motion of water within Earth's system at continental and global scales. We can now characterize changes in terrestrial groundwater storage ranging from continental-scale changes in water storage using GRACE, to regional and local changes using InSAR, GNSS, leveling, and relative gravity measurements of surface deformation accompanying aquifer-system compaction. Geodesy measures both the change in gravity and surface motion in response to natural and anthropogenic water-level changes. Aquifer-system responses to recharge and pumping are directly measured with a number of geodetic tools (gravity, leveling, GNSS, InSAR) and can be used to characterize the extent of the aquifer system as well as large-scale heterogeneities, including groundwater barriers such as faults.

Modeling these changes provides an understanding of the physics that drives the system and the implications of

the changes on the regional aquifers. As groundwater levels continue to be drawn down to new lows, the storage capacity of the aquifer system is reduced, primarily in the fine-grained units. Quantifying the global mass flux and volume of groundwater in storage at both the local and continental scales is needed to fully characterize the water redistribution process.

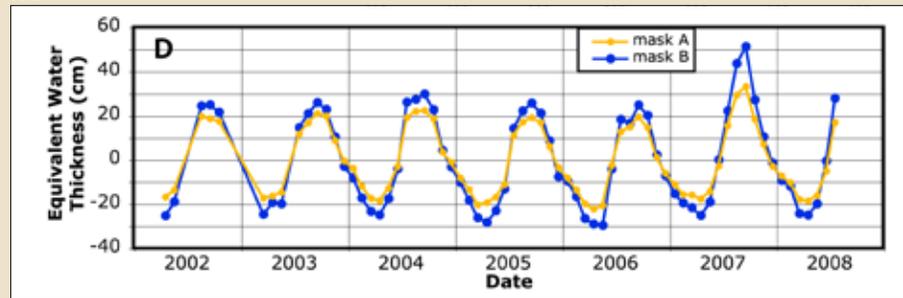
Geodesists, hydrologists, and snow scientists are beginning to develop the next generation of 3-D and 4-D snow-water equivalent (SWE) measurement techniques through the application of several geodetic tools: InSAR, Unmanned Airborne Vehicle SAR (UAVSAR), airborne LiDAR, ground-based LiDAR, and GNSS. Though several studies have shown the effectiveness of repeat-pass, differential InSAR to image snow depth change for a given storm, currently there are two limitations to this technique: the need for relatively short orbital passes to best image a given snow fall event while minimizing radar decorrelation, and the need to measure absolute snow depth. Airborne LiDAR can provide very good spatial snow depth coverage over areas of specific interest, but it is costly and cannot reliably measure snow depth change of less than 0.3 meters. Ground-based LiDAR has been used to track very detailed decimeter-level snow depth and SWE changes as input to regional climate models, but is cost-prohibitive at larger (watershed) scales. The application of reflected GNSS signals for measuring snow-depth change over time could provide a new measurement source to help understand regional snow pack.

Spotlight I

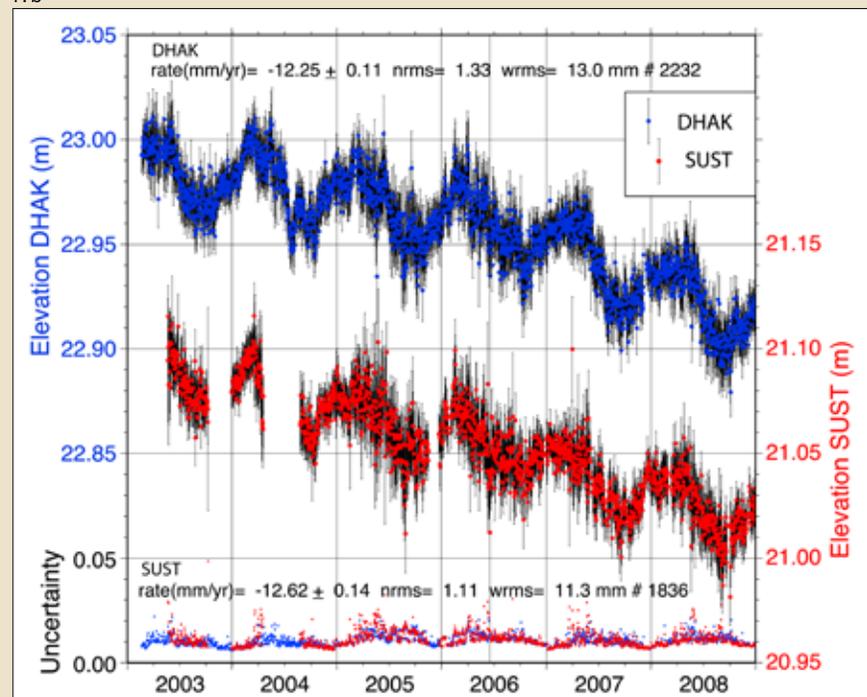
Geodetic observation of hydrological loading: A case study

The fertile delta formed by the convergence of the Ganges, Brahmaputra, and Meghna rivers is home to more than 200 million people. The discharge of water from this river system is exceeded only by the Amazon River, and floods caused by the summer monsoon rainfall occur on a regular basis, during which periods 20–30% of Bangladesh is typically submerged. The excess mass of water associated with these floods causes a gravity perturbation (expressed as equivalent water thickness) that is discernible in space (Figure I.a). Figure I.a shows time series of gravity changes, in units of equivalent surface water thickness, determined from GRACE gravity data. (The blue and yellow curves use slightly different spatial averaging.) The large seasonal variations in the water storage, peaking in September, are clearly visible. On the ground, the weight of the excess water loads the surface of Earth, causing large vertical motions, clearly evident from GNSS time series for two sites from the region, DHAK and SUST (Figure I.b). These time series of vertical station position reflect not only the seasonal loading signature for these sites, but local long-term subsidence associated with the withdrawal of groundwater by pumping. This study illustrates how new geodetic tools are enabling better understanding of the interaction between the climate and the solid Earth, and of natural and anthropogenic influences on freshwater.

I.a



I.b



If successful, this technique would not only extract snow pack SWE data from the available continuous GNSS arrays such as the PBO, but may also provide a way to improve the positional accuracy of snow-impacted sites in these arrays.

The continents are but one system of Earth wherein freshwater resides. Two others, Earth's oceans and cryosphere, are the subject of the following two Grand Challenges. An additional area in which geodesists have developed highly innovative approaches is the determination of atmospheric water vapor. Water vapor is difficult to observe and quantify at altitude, but carries a significant amount of atmospheric energy, and is therefore important for accurate weather forecasts, especially in warm, humid systems. The role of water vapor in atmospheric radiative heat transfer is also a major uncertainty in climate change models.



Figure 08

Over the last decade or so, geodetic measurement of atmospheric water vapor has advanced from nuisance parameter estimation to large ground-based networks and satellite constellations dedicated to providing this important information for weather forecasting. Assimilation of geodetic water vapor information into local-mesoscale numerical weather prediction models now provides significantly improved three-hour forecasts and warnings of heavy precipitation. Geodetic observations are also used in combination with meteorological instrumentation to study other important atmospheric phenomena, such as atmospheric rivers. Figure 08 is a representation of a Block IIF (i.e., fourth generation) GPS satellite as it passes over a cyclone that is reaching the coast.

For some geodetic observations, atmospheric water vapor is a challenging “noise” source due to its variable refraction at the radio wavelengths used by VLBI, GNSS, and InSAR. However, this noise is simultaneously an important source of information (Figure 08). Two techniques have been developed to take advantage of this dualism: Ground-based geodetic measurements are used to determine the total amount of water vapor in a column of atmosphere above the site. The COSMIC mission uses Earth-orbiting satellites with GPS receivers to determine the vertical distribution of water vapor and temperature as a satellite from the GPS constellation “sets” behind Earth. These measurements are now being assimilated into NOAA, European, and Japanese weather forecasts on a routine basis. These techniques also provide quality control for radiosonde profiles, and play an important role in the validation and calibration of spaceborne radiometric remote sensing systems.

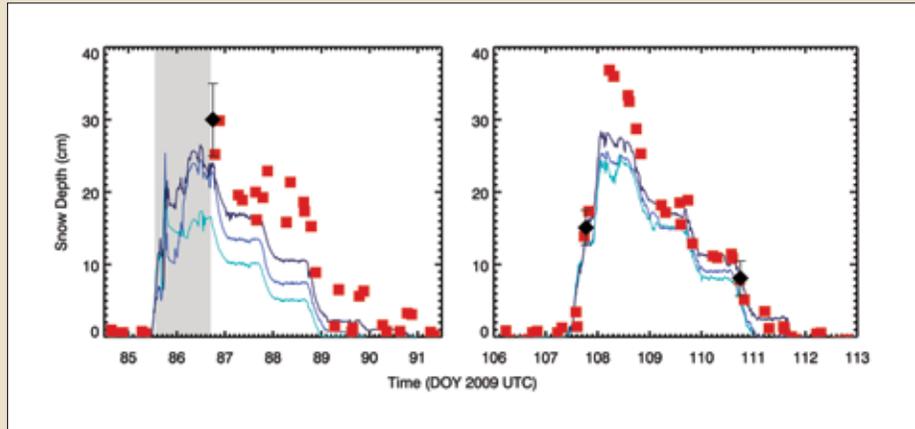
Understanding exactly how water moves through the hydrological cycle and resides in storage requires an interdisciplinary science approach. The new insights into this process afforded by geodetic observations have ushered in a new era of collaboration between geodesists and hydrologists, glaciologists, oceanographers, and atmospheric scientists. The geodetic community must collaborate with scientists in other disciplines to understand, model, and remove the influence of these non-solid-Earth motions and system noise in the geodetic data. In return, the geodetic community is providing new scientific observations and approaches to these colleagues. This is a classic example of a person's noise being another's signal.

Spotlight II

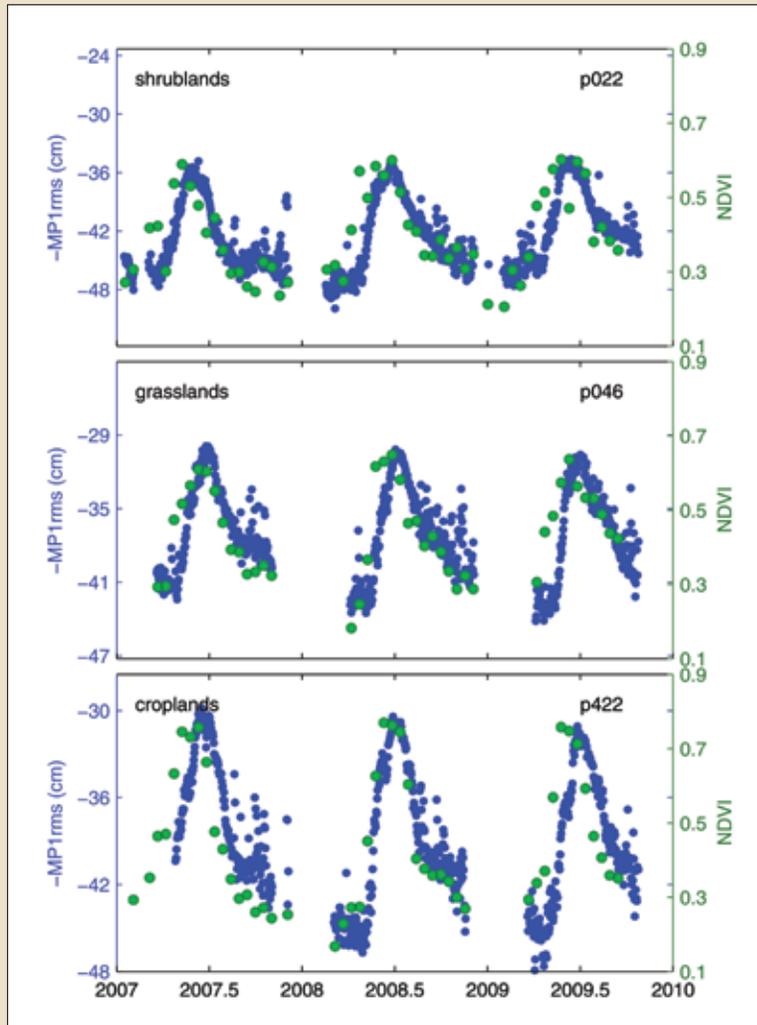
GNSS reflections: The value of understanding system noise

GNSS antennas are designed to receive signals from the entire sky with minimal signal attenuation in any particular direction, a design that makes them very effective at receiving both signal and problematic noise, including signals that have been reflected off the surface below the antenna. This situation is unfortunate for positioning applications because the reflected signal is difficult, if not impossible, to model. However, the perspective that "one's noise is another's signal" has enabled geodesists to figure a way to use this noise to characterize the surfaces that are reflecting the signal. In Figure II.a, for example, snow depth inferred from the GNSS observations (red squares) tracks well with estimates made with ultrasonic snow depth sensors (blue lines) and hand measurements (black diamonds). In Figure II.b, a measure of the reflection multipath from GNSS (MP1rms, blue) follows closely the Normalized Difference Vegetative Index (NDVI, green) for three different land cover classifications. Similar results have been obtained for soil moisture. These types of studies demonstrate that research aimed at understanding arcane signals measured by complex geodetic instrumentation can have unexpected practical application. They also point to the possibility that the thousands of GNSS receivers that are currently deployed for science, surveying, navigation, and other purposes could be utilized as a network of environmental sensors.

II.a



II.b



GRAND CHALLENGE 1 - KEY QUESTIONS:

How do the cryosphere, oceans, atmosphere, and solid Earth exchange water on a wide range of time scales and spatial scales?

In what ways is this exchange of water affected by climate change?

What is the impact of climate change on continental water storage?

What are the responses of the solid Earth to the redistribution of water?

How does atmospheric moisture change in space and time?

How does the redistribution of water at the surface impact ground water storage?

LONG-TERM GOALS FOR ADDRESSING KEY QUESTIONS:

Integrate multiple ground-based and space-based observing systems for measuring vertical and horizontal land deformation, snow height, and gravity.

Develop methods for integration of observations having different spatial and temporal resolutions.

Maintain a stable terrestrial reference frame with sub-1 mm/yr vertical accuracy.

Sustain multiple, concurrent, continuous satellite systems for sea-surface topography, and time-variable gravity without temporal gaps.

Improve the spatial resolution and accuracy of space-based gravity observations.

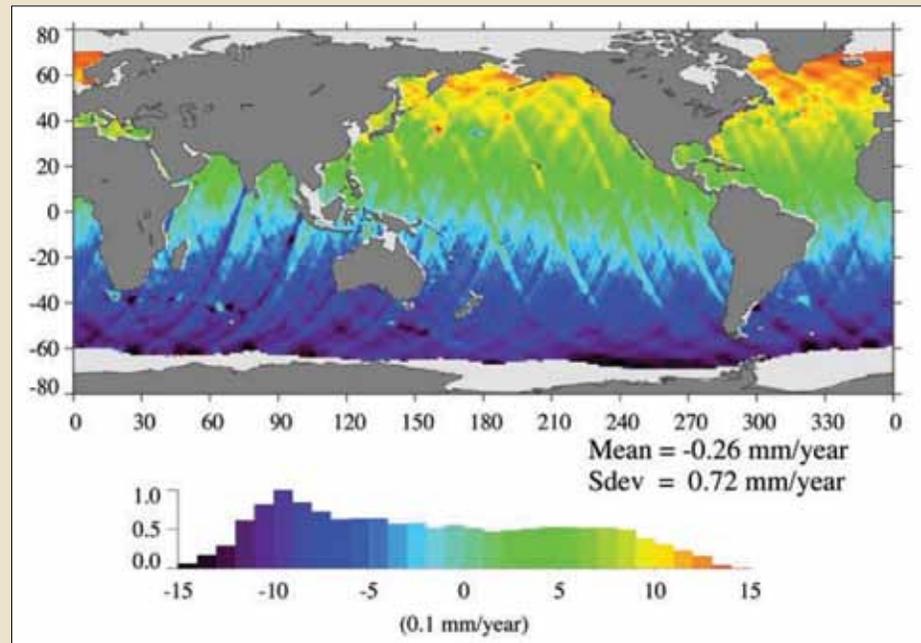
Carry out campaigns for calibration of geodetic measurements against local hydrological measurements.

Spotlight III

Fundamental importance of reference frames

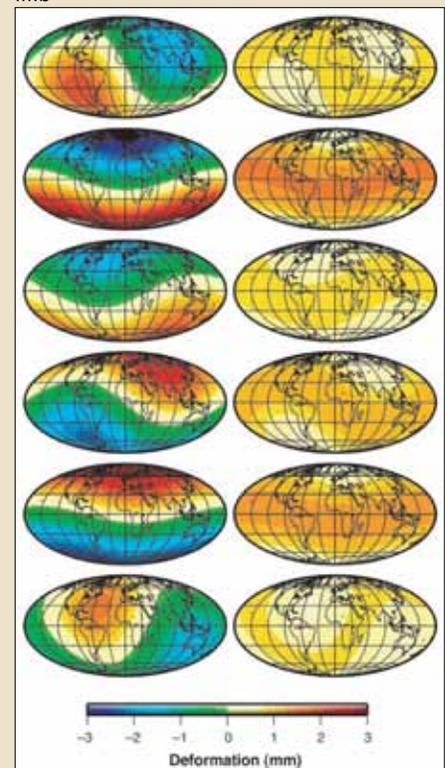
All spatial measurements require an appropriate frame of reference that establishes the context for the measurements. In geodesy, the terrestrial reference frame (TRF) is a consistent set of calculated three-dimensional time dependent coordinates for a network of globally distributed reference points that are used to define the locations of all other points. This straightforward definition conceals a great deal of complexity. Earth moves and deforms intricately over all time scales; using just six numbers (three for position, three for velocity) to describe the motion of a point means that non-linear motions (e.g. Earth's spin, wobble, precession, nutation, tidal, hydrological and, atmospheric loading) must be carefully defined within the terrestrial reference system (TRS), which is the theoretical framework that underlies the TRF. Development of the TRS is itself a complex process, involving large segments of the geodetic community agreeing on standards and definitions. To determine the TRF, observations from four geodetic observing systems (DORIS, GNSS, SLR, and VLBI) are combined. Each observing system has different sensitivities to the parameters defining the TRF and different sources of error, so that the combined solution is more accurate and less sensitive to errors in any one system. Sites with multiple observing systems strengthen the TRF further, but relatively few of these exist (see Appendix). Errors in the TRS and the TRF propagate into errors in all other geophysical observations that depend on their usage. For example, it is possible for the TRF to impart artificial deformation features to a ground-based network. Errors in TRF heights are especially common, and these errors propagate systematically into estimates of

III.a



atmospheric water vapor, sea level, satellite orbits, and other parameters. Figure III.a, for example, shows a systematic north-south pattern of differences between estimates of sea level rate made from the Ocean TOPography Experiment (TOPEX) (1993–2002) using orbits based on two different (now obsolete) TRFs. An accurate TRF can lead to important discoveries because it enables coherent global motions to be revealed. For example, Figure III.b shows observed deformation of Earth (top to bottom: Dec–Jan, Feb–Mar, Apr–May, Jun–Jul, Aug–Sep, Oct–Nov; left: vertical deformation; right: magnitude of horizontal deformation) due to the seasonal migration of water between northern and southern hemispheres.

III.b



GRAND CHALLENGE 2

How will Earth change as sea level rises?

One of the greatest threats of climate change is the anticipated rise of sea level associated with the thermal expansion from rising water temperatures and with the redistribution of ocean/continent water linked to melting of glaciers and ice sheets. The ocean absorbs much of the excess heat due to climate change and its thermal expansion is expected to contribute to sea level rise, perhaps a third of a meter by 2100. The exchange of water between the continents and the oceans has the potential to cause as much as two meters of sea level change by 2100, mainly due to the melting of ice on the land and the subsequent oceanic runoff. Greenland and Antarctica contain enough ice to raise global mean sea level by 7 m and 55 m respectively, so melting only a fraction of those large ice sheets can cause significant sea level rise. Mountain glaciers and other ice fields, which are rapidly melting, contain another meter of potential sea level change.

Sea level rise will not be uniform around the world, due to local variations in ocean density and to gravity change and surface deformation consequent to the redistribution of water load. Some ocean regions might even see sea level *fall*, while others will see a rise, but on average sea level is expected to rise significantly in response to climate change. The melting ice complexes cause distinct patterns or *fingerprints* in the regional distribution of sea level change. The freshwater entering the oceans from these ice complexes could significantly impact ocean circulation patterns, further impacting sea level. The

effects in some locations will be larger than the changes due to ocean water volume alone, because heat absorbed by the oceans will vary geographically and vertical land movement driven by tectonic and fluid production will affect sea level rise along the coasts. Therefore, the amount of sea level rise seen at individual locations around the world will be a complex function of the ice melting sources, the patterns of temperature change in the ocean, the changes in ocean circulation, and local land movement. We have furthermore become accustomed to thinking in terms of *the* mean sea level rate. As the effects of climate change occur more rapidly, the variability in sea level rate will also change on time scales of a decade or shorter. The simplest model is one of constant acceleration. However, it is unlikely that Earth's climate will continue to change in such a smooth manner.

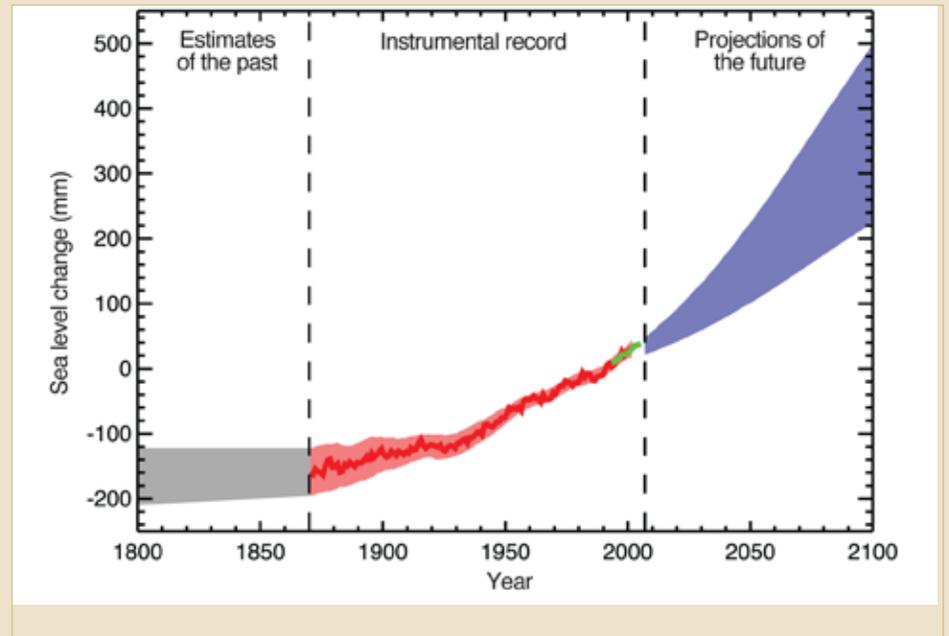
Scientists have concluded from two decades of spaceborne ocean-altimetry measurements that sea level has risen at an average rate of 3.4 mm/yr, nearly double the rate of 1.8 mm/yr for the mid-20th century. This increase is driven both by changes in the cryosphere as well as an increase in ocean warming.

Spotlight IV

Sea level rise: Past, present, and future

Reconstructions of sea level rise prior to the era of global measurements, and projections of future sea level rise, are highly uncertain when compared to geodetic measurements. Figure IV.a, from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), shows a time series of global mean sea level variability for these three periods. The gray shading on the left-hand section of Figure IV.a shows the range of uncertainty in reconstructions of long-term sea level change prior to 1870 when global measurements became available. The central section shows estimates of global mean sea level from tide gauges (red) and satellite altimetry (green). The blue shading in the right-hand section represents the range of model projections for a specific 21st century emissions scenario, calculated independently from sea level observations. As the green curve shows, accurate space geodetic determination of sea level has only been available for two decades (See Spotlight VI). As the time series of these observations lengthens, it will be possible to refine models that are used for predicting future sea level changes. Improvement in satellite altimetry and supporting geodetic systems will lead to refined reference frame and orbit determination, enhanced temporal and spatial resolution of sea level determinations, and provide better information on processes that drive sea level change.

IV.a



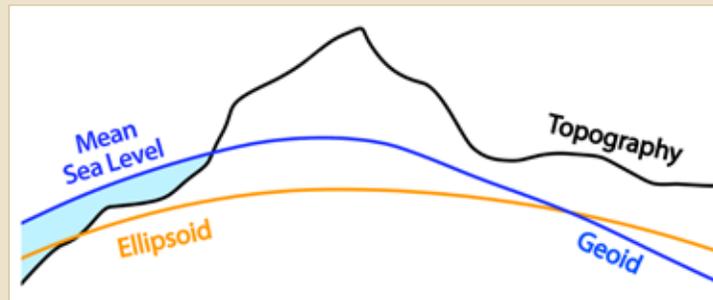
Spotlight V

Sea level, the geoid, and the solid Earth

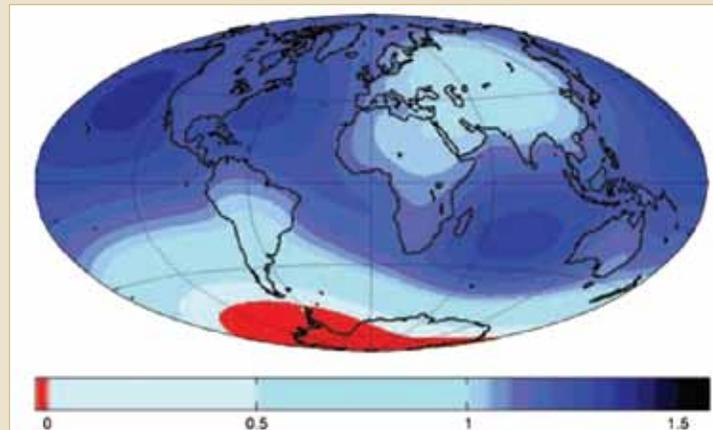
Movement of water on Earth represents a significant redistribution of mass on its surface, leading to measurable disturbances in its gravitational field. One way of representing these disturbances is through changes in the height of the geoid, the surface of equal gravitational potential that approximates mean sea level (MSL). Figure V.a in fact shows three different surfaces: the ellipsoid (a defined geometrical surface used as a reference for height measurements), the geoid/MSL, and topography. As water moves around Earth (by the melting of glaciers and ice sheets, for example) and the geoid is disturbed, the redistributed weight of the surface mass deforms the solid surface of Earth ("Topography" in Figure V.a). MSL also changes as the volume of water in the oceans changes. All three of these effects impact relative sea level (RSL), the difference between sea surface and the land. RSL is what we, as humans, care about because we live on the land. If one takes into account deformation of the geoid and the land, mass moved to the ocean causes a spatially nonuniform change in RSL. The term "sea level fingerprint" was coined to identify this phenomenon because a specific pattern of melting causes a specific pattern of sea level change, the implications of which can be significant. Figure V.b shows a normalized sea level fingerprint of RSL for the collapse of the West Antarctic Ice Sheet (WAIS), a scenario that climate scientists have warned is possible.

The global RSL rise for this scenario (indicated by a value of 1 in Figure V.b) is ~5 m, but a fingerprint analysis indicates that the concomitant pattern of sea level rise is highly nonuniform, with some coastal areas far from WAIS experiencing significantly greater impact. For example, areas of the east coast of North America would experience a sea level rise ~1 m higher than the global mean. Analyses such as this illustrate that changes in the solid Earth surface and the geoid must be considered when calculating changes in sea level.

V.a



V.b



There is considerable evidence that the loss of ice in Greenland and western Antarctica is accelerating. Rates of 10 mm/yr are possible by the end of this century. While projecting future sea level rise is still an uncertain undertaking, a 1 m rise in global mean sea level by 2100 is in the midrange of what scientists are expecting, and sea level will continue to rise after 2100. The last time temperatures were 3–5°C warmer than they are at present (during the last interglacial 125,000 years ago), sea level was 6 m higher than present, thus the more important questions are *when, where, and how much* sea level will rise, and not *if* sea level will rise.

Predicting future changes in sea level, including causes and regional variation, will require separating the different contributions to sea level change and understanding them individually. Melting of polar ice sheets is expected to dominate the sea level change budget by the end of the century. Separating the contributions from Greenland, Antarctica, Alaska, mountain glaciers, thermal expansion, and ocean circulation is a daunting task—but projecting those contributions into the future is even more difficult. Even if all of these processes can be understood, the contribution of vertical land motion must also be known in order to ascertain the regional effects of sea level rise. At regional scales, storm surge or hurricane landfall combined with rising sea level will produce the first early impacts.

Over the past several decades, geodesy has revolutionized our ability to measure sea level variations globally. Its main tool has been satellite altimetry, which measures the changes in the ocean surface. Altimetry provides excellent spatial resolution and coverage as well as the required temporal resolution. Prior to the advent of altimetry, sea level variability was determined by tide gauges. These instruments are restricted to

coastlines and therefore have poor spatial coverage. Their long history and measurement of relative sea level (i.e., sea surface relative to land) at specific coastal locations, however, make tide gauges complementary to altimetry. Combined with geodetic measurements of vertical land motion, tide-gauge observations will continue to play a useful role in determination of sea level change. A more recent addition to the repertoire of geodetic techniques useful for this problem is the global measurement of long-wavelength time variable gravity via the GRACE mission that measures the mass changes over the ocean, as well as the complementary mass changes over the continents and ice sheets necessary to understand the complete mass balance of the climate system.

Since both mean sea level change and its geographic and temporal variations are expected to continue to be on the order of millimeters per year, the Global Geodetic Observing System (GGOS) goal is to measure sea level change with an accuracy of <1 mm on a few-month time scale. To achieve this accuracy requires a coherent suite of geodetic systems working together to provide accurate long-term measurements. VLBI, SLR, DORIS, and GNSS positioning techniques will together be required to provide the accurate and stable terrestrial reference frames and geocenter variations required to track vertical motions at the sub-mm/yr level. In addition, precise GNSS orbits are needed to provide accurate orbital information for altimeters. Finally, altimetry, time-variable gravity, point measurements of relative sea level (from tide gauges), and oceanographic data and geodetic measurements of glacier volume (see Grand Challenge 3) are all required to unravel the mass and steric contributions to sea level change, as well as to determine the sources contributing to the oceanic mass changes.

Unfortunately, crucial observational systems may not be in place during the periods in which they are most needed. Continuity is of great importance when attempting to disentangle spatial and temporal variability. In particular, better support for the global VBLLI, SLR, DORIS, and GNSS networks is required to maintain global and temporal coverage for a sufficiently accurate reference frame. Additionally, the Ice, Cloud, and land Elevation Satellite (ICESat) mission has ended and the GRACE mission will end in the next several years; a gap in observations is likely. NASA's Operation IceBridge, exploiting the inherent strength of airborne measurements, will partially fill the gap in global data created by the end of ICESat until the launch of ICESat-II. ICE-Sat-II, GRACE-II, and the Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) missions are all recommended in the National Research Council (NRC) Decadal Survey, but the threat of significant data gaps remains, potentially limiting the ability to address this problem over the next decade.⁴ The time series of sea level measurements from the TOPEX/Jason series is less in jeopardy. The agreements signed for the Jason-3 mission include a planned six-month overlap with Jason-2.

⁴ As of this writing, the DESDynI mission is being descoped and currently includes only a L-band SAR for InSAR.

GRAND CHALLENGE 2 - KEY QUESTIONS:

How do changes in the cryosphere contribute to sea level change?

What are our best forecasts and uncertainties for spatially variable sea level change?

Can we separate the contributions of glacier melting vs. ocean dynamics, circulation, and expansion to sea level change?

What are the processes that control local variations in relative land and sea levels? How will patterns of flooding, drought, and storm surge change?

Is sea level change accelerating and at what rates?

LONG-TERM GOALS FOR ADDRESSING KEY QUESTIONS:

Continue operating long-standing observing systems that contribute to sea level measurements, particularly tide gauges, GNSS, and ocean altimetry.

Maintain a stable terrestrial reference frame with sub-1 mm/yr vertical accuracy.

Integrate sea level observations from tide gauges into the terrestrial reference frame at the sub-1 mm/yr level.

Improve the accuracy of precise orbit determination over shorter time scales.

Deploy and sustain concurrent satellite systems for sea-surface topography, ice topography, and time-variable gravity.

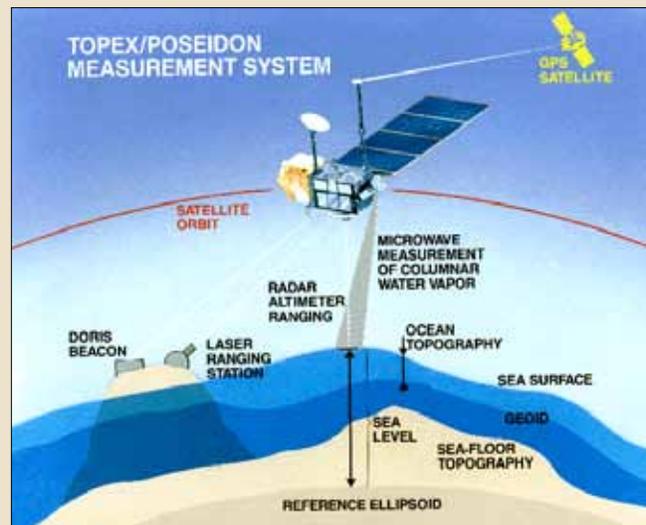
Improve understanding and predictability of short-term oceanographic effects.

Spotlight VI

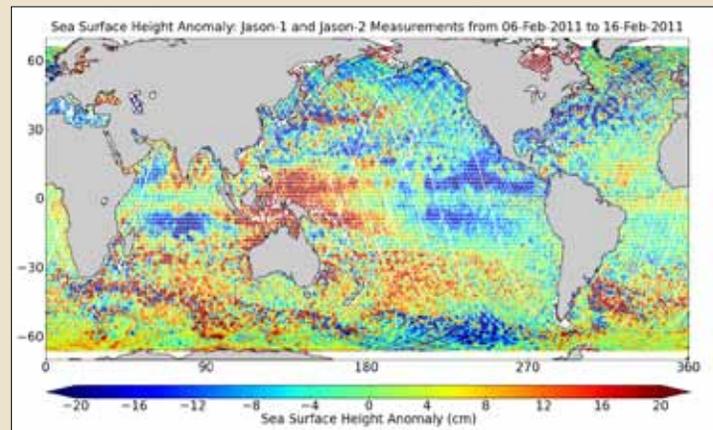
Measuring sea level change using altimetry

Ocean altimetry, a technique that uses spaceborne radar to measure the “topography” of the ocean (Figure VI.a), has revolutionized the way we think about sea level. The first ocean altimeter of the modern era, TOPEX, operated from 1992–2006. Jason-1 was launched in 2001 and Jason-2 in 2008. The orbital position of the altimeter is accurately determined by other geodetic systems with a ground component, such as GNSS, SLR, and DORIS. Thus, a suite of geodetic systems works together to provide these accurate measurements (error 4 cm globally averaged RMS). The surface of the ocean can then be measured in a stable and accurate reference frame, though at this point it is referenced to the solid Earth. The ocean topography is the difference between the sea surface at the time of the measurement and MSL. Tide gauges, located at coastal sites, are used for calibration of the altimeters. The combined result is a snapshot of sea-surface height, usually available less than one day after data collection. Figure VI.b is such a snapshot for the period 6–16 February 2011. La Niña, characterized by lower-than-average ocean temperatures in the equatorial Pacific, is clearly visible by the low sea surface west of the Americas. Figure VI.c shows the rate of sea level change as a function of location from altimetry over the period 1992–2010. By combining data from multiple altimetry missions, scientists have been able to obtain a high-resolution image of modern sea level change that can be used to study the detailed processes that cause sea level rise: increased ocean temperatures and volume increases due to glacier melting, both attributable to rising global temperatures.

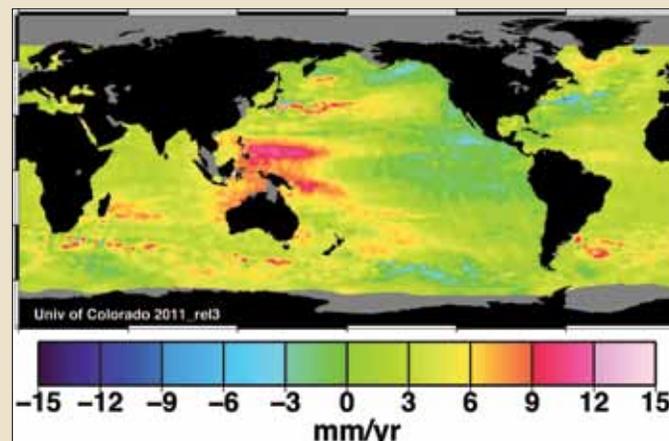
VI.a



VI.b



VI.c



GRAND CHALLENGE 3

How do Earth's glaciers and ice sheets change on timescale of months to decades to centuries?

Ice covers approximately 10% of Earth's land surface at the present, with most of the ice mass being contained in the Greenland and Antarctica continental ice sheets. Changes in these (see Introduction) and other ice sheets and glaciers result in redistribution of water across the planet but estimates of the net gain or loss significantly differ. On a more regional scale, decrease in the size of mountain glaciers in places such as the Himalayas and Peru are changing the timing of seasonal melt discharge that provides water to large population centers and serves as the primary water source for many fragile ecosystems.

Over the last two decades our understanding of the relation between recent climate change and ice mass fluctuations has been significantly advanced by geodetic satellite, aircraft, and field observations (Figure 09). Interpretation of modern ice changes in the context of long-term (hundreds to tens of thousands of years) and present-day climate is a challenge that is bringing together geodesists, glaciologists, geologists, seismologists, oceanographers,

and climatologists. Models that incorporate behavior on a range of timescales of the major contributions to ice system mass balance would lead to better explanations of ongoing glacier behavior and improve the mass balance predictions critically needed for glacier wastage and sea level change predictions.

Designing and undertaking geodetic experiments that enable researchers to improve our understanding of ice dynamics so that we can better predict (through numerical models) the response of the glaciers to climate change, and the feedback of this response to the climate, is an important challenge for geodesists.

The scope of measuring changes to Earth's glaciers requires multiple geodetic observing systems to resolve the complexity of this problem, for which relevant temporal and spatial scales range from seconds over tens of km (a calving event on a large outlet glacier) to annual/interannual/decadal on regional scales (mass balance of major ice complexes in response to present-day climate change) to thousand of years on a global scale (global viscoelastic deformation associated with glacial cycles). Because all these processes occur simultaneously, multiple observing systems optimized to measure a specific signal wavelength can be used to separate these different contributions. Adding to the technical challenge of collecting geodetic measurements, glaciers are often in the harshest environments on Earth with some targets, such as sea ice, highly inaccessible.

Figure 09

GNSS and other geodetic techniques are used both to measure deformation of Earth's glaciers and deformation of the solid Earth near the glaciers with unprecedented accuracy. This photograph shows the GNSS site at Pilappik in Eastern Greenland, part of the GNET network.



Spotlight VII

Evidence for shrinking ice sheets

In the last decade, geodesy has presented us with four independent measurements that indicate that Earth's major ice complexes are shrinking in response to increased global temperatures.

1. The surfaces of the major ice sheets and glaciers are lowering. Geodetic measurement of the height of glacier surfaces by airborne and spaceborne (IceSAT) laser altimetry indicates that the largest drops in surface elevation of the ice are occurring, especially in coastal Greenland (Figure VII.a) and West Antarctica (Figure VII.a.a-d), where the ice is also losing mass and speeding up.
2. The ice sheets are losing mass. Geodetic measurements of gravity changes, mainly by the GRACE mission, indicate that both the Greenland and Antarctic regions are

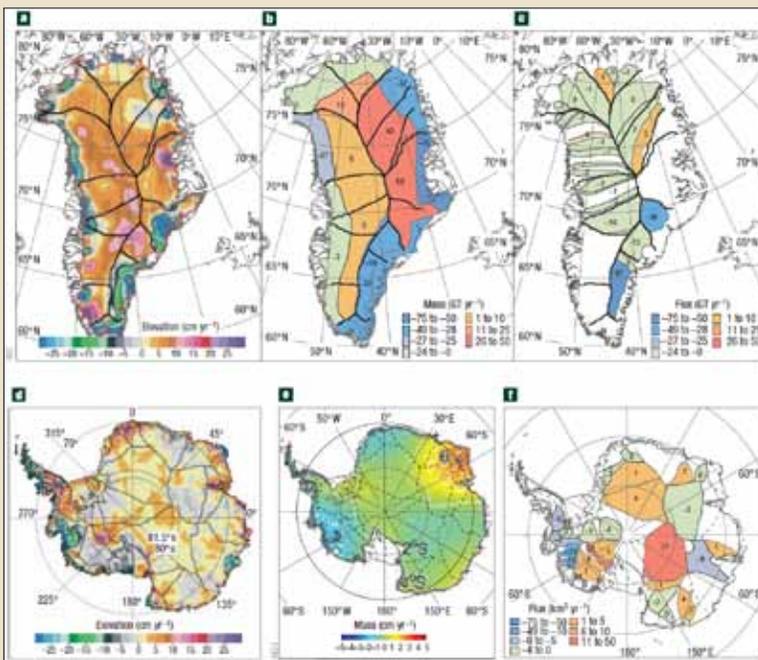
losing significant mass. Estimated rates of mass change in gigatons (GT) per year for Greenland are shown in Figure VII.a.b, and in cm/yr of equivalent snow/water thickness for Antarctica in VII.a.e. The mass change is variable, and even in some areas positive, but the net effect is a significant mass loss from both regions.

3. Glaciers and ice sheet speeds are increasing. When a glacier accelerates, it increases the rate at which ice volume leaves the glacier thereby decreasing volume flux. Geodetic determinations of glacier flux using InSAR indicate large negative fluxes in southeastern Greenland (Figure VII.a.c) and West Antarctica (Figure VII.a.f). Increased flux may also indicate increased water at the base of the ice, another possible result of warming.

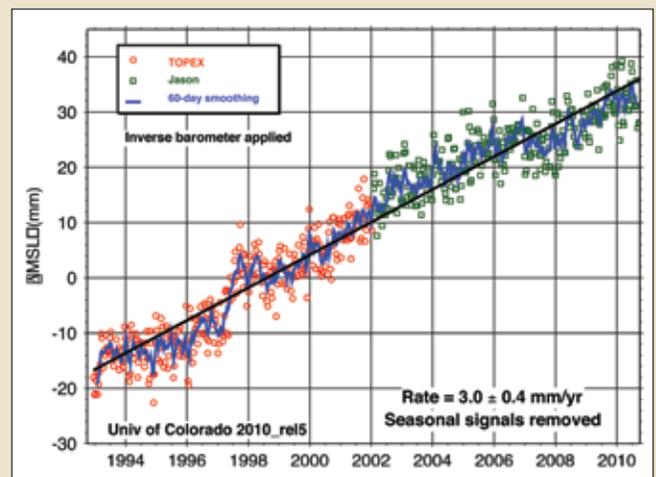
4. Global mean sea level is rising. Geodetic measurement of sea level by satellite altimetry over the last two decades yields a rate of ~ 3 mm/yr (Figure VII.b.). The two primary candidate causes of sea level change are increased water volume and thermal expansion. Calculation of the thermal expansion effect explains a little less than half of the signal. The increased volume is attributed to melting glaciers.

It is remarkable that a single geophysical discipline yields four independent measurements relevant to a single process. However, these measurements stem from four different measurement techniques, and illustrate that one of the main strengths of geodesy is the diversity of observing systems within the discipline.

VII.a



VII.b



One of the targets for geodesy is surface deformation associated with present and past ice-mass changes. Research on glacial isostatic adjustment (GIA) associated with previously existing (Fennoscandia, Laurentia) ice sheets provides information about both past climate change and Earth structure. Regional GNSS networks (e.g., BIFROST, EUREF, CBN) have provided the first accurate, three-component, crustal-velocity fields associated with this important process. Measurement of changes in present-day elastic loading by ice—thereby revealing the changes in the glaciers and ice sheets (e.g., Greenland, Antarctica, Alaska, Patagonia, Iceland)—is being provided by other regional GNSS networks (e.g., POLENET, GNET, PBO, Parca). Global networks of positional systems (GNSS, VLBI, SLR) can determine Earth's rotational variations in response to present-day and past mass redistribution. Positional crustal deformation measurements are complemented by global (i.e., spaceborne), regional (aircraft), and local (gravimeter) gravity measurements that yield direct information about present-day ice changes, as well as on the redistribution of mass within the solid Earth and vertical motions associated with past- and present-day ice changes. Together, the deformation and gravity measurements are giving us a picture of accelerated mass loss in Greenland and Antarctica.

Geodetic data alone or in combination with other data are providing our first understanding of changes to glaciers and ice sheets on a decadal time scale. Ice elevation measurements using laser altimetry enable us for the first time to produce 3D time-series of the complex spatial patterns of ice sheet growth and loss. In Greenland, for example, ice is building up in some locations at rates of a few centimeters per year, while in other areas ice is being drained back into the ocean at alarming rates of more than a meter per year. Ice elevation changes from repeated aircraft and satellite laser altimetry measurements and GRACE data have also been used

to estimate the recent mass balance of Alaskan glaciers, leading to the surprising result that ongoing melting in Alaska is contributing to present sea level rise at approximately the same level as melting of ice sheets of both Greenland and Antarctica.

InSAR data from ESA's ERS-1 and 2 tandem mission, radar data from Canada's Radarsat mission, and optical imagery from Landsat and other missions have been combined to detect sudden and dramatic accelerations of deep outlet glaciers, frequently at rates of tens of percent per year up to 500% in just two years. These dramatic changes over short time intervals illustrate the potential contribution to our understanding of the behavior of these systems that more extensive temporal and spatial SAR coverage of ice sheets, ice caps, and other glaciers would give. In Greenland, these outlet glaciers appear to be associated with the greatest mass loss from the system. Ground-based GNSS studies indicate that the mechanics of these systems may be quite complex. Seismologists have discovered that some of these systems can yield "glacial earthquakes." These as yet poorly understood phenomena could be triggered by ocean-tidal displacement for some glaciers in Antarctica. In Greenland, glacial earthquakes are correlated temporally with calving events whereby the glacier loses several cubic kilometers in a short period of time, as well as with glacier flow-rate variations. The glacial earthquakes occur in areas of greatest mass loss, and changes in their frequency may be associated with climate change. Ground-based GNSS study of these important glacier systems is so far the only way to achieve the high temporal resolution needed to make the connections between glacial earthquakes, glacier flow speed, calving, and ocean tides. GNSS studies have also been useful for making connections between ice-sheet speed in Greenland and surface melting that leads to changes in underlying hydrology of the ice sheets.

Spotlight VIII

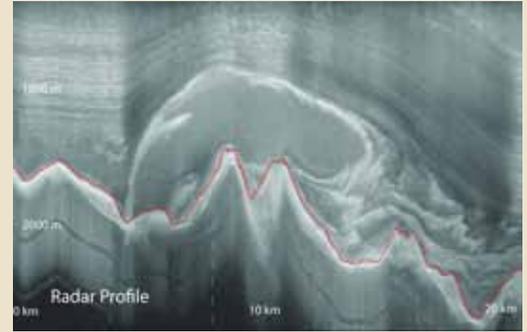
The geodetic toolbox for glaciology

A glacier is a complex system, and its behavior depends on its overall geometry, viscosity of the ice, bedrock topography, glacial hydrology, degree of grounding, calving rate, and a number of other characteristics. Geodesy is providing a suite of tools for studying glaciers that is adding greatly to the information about these systems. GNSS networks on the surface of glaciers (Figure VIII.a) give a high-temporal-resolution picture of glacier flow during the period of deployment. Such observations have been used, for example, to explore the phenomena of “glacial earthquakes.” Observations in Greenland have led to the discovery that glacial earthquakes are associated with calving events, and lead not to displacements in glacier position (as occurs in a “normal” earthquake), but instead to a near-instantaneous acceleration in the glacier flow (Figure VIII.b). In Antarctica, glaciers have been observed to have stick-slip events (solid lines in Figure VIII.c) that correlate strongly in time with predicted events (circles) based on the ocean tidal amplitude (line). (Gray shade indicates no geodetic observations were available.) Recently, researchers using airborne radar have found evidence that ice freezes onto the glacier from water located at its base (Figure VIII.d; base of the ice sheet is marked in red). These startling features have an impact on flow that is not captured in any present model. Glaciologists are also experimenting with ground-based terrestrial LiDAR (terrestrial laser scanning, or TLS) to study the detailed velocity structure of glaciers. Figure VIII.e, for example, shows a TLS image of velocity difference superimposed on an ALOS satellite image of Helheim Glacier. These geodetic techniques complement other airborne and spaceborne systems for measuring surface height, gravity, and glacier flow.

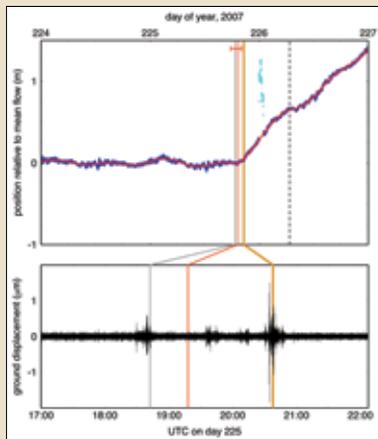
VIII.a



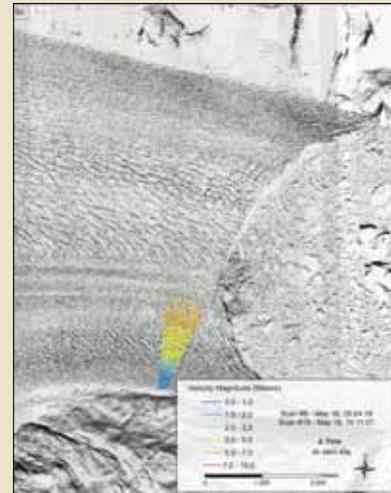
VIII.d



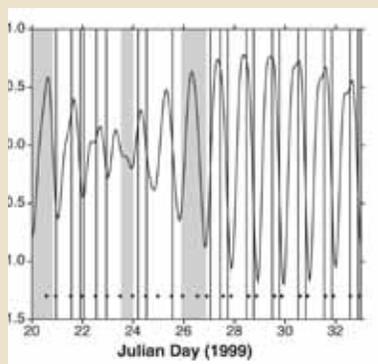
VIII.b



VIII.e



VIII.c

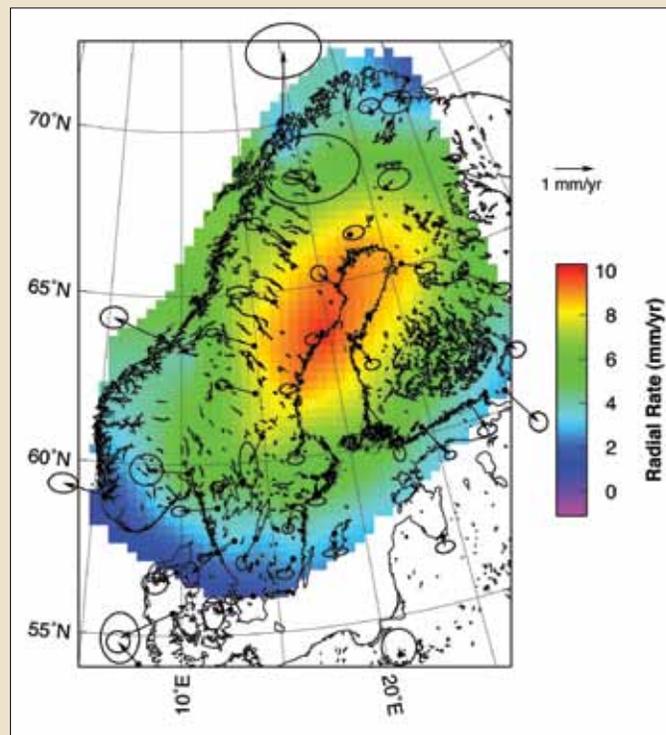


Spotlight IX

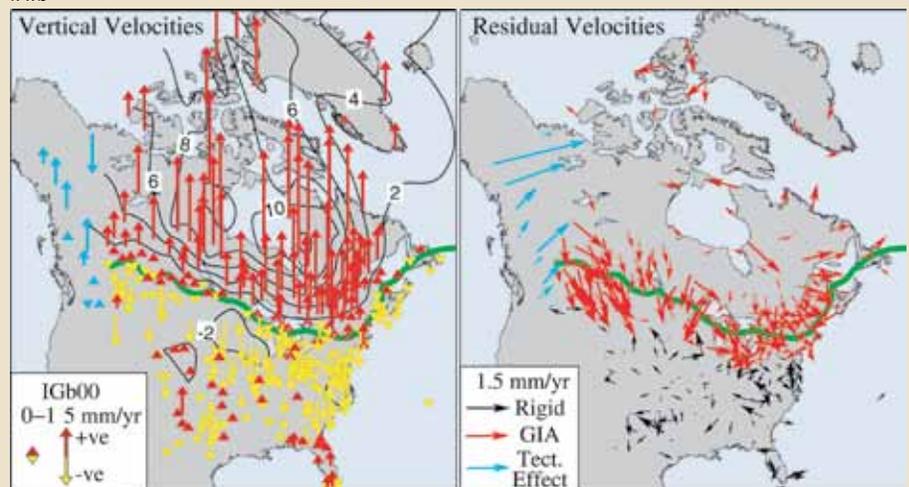
Glacial Isostatic Adjustment (GIA)

GIA⁶ is the ongoing viscoelastic deformation of Earth in response to past changes in Earth's ice sheets. Some of the most rapid significant changes took place beginning ~18 kyr ago at last glacial maximum (LGM), when the cooling climate over the preceding ~80 kyr period reached an end. After this time, the climate began to warm and the ice began rapidly to melt as Earth entered the current interglacial period. This melting, whereby water that was concentrated in the ice sheets flowed into the oceans, represented a then great redistribution of load that is still deforming Earth's surface and geoid, and changing sea level (Spotlight V). Some of the more extreme examples of present-day GIA are associated with the more recent glaciation and deglaciation during the Little Ice Age (Spotlight XIII). Until recently, GIA was inferred from sea level or local gravity measurements, both of which are indirect measurement of the crustal uplift. With modern, accurate geodetic techniques, however, the full three-component crustal velocity field as well as the global gravity field changes associated with GIA can be measured. Studies have been undertaken using geodetically observed GIA deformation in Fennoscandia (Figure IX.a), North America (Figure IX.b), Antarctica, Patagonia, Greenland, and Alaska (Spotlight XIII), as well as a global gravity-rate field that in part reflects GIA (e.g., Figure 5). These observations have been used to investigate, for example, present-day melting of large ice complexes, the extent of glaciation at the LGM, mantle rheology, the structure of the continents, past and present-day sea level change. As discussed in Spotlight XIII, GIA must be accurately accounted for in determining tectonic deformation. In this document, GIA studies represent an intersection between Sections I and II: the interaction between climate and plate tectonics.

IX.a



IX.b



⁶ The term "postglacial rebound" is also used for this process.

As summarized in a 2009 congressional briefing⁵, the very best climate models are good for predicting changes in ice sheet accumulation (snowfall) and melting—two major factors that contribute to ice sheet growth or shrinkage—but are dismal at predicting future changes to the ice, due to our limited understanding of the important processes responsible for dramatic change.

In this imperfect situation, sustained high-resolution monitoring of the global cryosphere is therefore extremely important, both to provide data to improve our predictive capability, and to provide up-to-date information about the current state of the system. Satellite, airborne, and ground-based geodetic measurements will continue to play a crucial role in monitoring the cryosphere. The NRC Decadal Survey has recommended geodetic missions (DESDynI, GRACE-II, ICESatII) that together have the capability for measuring ice mass, depth, and deformation as well as sea ice. In the temporal gap between these future and recent missions (GRACE, ICESat), airborne observations (e.g., Operation IceBridge), access to data collected by international space missions, and the expanding networks of ground-based GNSS systems, will play a vital role.

⁵ Testimony by R. Bindshadler to the House Committee on Appropriations, Subcommittee on Commerce, Justice, Science and Related Agencies, Hearing on Climate and the Role of Satellites in Understanding Climate and Prediction, March 18, 2009, available at <http://www.hq.nasa.gov/legislative/hearings/>.

GRAND CHALLENGE 3 - KEY QUESTIONS:

Where, and how fast, are the polar ice sheets and other glaciers changing in response to climate fluctuations?

How do rheology, basal conditions and topography, and glacier thickness affect glacier flow?

How are changes in ocean temperature, salinity, and flow patterns influencing near coastal ice sheet processes?

How do ocean tides moderate glacier flow for outlet glaciers?

What are glacial earthquakes and how do they influence glacial mass balance?

How can past changes in glaciers and ice sheets help us understand present-day changes?

LONG-TERM GOALS FOR ADDRESSING KEY QUESTIONS:

Establish continuity in current and future space missions focused on critical altimetry and mass change observations.

Improve spatial and temporal resolution for regional and global observations and extend the coverage of long-term observations.

Determine details in ice structure and bedrock topography for glacier systems.

Perform glaciological studies relating ice flow patterns to basal flow patterns influenced by bedrock topography, till rheology, and basal lubrication.

Integrate observations of the entire cryospheric input/output system, including major ice sheets, mountain glaciers, sea ice, permafrost, individual glaciers, and ocean mass.

Improve access to the terrestrial reference frame in polar regions.

"This must be left to the geodesists. I have no doubt that in the not too distant future we will be successful in making a precise measurement of the drift of North America relative to Europe."

Alfred Wegener, *The Origin of Continents and Oceans* (1929)

SECTION

02

Earth the Machine

A Foundation for Innovation: Grand Challenges in Geodesy

Earth and the tools we use to study it are constantly changing. The tectonic plates are continuously in motion, though so slowly that even with our highest precision instruments we need months or years of observations to measure them. Over the last several decades, the advent of space-based geodetic techniques has improved our ability to measure tectonic plate motion by several orders of magnitude in spatial and temporal resolution as well as precision, and to establish stable terrestrial and celestial reference frames required to achieve these improvements. The research with these systems has led to revolutionary progress in our understanding of plate boundaries and plate interiors. Some faults we once thought of as locked tight between major earthquakes are now known to have slow, seismically silent, creep events. Simple cartoon-like images of plate boundaries have been replaced with richly detailed strain maps that show how broad and complex these regions truly are. We can now measure how much the ground moves in an earthquake to millimeter precision for hundreds of kilometers away from the fault on time scales that rival traditional seismological measurements. The next decade will be an important time for improving the accuracy, spatial and temporal resolution, and latency of

geodetic observational systems focused on the exploration of the surface movements of the solid Earth. GNSS surveying will be significantly improved with the GPS III generation of satellites and with the development of international GNSS systems. Equally important are the improvements in telecommunications infrastructures which allows more researchers easy and rapid access to data acquired in the ground-based systems. High-rate and real-time GNSS measurements are still quite new, and there is great potential for new discoveries from this data stream and for integration with strain and gravity measurements, as well as with seismic and other data. The InSAR technique is revolutionizing studies of the earthquake cycle and volcanic activity, and is moving towards the capability of delivering line-of-sight velocity fields with ~ 1 mm/yr precision.

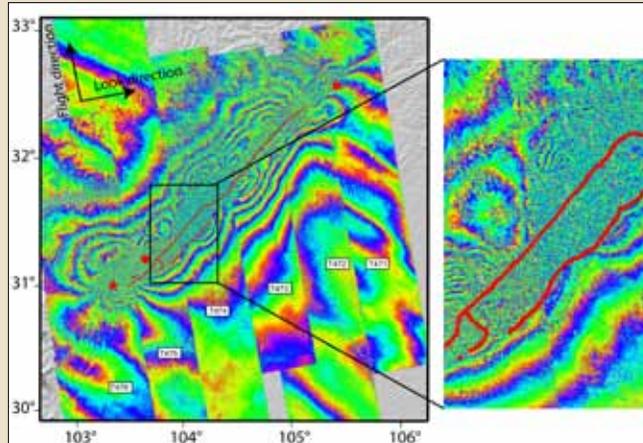
In this section, we present four Grand Challenges focused on understanding the underlying structure of Earth and the forces that shape and transform its surface.

Spotlight X

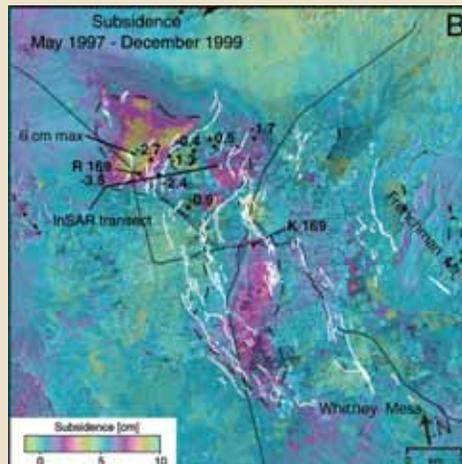
Interferometric Synthetic Aperture Radar (InSAR)

InSAR is an important geodetic technique that enables remote, highly accurate measurements of tectonic deformation, glacier movements, and surface changes due to anthropogenic activities such as ground water withdrawal, hydrocarbon recovery, and geothermal production. Radar “interferograms” are obtained by combining two SAR images acquired at different times from the same point in space on repeating orbits. Processing of radar interferograms benefits from accurate knowledge of the satellite positions, surface elevation, ionosphere variability, and atmospheric moisture. The results yield maps that detail the surface motion (projected along the line-of-sight to the satellite) with great accuracy, high resolution, and wide coverage. InSAR imagery of the 2008 M_w 7.9 Wenchuan China earthquake clearly imaged the earthquake rupture (Figure X.a; red line) with fringes that quantify the magnitude of the coseismic displacement. (The earthquake epicenter is shown by a red star; red dots denote epicenters of two large aftershocks.) An InSAR deformation map of Las Vegas, Nevada, shows land subsidences associated with groundwater withdrawal and identifies previously unrecognized faults (Figure X.b) that constrain subsidence bowls on several of the sides. InSAR maps of surface ice velocity in Greenland (Figure X.c) reveal that the largest velocities are near the coast. These velocities were used to estimate the amount of mass lost due to the discharge of ice into the ocean. Powerful techniques such as InSAR continue to expand the scientific applications of geodesy.

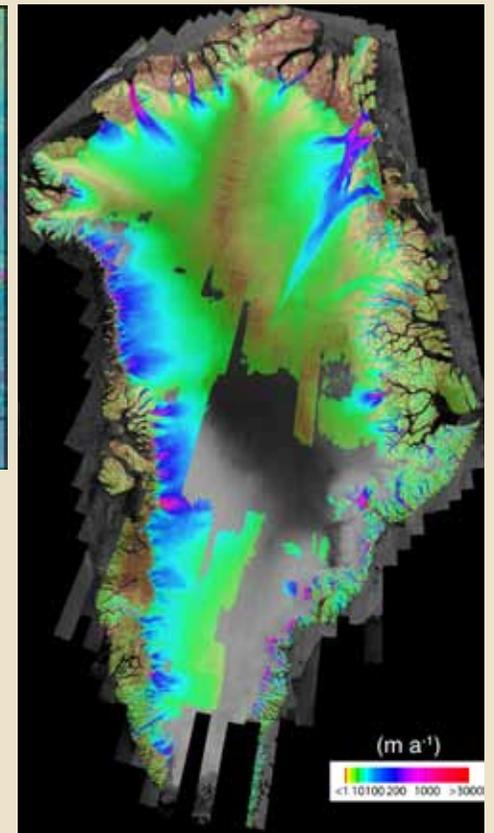
X.a



X.b



X.c



GRAND CHALLENGE 4

How do tectonic plates deform?

The advent of space geodesy brought with it the capability of measuring ongoing deformation of the crust at the millimeter level across global-scale distances between two points on Earth's surface. This breakthrough enabled the measurement of plate motions across and between continents with unprecedented precision. As methods improve and we continue to look in detail at smaller faults and shorter time periods, however, unexpected discoveries are made and paradigms dramatically shift.

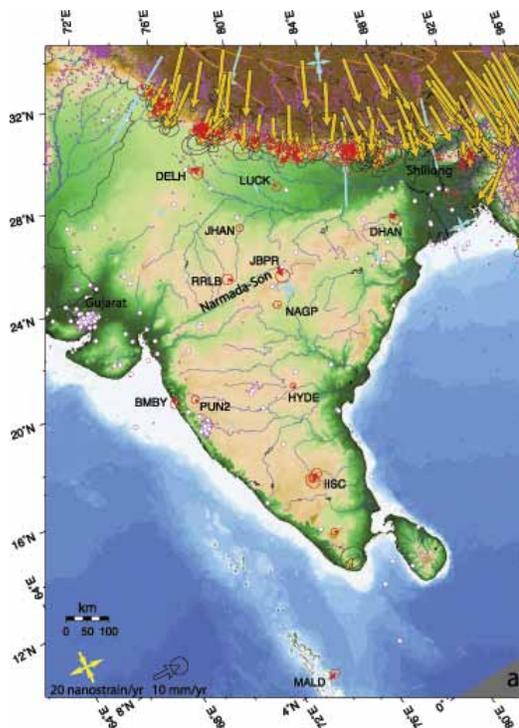
With deformation detected at a rich spectrum of scales, we have been able to measure tectonic and non-tectonic deformation in some areas of plate interiors that had been thought of as stable. Furthermore, the accommodation of relative plate motion

at plate boundaries involves considerable complexity, with faults slipping irregularly in time during large earthquakes, along with the recognition and measurement of postseismic strain and a variety of other transient deformation phenomena. The observed multitude of spatial and temporal scales of strain implies a complex rheology of tectonic plates and plate boundary zones that we are just beginning to incorporate into our physical models. As we all live on these not-so-stable plates and even more erratic plate boundaries, we are challenged to understand the basic mechanical underpinnings of the bending, stretching, buckling, and breaking of the tectonic plates.

Today, one of the major tools for deformation studies is GNSS surveying, which has been used for more than two decades across entire continental plates. The spatial density and temporal precision of these measurements have allowed us to resolve how strain varies across the plates and at plate boundaries in both space and time. These plate-scale measurements have been critical in constraining how plates respond to glacial loading and unloading, where strain occurs within the plate interiors, and how plate boundary forces are accommodated thousands of kilometers away from the boundary in regions such as western North America and the Tibetan Plateau. InSAR is not yet routinely used for measuring small-amplitude, long-wavelength deformation, but several studies indicate that it will be an important future tool. Every addition to our observational capabilities has led to a wealth of newly recognized phenomena that have challenged our understanding of the way in which plates interact and deform.

Figure 10

GNSS measurements of crustal velocity with respect to the Indian plate display a complex pattern of north-south convergence within the Eurasian plate. Red arrows are smaller velocities (<4 mm/yr), yellow are larger. The highly accurate measurements reveal not only the collision of India with Eurasia, forming the Himalayas and the seismicity (purple dots) near the plate boundary, but a north-south convergence in the plate interior.



Spotlight XI

Resolving small variations in crustal velocity

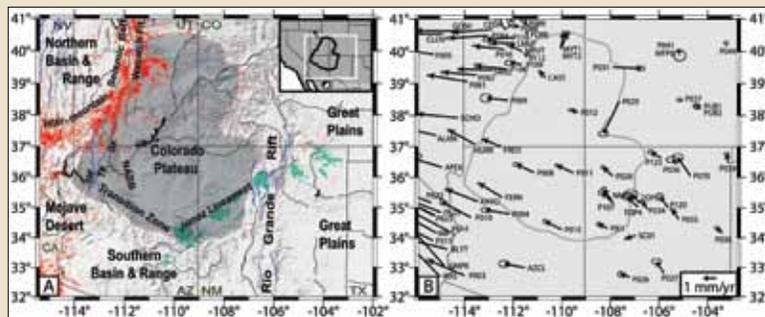
A high achievement of continuous GNSS is the ability to resolve details of ongoing deformation, even within large areas where the crustal velocity is nearly constant. For example, detailed studies using GNSS observations from PBO reveal deformation occurring on the boundaries of the Colorado Plateau (CP), as well as details of the clockwise motion of the CP relative to stable North America (Figure XI.a). In the northern Basin and Range, GNSS observations have been used to investigate possible changes in site velocity that researchers have hypothesized to be associated with transient slip on a megadetachment fault at depth beneath the Great Basin (Figure XI.b). Another frontier involves the difficulty of resolving deformation within very slowly deforming continental interiors, where large earthquakes have occasionally occurred. Surprisingly, GNSS observations detect little or no deformation in the Central U.S.'s New Madrid seismic zone, where large earthquakes occurred in 1811 and 1812, and which is believed to be a region of high risk for future seismic hazard. Geodetic studies in this region have led to the hypothesis that earthquakes may in fact migrate over time here and occur on pre-existing zones of crustal weakness such as ancient rift structures. Figure XI.c shows these areas (right), along with a sketch that illustrates how earthquakes may migrate over time.

Such a migration may result from a complex dynamic system in which faults are loaded by plate boundary forces, flow of the underlying viscous mantle, and surface loading associated with climatic effects such as the advancing and retreating of glaciers, and erosion-deposition processes. Understanding such systems poses a major

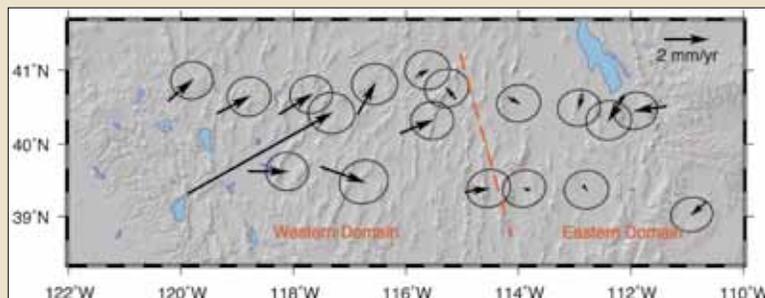
scientific challenge with important societal implications.

High-precision geodetic data are crucial for this purpose because they can indicate where strain is and is not accumulating. These data will be combined with information about past and recent earthquake locations, along with data on the mechanical properties of the lithosphere, to develop models of the complex stress evolution that results as the system evolves.

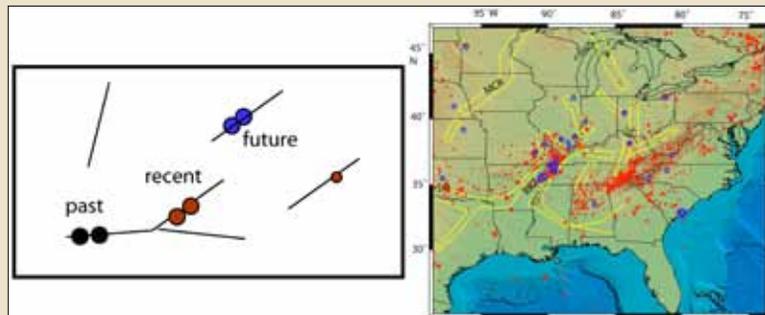
XI.a



XI.b



XI.c



How and why plate deformation varies over time is an open question among Earth scientists, with important implications for understanding whether elastic strain varies in time with clustering of seismic activity. Geodesy gives us an increasingly detailed picture of plate behavior on a range of time scales. The variations in localization of this deformation over hundreds and thousands of years can be tested by comparing geodetically determined fault slip rates and kinematic models to those constrained by paleoseismic and geologic observations. Dense deformation profiles from InSAR measurements have also helped to resolve debates about which types of crustal complexities drive the variations we can now see in plate deformation. These examples, however, represent studies from just a few regions that so far have spatially dense observations. As geodetic networks and SAR measurements expand their spatial and temporal coverage, we expect to discover more varieties of complex plate deformation and fault behavior.

Dense, high-precision geodetic observations have for the most part been limited to continental plates, though studies using seafloor transponder arrays and GNSS surveys have begun to illuminate the deformation on the ocean floor. These seafloor observations have been used, for example, to constrain locked regions of the Peru-Chile and Japan trenches. Scientists have known for many years that oceanic plates are compositionally very different from continental plates and so we cannot expect our models of continental plate deformation to translate very well to the ocean floor. Oceanic plates are key components of any subduction zone, where the world's largest earthquakes occur and where destructive tsunamis are generated. Understanding how these plates deform is fundamental to addressing questions about the largest seismic hazards on Earth.

Intraplate earthquakes, while generally smaller than their cousins on plate boundaries, have the potential to be equally or even more destructive, as earthquakes in inland China have demonstrated. Much less is known about these earthquakes, however, in part because they occur less frequently and outside the plate boundary monitoring networks. Global SAR coverage has provided uniquely detailed observations of intraplate earthquakes in recent years. Displacements from earthquakes as small as M4.4 have been reported, and these InSAR observations have dramatically improved knowledge about the location, source depth, and stress drop estimates which are otherwise poorly constrained yet critically important for seismic hazard assessments. Strain measurements provide another key element in understanding why, when, and where intraplate earthquakes are likely to occur, although the strain rates within the plates are orders of magnitude smaller than the rates along plate boundaries. Continued improvement in precision from continuous GNSS networks has allowed more subtle strain measurements than in the past, providing constraints on mechanical models for these intraplate events. Often the results from these studies are still ambiguous, however, and there is room for more improvement over the next decade. The installation of very stable monuments and the continuous operation of these permanent GNSS networks as well as improved modeling of the delays caused by atmospheric water vapor and understanding of the contribution of hydrologic ground motion are some of the more recent advances that have allowed for improved precision.

GRAND CHALLENGE 4 - KEY QUESTIONS:

What is the rheology and structure of the upper mantle and lithosphere?

How does the deformation of oceanic and continental plates differ?

Why are broad plate boundary zones so common in the continents, and what controls the extent and distribution of deformation within them?

What are the mechanics of plate boundaries?

On timescales of 1 second and longer, what is the rheological response of the crust and mantle to loading and unloading by ice, water, sediments, and tectonic events?

What are the driving mechanisms of intraplate earthquakes?

What are the relative contributions of recoverable (elastic) and permanent (inelastic) deformation of the upper crust to the total strain budget of major fault systems, and how do these contributions vary with time?

LONG-TERM GOALS FOR ADDRESSING KEY QUESTIONS:

Improve and extend (especially to the ocean floor) the spatial and temporal resolution and accuracy of deformation measurements.

Integrate deformation measurements with data from seismic networks on a range of temporal and spatial scales.

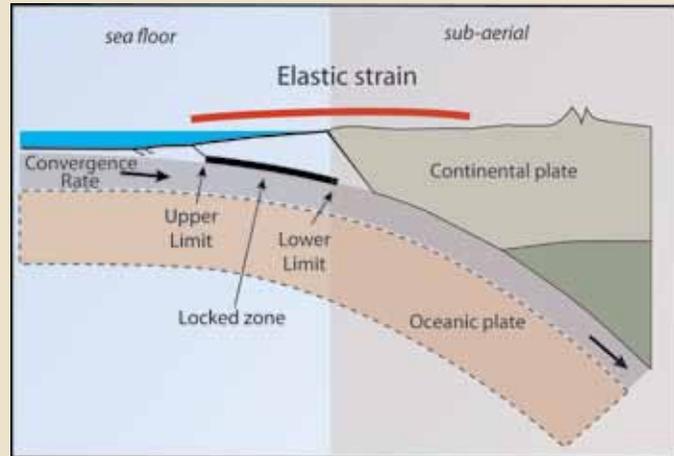
Integrate gravity and deformation measurements to separate mass motions and tectonic signals.

Spotlight XII

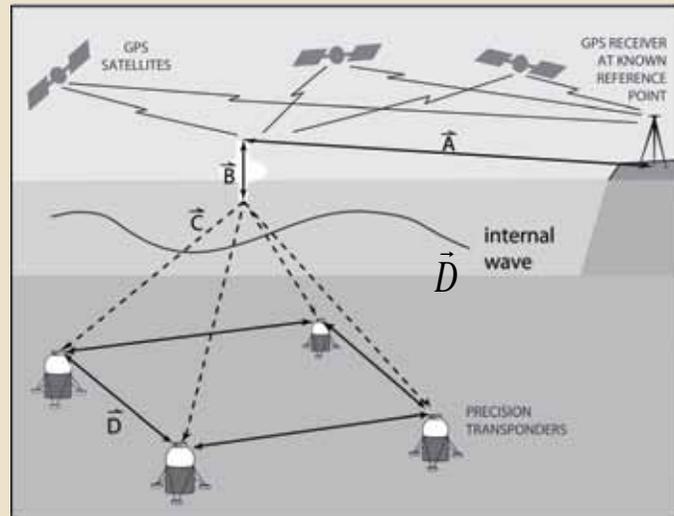
Seafloor geodesy

Seventy-five percent of Earth's crust lies under the oceans, and is thus unobservable using solely electromagnetic energy-based geodetic techniques. Seafloor geodesy can now expand geodetic positioning to off-shore environments devoid of land. In regions of subduction within continental margins, for example, elastic strain accumulation/release, afterslip/postseismic deformation, and the thrust fault itself all occur offshore (Figure XII.a). The GPS-Acoustic (GPS-A) approach (Figure XII.b) for seafloor geodesy combines kinematic GNSS on a floating platform (ship or buoy) and acoustic ranging to an array of seafloor transponders. The position of seafloor-based transponders whose relative vectors (\vec{D}) are known is determined by combining the vectors between a land-based GNSS receiver and a platform of GNSS antennas (\vec{A}), the vector between these antennas and an acoustic ranging transmitter (\vec{B}) and the acoustic ranging vectors (\vec{C}). Maintaining the platform near the array center assures that acoustic velocity variations due to internal waves can be averaged and do not bias the horizontal position estimates of the seafloor array. The technique can measure with centimeter resolution the horizontal position of the ocean floor in the same global reference frame as sub-aerial GNSS. The GPS-A method has permitted the accurate determination of plate velocities at a dozen or so locations on the ocean floor. For example, in offshore Peru, GPS-A was used to measure displacement of two seafloor arrays on the submerged continental slope, and discovered that the slope was moving towards the interior of South America. GPS-A measurements obtained offshore Japan measured interseismic strain and co-seismic strain release during the 2005 M_w 7.2 Off-Miyagi earthquake, followed by re-establishment of interseismic strain accumulation. Horizontal deformation near the offshore hypocenter of the March 11, 2011 (M_w 9.0) Tohoku earthquake was found using GPS-A to be ~ 24 m, with vertical uplift of ~ 3 m (Figure XII.c).

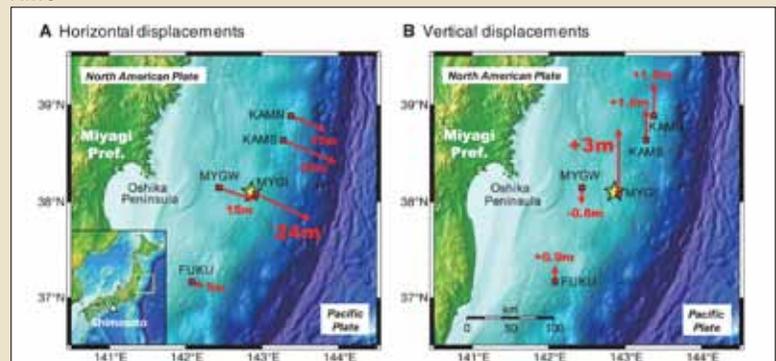
XII.a



XII.b



XII.c



Spotlight XIII

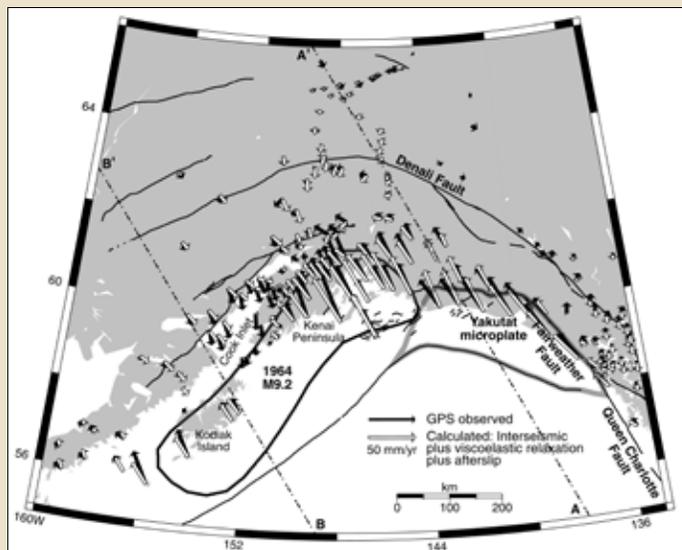
Alaska: A natural laboratory for investigation of multiple coupled geophysical and geological processes

Alaska is rich with opportunities to improve our understanding of the kinematics and dynamics of the subduction process, large-scale continental deformation, volcano deformation, transient strain phenomena, and glacial isostatic unloading signals. Many active tectonic features represent some of the most spectacular examples on Earth. Combined GNSS and InSAR provide numerous current and future opportunities to measure magma flux with time beneath Alaska's volcanoes. GNSS measurements have also revealed a crustal velocity field that represents contributions from an interseismic strain signal, associated primarily with the subduction of the Pacific Plate beneath North America, as well as large signals associated with postseismic viscoelastic and afterslip effects (Figure XIII.a). GNSS

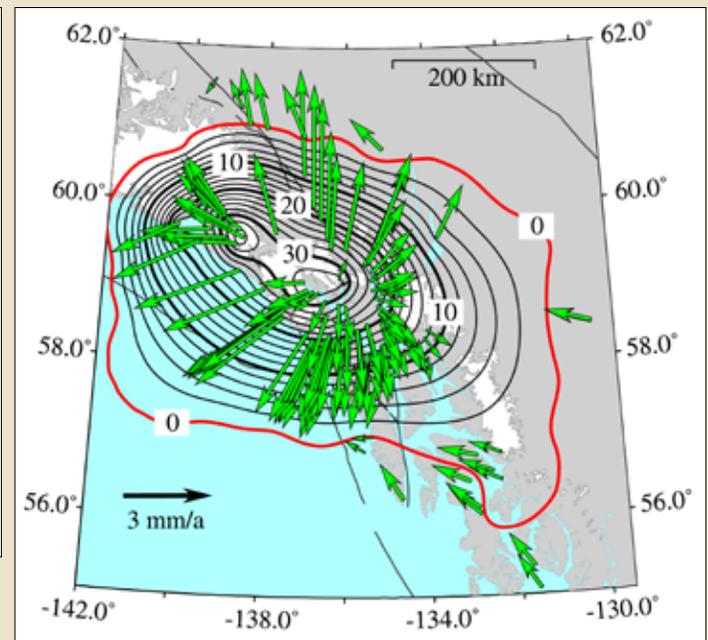
measurements have confirmed evidence of the long-hypothesized Bering Plate, which is rotating clockwise relative to North America about a pole in east Asia. Deformation within, and movement of, the Wrangellia Terrane and the Yukatat microplate produce rapid uplift rates on the Wrangell and St. Elias mountain ranges (the highest in North America). The Queen Charlotte-Fairweather and Denali Fault systems, the longest strike-slip faults within continental lithosphere, bound some of these terranes. Alaska is characterized by widespread seismicity. Significant earthquakes have included the great 1964 Alaska earthquake (M_w 9.2) and the 2002 Denali earthquake (M_w 7.9), the largest strike-slip earthquake recorded on the North American continent. These and other events have produced

substantial and far-reaching postseismic relaxation measured with GNSS and InSAR. These measurements have been used to infer postseismic process, providing model estimates of crust and upper mantle rheology and present-day rates. Southeast Alaska has lost large volumes of ice since the Little Ice Age. The isostatic adjustment from this ice loss results in an uplift rate exceeding 30 mm/yr (Figure XIII.b; also see Spotlight IX). This large signal must be accurately accounted for when modeling geodetic observations to infer interseismic tectonic rates. The response to the unloading history provides information about crust and upper mantle rheology and coupling of climate change with tectonics.

XIII.a



XIII.b



GRAND CHALLENGE 5

What physical processes control earthquakes?

As the population density increases and more people live in proximity to seismically active faults, understanding the nature of earthquakes remains a vital goal of the Earth sciences. Geodetic observations have led to fundamental advances in our understanding of earthquake behavior, from the formulation of elastic rebound theory to the discoveries of post-seismic transients, interseismic strain accumulation, and, more recently, slow slip events. Recent progress in remote sensing and space-based geodetic techniques now allow highly accurate measurements of surface deformation that can be used (either individually or in combination with other data) to determine the sub-surface structure of seismically active faults, and mechanical properties of rocks around them. Geodetic observations in tectonically active areas are motivated by models of the earthquake cycle. Above a depth of about 15–30 km (depending on tectonic setting), plate boundary deformation is primarily accommodated on discrete faults. Within the seismogenic zone (on continents, typically at depths less than 12–15 km), sliding is largely episodic because frictional resistance decreases with slip and/or slip-rate, such that elastic interaction with the surrounding crust leads to stick-slip cycles. At greater depth and temperature, friction is strengthening, promoting stable sliding behavior.

The time and depth variations in fault slip depend on a number of poorly constrained parameters as well as the orientation and intensity of the applied stress field. Geodetic measurements can reveal the distribution of surface strain with distance from the fault and thus

can be used to infer the slip distribution with depth. Dense networks of ground-based instruments (e.g., GNSS and strainmeters) and remote sensing (in particular, InSAR and optical imagery) are now routinely used to measure the coseismic, postseismic, and interseismic deformation due to active faults. Geodetic data additionally provide unique information that alone or in combination with seismic observations provide constraints on the earthquake rupture process.

Ongoing improvements in the quality and quantity of available data have enabled substantial progress in solving long-standing fundamental problems. Major unresolved scientific problems include the effective rheology of the lithosphere and underlying mantle, particular mechanisms of coupling of the seismogenic crust and mantle with the underlying ductile medium, interseismic loading of seismogenic faults, the average level of deviatoric stress in tectonically active crust, the nature of transient deformation due to major faults, and the possible existence of detectable precursory deformation. Geodetic investigations of deformation associated with the earthquake cycle address many of these questions. For example, detailed characterization of coseismic displacements is indispensable for determining sub-surface rupture geometry and slip distribution for large shallow earthquakes.

Well-constrained models of seismic slip are in turn crucial for investigations of postseismic response that attempt to relate the observed transient deformation to sudden stress changes imposed by

Spotlight XIV

The 2010 Haiti earthquake: Foreseen but still surprising

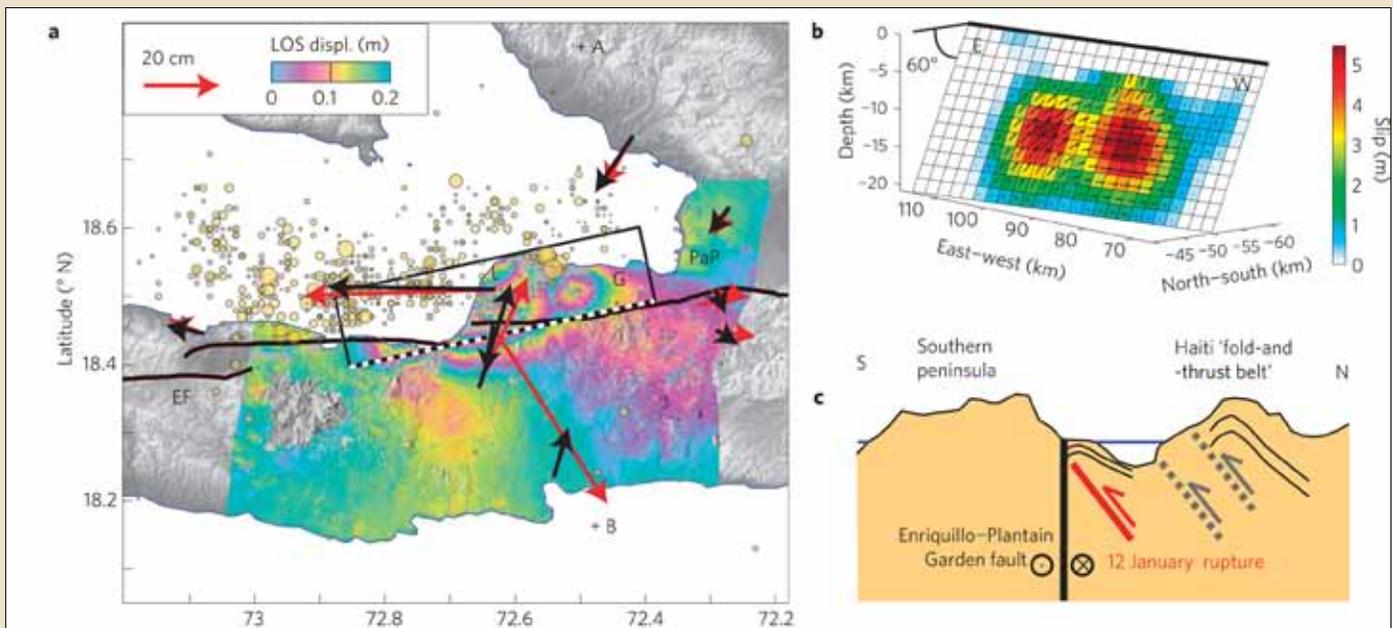
The January 12, 2010 M_w 7.0 earthquake in Haiti killed more than 240,000 people in an area known to be capable of producing an earthquake of that magnitude. Based on GNSS measurements begun in 2003 on the island of Hispaniola, it was recognized that the major east-west trending strike slip fault, the Enriquillo Fault (EF), was accumulating stress and might be capable of a magnitude 7.2 earthquake if the stress were released in a single earthquake. Yet the characteristics of the earthquake were also surprising—it did not actually rupture the vertical EF, but slip instead occurred on

a newly identified dipping fault for which the sense of motion is consistent with that expected from the pre-earthquake measurements.

Figure XIV.a.a shows an InSAR interferogram of line-of-sight (LOS) surface displacement and GNSS observed (black) and model (red) coseismic displacement from the earthquake. (Yellow circles show aftershock locations.) A model for slip on the fault plane, shown in Figure XIV.a.b, is estimated from the InSAR and GNSS observations. The black rectangle in Figure XIV.a.a shows the surface projection of

this modeled rupture, with the black-white dashed line showing its intersection with the surface. Figure XIV.a.c shows an interpretative cross-section based on the model, from which the vertical EF and the modeled slip surface (red line) can be distinguished. From these and other studies, it is clear that the future earthquake hazard on this fault system and on other faults in Hispaniola remains a concern.

XIV.a

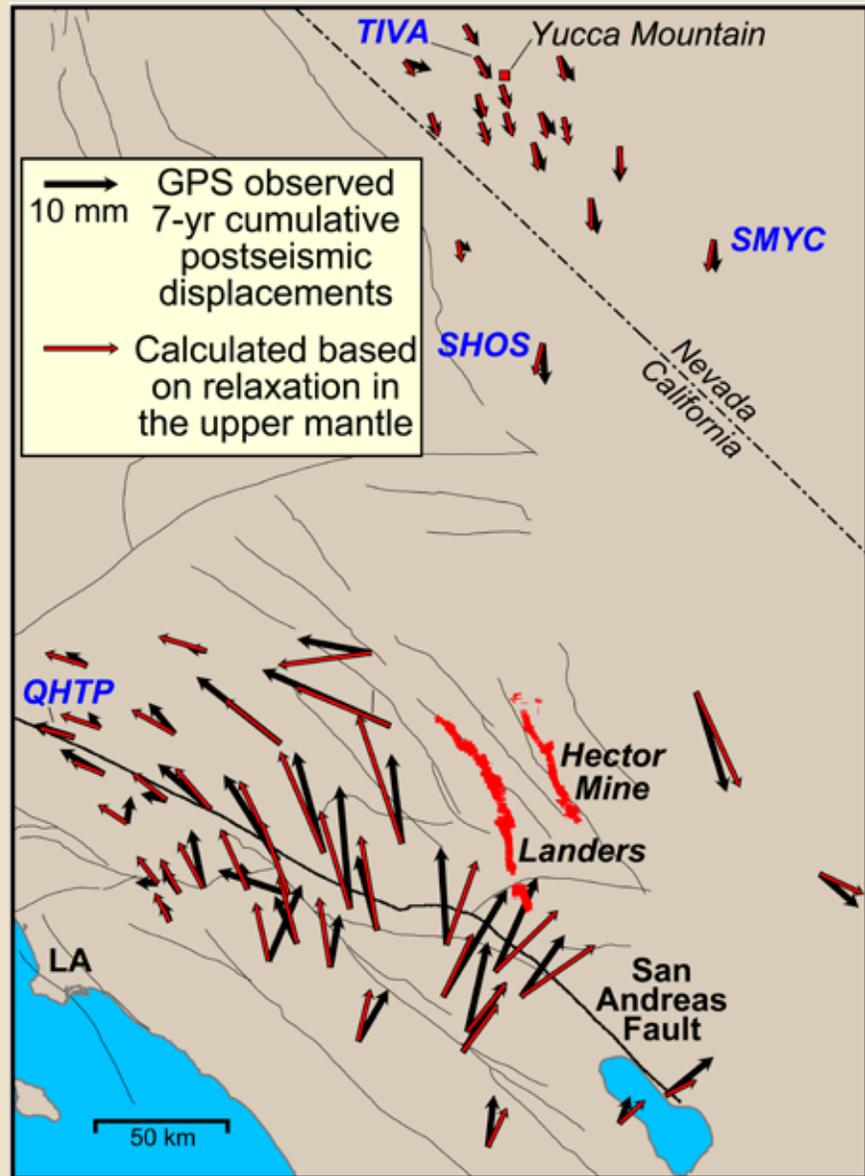


Spotlight XV

Postseismic deformation: A probe of rheology of the lower crust and upper mantle

Geodetic measurements of transient deformation following large earthquakes are used to constrain rheologic properties of rocks below the brittle-ductile transition. Such constraints are important for understanding coupling between the seismogenic crust and aseismic substrate, and stress transfer from the viscously deforming mantle to major crustal faults. Figure XV.a shows displacements (black arrows) estimated from GNSS observations during the seven years following the 1999 M_w 7.1 Hector Mine earthquake in the Eastern California shear zone. These displacements reveal a broad pattern of transient deformation throughout southern California and into Nevada, more than 200 km from the epicenter. Numerical models of postseismic relaxation indicate that this deformation pattern can be caused by the upper mantle flow beneath a ~50-km-thick competent layer (red arrows). Geodetic observations of postseismic deformation are also used to characterize the depth extent and rheologic properties of deep roots of major faults, and migration of pore fluids in the upper crust in response to the coseismic stress changes.

XV.a



an earthquake, and, thus, directly probe the effective rheology of ambient rocks. Proposed models of postseismic transients include, among others: enhanced creep on a seismic rupture or its extension below the brittle-ductile transition (after-slip); poroelastic rebound of fluid-saturated crust; and viscoelastic relaxation of the ductile lower crust or upper mantle. Improved geodetic observations help discriminate the proposed models and provide valuable insights into the mechanical properties and long-term behavior of the brittle and ductile parts of the lithosphere as well as the sublithospheric mantle. For example, spatiotemporal signatures of surface deformation may be used to infer the constitutive frictional parameters and depth extent of fault creep in case of afterslip, the presence of fluids and in situ permeability of crustal rocks in case of poroelastic rebound, the thickness of the elastic layer, and the rheology of the underlying substrate in case of viscoelastic deformation.

Ultimately, observations of postseismic response bear on a long-standing debate about the effective mechanical thickness and strength of the lithosphere. Competing views include a “thick lithosphere” model in which mature faults extend throughout the crust and perhaps well into the mantle, and a “thin lithosphere” model whereby faults localize strain only in the seismogenic layer, and interseismic deformation is accommodated by a broad viscous flow below the brittle-ductile transition. At least in the case of transform faults, both models can be reconciled with geodetic observations of interseismic strain accumulation in the seismogenic layer. Further progress will require merging observations of interseismic loading, coseismic strain release, and postseismic response in various tectonic environments with realistic numerical models, to develop quantitative understanding of fault behavior throughout multiple earthquake cycles, and the evolution of stress and strain in

space and time. Such understanding will also require incorporation of geologic estimates of fault slip-rates, paleoseismic determinations of earthquake recurrence intervals, laboratory constraints on frictional properties and bulk rheology of rocks below the brittle-ductile transition, and seismologic data (in particular, distribution of seismicity, imaging of sub-surface fault geometry and extent, and studies of seismic anisotropy in the ductile substrate).

Advances in data gathering also bear on a long-standing question of potential precursory deformation signals. Models based on laboratory-derived rate-and-state friction formulations predict that earthquakes are preceded by an accelerated creep in a nucleation zone. Whether this occurs over sufficiently large fault areas to allow geodetic detection of preseismic deformation, and if so in what circumstances, is still unknown. Observations so far have not revealed any reliable or repeatable precursory signals, but only a handful of earthquakes occurred in densely instrumented areas. Robust constraints on the magnitude of potential precursory slip events remain one of the pressing problems of earthquake geodesy.

Rapid transformation of earthquake geodesy, once data poor, into a data-rich discipline has major implications for estimates of seismic hazards. Current earthquake hazard maps have coarse resolution in both time and geography. Such maps depict probability of exceeding a certain level of shaking (generally that at which damage occurs) over the next 30 to 100 years, depending on the map and how much is known about the region. Spatial resolution is typically on the order of tens to hundreds of kilometers. These maps are based on information about past earthquakes observed in the geological or historical record.

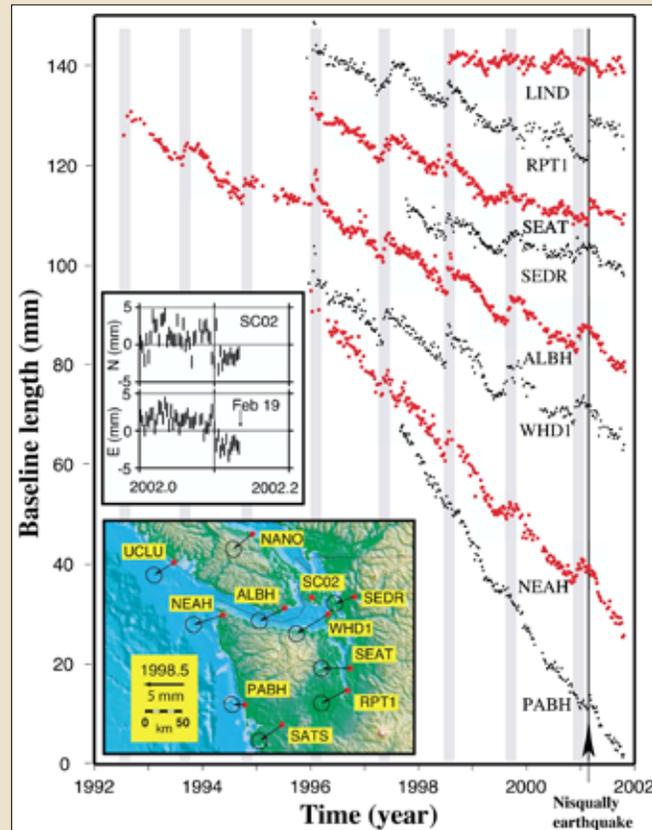
Measurements of crustal deformation now provide information about strain rates and generally there is evidence that earthquake rates are higher where strain rates are higher. A comprehensive geodetic monitoring of active fault zones will yield insights into earthquake behavior, how secular loading gives rise to the initiation of failure on a fault or quiet release of stress, and how stress is transferred to other faults. These studies will lead to science findings for improvement of earthquake hazard maps both spatially and temporally.

Spotlight XVI

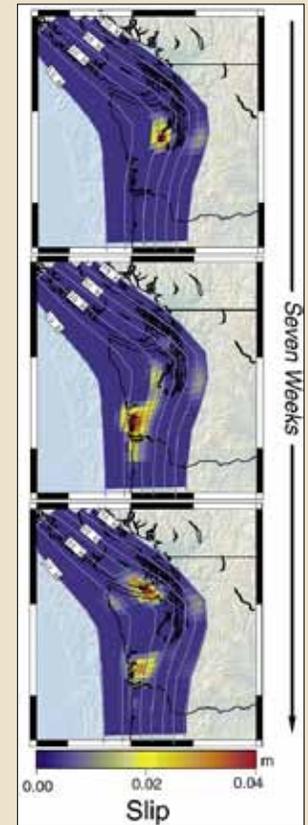
Positioning for discovery: Episodic Tremor and Slip (ETS)

One of the most exciting discoveries in the field of earthquake physics over the past decade is the fact that fault zones have slow earthquakes on nearly regular intervals and that these slow earthquakes are not silent, but are associated with seismic tremor. The events were first recognized as short periods (several weeks) of deformation in GNSS time series from the Pacific Northwest, but were quickly linked to tremors that were previously thought to be unimportant. The now-classic collection of GNSS time series from the PANGA network (Figure XVI.a) illustrates the network coherency and periodicity of the crustal deformation events. Geodetic data have been used to explore a number of properties of ETS, including the influence of tidal stress and the time dependence of slip. Slip derived from GNSS data during an ETS event in 2003 in Cascadia (Figure XVI.b) indicate that the location of slip evolves significantly during an ETS event. ETS has also been observed in other areas around the world. Figure XVI.c shows the evolution of slip on four faults (defined in the map) over a 2006 slow-slip event in Guerrero, Mexico. Ongoing seismic and geodetic studies are better characterizing the properties of ETS, but more than a decade past their discovery, the fundamental origin of this process remains obscure.

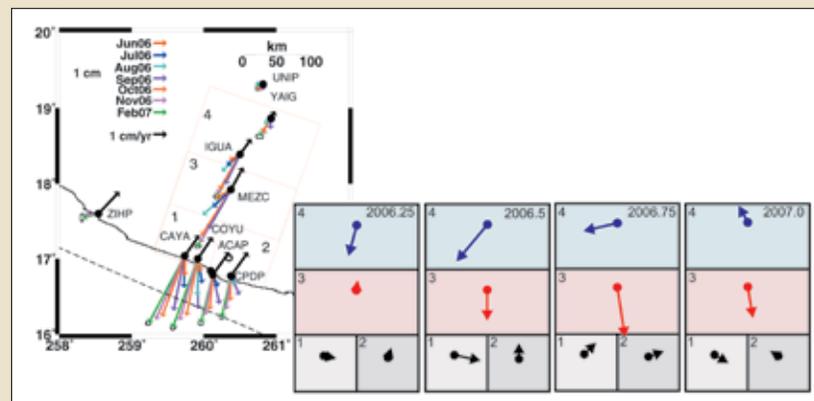
XVI.a



XVI.b



XVI.c



GRAND CHALLENGE 5 - KEY QUESTIONS:

What are the mechanisms of interseismic loading, coseismic strain release, and transient deformation events?

Are there detectable precursory deformation signals associated with large earthquakes?

Do some attributes of ETS events (period, updip extent, amplitude) vary with time as the next large earthquake approaches?

What controls the occurrence of slow-slip events and why do these differ from typical dynamic earthquakes?

What is the role of ETS on the occurrence of large earthquakes in subduction zones? Can improved understanding of ETS and loading processes lead to improved forecasts of damaging megathrust events?

What is the average magnitude of stress supported by active faults?

LONG-TERM GOALS FOR ADDRESSING KEY QUESTIONS:

Integrate geodetic measurements of interseismic deformation, geologic fault slip rates, and paleoseismic determinations of earthquake recurrence intervals.

Improve the accuracy of continuous, stable celestial and terrestrial reference frames, as well as other products required for positioning, such as high-accuracy orbits for GNSS satellites.

Integrate continuous geodetic and seismic networks with high rate and low latency, and develop early warning systems for earthquakes, tsunamis, and other natural hazards.

Improve the spatial and temporal resolution of crustal deformation measurements in earthquake zones.

Develop the capability for rapid deployment of high-resolution measurements in response to seismic events, through some combination of ground observations (e.g., GNSS) and satellite systems (e.g., InSAR).

GRAND CHALLENGE 6

How does Earth's surface evolve?

The continual reshaping of Earth's surface by steady and catastrophic tectonic and hydrogeologic events, sea level rise and fall, and gravitational collapse of landforms and volcanic edifices has a profound impact on terrestrial water supply, ecosystems, landscape evolution, and the built environment. Over time scales of thousands to millions of years, the surface morphology of the continents and the processes that mold them result from, and thus may be used to decipher, the rich record of the interaction between tectonic and climatic forces. With a comprehensive understanding of how these factors contribute to the morphology and evolution of landforms, high-resolution surface observations of topography can provide the means to disentangle the contributing signals and extract a better understanding of tectonic and climatic processes operating over a broad range of temporal and spatial scales.

Geodetic approaches are for the first time enabling the broader science community to characterize the full set of parameters that govern land surface evolution: kinematics, the tectonic driving forces that move the landscape; mass balance (volume of material that is redistributed across the landscape); sediment transfer; regional factors (local geologic, hydrologic, biomorphic, geochemical, ecosystem, and climate); and catastrophic events (infrequent large-scale events that redefine the inter-period rates). High-resolution images and 3-D/4-D topography maps both inspire and facilitate field-based tests of a new generation of quantitative models of mass transport mechanisms. These

images and maps allow us to characterize Earth's surface at the appropriate spatial scales and provide the means to characterize land-forming processes. Topographic signals of the interactions between tectonic and surface processes and the climatic modulation of process rates can be characterized by using innovative topographic metrics. The ability to characterize and monitor mass transport mechanisms and their relation to the development of the characteristic scales of landscapes provides insight into the interaction of the substratum and climatic forcing. Repeat measurement of man-made structures and natural surfaces over hours, days, and years, unattainable with conventional methods, provides new opportunities to understand the formation and movement of landslides and sand dunes, to assess differential subsidence associated with migration and extraction of subsurface fluids, to characterize seismic and aseismic slip along faults (including creep following earthquakes), and to quantitatively constrain rates of erosional processes.

The incorporation and calibration of these new technologies as an extension of geodetic research is a burgeoning opportunity that is being avidly embraced by the scientific community.

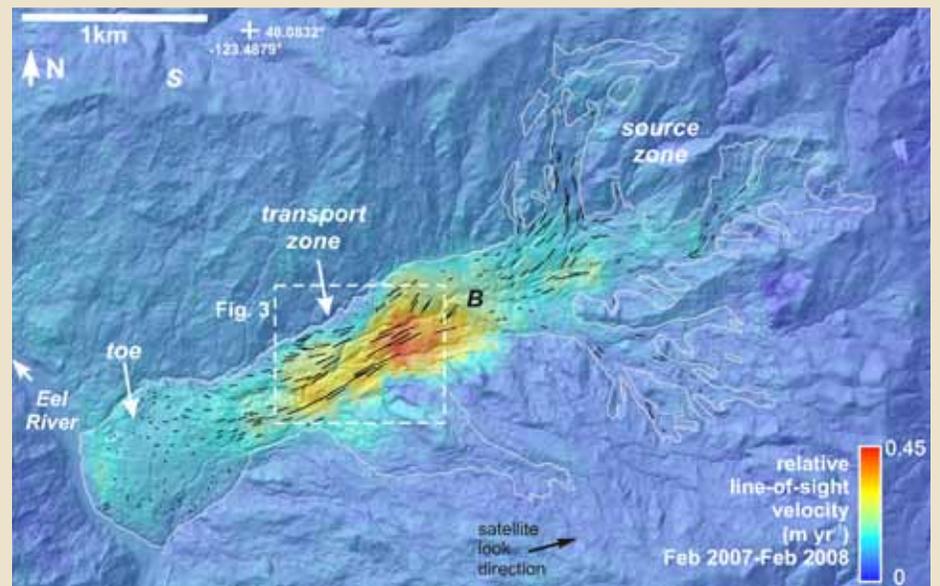
Spotlight XVII

Studying landslides with InSAR, LiDAR, and aerial photos

Landslides are a key factor in the erosion of mountainous regions, but quantifying their impact has been difficult in the necessarily steep, inaccessible terrain. Imaging geodesy, however, provides tools that can be used to measure the rates of movement of slow moving landslides (< 1 m/yr). InSAR has been used to make continuous maps of ground displacement in the line of sight of the radar in the Eel River drainage of northern California (Figure XVII.a). Combined with an airborne LiDAR digital elevation model (from ALSM with 1 m/pixel spatial resolution) and mapping of tree movements between air photos separated by decades, the characteristics of mass transport can be constrained. Interferograms overlay on the airborne LiDAR digital

elevation map show ground motion over a one-year time period (February 2007 to February 2008) in the direction of the LOS of the satellite radar (shown as black arrow). The letter "S" in Figure XVII.a shows the point that is assumed to have zero motion for the InSAR determined motion, while the letter "B" shows a break in slope caused by a mechanical or compositional change in the surface rocks. Studies show that these slow moving landslides located on hills with gentle slopes encompass only a small fraction of the Eel River drainage yet account for a substantial fraction of the erosion.

XVII.a



GRAND CHALLENGE 6 - KEY QUESTIONS:

How does the surface morphology express and record the interaction between tectonic, hydrological, and gravitational processes and their modulation by climatic variation?

What is the relationship between topographic form and near-surface hydrologic response during individual storm events?

What is the budget for strain loading and release during the earthquake cycle and to what extent does permanent deformation lead to observed surface structures and morphology?

How does the topographic form of the landscape relate to mass transport processes and what are the physics- and chemistry-based geomorphic transport laws that govern production and alteration of regolith, erosion, transport, and deposition? What defines both the operational regime of given processes and the transitions between process domains?

What are the topographic metrics (such as slope-area; wavelet-based, spatial power spectra) that can efficiently illuminate meaningful process signals in high-resolution topography?

How does plant root tensile strength and biological activity influence mass transport rates and the geomorphic evolution of landscapes?

LONG-TERM GOALS FOR ADDRESSING KEY QUESTIONS:

Acquire multiplatform remote sensing observations with sub-meter to sub-centimeter resolution of the spectral and morphological characteristics of geologic materials with centimeter geospatial (Earth-centered, Earth-fixed) accuracy, including GNSS positioning of suitable accuracy where required.

Develop new imaging techniques for measuring ground elevations and displacements below the water surface, and provide access to these techniques to the community.

Provide open access to data, tools, and facilities for processing, analyzing, visualizing, and developing new algorithms and workflows.

Expand tools for error analysis and LiDAR 3-D point-cloud comparison over a wide-range of length scales to enable optimal time-integrated, 3-D surface change measurement.

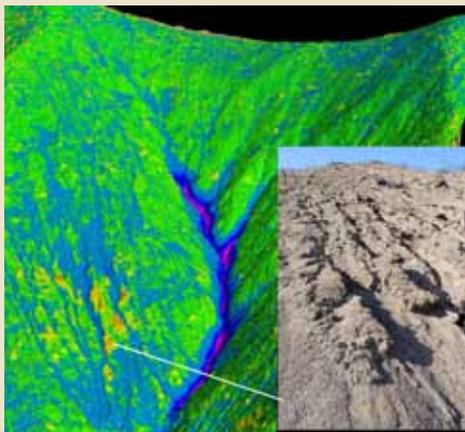
Develop rapid deployment protocols and accessibility to equipment to respond to event-based monitoring.

Spotlight XVIII

Ultra-high-resolution (UHR): 4-D imaging across Earth science

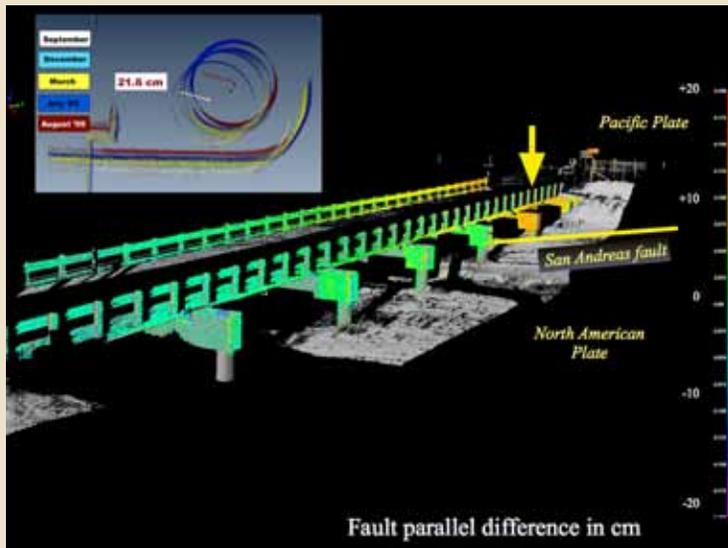
Ground-based Tripod/Terrestrial LiDAR (T-LiDAR, aka Terrestrial Laser Scanning) is an emergent geodetic technology enabling scientists from multiple disciplines to address questions that were unanswerable only five years ago. T-LiDAR has unsurpassed ability to collect UHR (sub-centimeter) 3-D and 4-D point-cloud measurements on scales ranging from individual tree branches and small outcrops to areas of a few square kilometers. This new tool is ushering in an era of geodetically driven mesoscopic-scale science with true 3-D site characterization and 4-D change detection. For example, deformation of a bridge spanning the San Andreas Fault was tracked with UHR T-LiDAR following the 2004 M_w 6.0 Parkfield earthquake to measure postseismic deformation (Figure XVIII.a). From the imagery, 10.0 cm of right-lateral postseismic motion (relative to the North American side, which was held fixed) parallel to the main trace of the fault in the 10 weeks following the earthquake were observed, with a total of 21.6 cm of motion by August 2009. T-LiDAR can also image the response of a basin to aeolian and fluvial processes following major fires. For example, repeat UHR T-LiDAR imagery collected in a burned basin following the 2009 Station Fire in southern California (Figure XVIII.b) shows that aeolian and dry ravel processes moved

XVIII.b

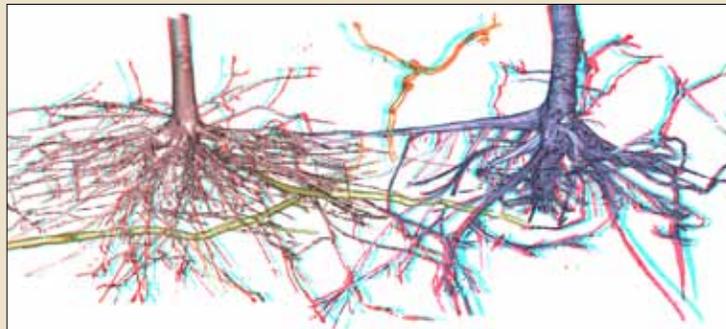


material from the denuded landscape into channels and breaks in topography and was then mobilized during a thunderstorm during which 340 m³ of material was removed from the basin for a mean land-surface lowering of 2.6 cm. About 70% of the material loss during the storm was from the channels. (Green shows little change; yellow/red shows 0.5 m of deposition; and blue/magenta shows a maximum of 1.8 m erosion; the inset is a photo of an area with deposition). UHR T-LiDAR is also making it possible to measure biomass accurately and non-destructively using a methodology that preserves the target while providing

XVIII.a



XVIII.c



a wealth of information about the target in its surrounding ecosystem. For example, scans of an excavated tree root system (Figure XVIII.c) provide detailed biomorphic information that relates surface slope, solar angle, and water source with root growth as a function of depth below the land surface and distance from the tree. The imagery reveals tree roots from two valley oak trees (red and blue) with roots from two separate Cottonwood trees located well outside the field of view. (This anaglyph image can be viewed in 3-D with red/blue glasses.)

GRAND CHALLENGE 7

What are the mechanics of magmatic systems?

Volcanic eruptions have a profound impact on society, including the destruction of life and property, shutting down international airspace for weeks, and changing global climate patterns (Figure 11). Magmatic activity is a vivid and deadly illustration of the heat engine that powers Earth's tectonics, and plays a major role in construction of Earth's crust. Among the most spectacular manifestations of the ongoing magmatic processes are mid-ocean ridges and volcanic chains associated with hotspot tracks and subduction zones. Volcanic eruptions impact many people: local populations in the direct path of volcanic flow; regional populations devastated by caustic gases and ash fall; air travelers; and even populations around the globe as the largest events affect short-term global climate.

When magma moves through the Earth's crust it displaces the surrounding rock, producing earthquakes and causing land surface deformation that can often be geodetically measured prior to eruption. Advances in ground-based and satellite

measurement techniques, analytical and computational tools, and basic knowledge of volcanic systems have allowed for vast improvements in understanding the sources of volcanic deformation. Geodesy is now recognized as an essential tool that complements geologic studies, remote sensing of gas emissions, and seismic monitoring, in the identification of pre-eruptive activity and subsurface magma movement. It is fundamental to an integrative understanding of subsurface magmatic processes.

Because continuous GNSS can provide information on how the surface is moving with high temporal resolution, the tool is highly valuable for tracking magma movement. InSAR provides a synoptic view of the ground displacement field and can be used to survey global subaerial volcanoes to identify new activity. Volcanic unrest may also be accompanied by changes in the gravity field. In recent years, geodetic measurements have been extended to the ocean floor to study submarine volcanic systems.

While instrumentation and computational capabilities have aided in illuminating the behavior of magma, we do not yet have a full understanding of the processes that control its production and ascent; hence, our ability to predict eruptive events remains rudimentary. Seismic activity and deformation are linked in volcanic systems and may remain the two most important indicators of an impending eruption. Identifying the scales over which deformation and seismic activity manifest magma motion at depth, and developing consistent models to explain both behaviors would lead to improved forecasts.

Figure 11

The 2010 eruption of Eyjafjallajökull volcano, Iceland, sent a plume of ash high into the atmosphere, disrupting air travel and costing billions of dollars to economies around the world. Geodetic techniques such as InSAR, GNSS, and in situ strain measurements are used to measure volcano deformation prior to, during, and after eruption in order to study the internal "plumbing" of the volcano.



Spotlight XIX

The 2010 eruption of Eyjafjallajökull Iceland

In the spring of 2010 explosive eruption of the Eyjafjallajökull volcano in Iceland severely disrupted air traffic in Europe for several days, causing an economic impact around the world of several billion dollars (Figure XIX.a below). While there was no immediate, obvious change in the deformation during the hours to days before the eruption, deformation

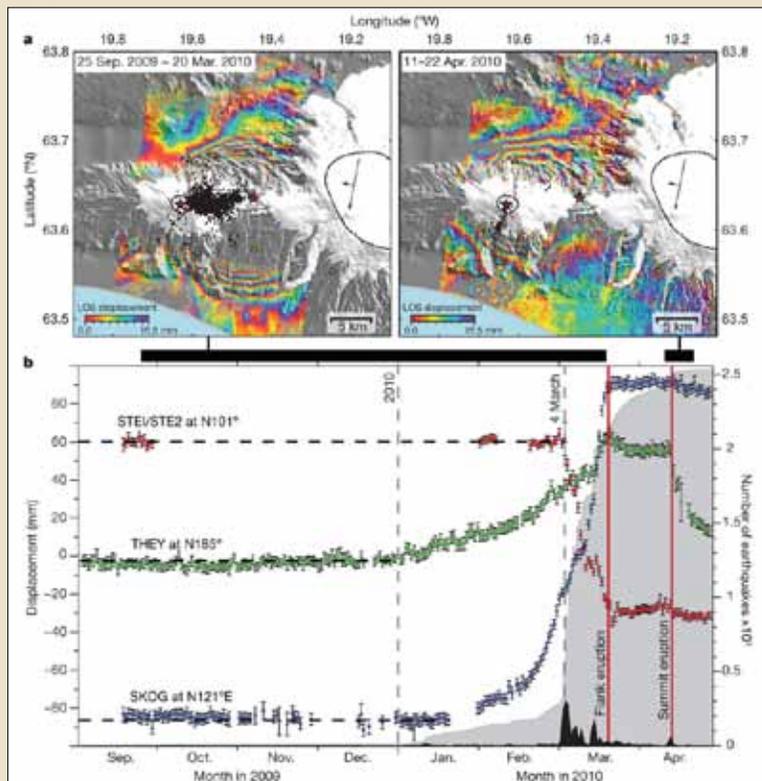
XIX.a



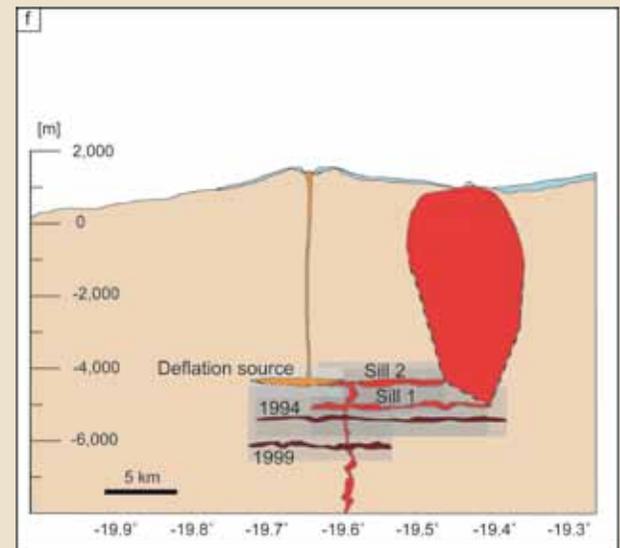
was observed geodetically in the months before the eruption. Interferograms (Figure XIX.b.b) detail the deformation of Eyjafjallajökull during the pre-eruptive intrusive period (left) and the initial days of the explosive eruption (right). The black dots show earthquake epicenters for the corresponding period. The red stars are continuous GNSS locations, located near eruptive vents. GNSS data present a detailed temporal sampling of the volcano deformation, but only at the relatively few GNSS sites (Figure XIX.b.b). Together, the GNSS and InSAR measurements provide constraints on the subsurface magma “plumbing system,” including the finding that the magma must have flowed from considerable depth, instead of from a shallow magma chamber (Figure XIX.c).

This finding is consistent with the “cold” tectonic setting of this volcano away from the main volcanic activity in the rift zone. Researchers continue to monitor deformation during the eruption at Eyjafjallajökull and to see if Katla, a larger volcano to the east, shows any new signs of deformation. All three historic eruptions of Eyjafjallajökull have been associated with eruptions at Katla.

XIX.b



XIX.c



Prior to the 1980 eruption, Mt. St. Helens bulged at more than one meter per day. On the other hand, the 2004 eruption showed essentially no detectable precursory deformation. Clearly, not all eruptions are preceded by measurable deformation. Are the biggest deformation events the most dangerous? Volatile content is likely to influence how magmatic systems develop, and may play a role in geodetically detectable signals. It is important to observe many more volcanoes of different types and in a range of tectonic environments to learn how they behave.

To determine the long-term style of deformation in a neovolcanic system it may be necessary to combine modern space geodetic techniques with traditional geodetic surveying methods such as leveling and studies of natural geologic or biologic markers in coastal and lakeshore environments (e.g., mollusk growth on columns in Pozzuoli, Italy, displaced by the Campi Flegrei caldera or uplifted terraces along lakes and rivers by the Yellowstone caldera). Airborne and terrestrial laser scanning may likewise be combined with earlier air and satellite photography to interpret large-scale deformation, particularly near and inside volcanic craters.

Characterizing the scales of deformation along oceanic ridges, Earth's most productive volcanic systems, requires widespread observations of short- and long-term seafloor deformation. Improvements in seafloor geodetic methods are necessary to reduce cost, and allow long-term and high-rate sampling, much like continuous GNSS.

Understanding interactions between volcanic events and seismic activity will further our understanding of processes that ultimately drive volcanic eruptions. Developing physics-based models that link volcanic deformation (determined from geodetic observations) and seismic activity may well lead to improved eruption forecasting, and, hence, remains an important challenge. Improved imaging of the changes in deformation and associated stress during volcano-tectonic interactions can come from precision high-rate geodetic measurements of surface deformation, and borehole strainmeters in combination with local microseismic recordings, geologic constraints, and degassing. These integrated data sets will support comprehensive modeling of volcano systems that has not previously been achievable.

GRAND CHALLENGE 7 - KEY QUESTIONS:

1. What are the temporal and spatial scales, signature pattern, and magnitude of deformation preceding volcanic eruptions? How do they vary with eruption size and style at individual volcanoes and in different volcanic regions?
2. What mechanisms (e.g., rheology, structure, magma/volatile input, pressure) control deformation and gravity changes in volcanoes?
3. What are the sizes and depths of magma reservoirs? Where and why are there magma reservoirs at multiple depths?
4. Where is magma stored before eruptions? Under what circumstances is magma transported through the crust, and what shapes its transport pathways?
5. How do changes in dynamic and static stress due to earthquakes affect magmatic systems?
6. How do pressure changes in subsurface magma bodies affect regional stresses and seismicity?
7. How do nearby volcanoes interact with each other?

LONG-TERM GOALS FOR ADDRESSING KEY QUESTIONS:

Develop approaches for measurement of deformation and gravity in real-time before, during, and after volcanic eruptions.

Perform high-resolution monitoring of deformation on all of Earth's major volcanoes.

Develop instrumentation (including satellite-based) for seafloor geodesy and deploy on targeted submarine volcanic centers.

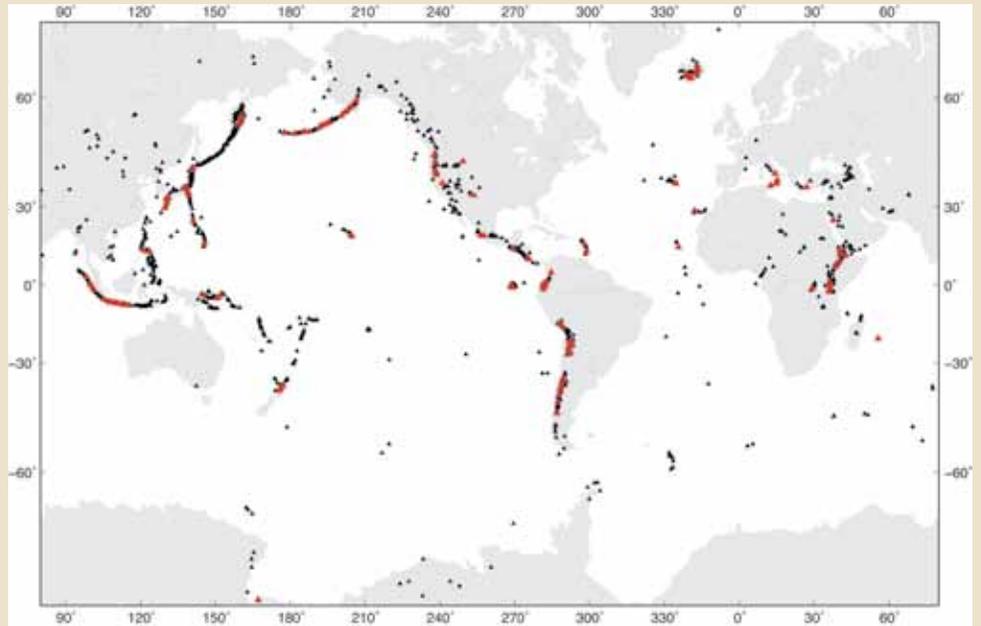
Support open source modeling software capable of integrating diverse data types and physically realistic models for rapid assessment in volcano monitoring situations.

Spotlight XX

How many of the world's volcanoes are active?

A complete census of deformation at all of the world's subaerial volcanoes is lacking, but the widespread application of satellite InSAR has increased the number of known deforming volcanoes from 44 in 1997 to 131 in 2011. All (~1500) volcanoes from the Smithsonian Institution's Global Volcanism database are shown in Figure XX.a in black. Volcanoes known to be deforming as of 2011 are shown in red. Many volcanoes of the world have not yet been surveyed. A major limitation to the global census is the lack of persistent observations over all of the world's volcanic regions (including remote ocean islands) that are frequent enough to avoid aliasing of deformation events. A dedicated InSAR mission such as DESDynI would fill this gap.

XX.a



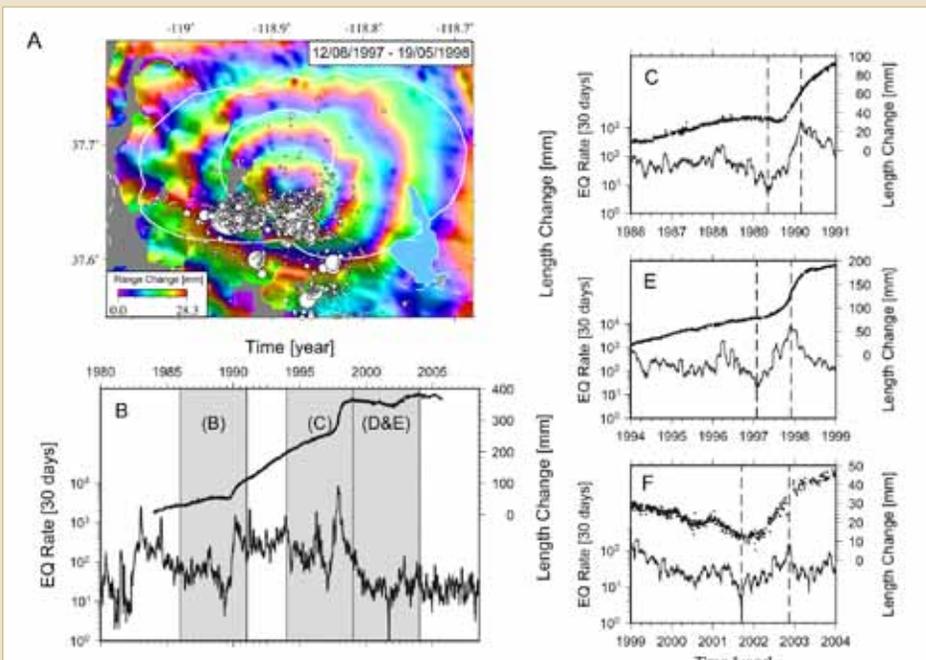
Spotlight XXI

Volcano-tectonic linkages

Interaction between magmatic and tectonic systems is often observed, but physical models that explain this behavior are in their infancy. Interactions can occur over a large range of time scales. Tectonic stresses may govern the geometry and orientation of pathways for magma migration. Stress changes due to seismic activity may affect the dynamics of magmatic systems (and vice versa). Stresses may be manifest in static forcing of the crust, changes in pressure of magmas and pore fluids, or dynamic shaking from earthquakes. Understanding the interaction between these systems can lead to improved short-term hazard forecasting and mitigation. Figure XXI.a, for example, illustrates the interplay of tectonic seismicity and volcanic inflation at Long Valley Caldera. The bulls-eye pattern of InSAR fringes in Figure XXI.a.a shows an inflation event that lifted the center of the caldera >10 cm in a few months, correlating

with the high activity of seismicity just before and during that period (gray circles; white circles show seismicity in the three years previous to this period). In fact, over ~30 years the system has gone through a series of episodic uplift events, shown in Figure XXI.a.c. In each event, seismicity along the south moat, though primarily driven by large-scale dextral motion of the Eastern California shear zone, is modulated unmistakably by magmatic inflation events. Three uplift events (1989, 1997, and 2002) are shown in more detail in Figures XXI.a.C–F. During each event, seismicity along the south moat falls off dramatically just prior to the initiation of magmatic inflation, and reaches a maximum when the surface uplift rate begins to decay.

XXI.a



"With the quiet revolution of NAVSTAR GPS, it can be seen that the potential uses are limited only by our imaginations."

B. Parkinson in *Global Positioning System* (1980)

SECTION

03

In the Public Interest: Societal Benefits

A Foundation for Innovation: Grand Challenges in Geodesy

Significant direct and indirect societal benefits arise from geodetic research. This section briefly reviews two of these benefits, and illustrates how geodetic research can promote improvements in public safety and commerce, and can have major impact on scientific fields beyond the Earth sciences, and on the everyday lives of ordinary citizens.

Early warning for natural hazards

Natural hazards occur over many time scales and are studied using geodetic techniques that sample across the temporal spectrum. Few hazards have clear and established precursory signals suited for prediction of specific events. Events that have eluded us for short-term predictability include landslides, earthquakes, tsunamis, and catastrophic ice wasting events. Because of this, hazards mitigation research commonly focuses on establishing the vulnerability for a region through event frequency and magnitude characterization, allowing for planning that anticipates the effects of a likely event that cannot be predicted with great specificity.

Increasingly, however, the onset of a hazardous event lasting seconds, minutes, or more, can be observed using geodetic tools, creating the possibility for an alarm system. In this scenario, the event and its likely impact might be communicated in advance, providing opportunity for “early warning” that mitigates associated risk. Extreme events that lend themselves to early warning include earthquakes, tsunamis, volcanic eruptions, landslides, and extreme weather events such as hurricanes.

Early warning depends on three key capabilities:

- I. The relevant hazards science must be sufficiently understood to allow useful identification and characterization of the evolving hazardous event. For instance, sufficient GNSS imaging of water in the atmosphere during a hurricane can significantly improve hurricane track intensity and prediction. Sufficient real-time GNSS detection tools can adequately identify catastrophic displacements associated with large earthquakes, giving rapid warning of impending tsunami inundation.

2. Data transmission and accurate on-the-fly analysis must be possible on a timescale shorter than the evolving extreme event. For instance, seismic waves are slower than modern telecommunications. Thus, approaching ground shaking may be communicated before its arrival. Similarly, tsunamis travel more slowly than seismic waves; a great earthquake can herald a subsequent tsunami with a delay that increases with distance from the event.
3. The third capability is preparedness. Public awareness, planning by hazards management agencies, and early warning communication protocols must be sufficiently evolved to exploit the opportunities posed by modern hazards science and data communications.

For certain hazards, special capabilities pertain. In the case of tsunamis, an additional challenge is developing

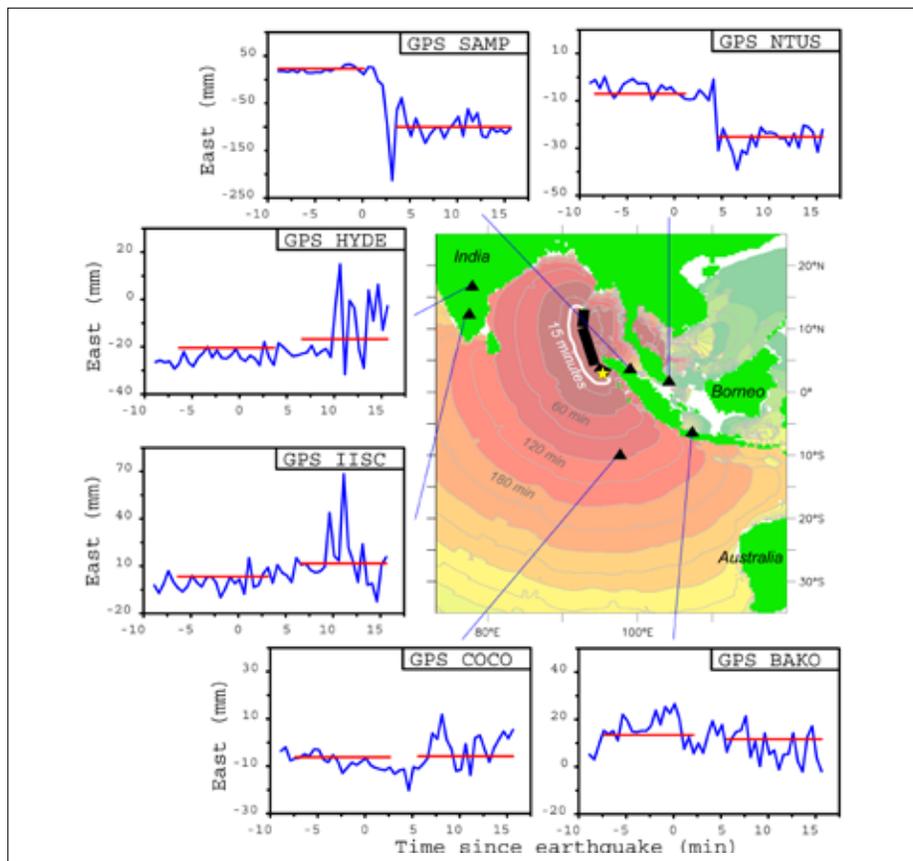
tools for measuring deformation occurring solely on the seafloor. Whereas submarine volcanic eruptions, earthquakes, and landslides pose large tsunami hazards, the associated seafloor deformation—the ultimate indicator of tsunami potential—is detectable only with real-time seafloor geodetic instrumentation. Such technology is in its infancy.

For evolving earthquakes or hurricanes, high-frequency and low-latency GNSS observations are essential to securing the benefits of early warning. The USGS has recently retrofitted a number of GNSS stations with capabilities for high-rate data acquisition and real-time data transmission. The goal of this work is to increase the integration of seismic and geodetic data for earthquake early warning. The USGS system is built around the Advanced National Seismic System (ANSS), which has earthquake early warning as one of its fundamental goals. Recent upgrades to the EarthScope network in Cascadia supported by NSF also provides infrastructure that can be used to develop an early warning system.

There is great potential benefit to society by extending and hardening our early warning capability. The technical challenges posed to geodesy are great, but already strides have been made in developing techniques to provide rapid geodetic products. Research also continues on seafloor geodesy and high-rate GNSS data streaming and rapid analysis. In addition, continued progress requires the advancement of hazards science (Figure 12), the exploitation and development of modern communication systems, and the establishment of a serious and sustainable collaboration between the science and emergency planning and response communities. Of these three, the third challenges us most to change the context, culture, and communication of geodesy research.

Figure 12

The true danger of a major tsunami may be underestimated using seismic data, due to the problem of magnitude saturation. Initial magnitude estimates from seismic data of the M_w 9.1 December 26, 2004 Sumatra earthquake were, for example, quite low (M_w 8.0–8.5). This event nevertheless generated a deadly tsunami. An earthquake's tsunamigenic potential, however, can be determined using regional GNSS observations. This figure shows time series of the east component of site displacements for a network of continuously operating GNSS sites, along with arrival times of the Sumatran tsunami. This research suggests that GNSS could become an effective component of regional and global tsunami warning systems.



Collateral benefits for science and society

Geodesy is closely related to the fields of surveying and navigation, and each field benefits from advances in either of the other two. The Global Positioning System was originally developed by the U.S. Department of Defense as a real-time positioning and navigation system. Systematic investments in both geodetic science and applications expanded its benefit to science and civic sectors. Such broad use attests to the power of this technology and seeds natural collaborations among disparate communities of users. Science applications were the early impetus for precision, accuracy, and geophysically meaningful global reference frames. Civil applications were the early drivers of requirements for low latency and high sampling rates. Commercial users in great numbers have made rapidly evolving capabilities affordable across the spectrum of users; further, science applications are sufficiently numerous to allow tailored instrument specifications to also become affordable.

Because of these synergies, GNSS user communities enjoy rapidly evolving, sophisticated, and affordable instrumentation. Public data sets are widely shared among users, and science applications have been a vigorous driver of improved technologies. Geodesists are well poised to influence monumentation standards and open data protocols as civic and commercial real-time GNSS networks proliferate around the world.

Geodesy also has a role to play in planning for human infrastructure and mitigating risks posed by the natural and political environment. While the understanding of sea level rise and coastal subsidence is a prime science focus of geodesy, the built environment is similarly characterized by the same and related geodetic data sets.

Society's ability to characterize the inventory of human infrastructure, its changes with time, exposure to inundation, high winds, seismic shaking, or other natural hazards, and responsive planning could be significantly strengthened by exploiting modern geodesy data sets and capabilities including GNSS, LiDAR, InSAR, and other techniques.

*"La chance ne sourit qu'aux esprits bien préparés."
In the fields of observation, chance favors only the mind that
is prepared.*

Louis Pasteur from a speech quoted by Renel Vallery-Rudant in *The Life of Pasteur* (1927)

SECTION

04

The Global View

A Foundation for Innovation: Grand Challenges in Geodesy

The challenge of sustainable development faced by humanity today can be addressed only if Earth observations can be organized and analyzed within a global framework, and the results shared with others in a timely, succinct, and useful manner. Geodesists are committed to this principle because modern geodesy itself is inherently a global science, and modern geodetic research focuses not only on analysis of geodetic data but on understanding and modeling of observed changes within the Earth system revealed by these observations.

The commitment to organizing, analyzing, and sharing observations from multiple global observing systems is manifest in many of the activities of the international geodesy community. This community has through great effort succeeded in acquiring, archiving, distributing, and analyzing geodetic observations according to self-promulgated standards that have enabled the achievement of tremendous accuracy. Realization of the International Terrestrial Reference Frame (ITRF), for example, requires that an enormous collection of global observing systems and data analyses work in concert according to these standards. These efforts have

led to the creation of the “global geodetic services,” including the IDS, IGS, ILRS, IVS, as well as the GGOS initiative and other international organizations such as the IERS. Geodesists from around the world participate together in these organizational endeavors, largely on a volunteer basis, securing support from organizations within their home countries. In addition, many research groups individually serve this overall effort by performing software development, data analysis, or other activities to the standards set by the global community.

These global organizational activities are beneficial on a number of levels. They are a crucial component of modern geodetic research because the organizations serve as a global forum for setting, promulgating, and advancing standards for the most technical aspects of geodetic observing system hardware, data reduction and system combination techniques, and the distribution of data, metadata, and data products. These organizations serve not only to coordinate activities in different regions across the globe, but to build global geodetic capacity as well, often through support of regional efforts. Indeed, local or regional capacity building

often benefits the global community. Significant examples include Africa (Africa Array), the Caribbean (COCONet), and Earth's polar regions (POLENET).

One of the most stunning transformations over the last few decades is the extent to which geodesy is radically altering the observational approaches within other fields of the Earth sciences. The tremendous impact of geodesy on other fields is made possible by the organization of geodetic activities under the global framework discussed above. One of the important goals of these activities is to streamline the global data analysis process and to provide data products that are well defined and straightforward to integrate into any type of data analysis. Thus, the greater scientific community benefits from a wide array of crucial geodetic data products, including precise GNSS ephemerides, Earth orientation parameters, and atmospheric and ionospheric information, all resulting from global analyses delivered in a timely manner in well-documented formats. For example, accurate analyses of regional geodetic networks, such as the Plate Boundary Observatory (PBO), depend on precise satellite ephemerides that are derived from analysis of a global network of GNSS receivers coordinated by the IGS. The reliance on global infrastructure and observations is practically transparent to the non-geodesist, and the geodetic community has worked tirelessly to make it so.

Indeed, geodesy underpins a wide range of Earth-observation systems; it is therefore an important component of the Global Earth Observation System of Systems (GEOSS) that is being built by the Group on Earth Observations (GEO), a voluntary partnership of governments (85 countries plus the E.U.) and international organizations.

The International Association of Geodesy (IAG) is a "Participating Organization" in GEO and is represented by GGOS. In fact, GGOS has a number of potential benefits for society in areas shared by those of GEOSS, including natural disaster mitigation, improved understanding of global climate, tracking and understanding mass motions of water over the surface of Earth, improved weather prediction, and more efficient and sustainable agriculture.

Geodetic scientists and agencies in the U.S. provide essential contributions to the international geodetic research programs and global observing systems, and play many leading roles. The U.S. is a significant contributor to the GGOS initiative and to the global geodetic services. In addition, the U.S. operates and maintains its share of the global geodetic infrastructure, what a recent NRC study has called "a shared national resource." The commitment by U.S. geodesists to international endeavors will increase the already broad range of scientific and societal benefits of geodesy.

"Freedom is the first-born daughter of science."

Thomas Jefferson, to Francois D'Ivernois (1795)

SECTION

05

Teaching Our Children

A Foundation for Innovation: Grand Challenges in Geodesy

Public education is the cornerstone of democracy, yet the erosion of education—specifically science education—is a matter of great national concern. While Thomas Jefferson spoke first and foremost to the need for an informed electorate, he recognized that education further developed the next generation of scientists and statesmen.

Both of these goals underlie a central challenge for Geodesy:

Nurture a deeper public understanding of geodesy and its benefits, and engage the children who will become the next generation of talent for advancing science and informing policy and planning.

Geodesists live in daily awareness that we inhabit a restless and dynamic planet. The movements of faults and volcanoes that we record reflect rafting of continents on ocean floor conveyor belts. When a geophysicist describes Yellowstone as a “living and breathing” caldera, his audience understands his statement as a metaphor for how underlying fluid and magma deform this small portion of an elastic, plastic and breakable Earth. The planet’s fluid envelope is in a state of flux, both on daily and decadal time scales; geodesy increasingly concerns itself with the loss of the fragile ice in Greenland, Antarctica, Alaska, and elsewhere; the signature of sea level change as nearby coastlines rebound or subside is familiar. Sea surface elevation rises from both added water and heated water, in turn reshaping both populated and isolated coastlines; landscapes are lost, peoples are displaced. Moisture plays a critical role in changes to the atmosphere in ways we don’t yet fully understand, but the increasing intensity of hurricanes in our lifetimes teases our curiosity.

Many changes that geodesists observe on the dynamic planet and in the relationships of the “solid” Earth to its enveloping oceans, ice caps, surface waters, and atmosphere, relate directly to events and processes with great societal impact. The public hears prompt and frequent reports of loss of life or infrastructure damage from large earthquakes or volcanic eruptions, but they often misunderstand the causes, predictability, and implications of those events. The role of geodetic technologies and measurements in observing ice sheet mass loss, sea level rise, land subsidence, or aquifer depletion is not widely known. By engaging directly in the teaching of our children—in public forums, by educating and empowering teachers, by providing easy access to real-world examples and fresh data, by helping to craft educational policies—science meets its urgent responsibility to create a science- and Earth-literate citizenry and government, and to attract and train the future scientific workforce.

Geodesy offers both the excitement of basic science discovery and great relevance to an increasingly global society and to the nation that supports our work. The questions embedded in these topics beg to be put before children.

Yet the parents among us note only antiquated threads of seismology and a dearth of current geodesy in the classroom and curriculum of our children. GNSS geodesy is among the finest and freshest examples of science discovery that is tightly coupled with the technological innovation of our age. The proliferation of applications to hazards and environmental sensing is astounding: earthquake cycle

deformation and forecasting, volcanoes in unrest, hurricane track prediction, ice mass loss and complex coastline rebound on global and local scales, soil moisture, snow loading, changing atmosphere, and the attendant role of the clouds in heat transfer in the atmosphere.

Neither these critical science questions nor the remarkable innovations available to address them have reached our children’s classrooms.

This is a fundamental challenge to geodesists: to bring the problems and innovations of our time into the classrooms, so that we can call the next generation to action, and to pursue science, policy, and civic duty. The science applications of geodesy must become part of the conventional wisdom. A major purpose of public education in a democratic society is to create an informed electorate; geodesy has great—but unrealized—potential to advance this goal.

Spotlight XXII

Geodesy and Earth Science Literacy

The Earth Systems Literacy Initiative (ESLI), a partnership between geoscientists and educators, has developed a set of “Big Ideas” and “Supporting Concepts” (BlaSC) of Earth Science that an educated citizenry should know. The “Big Ideas” (summarized in Table XXII.a) are put forward in the 2010 document Earth Science Literacy Principles. Geodesy could have an important role in bringing the Big Ideas to life for the public. One of the major themes is change: Earth and its systems change on long and short timescales; humans change Earth and are affected by rapid change of Earth; science and technology changes our understanding of Earth; changes in a complex system occur in surprising and complex ways; water and ice are especially powerful agents of change. It is not always easy to demonstrate that Earth is changing in the present day. Big changes (hazards such as earthquakes, hurricanes, etc.) are evident, but the controversy in the minds of the U.S. public

regarding global warming demonstrates that subtle impacts are more difficult to convey, yet subtle impacts are geodesy’s focal point. Global temperatures are changing by 1-2°C per century, and it is therefore difficult to ascribe any particular extreme weather event to this process. The present-day loss of mass in Greenland, on the other hand, is measurable by modern geodetic systems. Figure XXII.b shows the mass loss in two time periods. Even the change in location of that mass loss, (XXII.b.a) 2/2003–2/2007 and (XXII.b.b) 2/2003–2/2009, can be displayed in an easily understood manner. Other examples (some in this document) for which geodesy can be used to visualize change include slow interseismic tectonic deformation, time-variable displacements during earthquakes, sea level change, and the human impacts on Earth. The BlaSC can provide a focus for such efforts. Geodesists must work diligently to make their work, which is often highly technical, accessible to

educators and students, as well as to policy makers and the general public. Partnering with educators is an important component in the success of these goals. Figure XXII.c shows educators studying geodetic time series at the Geophysical Information for Teachers (GIFT) Workshop sponsored by the American Geophysical Union (AGU) and the National Earth Science Teachers Association, held at the 2010 Fall AGU Meeting.

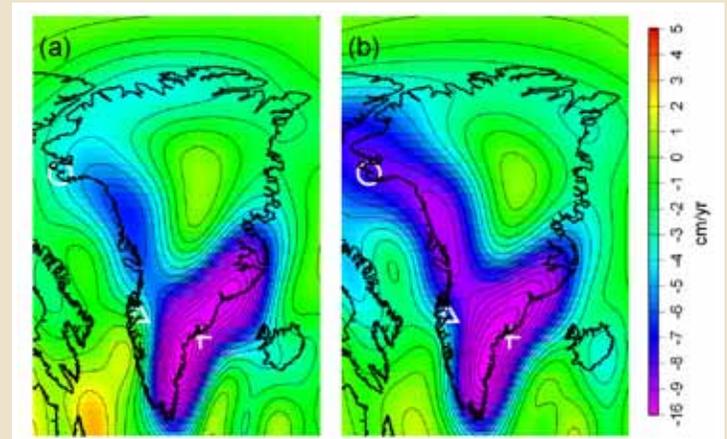
XXII.c



XXII.a

Table XXII.a. Big Ideas of the Earth Systems Literacy Initiative
1. Earth scientists use repeatable observations and testable ideas to understand and explain our planet.
2. Earth is 4.6 billion years old.
3. Earth is a complex system of interacting rock, water, air, and life.
4. Earth is continuously changing.
5. Earth is the water planet.
6. Life evolves on a dynamic Earth and continuously modifies Earth.
7. Humans depend on Earth for resources.
8. Natural hazards pose risks to humans.
9. Humans significantly alter the Earth.

XXII.b



"...the scientific and technological building blocks critical to our economic leadership are eroding at a time when many other nations are gathering strength."

From *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, National Research Council (2007)

SECTION

06

The Next Generation: Geodesy Workforce

A Foundation for Innovation: Grand Challenges in Geodesy

"We live in a society exquisitely dependent on science and technology, in which hardly anyone knows anything about science and technology..."

Attributed to Carl Sagan (1934-1996)

The national interest commands a forward looking and sophisticated professional workforce that can use the tools of geodesy to address a spectrum of hazards, planning, and science applications. Geoscientists pursue careers that range from engineering to academia, from urban planning to the military to resource recovery, from hazards characterization to modeling economic markets. The grand challenges posed in this document, and their role in supporting the national interest in global competitiveness, require that we attract and prepare the next generation of investigators. While the current erosion of national scientific and technical prowess occurs throughout geophysics and other highly evolved technical fields, the field of geodesy, with its interdependent mix of geodetic science and applications, faces particular vulnerabilities.

As geodetic applications have flourished over the past decade, fundamental education and research in geodetic science and infrastructure has experienced an acute decline and the challenge of deep integration of geodesy into geophysics curricula remains unmet. The absence of a next

generation of geodesists in training puts our extraordinary science and its broad applications at risk.

Aspiring geodesists confront the fundamentals of positional geodesy, including geodetic astronomy, relative positioning, and point positioning. Positioning will necessarily include the theory and methods for defining reference frames and reference systems. Students of geodesy also explore geophysical geodesy, orbit determination, the modes of crustal deformation on a range of timescales, inversion theory and error analysis, and electromagnetic wave propagation and signal detection. Assembled from a variety of academic disciplines, this broad combination of topics constitutes the unique and challenging geodesy curriculum.

Unlike in Europe and Asia, very few students in the U.S. receive a Ph.D. in geodesy. No geodesy programs for undergraduates exist at U.S. universities and integration of geodesy into the national curriculum has lagged. The NASA Crustal Dynamics Project (1979–1991) was notable for its support for education in fundamental geodesy, but NASA funding in that area is much smaller today, and no other agency currently systematically sustains support for fundamental geodesy.⁷ Nearly all domestic geodesy-related funding today is for applications of geodesy, potentially creating a danger that the U.S. will lose its leadership position in this field that plays a crucial role in scientific, national security, and commercial spheres.

A recent NRC report⁸ guides us to “sustain and strengthen the nation’s traditional commitment to long-term basic research that has the potential to be transformational to maintain the flow of new ideas that fuel the economy, provide security, and enhance the quality of life.” We recommend, however, a more vigorous and more focused effort on geodetic science and education as an urgent and transformational priority. The geodetic community must work with government funding agencies to sustain the science of geodesy as a critical element of undergraduate and graduate geosciences curricula, in order to support its rapidly evolving applications. A creative and widespread effort to increase awareness of, experience with, and interest in geodetic science among undergraduates must lie at the heart of this collective undertaking. With its broad and often practical applicability, real-time data access, and attractive, challenging field settings, geodesy is well poised to lead a revitalization of the geophysics workforce.

⁷ Space Geodesy is a thematic area within NASA’s Earth Surface and Interior program, but this program is not competed every year.

⁸ NRC (2010), *Precise Geodetic Infrastructure: National Requirements for a Shared Resource*, National Academies Press, 157 pp.

"This recent period provides many examples to illustrate the truth that technological advances rather than revolutions in thinking have often been the spurs of progress in our discipline."

From W. S. B. Paterson, *Physics of Glaciers*

SECTION

07

Summary and
Recommendations

A Foundation for Innovation: Grand Challenges in Geodesy

The achievements of modern geodesy in the wide array of scientific and societal applications reviewed in this document have benefitted from a long-term, concerted, and sustained investment in infrastructure and intellectual resources, by federal agencies, universities and other research organizations, and industry. Historical observations and their preservation have great value in geodesy, a science that relies on long-term observation from previous decades and even centuries to reference changes in the dynamic Earth, ice, and atmosphere. Significant progress within the field of geodesy, and the furthering of techniques, observations, and infrastructure that revolutionize many fields of science now depend on a critical assessment of geodesy's strengths, needs, and directions.

As documented in this report, geodesy is steadily advancing, providing increasingly accurate information more rapidly and with greater resolution and coverage. In terms of positioning precision, the improvement has approximated one order of magnitude per decade since the mid-1970s. It is difficult

to imagine another three orders of magnitude in the next three decades, so the focus has begun to shift to improvements in temporal resolution, spatial resolution, geographic coverage, data latency, speed of data analysis, and distribution of data products. Because of this shift in emphasis, Precise Geodetic Infrastructure: National Requirements for a Shared Resource [NRC, 2010] noted:

The current trend is toward what might be called "geodetic imaging," a description of the Earth's continuous deformation at a high temporal and spatial resolution in near real time...

Thus, we should boldly set the central long-term goal for geodesy:

Accurately image Earth's solid surface and glaciers in three dimensions, the height of the sea surface, and the gravity field, on a continuous temporal basis, with high spatial resolution, in near-real time.

In the shorter term (during the next decade), it is reasonable to adopt the goals for accuracy for a wide range of scientific and societal applications established by GGOS, detailed nicely in Chapter 7 of *Global Geodetic Observing System*⁹ and not reprinted here.

Recommendations are presented in Chapter 11 of the GGOS publication; the GGOS recommendations are stated in a way that is appropriately more specific to GGOS and the international geodetic community. Nonetheless, they resonate strongly with the following recommendations.

The recommendations that follow are intended to set realistic goals for geodesy for the next decade. Whereas several recommendations build on themes developed in other studies, they all derive from the challenges posed here. These recommendations are intended to position geodesy to continue the spectacular innovation that has become its hallmark.

⁹ H.-P. Plag and M. Pearlman eds. (2009), *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020*, Springer, 332 pp.

RECOMMENDATION

1

Undertake geodetic missions recommended by the Decadal Survey.

*The NRC Decadal Survey*¹⁰ recommended three geodetic missions among the 17 missions that “[contribute] to the most important scientific questions facing Earth sciences today.” Among other criteria for these recommended missions are relevance to policy making, contribution to the long-term observational record of Earth, and affordability. Of the 17 recommended missions, three resonate strongly with the Geodesy Grand Challenges posed in this document. Given their scientific value they should receive high funding priority among planned missions. In particular:

- a. DESDynI will provide accurate measurements of deformation of land and ice at high spatial and temporal resolution. These mission goals directly support the “Long Term Goals for Addressing Key Questions” listed after each Grand Challenge. This mission will provide the U.S. with its first dedicated InSAR satellite for addressing goals of national interest (such as mitigation of natural hazards), and is all the more crucial in view of the failure of ALOS-PALSAR, the decommissioning of ERS-2, and lack of precise orbit control for ENVISAT. The planned DESDynI mission will provide L-band SAR data with unprecedented temporal coverage, in accordance with NASA’s open data access policy. [Sections 01, 02, 04]¹¹
- b. GRACE-II will provide time-dependent determinations of the global gravity field for climate and geodynamics. This mission will follow the highly successful GRACE mission that is still in operation. The GRACE mission has been the source for a number of important discoveries, including the loss of ice mass from Greenland, Antarctica, and Alaska. GRACE data have been used to investigate the depletion of groundwater in the U.S. and other areas, and to investigate the impact of monsoons and floods. [Sections 01, 02]
- c. ICESat-II will provide time-dependent determinations of ice-sheet thickness, a crucial component of characterizing the impact on the ice sheets of global climate change. The ICESat-II mission will be a laser altimeter and will obtain repeat observations to separate the seasonal and longer-term variability. Combining the altimetry measurements with gravity measurements from GRACE-II would enhance our understanding of the behavior of ice sheets significantly. [Section 01]

Several other recommended *Decadal Survey* missions, notably LIST (land surface topography), SWOT (ocean, lake, and river water levels), and GPSRO (radio occultation with GPS) might be described as fundamentally geodetic in nature, but would engage the geodetic community less generally. In the period preceding the mission implementation, funding agencies need to ensure that the U.S. research community has access to relevant data collected by international space agencies.

¹⁰ NRC (2007), *Earth Science and Applications from Space*, National Academies Press, Washington, D.C., 428 pp.

¹¹ Following each recommendation, the list of sections relevant to the recommendation is cited in brackets.

RECOMMENDATION

2

Obtain continuous observations of the dynamic Earth and its environment.

Satellite missions have finite duration, but temporal continuity in records of sea level, gravity, ice, and surface deformation is crucial both for scientific and societal applications. Rapid changes occur to Earth, having potentially devastating consequences, and acquiring continuous observation of these changes is equivalent to monitoring weather for forecasting purposes. The geodetic community should work with policy makers to establish a combined ground- and satellite-based continuous Earth observing system, augmented by focused airborne observations. [Sections 01, 02, 03, 04, 05]

RECOMMENDATION

3

Advance open real-time access to data and data products.

The vitality and success of geodesy has critically depended on open data protocols coupled with decreasing delay in data distribution as telecommunications improve and associated costs decrease. While policies vary with geodetic technique and across national boundaries, within the U.S. the trend towards immediate, open and free data access has clearly fueled science innovation across a spectrum of geodesy and its applications. The need for real-time access to data sets and data products is also expected to continue its rapid growth. Early warning applications depend on access to real-time data, and real-time data and analysis have the potential to be great driving forces for innovation over the next decade. Therefore, we make the following recommendations:

- a. Deployment of new observing systems, whether satellites or ground networks, should be designed *ab initio* to deliver data and products in as near to real time as feasible. [Sections 01, 02, 04, 05]
- b. The science community should promote free and open data protocols across geodetic techniques and international boundaries. [Sections 01, 02, 04, 05]
- c. The U.S. geodetic community should continue to advance open data sharing through leadership, and should work with national and international professional communities and societies to develop policies regarding scientific precedence in an open data era that apply accepted professional ethics. [Sections 01, 02, 03, 05]
- d. The scientific community should invest in infrastructure, including cyberinfrastructure, for dissemination of low-latency data and data products to stimulate the broadest possible spectrum of innovative science applications for both satellite and ground-based observations. [Sections 01, 02, 04, 05]

RECOMMENDATION

4

Improve the robustness of the global geodetic reference frame.

The geodetic reference frame is fundamental for all positioning applications, including precise orbit determination for a wide range of satellite missions. As reviewed in the Appendix, the recent NRC report *Precise Geodetic Infrastructure*¹² found a core national geodetic infrastructure that is in decline and is “far below its optimal state, both in terms of number of sites and in modernization of instrumentation.” This crucial infrastructure serves not only to determine the terrestrial and celestial reference frames, but is a fundamental element in providing access to the highest achievable accuracy for virtually all the applications reviewed in this document. In support of these goals, we make the following recommendations to maintain positioning accuracy in the horizontal component (≤ 1 mm/yr), to achieve sub-mm/yr positioning capability in the vertical component, to improve the capability for high-rate positioning, and to support a variety of geodetic and non-geodetic space-based missions. :

- a. The recommendations of the NRC report *Precise Geodetic Infrastructure* in regard to maintenance and enhancement of a robust reference frame should be implemented with high priority. [Sections 01, 02, 03, 04]
- b. The U.S. should collaborate with international partners to establish a solid international agreement for the upgrade and continuous long-term operation of the precise global geodetic infrastructure. GEOSS and GGOS provide international frameworks to build on; given the current deteriorating state of the global infrastructure, it is important to make this goal a high national priority, as described in *Precise Geodetic Infrastructure*. [Sections 01, 02, 03, 04]
- c. The U.S. should improve coordination and long-term operation of the national geodetic infrastructure to ensure convenient, rapid, and reliable access to consistent and accurate geodetic data and products by government, academic, commercial, and public users. The difficulty of interagency coordination was the focus of a recent NRC report¹³, which found “...development and implementation of [multiagency] Earth-observing or space science missions are often intrinsically complex...” and recommended “...specific incentives and support for the interagency project should be provided.” The findings and recommendations of *Precise Geodetic Infrastructure* are consistent with the more recent report; some of the “incentives” would come from a coordinating body that would have authority to impose standards, set priorities, develop budgets, etc. [Sections 01, 02, 03, 04]

¹² NRC (2010), *Precise Geodetic Infrastructure: National Requirements for a Shared Resource*, National Academies Press, 157 pp.

¹³ NRC (2011), *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*, National Academies Press, 70 pp.

- d. Participation in the international services and contributions to the ITRF, all of which are crucial to Earth science applications of geodesy, is done on a voluntary basis. To ensure the accuracy and stability of the reference frame on which so many scientific studies rely, the U.S. should make a long-term commitment to maintain the ITRF and to participate in GGOS. [Sections 01, 02, 03, 04]
- e. There is a great deal for us to learn about combining geodetic techniques to realize accurate reference frames. Each technique has different observables, analysis approaches, and error sources. Achieving sub-mm/yr vertical positioning is a particularly difficult problem, but is crucial, especially to sea level studies. Research focused on improvement of the reference frame needs to be undertaken. [Sections 01, 02, 04]
- f. The importance of a stable and accurate reference frame is difficult to communicate. The reference frame supports all geodetic applications, and users might simply assume its existence. The community should communicate with funding agencies regarding the fundamental importance of the reference frame to all sponsors so that research and other activities that sustain and improve the reference frame, such as participation in the international services and GGOS, can obtain financial support. [Sections 01, 02, 04]

RECOMMENDATION

5

Enable seafloor geodesy.

Seafloor geodesy is a critical technology that holds the potential to enable discoveries on geodetically unexplored parts of Earth, and promises new advances in our understanding of plate boundary zone kinematics and dynamics. It is an especially useful tool for exploring strain phenomena along the entire locked subduction interface of subduction zones. Seafloor geodesy is currently expensive, and only a few investigators focus on this technique. Although seafloor geodesy continues to pose significant challenges, it promises transformative science and should be actively pursued, with near-term goals of improving accuracy and reducing costs.

Emphasize system integration and interdisciplinary cooperation.

Increasingly, new discoveries arise when observations from two or more fields are combined. However, data “combination” presents difficulties. Different observational systems have different sensitivities and error sources, and different spatial and temporal resolution. Nevertheless, the potential for future innovation depends on this capability. The integration of systems from different fields of study is achieved in part by making the data, data products, and analysis tools accessible to one another. Specifically, steps that can be taken over the next decade include:

- a. Integration of geodetic data types will lead to discoveries in a wide range of areas, including glaciology, volcanology, tectonics, and earthquake physics. Research leading to methods for integration of geodetic observations having different sensitivities and resolution should have high priority, including: GNSS; ground-based absolute gravity; in situ strain; airborne gravity, radar, and LiDAR; and space-based observations. In addition, research leading to integration of GNSS and seismic networks should be undertaken, to benefit both scientific studies and the development of early warning systems. Particular attention should be paid to error analysis and understanding of temporal and spatial resolution. [Sections 01, 02, 03, 04]
- b. New software tools for data analysis, visualization, and error analysis should be developed. Particular need for visualization exists for those techniques with very high spatial resolution, such as LiDAR and TLS. Development of common data and data product formats is a high priority. [Sections 01, 02, 04, 05]
- c. The detailed understanding of the impact of water on geodetic measurements is still at its early stages, and has proven to be an engine of innovation. Further study along the lines of data integration could improve geodetic accuracy while simultaneously providing new observations to fields that study water in its various forms. In particular, the fields of hydrology, glaciology, atmospheric science, and oceanography have a great deal to benefit from the exchange of ideas with geodesy, and geodesy would likewise benefit greatly. Collaboration between hydrology and geodesy seems particularly likely to yield significant reward because the signals of one discipline are so intertwined with the noise of the other. Avenues for joint exploration that will benefit multiple fields must be developed and expanded. [Sections 01, 02]

RECOMMENDATION

7

Use geodesy for Earth Science education and public outreach.

Continued innovation in geodesy requires a workforce trained in geodetic theory and observation. The NRC report *Precise Geodetic Infrastructure* found that a lack of such a workforce was a potential “weak link.” The foundations for a geodetic workforce, however, are a student population with high mathematics, physics, and Earth science literacy and a public that understands the importance of Earth science and is willing to support its endeavors.

- a. The potential for geodesy to contribute to literacy in the Earth sciences needs to be developed. Research should be undertaken to determine the best ways that geodesy can be used to increase Earth Science literacy. In particular, how can geodesy’s capability for documenting and visualizing change on our planet be used to address the Big Ideas. [Section 05]
- b. Geodesists need to partner with educators to help shape K–12 science curricula to include interesting, exciting, accurate, and relevant geodetic results. [Section 05]
- c. We must systematically explore ways that geodesy can be used to foster interest for Earth Science within the general public. Which geodetic results capture the imagination of the public? In what formats and context do geodetic results reach the public? What misconceptions exist that obstruct our ability to communicate the results of geodesy? [Sections 04, 05, 06]
- d. Currently, due to the structure of the funding agencies, there is no sustained, systematic support for fundamental geodetic research that in turn allows and supports Ph.D.-level education of geodesists. The community must work with the funding agencies to communicate this problem and to seek a solution. [Section 06]
- e. The geodetic community must communicate the broader impact to the entire Earth science community of fundamental geodetic research and scientific activities associated with, for example, the international services.
- f. Partnerships must be forged between the geodetic community and undergraduate programs in math, physics, and the Earth sciences. Opportunities in geodesy must be communicated to students early in their undergraduate education to foster interest in the field. The geodetic community must develop innovative and attractive programs to recruit and retain a broad and diverse population of students. [Sections 05, 06]

Appendix: State of the Global Geodetic Infrastructure

A report by the NRC from 2010 on the nation's precise geodetic infrastructure¹⁴ identified it as a “shared national resource” due to the wide range of societal benefits and scientific research it supports. According to this NRC report,

Geodetic observing systems provide a significant benefit to society in a wide array of military, [scientific] research, civil, and commercial areas, including sea level change monitoring, autonomous navigation, tighter low flying routes for strategic aircraft, precision agriculture, civil surveying, earthquake monitoring, forest structural mapping and biomass estimation, and improved floodplain mapping...The strength of this infrastructure lies in its longevity, continuity, stability, robustness, accuracy, speed of accessibility, and capability for supporting innovation through the development of new observing systems that exploit the accuracy of the infrastructure.

This report describes core geodetic infrastructure in decline and states that it is “far below its optimal state, both in terms of number of sites and in modernization of instrumentation.” This finding was consistent with the findings of the Decadal Survey, an earlier NRC report¹⁵ on the application of satellite missions to the Earth sciences:

The geodetic infrastructure needed to enhance or even to maintain the terrestrial reference frame is in danger of collapse.... Improvements in both accuracy and economic efficiency are needed. Investing resources to assure the improvement and the continued operation of this geodetic infrastructure is a requirement of virtually all the [satellite] missions of every Panel in this study.

One measure of the state of the infrastructure is the number of locations having multiple observing techniques that are used to determine the reference frame, a crucial feature for establishment of a stable terrestrial reference frame. In fact, this number is very small. Only two sites have all four collocated geodetic techniques contributing to the ITRF.

One reason identified by *Precise Geodetic Infrastructure* for the critical state of the geodetic infrastructure is that there is no formal governance structure or lead agency explicitly responsible for this infrastructure. Thus, it is often difficult to obtain funding for geodetic infrastructure,¹⁶ even though it is critical to scientific research and other activities.

¹⁴ NRC (2010), *Precise Geodetic Infrastructure: National Requirements for a Shared Resource*, National Academies Press, 157 pp

¹⁵ NRC (2007), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, National Academies Press, 428 pp.

¹⁶ The term “infrastructure” has a variety of meanings depending on context. In the context of this document, infrastructure refers to observing systems and activities for which the main purpose is to make other observing systems more accurate.

The geodesy community is committed to improving the geodetic infrastructure, to making it accessible to a wide range of scientific applications, and to continue increasing the range of benefits that the geodetic infrastructure offers, including:

- Accurate position estimates can be made with regional or smaller networks, using precise GNSS orbital products
- Capability for real-time deformation measurements, using predicted and observed ultra-rapid GNSS orbital products
- Determination of regional water vapor and ionosphere thickness (space weather) supported by precise GNSS orbits
- Common, stable terrestrial reference frames for changes in site position over long time scales and for studying global deformations
- Precise orbit determination in support of satellite missions and requiring accurate positioning, including COSMIC, InSAR, DESDynI (or similar mission), and ICESat
- Accurate location of aircraft-borne instrumentation
- Precise spacecraft navigation

This commitment requires international efforts to strengthen the infrastructure such as GGOS, IERS, and the International Services. These efforts result in high quality global geodetic data sets that are then analyzed to provide data products in simple-to-use formats that are then used throughout the Earth sciences. Through these and other commitments of time, energy, and intellect, the geodetic community is dedicated to continuing the exciting innovation throughout the Earth sciences that geodesy has stimulated over the last several decades.

Acronyms and Abbreviations

AGU	American Geophysical Union	IDS	International DORIS Service
ALOS	Advanced Land Observing Satellite (Japan)	IERS	International Earth Rotation Service
ALSM	Airborne Laser Swath Mapping	IGS	International GNSS Service
ANSS	Advanced National Seismic System	ILRS	International Laser Ranging Service
BlaSC	Big Ideas and Supporting Concepts	IPCC	Intergovernmental Panel on Climate Change
COCONet	Continuously Operating Caribbean GPS Observational Network, funded by NSF	IVS	International VLBI Service
CONUS	Conterminous United States	InSAR	Interferometric Synthetic Aperture Radar
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate: Joint Taiwan/U.S. mission.	ITRF	International Terrestrial Reference Frame
DESDynI	Deformation, Ecosystem Structure and Dynamics of Ice satellite mission (NASA)	LiDAR	Light Detection and Ranging
DoD	U.S. Department of Defense	LOS	Line of sight, between an observing system and its target
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite (ESA)	MSL	Mean sea level
ERS	European Remote Sensing Satellite (ESA)	NASA	National Aeronautics and Space Administration
ESA	European Space Agency	NCALM	National Center for Airborne Laser Mapping
ESLI	Earth Science Literacy Initiative	NESTA	National Earth Science Teachers Association
ETS	Eposodic Tremor and Slip	NOAA	National Oceanic and Atmospheric Administration
EUREF	IAG subcommision for European reference frame	NRC	National Research Council of the National Academies
GEO	Group on Earth Observations (intergovernmental)	NSF	National Science Foundation
GEOSS	Global Earth Observing System of Systems	PBO	EarthScope Plate Boundary Observatory, funded by NSF
GGOS	Global Geodetic Observing System	RSL	Relative sea level
GIA	Glacial Istostatic Adjustment	SAR	Synthetic Aperture Radar
GNSS	Global Navigational Satellite System	SLR	Satellite Laser Ranging
GPS	Global Positioning System (DoD)	SWE	Snow/water equivalent
GPS-A	Combined GPS (GNSS) and acoustical measurements for seafloor geodesy	T-LiDAR	Terrestrial LiDAR
GRACE	Gravity Recovery and Climate Experiment (NASA)	TOPEX	Topography Experiment Satellite (NASA)
IAG	International Association of Geodesy	TRS	Terrestrial Reference System
ICESat	Ice, Cloud, and land Elevation Satellite (NASA)	UHR	Ultra-High Resolution
		USGS	U.S. Geological Survey
		VLBI	Very Long Baseline Interferometry
		WAIS	West Antarctic Ice Sheet

Credits

Figure 01: Adapted from S. Wdowinski and S. Eriksson (2009), Geodesy in the 21st century, *EOS Trans. AGU*, 90, 153–155. (a) Z. Altamimi et al. (2011), ITRF2008: an improved solution of the international terrestrial reference frame, *J. Geodesy* (online), doi:10.1007/s00190-011-0444-4; (b) B. Tapley et al. (2005), GGM02—An improved Earth gravity field model from GRACE, *J. Geodesy*, 79, 467–478; (c) <http://iono.jpl.nasa.gov>; (d) C. Amante and B. W. Eakins (2009), ETOPO1 1 arc-minute global relief model: Procedures, data sources and analysis, *NOAA Tech. Mem. NESDIS NGDC-24*, 19 pp; (e) M. Lidberg et al. (2007), An improved and extended GPS-derived 3D velocity field of the glacial isostatic adjustment (GIA) in Fennoscandia, *J. Geodesy*, 81, 213–230, doi:10.1007/s00190-006-0102-4; (f) S. C. Swenson and P. C. D. Milly (2006), Climate model biases in seasonality of continental water storage revealed by satellite gravimetry, *Water Resour. Res.*, 42, W03201, doi:10.1029/2005WR 004628; (g) <http://www.cosmic.ucar.edu>; (h) D. J. Geist et al. (2008), The 2005 eruption of Sierra Negra volcano, Galápagos, Ecuador, *Bull. Volcanol.*, 70, 655–673, doi:10.1007/s00445-007-0160-3; (i) <http://rse.anu.edu.au>; (j) R. R. Muskett et al. (2008), Acceleration of Surface Lowering on the Tidewater Glaciers of Icy Bay, Alaska, USA from InSAR DEMs and ICESat Altimetry, *Earth Planet. Sci. Lett.*, 265, 345–359; (k) <http://topex-www.jpl.nasa.gov/>; (l) M. Rodell et al. (2007), Estimating ground water storage changes in the Mississippi River basin (USA) using GRACE, *Hydrogeol. J.*, 15, 159–166, doi:10.1007/s10040-006-0103-7.

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Figure 03: Courtesy of J. Davis; data from <http://podaac.jpl.nasa.gov/grace/>.

Figure 04: From W. E. Carter et al. (2007), Geodetic laser scanning, *Phys. Today*, 60, 41–47, doi: 10.1063/1.2825070.

Figure 05: PBO velocity field estimates from <http://www.unavco.org>.

Figure 06: Courtesy of Y. Bock after data and analysis in Y. Bock et al. (2011), Real-time strong-motion broadband displacements from collocated GPS and accelerometers, *Bull. Seismol. Soc. Am.*, 101, 2904–2925, doi:10.1785/0120110007.

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Figure 08: GPS satellite illustration courtesy of Boeing. Earth image courtesy of SeaWiFS Project (<http://oceancolor.gsfc.nasa.gov/SeaWiFS/ORBIMAGE>); combined illustration courtesy of S. Guthman.

Figure 09: Photo from <http://www.unavco.org/>.

Figure 10: From P. Banerjee et al. (2008), Intraplate deformation of the Indian subcontinent, *Geophys. Res. Lett.*, 35, L18301, doi:10.1029/2008GL035468.

Figure 11: Photo from the Christian Science Monitor <http://www.csmonitor.com/>, credited to Arni Saeberg/Morgunbaldid/AFP/Newscom.

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- Spotlight XVIII: Figure XVIII.a courtesy of G. Bawden and S. Bond; Figure XVIII.b courtesy of G. Bawden, K. Schmidt, and J. Howle; Figure XVIII.c courtesy of G. Bawden and A. Berry.
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Panorama: A PLUTONS project collaborator visits a cGPS station to collect recently logged data. The station is one of three permanent GPS sites, installed by UNAVCO, on and around Uturuncu volcano in Bolivia's high desert. PLUTONS is a multinational research project dedicated to monitoring crustal intrusion and formation at volcanic areas in Bolivia as well as Chile.

Background: This cGPS system, near Mt. Howe in Antarctica, is a part of the POLENET network and is set on the southernmost chunk of exposed bedrock in the world (everything south is ice all the way to the south pole). A rough wind caused a biting spindrift of snow.

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