Measuring the Restless Earth

Grand Challenges in Geodesy


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Executive Summary

Geodesy is the measurement of variations in Earth's shape, gravity field, and rotation to study dynamic processes in the realms of geophysics, hydrology, cryosphere, atmospheric science, oceanography, and climate change. Geodetic observations from both ground and space reveal an Earth that is continually deforming due to active processes both internal and external to the solid earth and its fluid layers. Measured changes span timescales from seconds to decades, and some of the underlying processes continue over timescales of thousands (such as glacial isostatic adjustment, or GIA) or millions (such as tectonics) of years. From simultaneous monitoring of sea level change and coastal land motion to tracking the distribution of surface and ground water to capturing the unique signatures of surface evolution and seismic processes, geodesy provides a foundation for understanding causality in the Earth system and for developing strategies to sustainably adapt human behavior to a changing planet.

Geodesy has evolved rapidly over the last few decades. Improvements in the accuracy and availability of geodetic observations has led to an explosion in the range of Earth science disciplines that benefit from information coming from geodesy. Two trends in the evolution of geodesy and its contributions to Earth sciences are particularly notable. First, scientific focus has moved away from steady-state processes to time-varying and transient processes. Second, formerly distinct sub-fields within geodesy are converging, such as in the use of combined deformation measurements from Global Navigation Satellite System (GNSS), Interferometric Synthetic Aperture Radar (InSAR), and gravity changes to study mass transport. Both of these trends result from improvements in measurement precision and accuracy, and from improved knowledge and models gained from previous generations of studies.

The Grand Challenges in Geodesy were considered in 2009 by a group of domain experts, who produced a remarkably forward-looking document that is now a decade old (Davis et al., 2010). This new Grand Challenges document reflects the rapid changes of the last ten years due to technological advances, increased access to data and to computational resources, and new demands for and on scientific knowledge. This document reflects the perspective of 50 experts who attended a 2-day workshop at Michigan State University in November 2018 to discuss the current state of the original Grand Challenges, and to identify promising future directions in geodesy. This document echoes the themes of the first, but reflects the changes which have taken place in geodesy and major discoveries over the last decade.

The Introduction of this new report highlights the evolving nature of geodesy, and addresses how geodesy serves humankind by providing services and products with broad utility across science and society. The remainder of the document is organized in eight chapters, each of which highlights a single theme, the key questions it encompasses, and relevant high-priority scientific, technological, and community-building targets for future investment. Illustrative examples are woven in to each of the chapters.

Eight thematic Grand Challenges are discussed:

1. How are Ice, Oceans, and the Solid Earth Coupled in Space and Time?
2. What Does Geodesy Reveal About the Terrestrial Water Cycle?
3. How Do Fault Mechanics Influence Earthquakes and the Earthquake Cycle?
4. How Do Solid Earth's Material Properties Vary with Location and Over Time?
5. What Can Observations of Surface Deformation Reveal About Magmatic Processes and Volcanic Hazard?
6. What is the Connection Between Solid Earth Processes and Surface and Landscape Evolution?
7. What Do New Approaches Promise for Hazard Forecasting, Warning, and Rapid Response?
8. How Can Geodesy Meet the Challenge of Big Data?

These chapters are followed by a Summary and Recommendations.

Introduction

Humanity faces existential challenges from a rapidly growing global population and mounting human pressure on Earth's life-support system. Coping with this global challenge requires scientific knowledge integrated across a wide range of disciplines to support evidence-based decision and policy making. From sea level trends and the distribution of terrestrial water to patterns of surficial and seismic processes, the mapping and modelling of complex Earth systems provides a foundation for understanding causality and for developing strategies to sustainably adapt human behavior.

Many of the advances in Earth observations and data analysis for observing planetary-scale processes and extracting timely scientific knowledge are rooted in or enabled by geodesy. Modern geodesy, which is the study of the changing shape of our planet over time, focuses on observing temporal variations in geometry, gravity, and rotation (the "three pillars" of geodesy) to study dynamic geophysical, hydrological, glaciological, atmospheric, climatic, and other processes within the Earth system. Geodesy also provides terrestrial reference frames for use by all other Earth observations.

Ground-based space-geodetic techniques (GNSS, VLBI, SLR, DORIS) and dedicated satellite missions are both used in the measurement and monitoring of the motion and deformation of the Earth's surface. They reveal an Earth that is in constant change, whose shape and internal mass distribution vary continually at timescales ranging from seconds to decades. These changes are driven by a variety of active processes, both internal and external to the solid Earth. For example, the movement of mass within the Earth in the form of mantle flow, results in internal stresses and deformation that are linked to changes in the gravity field and which create topography at Earth's surface. At the same time, changes in mass on Earth's surface, primarily in the form of water and long-term sediment transport from erosion, can impose stresses that subtly modify internal processes such as those that generate earthquakes. Geodetic measurements show these deformations and gravity changes on a wide range of timescales, some of which are not yet well-described by theory or models.

A representative group of experts examined the Grand Challenges in Geodesy in 2009 and produced a remarkably forward-looking document that is now a decade old (Davis et al., 2010). Rapid societal, technological, and environmental change in the ensuing decade demands that we revisit these grand challenges in the context of new technologies, scientific opportunities, and demands for knowledge. About 50 participants attended a two-day workshop in East Lansing, Michigan, in November 2018 to discuss the current state of the Grand Challenges identified in the previous document, and to highlight promising future opportunities. This document echoes the themes of the previous one, but it reflects the current state of the field and the discoveries of the last decade.

The areas of Earth Science impacted by geodesy are more diverse than a decade ago, as increasing observational resolution and accuracy enable new scientific discovery. Additionally, the key topics identified in this document are linked to each other and to other scientific endeavors, often in multiple ways (for example, as described in the white paper, Modeling Earthquake Source Processes). We believe that identifying and investigating these interconnections will be the main focus of geodesy over the next decade. We describe several cross-cutting themes in the remainder of this Introduction, then use the following chapters to address Grand Challenges specific to different fields of geodesy.

The Evolving Nature of Geodesy

As geodetic instruments and networks have proliferated, techniques have been developed to use geodetic instruments as environmental sensors, thus evolving the definition of geodesy itself. Initially GPS/GNSS, DORIS, and InSAR were primarily used to measure deformations of the solid Earth, but increasingly these tools are used for atmospheric, climatic, and environmental sensing and other forms of Earth observation.

Much of this change has been organic, reflecting technique and modeling advances that went hand-in-hand with improved observational networks, precision, and accuracy. In some cases, environmental signals were the limiting error sources in traditional positioning applications of geodesy. For example, early VLBI developers required better models for refractive delays in the atmosphere. Later these modeling improvements were applied on a broad scale in large GPS/GNSS networks to measure variations in precipitable water vapor within the troposphere. GNSS water vapor measurements have the benefit of much higher temporal resolution than traditional twice daily radiosondes and are currently used in operational weather prediction. As another example, GPS/GNSS can sense the effect of water loads in various forms. Seasonal snow, surface water, and soil moisture loading depresses the crust, producing deformation that can be analyzed to infer water storage variations. Deformation due to aquifer pumping also produces localized subsidence that is readily observed, especially by InSAR. A better understanding of how hydrology impacts crust deformation is also leading to more accurate tectonic analyses.

Another geodetic error source now being used for environmental sensing is related to signal reflections or multipath. Essentially, a GPS/GNSS site is a bi-static radar, measuring surface changes below the receiving antenna. These reflections provide in situ measurements of soil moisture, snow depth/snow water equivalent, and vegetation water content. For sites close to the ocean, lakes, and rivers, GPS/GNSS reflections can measure changes in water or sea levels. In space, GNSS-R forward scattering technique from Low Earth Orbiters (LEOs) can measure non-directional wind speed, classification of land cover including water/flood extents, soil moisture, and potentially lake, river, and sea level. Additionally, GNSS occultation technique from LEOs enables profiles of atmosphere pressure, temperature, and water vapor within the troposphere to be observed with the distinct advantage of fine vertical resolutions.

The evolution of the field is reflected in the evolution of documents such as this report. In the 1980s and 1990s, measuring the kinematics of plate motions and plate boundary deformation was the primary focus of much of our community. In this report, that area of research is now part of two chapters that focus on dynamic processes or mechanical properties (Chapter 3, How Do Fault Mechanics Influence Earthquakes and the Earthquake Cycle?; Chapter 4, How Do Solid Earth's Material Properties Vary with Location and Over Time?). As a field, we are moving from kinematic to dynamic descriptions, which requires the measurement and modeling of time-variable phenomena. There is much more time variation in Earth deformation than was suspected a few decades ago!

As geodesists focus more closely on time-dependent phenomena, we are also moving to problems that require higher-rate, lower-latency observations. A natural outgrowth of this shift is the increasing focus on hazard mitigation (Chapter 7, What Do New Approaches Promise for Hazard Forecasting, Warning, and Rapid Response?), not only by assessing threats over the longer term, but also by enhancing warning systems. Since warning systems require robust measurements and scientifically-sound products, there is increasing demand for improved modeling of time-dependent processes and the identification and reduction of observational errors. This has led to a virtuous cycle whereby breakthroughs in observational technology are driving improvements in data modeling, which in turn lead to increased demand for new observational capabilities.

Underpinning all of geodesy is the existence, improvement, and maintenance of a terrestrial reference frame with the highest possible degree of precision and accuracy. Today's areas of cutting-edge research would not be possible without the infrastructure, products, and intensive research into global kinematics that have provided us with coordinate and reference systems capable of relating geodetic instrument observations to Earth. The next decade's discoveries will depend on continued improvements in both the self-consistency of the reference frame (internal precision) and the accuracy with which the frame can be aligned to the actual motions of Earth's surface.

Geodetic reference frames are critical to the measurements made by many satellite missions as well as to applications as seemingly remote and invisible as precise time synchronization. The satellite systems used to monitor global sea level (TOPEX/Poseidon, Jason, ERS, Sentinel-3), dedicated time-variable gravity missions used for monitoring terrestrial water storage change and ice reservoir mass variations (GRACE, GOCE, Swarm), and any other system that is based on precise orbits and distance measurement all rely on the terrestrial reference frame and related geodetic tools. Other measurements that are based on distance/timing measurements (InSAR, LIDAR, laser and radar altimetry, GNSS meteorology and reflectometry), or that rely on geolocation or accurate timing (almost everything, including time synchronization) ultimately depend on the foundation provided by geodetic measurement infrastructure, related Earth System models, and tools.

Future emphasis should be dedicated to improving the measurement and modeling of geocenter motion, defined as center of mass of the Earth relative to the center of the figure, in particular for remaining uncertainty in the accuracy of the terrestrial reference frame. We need to be able to accurately describe these changes within the Earth and develop physics-based models that explain why they occur. This is of particular importance because the next generation of scientists will expect to be able to use small variations in deformation to determine time-variations in slip on faults, fluxes of water, and other Earth system changes. As a result, minor uncertainties or inaccuracies in the underlying reference system will lead to major errors in quantities of scientific interest.

Integrating Geodetic Science into Society: Making our Knowledge Usable

As the quantity, breadth, and accuracy of geodetic data and techniques have increased over time, so have their societal applications. Linkages between the research community and applied problems, and the overall accessibility of the science and its applications, greatly expand the possible impacts of this work. Geodetic science and precise geodetic infrastructure enable scientific investigations and support engineering, industrial, commercial, and defense applications. However, the dependence of modern society on geodetic infrastructure is not readily visible to end users, who thus take its existence for granted.

To increase the visibility of geodesy and its many impacts, we should prioritize tailoring geodetic products to the needs of stakeholders; creating outreach tools to illustrate how geodetic techniques can serve as force-multipliers for research in other disciplines; and cultivating interdisciplinary partnerships that reflect international priorities and leverage private sector participation.

In addition, increasing the quantity and quality of operationalized geodetic products will enable new science and make geodetic data more broadly accessible and impactful. While the last decade called for more data sharing, the next decade's challenge is to make the data actionable for societal applications. These products are resources that agencies, researchers, and the general public can reliably use in preparedness or emergency situations. The development of operational tools for water resources management, coastal vulnerability, risk assessment, forecasting or responding to volcanoes, earthquakes, landslides, tsunamis, and coastal flooding are regularly requested by the public. The funding process may need to incent projects that feed into or include the development of operational tools, while also accounting for the partnerships and added resources needed to successfully implement these efforts. Diverse and knowledgeable spokespeople sharing operational tools, research advances, and emergency response strategies can help communicate these most effectively to affected communities.

Geodesy is a global, interdisciplinary science. Its holistic nature draws strength from integrating a variety of data streams, so partnerships and collaboration are requirements for success. As an intrinsically interdisciplinary science, geodesy already excels in bridging disciplines, but there is still room for improvement, particularly within the international community and with the private sector. For example, the United Nations Sustainable Development Goals yield a new opportunity to showcase the global utility of geodetic applications. Its internationally-embraced agenda provides a highly relevant and actionable framework for linking geodetic research to societal challenges and cultivating the partnerships necessary to making this happen. Specifically, we aim to expand the geodetic community, both through formal partnerships and through better outreach to diverse stakeholders, including state and local agencies such as geophysical surveys and transportation departments; international observation network operators; other scientists focused on seismology, computer science, hydrological sciences, weather forecasting, atmospheric modelling, and oceanography; and federal agencies such as USGS, NOAA, DOE, NASA, and DOD that are involved in hazard monitoring and preparedness, particularly with regard to tsunami warnings and shake alerts.

Some of the ways to expand access to existing geodetic products include data format and terminology standardization, and better utilization of widely-recognized data clearinghouses. Standardized data classification systems, such as the NASA Earth Observing System Data and Information System Levels or USGS National Geospatial Program Lidar Base Specification, can familiarize new and diverse users with various data categories, particularly when paired with example applications. Clear and consistent communication is especially critical in disaster situations, so advanced socialization of geodetic terms empowers responders to make better use of geodetic tools while under pressure.

Expanded incorporation of social scientists, economists, planners, politicians, and other end users in the geodetic research process generates products that align with pressing societal needs. These relationships not only enhance research outcomes, but also provide opportunities for sustaining geodetic infrastructure, adding new data streams, and gaining interdisciplinary insights. For example, partnerships with local water districts expose local and regional challenges that can be met with geodetic solutions, while simultaneously opening the door to useful local data sets (see spotlight below). A natural outcome of increased interaction with users throughout the investigative and product development process is the creation of new derivative products that encourage broader consumption of data and findings, particularly for local risk assessment and mitigation. Derivative products that are use-tailored, or grab-and-go data processing services that are easily accessed and customized, will allow the fruits of geodesy to reach new and diverse audiences; for example, to inform post-earthquake or tsunami disaster management.

We have designed this document to communicate a vision for the future of geodesy to many different kinds of readers with a wide range of interests and expertise.This structure is intended to model how the geodetic community can make our science more usable and visible.

Diverse Scientists for Diverse Science

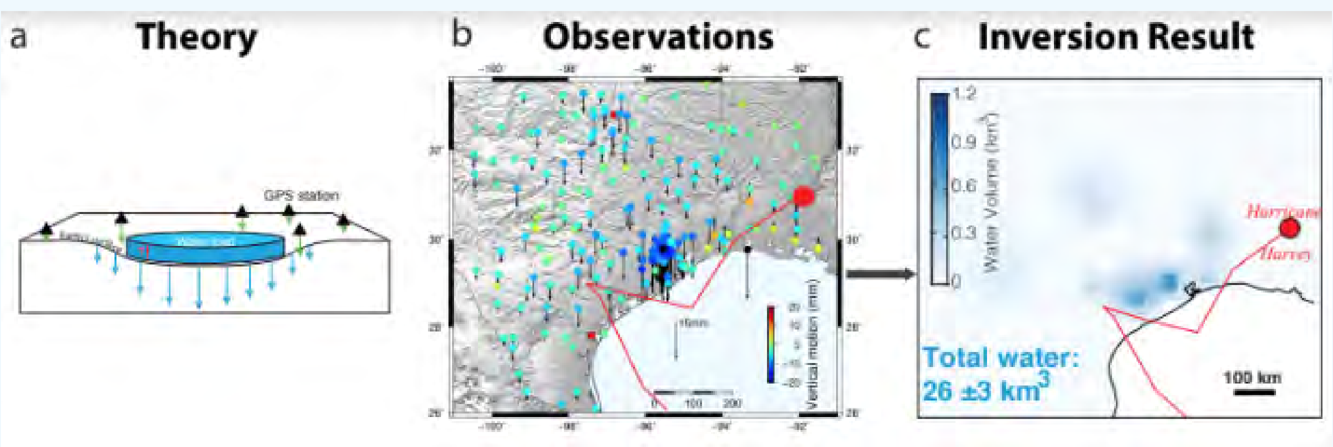
A diverse workforce is key to ensuring that end users can utilize geodetic data. It is not enough to recruit more and different people to the field; we must also expand training in the use of geodetic methods, tools, and data by non-geodesists. By including geodetic principles at all educational levels, even students that do not become geodesists will be more aware of the ways that geodesy contributes to our understanding of the world. Familiarizing scientists in other disciplines with geodetic principles will enable them to advance their science with geodetic data (e.g. deforestation models, biomass estimation, hydrologic engineering), and expand opportunities for interdisciplinary cross-over.

We critically need to foster a next-generation geodetic workforce, which is no small task given the dearth of undergraduate geodesy programs in the United States. Some community-wide recommendations to expand the field include: broader distribution of geodetic educational modules; communication of geodetic career opportunities on undergraduate college campuses, in professional trade journals, in the media, and through social media; creation of scholarships, funding, and recruiting support for existing geodesy programs at U.S. universities; development of internships that expose students to the interdisciplinary elements of geodetic science; policies that emphasize inclusivity in the geodetic community; partnerships with related disciplines for research and training opportunities; and creation of more citizen science opportunities. In addition, the education of future geodetic scientists in the United States is largely dependent on support for applications research, and the US significantly lags behind Europe, China, and others even in terms of basic geodetic science.

Spotlight: Floodplain Preparedness Informed by Geodetic Advances

The Harris-Galveston Subsidence District (HGSD) was created by the Texas Legislature in 1975 to provide for the regulation of groundwater withdrawal for the purpose of preventing land subsidence, which was leading to increased flooding. To achieve this goal, it relies on geodetic observing systems (leveling, extensometers, GNSS, InSAR) and geodesists working together with hydrologists and geologists to understand where subsidence is occurring, or has the potential to occur. HGSD uses products of geodetic research to inform local planning decisions like well water permits, an example of applied geodetic science in action. HGSD geodetic infrastructure provides observations of ongoing subsidence (operationalized). These data have been used by scientists to study processes such as compaction of sediments, a process that is known empirically to produce substantial subsidence in river deltas (rates of millimeters per year), but for which the underlying process rates on human timescales are poorly quantified.

Geodetic observations measured the amount and timing of water delivered to the area by Hurricane Harvey. These results quantified the exceptional volume of water, and showed how maps of flooding hazard under-predicted the extent of flooding. Many of the flooded areas not identified as areas of high hazard on the pre-Harvey flooding hazard maps were found to have subsided substantially, using InSAR measurements studied after the event. It appears that the integrated subsidence was large enough to have impacted surface water flow and ponding in this area of flat topography.



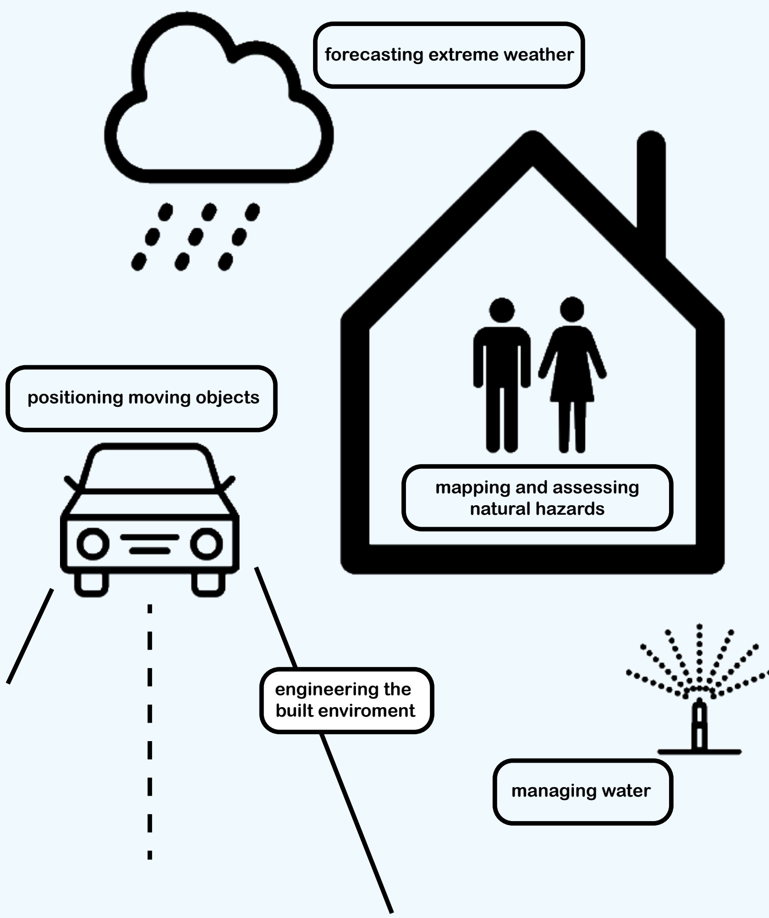
(a) Continuum mechanics provides physics-based constraints on the deflection of the Earth's surface due to a mass load, such as water from precipitation. This deflection can be measured with GPS. (b) Observations of downward surface deflections during the anomalous rainfall in Hurricane Harvey, (c) and an inversion for the total water mass and its distribution in space.

Box 1: What is geodesy?

Geodesy is the measurement and study of the shape, gravity field, and rotation of the Earth, and how those change with time. Since early man recorded the changing seasons and the distances between landmarks, understanding Earth's form and size has been an important part of understanding our place within Earth systems. With the advances of Greek geometers and their first estimates of Earth's radius, geodesy became an explicitly quantitative science, focused on ever more precise quantification of shape.

In the modern era, repeated observations of shape made at very high precision allow us to measure how Earth's surface moves and changes over many different length and time scales. For example, we can now measure how the shape of the whole planet changes as a result of a single earthquake, and how that change in shape changes the gravity field and the speed of our planet's rotation. We can evaluate how changes in human land use influences the evolution of landscapes and the risk of natural disasters. We can directly measure the transfer of water from land-based glaciers and ice sheets into the sea, raising global sea level. Such measurements afford us a basic understanding of the physical properties of our planet, and they give us ever-improving tools to anticipate and mitigate processes that affect the welfare of human communities.

Geodesy also underpins many of the advanced technologies that we use every day. Navigation satellites, high-precision mapping and imagery, and time synchronization all rely on reference frames, instrumental technologies, and computational methods developed for geodetic applications. Even though most people have never heard of geodesy, they depend on it every single day.

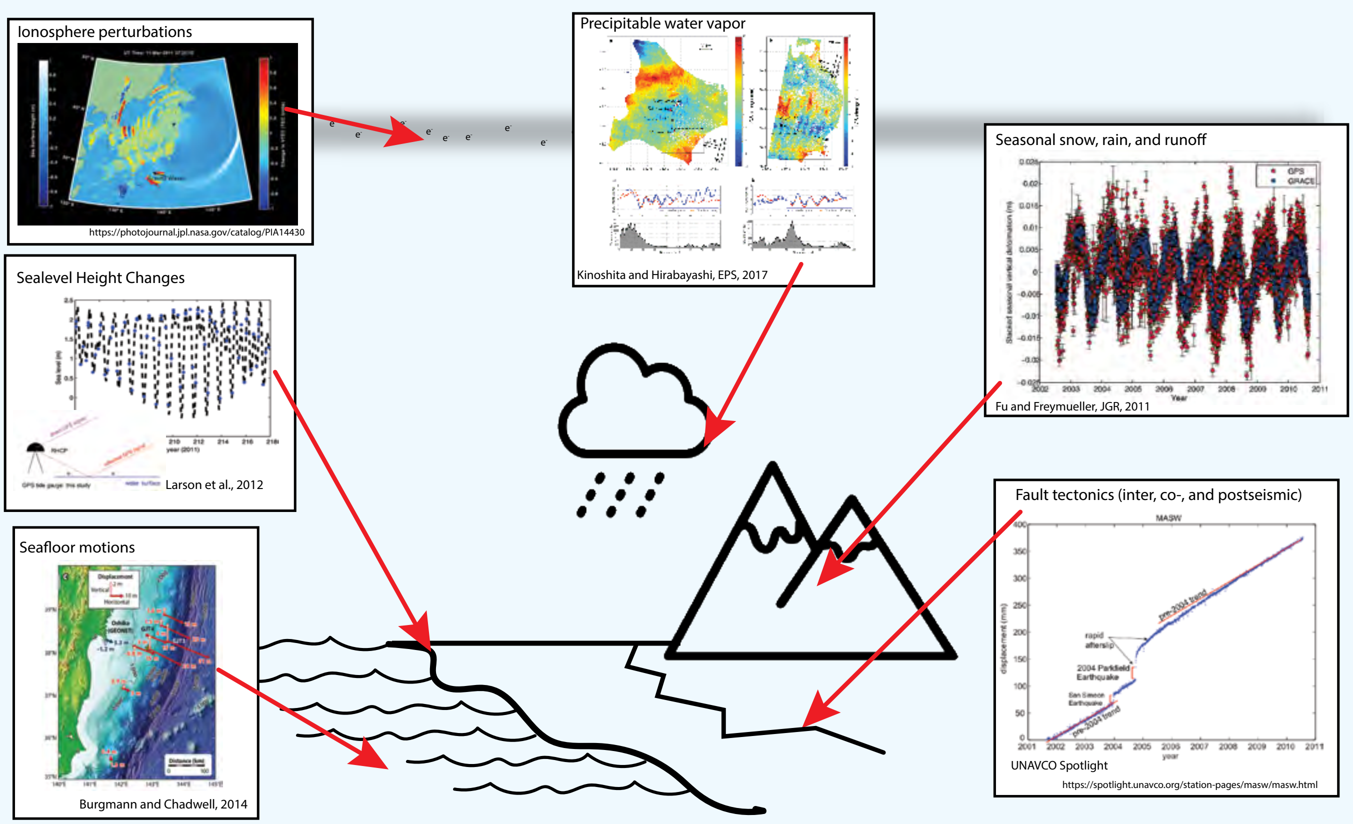


Box 2: Geodetic methods and geodetic signals

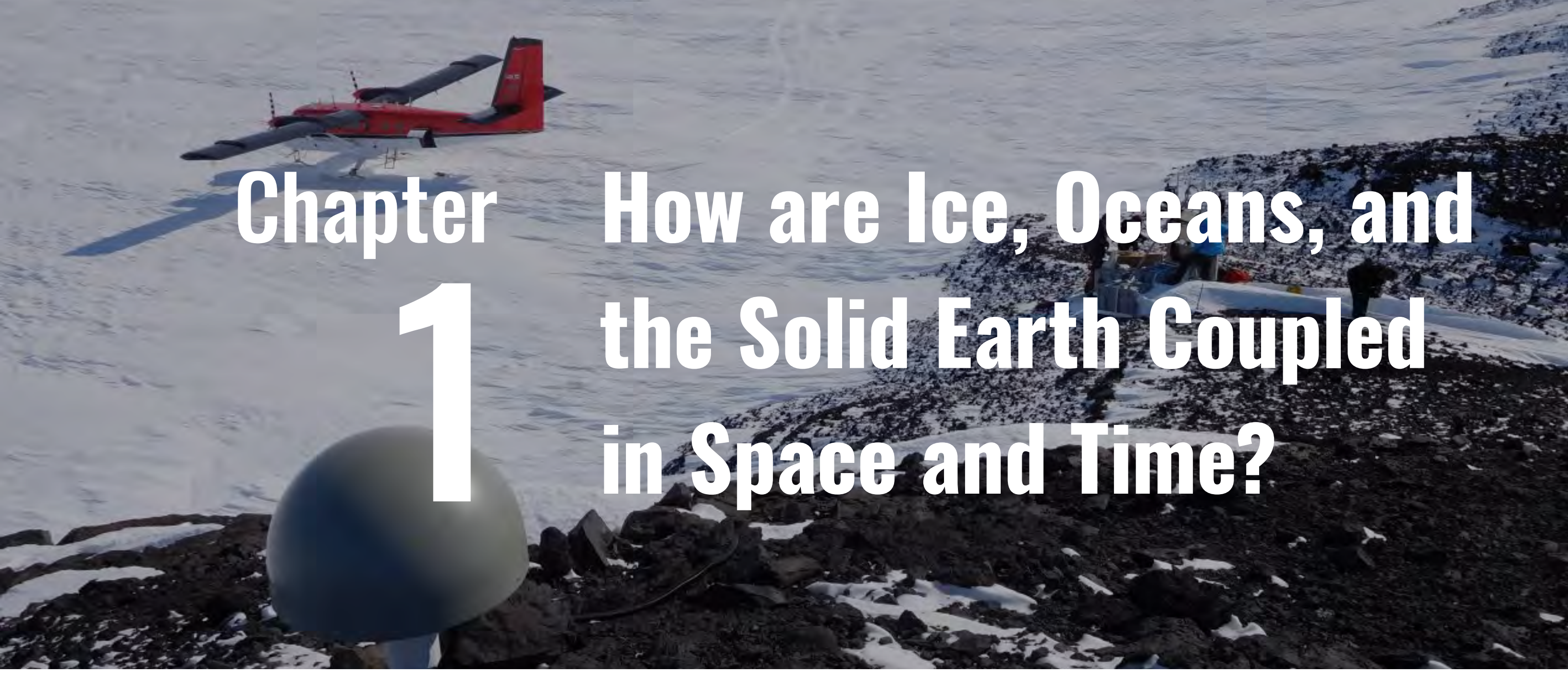
Geodetic sensors measure Earth systems over a very wide range of distances and timescales. This broad sensitivity and variety of different techniques means that geodesists can observe and quantify many different Earth processes. In general, ground-based instruments have the highest spatial resolution (the finest spatial sampling), but have the smallest "footprint". Airborne or orbital instruments have a lower spatial resolution but can look over a broader area or average over longer times.

Some common ground-based geodetic techniques include: traditional surveying, for measurements of distance and height; ground based laser scanning for high-resolution 3D maps of the Earth's surface; and strain and tilt meters that measure ongoing deformation around active earthquake faults and volcanos. Airborne laser, radar, and optical instruments can measure the earth's surface over larger areas, still with very high resolution.

Today the most dominant space-based geodetic technology is GPS, an example of a Global Navigation Satellite System (GNSS), in which orbiting satellites broadcast signals are recorded by ground-based instruments that estimate their position. This tool can be used for many different kinds of measurements (see figure). Space-based laser, radar, and optical sensors also provide critical measurements of surface processes, such as tectonic deformation and landscape changes after natural disasters. Signals from GNSS, Satellite radar and precise gravity, provide a range of observations beyond ground deformation on land and underwater, including how mass moves around on the planet, including water shifting from place to place with the seasons, weather events, and climate change.



The Grand Challenges



Chapter 1 How are Ice, Oceans, and the Solid Earth Coupled in Space and Time?

Key questions

1. How much water is being transferred from Earth's ice reservoirs into the oceans?
2. How will future sea level rise and its impacts be distributed around the globe?
3. How will changes in ice and oceans interact with the solid Earth to change its elevation and coastlines, and with what consequences?

Over the past three decades, geodetic techniques have revolutionized the observation and monitoring of Earth's glaciers and ice sheets. Landsat images have documented changing ice extent; radar interferograms are revealing the details of glacier and ice stream dynamics; and a suite of complementary observations from satellite gravimetry, satellite altimetry, and GPS is faithfully documenting the accelerating loss of water from Earth's ice sheets. From these data, we've learned that the change in ice mass is highly variable in space and time, that the increased flow of ice into the oceans due to global warming is equivalent to mass loss from direct melting, and that glacial isostatic adjustment cannot be adequately modeled using simple assumptions about Earth structure.

To better predict sea level rise, we need a better understanding of present-day melting and the response of the Earth to past ice loading. Approximately 10% of the world's population and 65% of cities with more than five million people are located less than ten meters above sea level and would be affected by even moderate increases in local sea level. The Intergovernmental Panel on Climate Change 5th Assessment Report projects global mean sea level rise ranging from a few tens of centimeters to more than a meter by the end of the 21st century, with significant regional variability. Given the vulnerable populations that live at the edge of the sea, better constraints on future sea level rise are needed.

Sea level is no longer rising linearly. Instead, tide gauge and satellite altimetry observations show that sea level rise has begun to accelerate. However, the feedback mechanisms between increasing ocean and atmospheric temperatures, ice melt and flow, and sea level rise are still poorly understood. Improving our scientific understanding requires time series of glacier, ice sheet, and sea level evolution on temporal scales ranging from months to centuries. Furthermore, interpreting present-day changes in ice and oceans is not sufficient for predicting future sea level rise. The ongoing response of the solid Earth to past ice loads also affects our interpretations of geodetic observations, necessitating better constraints on glacial isostatic adjustment.

Scientific Challenges

Understanding the ice-ocean-earth system requires simultaneous observation of four distinct but coupled phenomena: ice elevation change, ice mass change, glacial isostatic adjustment (GIA), and sea level variability. Each is measured using a unique combination of geodetic tools.

Ice Elevation Change: Ice sheet topography responds to changes in ice dynamics and surface mass balance over time. Digital Elevation Models (DEMs) of ice sheet surfaces provide input boundary conditions for numerical flow modeling and are necessary for the processing needed to make InSAR mass balance estimates of glaciers and ice streams. Measured elevation changes also validate prognostic models that simulate recent ice sheet evolution. Finally, elevation change estimates are used together with models of firn densification and snow accumulation to assess the mass balance of the ice sheets. Ice elevation data extend back to the early 1990s and provide invaluable information about ice volume changes. For instance, compilations of elevation data over Greenland from 1993 to 2012 show the now well-known nonlinear evolution of ice mass loss and reveal that nearby marine-terminating glaciers behave differently, suggesting that a single controlling mechanism for glacier dynamics is unlikely.

Ice Mass Change: From April 2002 through August 2016, the Gravity Recovery and Climate Experiment (GRACE) satellite mission provided monthly observations of Earth's gravity field that tracked temporal changes in the mass distribution of the ice sheets and underlying rock in Greenland, Antarctica, and other large perennial ice complexes. Between 2002 and 2016, the Greenland Ice Sheet lost on average 280 gigatons of mass annually, causing global sea level to rise by 0.8 mm/y during this period. Little to no change in ice mass occurred in the higher elevations of the ice sheet, while lower elevation and coastal areas experienced up to 4 meters of ice mass loss. Over the same period, the Antarctic Ice Sheet lost only 125 gigatons of ice, contributing a much smaller 0.35 mm/y to global sea level rise. Ice impacts were variable across Antarctica, with little change in East Antarctica, but significant mass loss over the West Antarctic Ice Sheet. While GRACE has provided valuable insight to our understanding of how the ice sheets and large glacier complexes are changing with time, its coarse spatial resolution (several hundred kilometers) limits studies of regional ice change.

Glacial Isostatic Adjustment: GIA is the process by which Earth's crust evolves toward isostatic equilibrium with the upper mantle in response to deglaciation of the Pleistocene Ice Sheets and to the advance and retreat cycles of the Antarctic and Greenland ice sheets since the Last Glacial Maximum. Estimates of ice sheet mass balance are sensitive to vertical motion of the underlying bedrock from glacial isostatic adjustment (Chapter 4, How Do Solid Earth's Material Properties Vary with Location and Over Time?), which is Earth's present-day response to the history of mass loading from the end of the last ice age. Modeling GIA is challenging, and uncertainty in the GIA models is a primary contributor to uncertainty in GRACE estimates of Antarctic mass loss and overall estimates of sea level rise. While GIA can be observed with GNSS and gravimetry, to accurately isolate GIA from other effects requires modeling that incorporates a 5000-year history of ice mass change and relies on poorly constrained estimates of Earth's rheological properties. Numerous models exist for GIA in Greenland and Antarctica, but differences between models can be as large or larger than the GIA signal itself.

Sea Level: Reliably predicting sea level will require better understanding of many processes, some of which are coupled in unusual ways. For instance, future ice loss in Greenland and Antarctica will have variable effects on Earth's oceans depending on where the loss occurs. This is because the ice sheets exert a gravitational pull on the surrounding ocean. As the mass and corresponding gravity of the ice sheets decrease under global warming, nearby ocean levels fall. However, since overall sea level rises in response to melting, sea level increase in areas far from the ice sheets is necessarily higher than the global average. Consequently, contribution to sea level rise will vary depending on whether the melt occurred in Greenland, Antarctica, or smaller ice bodies such as mountain glaciers.

Scientific targets for deciphering these effects and their interactions include:

1. Determining best-in-class forecasts and uncertainties for spatially variable sea level change.
2. Identifying and quantifying the processes that control local variations in relative land motion and sea level change.
3. Modeling how the redistribution of water interacts with the solid Earth to modify the position of coastlines and potential impact of natural hazards.

4. Understanding whether sea level change is accelerating and at what rates.
5. Measuring and modeling how ice rheology, basal conditions, sub-glacial topography, and thickness affect glacier flow.
6. Synthesizing ocean and climate effects on natural hazard frequency and location.
7. Exploring how changes in ocean temperature, salinity, and flow patterns influence near-coastal ice sheet processes.
8. Separating the contributions to sea level change of glacial melt, ocean dynamics, circulation, and seawater expansion.

Technological Challenges

Although much progress has been made to address these scientific targets using existing geodetic methods and technologies, additional observational constraints are required to deconvolve multiple effects or to improve forward simulations. Particular measurement and instrumentation targets include:

1. Robust and reliable bottom pressure recorders in the Pacific to directly measure the contribution to sea level rise of ocean mass change (in contrast to steric effects).
2. Extended IceBridge airborne gravity mapping of ice sheet basal topography.
3. In situ data from reflected GNSS signals to measure ice sheets and coastal sea level (e.g. GNSS-IR).
4. Sensors and data reduction methods to observe water at the base of glaciers.
5. Numerical and theoretical tools to integrate GRACE/ GRACE-Follow On (GRACE-FO) and GNSS observations in order to mitigate the limited spatial resolution limitations of GRACE.
6. Improvements to ice sheet modelling, including better assimilation of observations.
7. Maintenance and continuation of long time series records at critical locations.

Community-building Challenges

The most important community-building goal with respect to ice-ocean-earth coupling is better integration of geodetic, oceanographic, and cryosphere research groups. Several notable research initiatives are built on collaborations between geodesists and ice sheet modelers, but in many cases the numerical simulations have outpaced or overlooked useful observational constraints. At the same time, ice sheet models could be used more efficiently to guide where observations are made and what kinds of measurements will be most useful. Some key community targets include:

1. Developing digital collaboration infrastructure.
2. Encouraging interdisciplinary partnerships and initiatives.
3. Developing education and outreach tools to better communicate sea level rise concepts including relative vs. absolute sea level rise, spatial variability, and implications for natural hazards.

Spotlight: Cryospheric Change and Sea Level

Geodetic measurements have become critically important for constraining the rate and spatial distribution of mass loss within the cryosphere, and the rate and spatial pattern of sea level rise. Satellite altimetry and gravity change (GRACE) are critical tools, and load changes, glacier motions, and deformation measured by GNSS and InSAR all contribute to these linked problems.

Mass loss in the Greenland and Antarctic ice sheets is measured primarily from gravity changes measured by the GRACE satellite mission. The detailed spatial distribution of mass loss requires additional information from altimetry measurements, GNSS, InSAR, and ground-based measurements of changes to glaciers, snow cover, and firn (the consolidated snow that is not yet compressed to ice). Mass changes on mountain glaciers also contribute significantly to sea level. All of these mass changes produce elastic uplift of the surface, for which GNSS and InSAR are critical measurement tools, and potentially a viscoelastic response of the mantle depending on the local rheological structure.

The average rate of sea level rise over the 1992-present time period of satellite altimetry is 3.0±0.4 mm/yr, which is at least 50% faster than the average rate of 20th century sea level rise. The global average rate of sea level rise results not only from the addition of meltwater into the ocean, but also from warming of the ocean water, changes in continental water storage (groundwater, surface water), and changes in salinity. An acceleration of sea level rise has recently been detected in the altimeter data. The spatial pattern of sea level is highly non-uniform, mainly because of variations in the ocean (spatially variable changes in ocean temperature, salinity, dynamic ocean topography due to currents, etc), but also because of changes to the gravity field that warp the expected sea level surface (the geoid).

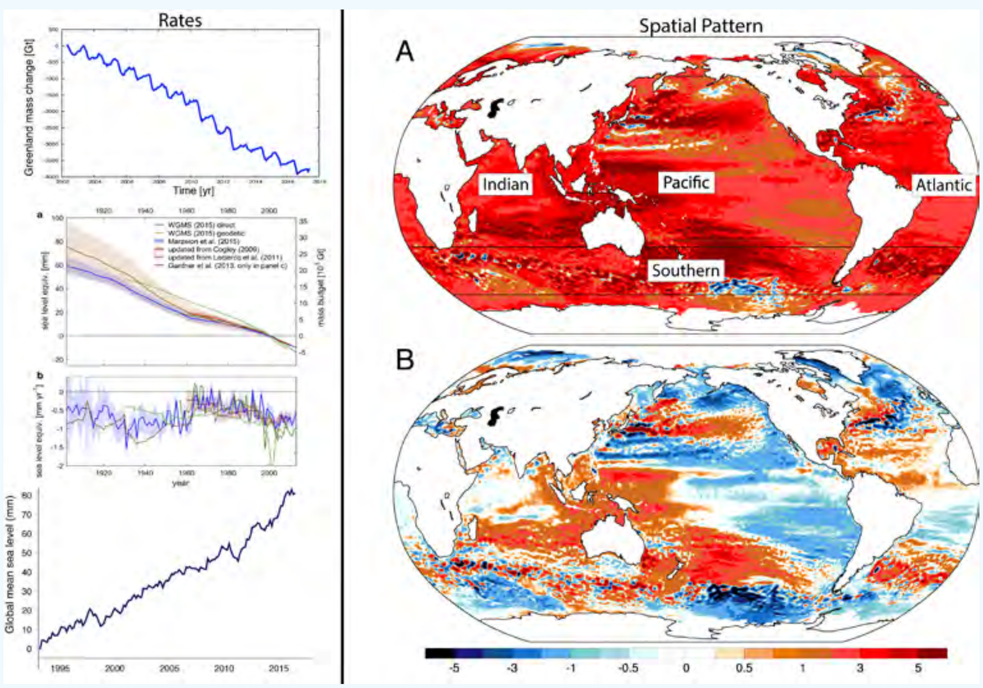
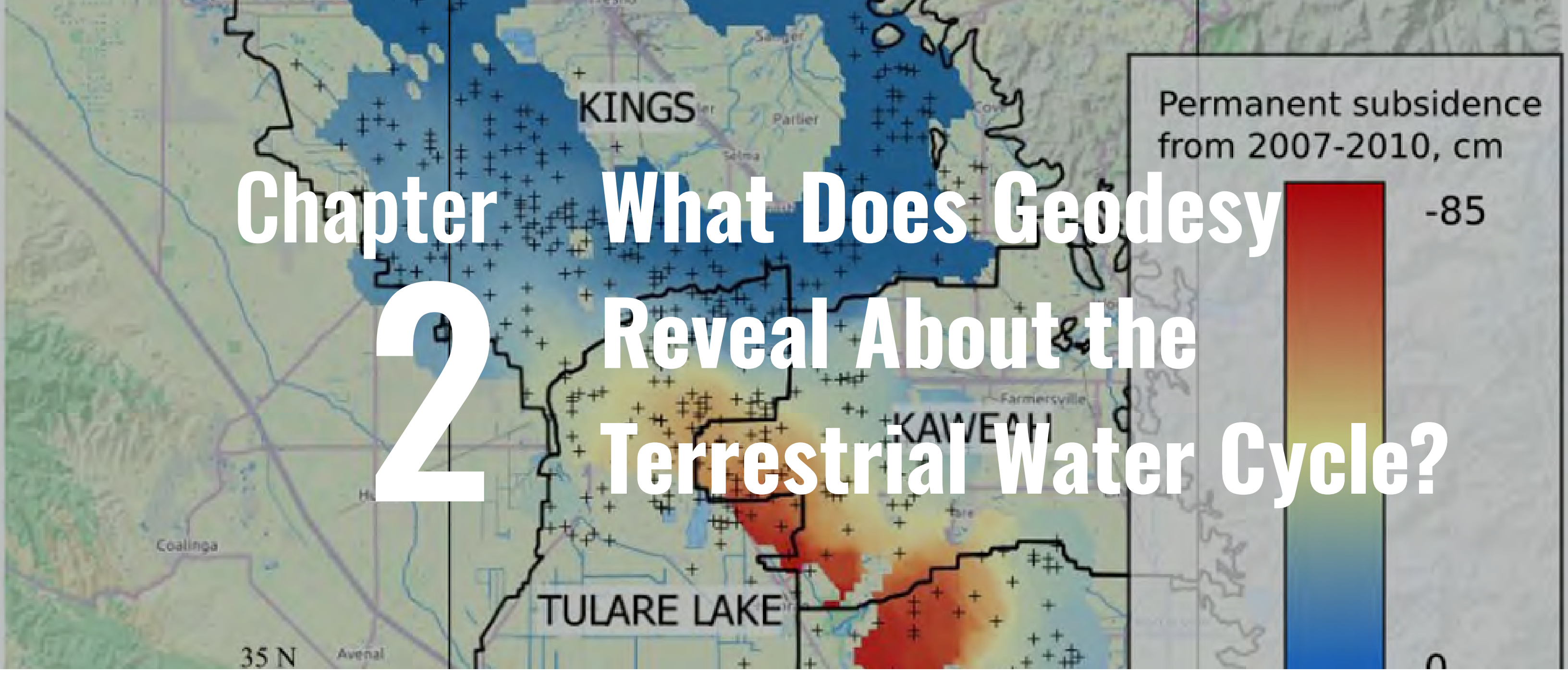


Figure 1. Rates and patterns of cryospheric mass balance and sea level change. (left column) top: Greenland mass losses over time (Gt), from GRACE data; (center) global glacier mass balance 1900-2009, (sea level equivalent mm on left axis, Gt on right axis), (a) cumulative change over time, (b) rates. (right column) Spatial pattern of sea level change, mm. (A) sea surface height rate of change, (B) change with the global mean rate subtracted.



Chapter 2 What Does Geodesy Reveal About the Terrestrial Water Cycle?

Key questions

1. How can geodesy help track the movement of water through the Earth system in response to climate change and human activity?
2. How do changes in terrestrial water storage modulate displacement, strain, stress, and stress transfer in the solid Earth?
3. Can geodesy provide information about the water cycle at the water management scale?

Terrestrial water storage is the sum of all freshwater reservoirs on Earth, including lakes, rivers, groundwater, soil moisture, snow, and glaciers. Ecosystem balance and human civilization depend on the accessibility and quality of fresh water, which moves continuously between these reservoirs and between the continents, oceans, and atmosphere. Water fluxes and the accompanying changes in terrestrial water storage occur on all time scales: from short-term changes related to storms to long-term variability related to climate change.

Integrated geodetic observational networks can precisely measure and monitor the redistribution of Earth's water at continental to global scales, with high scientific and societal payoff given how critical water resources are to the health of our planet. The GRACE and GRACE-FO missions measure gravity changes caused by large-scale water redistribution. GNSS and InSAR accurately measure tiny displacements of Earth's surface caused by variability in surface water loads and groundwater volume. Reflected GNSS signals (GNSS-IR) can be used to monitor different components of surface water, such as soil moisture, snow depth, and lake levels. Finally, atmospheric water vapor can be estimated from the refraction of GNSS signals. Measurements such as these have been remarkably successful in measuring water mass changes from continental scales (GRACE) down to individual aquifers (InSAR, GNSS), and have helped identify severe groundwater depletion, groundwater and snowpack loss during the recent western U.S. drought, and subsidence of the Houston area under the weight of Hurricane Harvey's rainfall.

Significant challenges must be overcome to achieve the full potential of geodesy for hydrological applications, however. GRACE/GRACE-FO data are not sensitive to short-wavelength variations in water mass, and the resolving power of GNSS networks is limited by station density. InSAR is not well-suited to observing long-wavelength loading signals, although it does excel at identifying localized areas of uplift or subsidence due to groundwater changes. Integrating these observations across length scales remains a challenge, and long-term trends in water mass need to be separated from secular changes in surface geometry and gravity caused by tectonics and other forcing. Finally, because geodetic data generally constrain the integrated total water mass rather than individual components (GNSS-IR is the exception), they must be integrated with other observations for the study of specific components of the water system.

Scientific challenges

Measuring the Water Cycle: The movement of water through the Earth system is shifting as a result of climate change and the associated anthropogenic response. In particular, new patterns of rainfall, snowfall, and temperature are altering the timing and magnitude of snowpack development, groundwater recharge, and surface water runoff. These in turn spark human intervention into the water cycle, most notably through surface water storage/diversion and groundwater extraction. Moreover, the long-term movement of water between continents and the oceans is the primary driver of sea level change (Chapter 1, How are Ice, Oceans, and the Solid Earth Coupled in Space and Time?). Modern geodetic techniques can estimate changes in time-variable continental water storage at different temporal and spatial resolutions, allowing us to address several key scientific questions:

1. To what extent is the continental water cycle amplified, suppressed, and/or altered by climate change and human activity?
2. How does terrestrial water storage respond to both short-term (e.g. El Niño and La Niña) and long-term global climate change?
3. How does human activity alter water availability and redistribution on land?

Solid Earth Response to Water Storage Changes: Fluctuations in water storage measurably displace Earth's surface in two ways. Water mass changes cause the solid Earth to deform viscoelastically (Chapter 4, How Do Solid Earth's Material Properties Vary with Location and Over Time?), with a response that is dependent on the properties of Earth's interior. In addition, water volume changes within groundwater aquifers cause local poroelastic deformation due to the expansion and contraction of the aquifer itself. In places such as California's Central Valley, for example, pumping of groundwater from the extensive aquifer system has resulted in widespread subsidence whose magnitude is much larger than the viscoelastic response to the lost water. Deformation caused by water depends on both water volume changes and the properties of Earth's interior, and can be used to infer information about both. Relevant questions include:

1. How can we improve the spatial resolution and accuracy of terrestrial water estimates measured or modeled by geodesy?
2. How can we constrain Earth's elastic and viscoelastic structure using geodetically-observed Earth surface deformation by water redistribution?
3. How can we incorporate geodetically-derived terrestrial water variations into hydrological models?

Hydrologically Induced Stresses and Strains: Water storage changes that cause deformation of Earth's surface also induce stresses in Earth's interior. These stresses can alter natural patterns of seismicity, depending on whether they increase or decrease the likelihood of faults rupturing in an earthquake. Increased water infiltration or direct injection into fault zones may also play a role in triggering induced seismicity (Chapter 3, How Do Fault Mechanics Influence Earthquakes and the Earthquake Cycle?). Understanding the coupling between hydrology and the solid earth requires measuring water load changes with increased spatial resolution, as stress changes are sensitive to short-wavelength features in the water distribution near active faults. Progress in this area will hinge on the answers to several questions:

1. How do terrestrial water changes modulate tectonic stresses on fault systems?
2. Will high-resolution models of surface water and groundwater load changes help us predict stress changes on seismogenic faults in the lithosphere?
3. What is the relationship between water and induced seismicity, and how does it vary spatially and across different tectonic structures (e.g. subduction zones, strike-slip fault systems, and nominally stable continental interiors)?
4. Will terrestrial water changes due to climate change, such as parching from extreme drought and rapid snow- and glacier-melting, cause stress changes large enough to trigger earthquakes?

Water Availability and Quality: To be useful for water management, geodesy must provide estimates of changing water availability at watershed or catchment scales, and for specific aquifer systems. Since these targets require higher spatial and temporal resolution than observations from GRACE can provide alone, geodesists will have to integrate observations from various sources, including GRACE, InSAR, and GNSS. For geodesy to become an effective management tool, geodetic datasets will also have to be integrated into hydrological models (Chapter 8, How Can Geodesy Meet the Challenge of Big Data?). To achieve this, we will need to better understand intrinsic noise in geodetic data and improve methods of separating long-wavelength and short-wavelength signals. Additional challenges include:

1. How can we integrate geodetic data sets with other information (e.g. hydrological models) to obtain the spatial and temporal resolution needed for watershed-based management?
2. How can geodesy help constrain water fluxes on long time scales to inform sustainable water management? How can geodesy identify locations with a substantial imbalance in water fluxes, especially those related to groundwater exploitation and depletion?
3. How can precipitable water (PW) estimates form GNSS and InSAR help to predict extreme rain and storm events, and surface deformation estimates to constrain rainfall distribution?

Geodesy cannot directly measure water quality, but it can indirectly support quality assessment in several ways. In groundwater regions, geodesy can show where pumping and injection are occurring, thus highlighting areas possibly at risk. Innovative geodetic techniques can be used to measure surface water quality. For example, electromagnetic signals from geodetic satellites may be used to detect the scattering properties of water surface, which may change due to oil spills or water contamination. Finally, tracking snowpack/glacier runoff (Chapter 1, How are Ice, Oceans, and the Solid Earth Coupled in Space and Time?) via changes in surface deformation, is relevant for understanding the health of alpine aquatic ecosystems such as those in the Rockies and Sierra Nevada. For these ecosystems, a key water quality indicator is temperature, which is indirectly related to runoff volume.

Technological Challenges

Measuring Gravity: For GRACE and GRACE-FO, achieving higher spatial resolution and better temporal resolution is a necessary but challenging goal, as is filling the temporal gap in the time-variable gravity field between the GRACE and GRACE-FO missions. We also need to develop improved models for known time-variable components of the gravity field so that we can more effectively estimate the components we do not know, and we need innovative approaches to combine satellite gravity and GPS data globally. Future GRACE-like missions will have to turn to multiple satellite configurations to enhance temporal and spatial resolution, and will require better methods for removing atmosphere and tidal effect on the gravity field estimate.

InSAR: New InSAR missions such as NISAR provide high temporal sampling of surface deformation, but they still lack effective atmospheric correction. In agricultural areas where the height and radar scattering properties of the ground surface are constantly changing due to human activity, plant growth, and irrigation, measuring deformation remains a challenge. This is particularly important given that much groundwater pumping occurs in these areas, especially in arid climates, and how critical InSAR is to estimating groundwater extraction intensity. InSAR infrastructure and computational algorithms need to be more efficient to derive deformation time series, especially over large areas and long time spans. Errors and uncertainty in InSAR products should be better understood and quantified.

GNSS: More ground stations with longer observational spans are needed to record geophysical signals with fewer temporal and spatial gaps. We need to more completely understand the errors in GNSS products, and to exploit multi-GNSS constellations to drive down measurement noise and/or identify systematic errors. Past work has demonstrated that GPS signals alone can be used for reflection applications, but now should utilize the full set of GNSS signals. Software for near real-time GNSS-IR measurement of soil moisture, snow accumulation, vegetation water content, and water levels (e.g. tides and storm surge) needs to be validated and made available to the wider community.

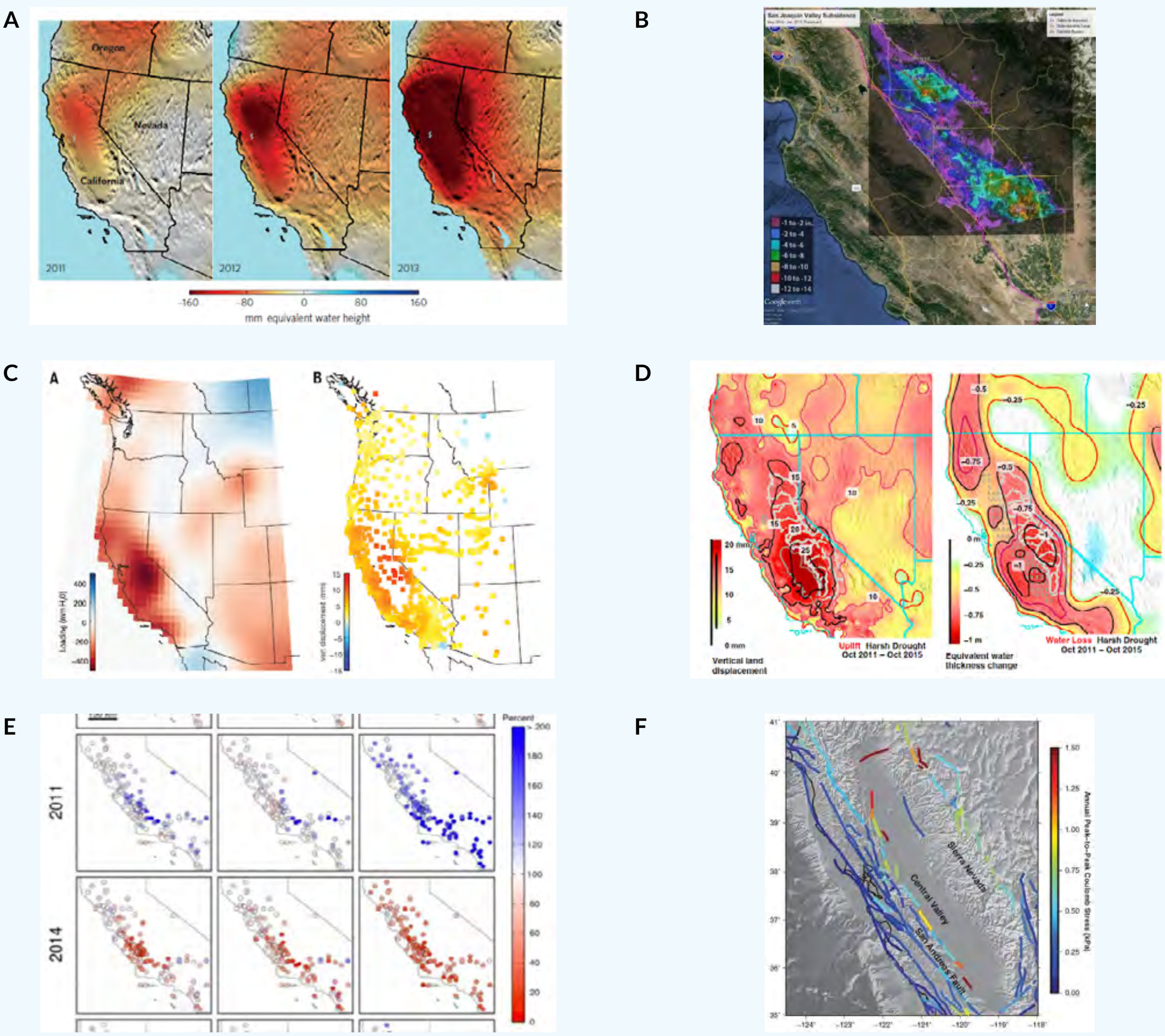
Geodetic Data Integration: Individual geodetic techniques (e.g. GRACE, GPS, and InSAR) provide information on terrestrial water storage at different temporal and spatial scales, but integrating these data sets would provide a more complete picture of Earth's water cycle. In addition, the combination of observations from the Soil Moisture Active Passive (SMAP), Soil Moisture and Ocean Salinity (SMOS), and upcoming Surface Water and Ocean Topography (SWOT) missions would enable monitoring of variations in different hydrologic parameters at global and local scales. Since each of these missions measures water on different spatial scales and with different spatial resolution, combining and assimilating them will be a major technical challenge requiring calibration and validation with in situ collocated geodetic sensors. We also need new instrument designs to reduce the cost of long-term sensor operation and data transfer within sensor networks.

Community-building Challenges

Geodetic data, especially GRACE data, are already being incorporated into large-scale hydrological models to better understand continental-scale water storage. A grand challenge for the coming years will be to contribute water mass products at shorter time scales so they can be used for management at the watershed, or even smaller, scale. Other key community objectives include:

1. Collaboration among geodesists, hydrologists, and water agencies to incorporate geodetic water products into hydrologic assimilation models so that decision makers can rely on them for water resource management and policies.
2. Improved spatio-temporal resolution and faster availability of geodetic terrestrial water storage products to support water-related policy making and resource management.
3. Improved algorithms for estimating elastic and viscoelastic deformation by water loads, incorporating heterogeneous Earth structure.
4. Maintaining a reliable reference frame (Box 3, Reference Frame).
5. Outreach and education efforts to teach students and next-generation geoscientists the role of geodesy in water science and engineering.

Spotlight: Integrated Geodetic Monitoring of the 2011-2015 California Drought



Integrated Geodetic Monitoring of the 2011-2015 California Drought. **(A)** Water storage anomalies measured by GRACE (Famiglietti, 2014). Result is from NASA's JPL GRACE Mascon solutions (Watkins et al., 2015). **(B)** Subsidence in the San Joaquin Valley between May 2014 and Jan 2015 measured by Radarsat-2 InSAR data (Farr et al., 2015). **(C)** Water loading decrease by March 2014 estimated from GPS vertical displacement for the western U.S. (Borsa et al., 2014). **(D)** GPS vertical displacement and estimated water loss between Oct 2011 and Oct 2015 (Argus et al., 2017). **(E)** Comparison of GPS-reflections (GPS-IR) vegetation index between 2011 (wet year) and 2014 (drought year) (Larson, 2016). Columns from left to right are GPS reflections, optical remote sensing (NDVI), and Percent of Normal Precipitation. **(F)** Annual Peak-to-Peak Coulomb stress change on the faults in Northern California by seasonal terrestrial water load change (Johnson et al., 2017).

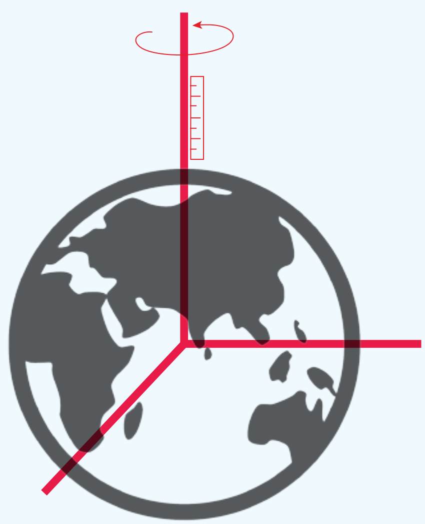
Box 3: Geodetic Reference Frame

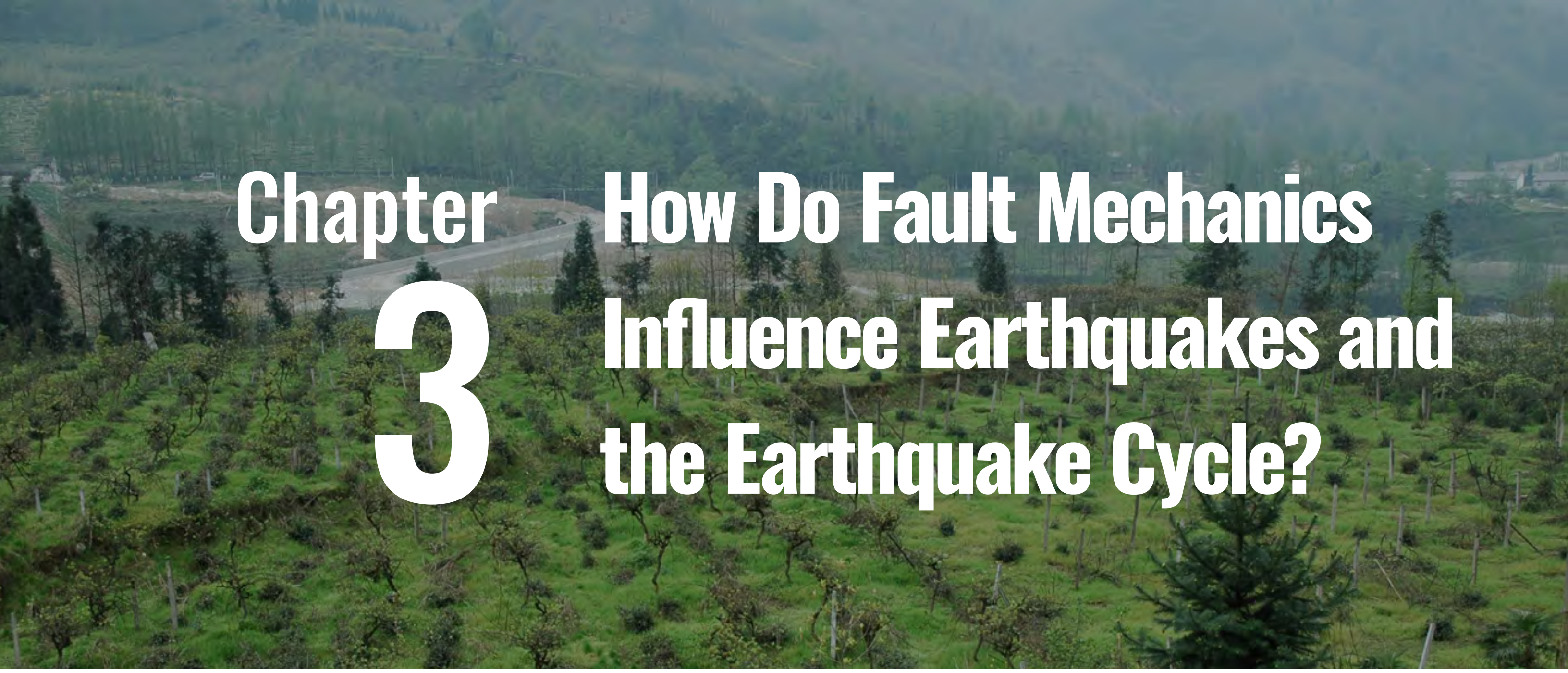
The "Reference Frame" is the fundamental coordinate system and related definitions that underlies all geodetic work. For the most part, this refers to the International Terrestrial Reference Frame (ITRF), which provides the basis for positioning, orbit determination, and Earth orientation measurements; it is the reference system for all modern geodetic measurements. The ITRF is linked to a celestial reference frame, which similarly describes the locations of radio sources such as quasars. The ITRF defines the origin of the coordinate system to be at the center of mass of the Earth system (solid Earth plus fluid layers), the coordinate axis directions, and the scale needed to measure distances. In concept these definitions are simple, but in practice they require exacting work and careful analysis.

There are two principle challenges in defining the reference frame. One is the simple fact that coordinate axes are not marked on the surface of the Earth for us, nor can the geocenter be measured directly – they are not directly observable. They must be defined in practice by adopting a self-consistent set of coordinates for measurement sites around the world, as those locations are observable. The second challenge is that nothing on Earth is static. The oceans and atmosphere are constantly in motion, so points on the surface are always moving relative to the geocenter. Tectonic motions, mass redistribution, and other causes of motion and deformation mean that the reference frame definition has to be consistent with the effects of linear, seasonal and non-linear motions globally, gravity field changes, and Earth orientation variations.

Until the most recent version, the ITRF was a strictly secular coordinate system, in which all coordinates of sites used to realize the frame (define it in practice) were assumed to change linearly with time (piecewise-linear, so that offsets and changes in trend could be accommodated). The latest ITRF2014 now includes seasonal variation terms and non-linear postseismic deformation models for a number of earthquakes. These additional terms make the ITRF more usable and accurate, but will likely need further improvement.

The biggest future task for improving the ITRF is to more accurately define the origin, the center of mass of the Earth system. Mass redistribution from the cryosphere to the ocean and Glacial Isostatic Adjustment can cause both seasonal and longer-term motions of the Earth's surface relative to the geocenter. Furthermore, these motions are mainly constrained by the Satellite Laser Ranging (SLR) network, which has a poor global distribution of stations; this system is nevertheless crucial because SLR measures relative to the orbits of simply-shaped satellites whose orbits can be stably described over long time intervals. Satellites orbit around the center of mass of the Earth system, and thus are a direct link to the origin of the reference frame.





Chapter 3 How Do Fault Mechanics Influence Earthquakes and the Earthquake Cycle?

Key questions

1. What are the mechanisms that drive the nucleation, propagation, and cessation of all forms of fault slip behavior?
2. How can Geodesy inform the behavior of the solid Earth during the entire earthquake cycle, and how do patterns of slip change within and between cycles? What controls whether slip will remain slow, or accelerate to seismic speeds?
3. What can Geodesy inform about the location, timing, and magnitude of future earthquakes?

Earthquakes are a manifestation of a restless lithosphere on a dynamic planet. They result from sudden fault slip, generally occurring when centuries of steady accumulation of tectonic stress exceeds the frictional forces pinning the sides of the fault against each other. Although we can describe rapid slip on faults using the elegant but empirical laws of fracture mechanics, many questions remain about the processes involved. Additionally, some sections of active faults respond to stress changes by creeping, steadily or episodically, in a process known as "slow slip." To understand all modes of fault behavior, we need a better understanding of faulting and the evolution of stress over the entire earthquake cycle, both within the fault zone and in the surrounding earth. This includes timescales spanning high-frequency seismic shaking all the way to earthquake repeat times of decades to millennia. We are particularly motivated to pursue this work because of the destructive power of earthquakes, which poses substantial risk to humans and infrastructure in many regions across our planet.

Geodetic observations have fundamentally advanced our understanding of earthquake behavior, from observations of interseismic strain accumulation and coseismic release that led to the formulation of elastic rebound theory, to the discoveries of post-seismic transients and slow-slip events. Recent progress in remote sensing and space-based geodetic techniques now allow highly accurate measurements of the rupture geometry and slip distribution of large earthquakes, as well as slower surface deformation that can be used to help determine the structure of seismically active faults and the mechanical properties of rocks around them (Chapter 4, How Do Solid Earth's Material Properties Vary with Location and Over Time?). However, major unanswered scientific questions remain on topics such as the effective rheology of the lithosphere and underlying mantle, the mechanical coupling of brittle seismogenic faults with the underlying ductile mantle, the average level of deviatoric stress in tectonically active crust, and the nature of transient deformation on major faults. Geodetic investigations of deformation associated with the earthquake cycle address many of these questions.

Scientific Challenges

Most faulting occurs in broad zones of active deformation. This is particularly true on continents, where plate boundary zones can be hundreds of kilometers wide. Thus, questions about fault mechanics are inextricably tied to lithospheric rheology and plate boundary evolution. In most locations, geodetic observations reveal steady horizontal crustal deformation, indicating stable tectonic loading on faults. However, after major earthquakes, the magnitude and direction of this steady surface motion changes, followed by a longer-term return to their pre-earthquake state, all of which are constrained by geodetic observations. These changes provide a glimpse into the linked dynamics of faults, the surrounding crust, and the mantle beneath.

The Earthquake Cycle: The term earthquake cycle is commonly used to describe the evolution of stress and slip from one large earthquake to the next. After the coseismic slip accompanying an earthquake, the ruptured fault locks again and the surrounding region eventually returns to relatively steady motion. Coseismic and post-seismic deformation redistribute stresses in the deep fault zone, surrounding crust and lithosphere, mantle, and on neighboring faults, and geodetic observations record the accompanying displacement and strain at Earth's surface. These observations can be inverted to estimate fault slip and, when combined with other information or with models, can be used to infer subsurface stress and rheology. Measurements of transient deformation after large earthquakes are particularly important for understanding the earthquake cycle, as non-linear perturbations after a sudden stress change reveal Earth's underlying mechanical properties.

Geodetic data have been spectacularly successful at elucidating tectonic patterns and fault slip rates, and in mapping out spatial variations in fault friction. However, all of these inferences require assumptions about the underlying rheology of Earth materials, and recognition of any deformation components that do not represent steady-state processes. The future application of geodesy to the earthquake cycle includes:

1. Harnessing high-rate geodetic observations to identify the processes that control the nucleation, evolution/propagation, and termination of both rapid and slow seismic slip (Chapter 7, What Do New Approaches Promise for Hazard Forecasting, Warning, and Rapid Response?).
2. Providing better constraints on patterns and timescales of stress loading, which depend on applied tectonic and other stresses and on the rheology of the lithosphere and sub-lithospheric mantle (Chapter 4, How Do Solid Earth's Material Properties Vary with Location and Over Time?).
3. Long-term monitoring of individual faults or fault systems to elucidate the mechanisms behind slip patterns and their evolution within and between earthquake cycles (Chapter 4, How Do Solid Earth's Material Properties Vary with Location and Over Time?; Chapter 8, How Can Geodesy Meet the Challenge of Big Data?).

Slip Nucleation and Evolution: Geodetic observations help to address fault mechanics by inferring fault slip estimates from displacements or strains measured at or near the surface. The final, static displacements caused by earthquakes have been measured for decades using GNSS and InSAR. Today, dynamic displacements associated with ground shaking can also be measured with great fidelity, provided they are large enough. Modern GNSS receivers can measure position changes at sampling rates of 20 Hz or higher, providing significant overlap and synergy with seismometer observations. Geodetic observations are also sensitive to creep distribution and rate on parts of a fault, and how those change with time. Geodesy can be used to determine where slow slip happens, and what kind of slow slip is associated with which faults. Where resolution is sufficient, geodesy can determine whether slow and fast fault slip can occur on the same parts of a fault at different times and can allow us to model the spatial and temporal relationships between slow slip and shaking to study their interactions.

To infer the depth distribution of fault slip from surface displacements is an inverse problem that requires independent information about fault geometry and the elastic properties of the surrounding material. Increasingly, studies are using more realistic elastic models of the Earth to relate surface displacements to fault slip. Innovative applications of model regularization in slip inversions (e.g. minimizing the stress drop rather than some arbitrary characteristic of the slip distribution) have been developed, but further work must be done to increase the fidelity of slip estimates. In particular, we need to better evaluate and express data constraints, since models based on different approaches and/or data sets often have different resolution, making direct comparisons of slip difficult. We also do not understand how model regularization can impact quantities derived from the slip distribution, such as stress changes, even though these can be critical for assessing whether or not models are successfully predicting aftershock patterns, postseismic deformation, or other phenomena. Key questions concerning slip behavior include:

1. What are the mechanisms that drive the nucleation, propagation, and cessation of slow slip?
2. What truly differentiates slow-slip environments from those that generate earthquakes? Do slow-slip events trigger regular earthquakes, and do precursory signals seen before some large earthquakes differ from other slow slip? Does fault structure control the temporal and spatial variability of creep rates, and can we relate creep rates estimated from geodetic data to fault properties?
3. How does fault slip near the free surface evolve differently from slip at greater depth?
4. Why does slip in an earthquake sometimes jump to an adjacent fault, or in the case of megathrust faulting, why do these ruptures sometimes propagate up onto high angle splay faults?
5. How and why do earthquakes stop propagating?

Technological Challenges

Over the last three decades, the development of GNSS and InSAR have transformed geodesy from a data-poor to a data-rich field. Individual researchers or groups dedicated to generating deformation products (e.g. displacements, time series) from raw data have had to adapt to processing the increasing volume of raw data. Similarly, the methods investigators use to model geodetic data have to scale with data availability, which has proved a challenge (Chapter 8, How Can Geodesy Meet the Challenge of Big Data?).

Developing new seafloor geodetic techniques is also a critical priority, because we remain extremely data-poor in terms of imaging seafloor deformation. Many important tectonic and faulting problems involve continental/oceanic plate margins, such as the propagation of strain accumulation and fault slip into the offshore environment, where almost all megathrust earthquake activity occurs. On-land geodetic data are severely limited in their ability to resolve fault slip offshore, even though slip responsible for the largest earthquakes and most devastating tsunamis can occur over 200 km from land. New tools have been developed to perform high-precision geodesy on the seafloor, mainly GNSS-Acoustic (GNSS-A) measurements for horizontal motions, and seafloor pressure gauges for vertical motions. Recent advances have allowed GNSS-A measurements to be made using autonomous vehicles, thereby removing the need for repeated shipborne campaigns and reducing costs a hundredfold. Improvements in drift calibration methods have been made to pressure gauges, leading to more accurate, long-term observation of vertical seafloor motion. These tools still lag their terrestrial counterparts in precision and accuracy, however, and they are expensive to deploy and operate.

The biggest technological challenges in the realm of tectonics include:

1. Developing user-friendly software tools and workflow for large and low-latency data sets.
2. Disseminating advanced inversion and regularization software with robust error propagation.
3. Building tools for rapid assessment of crustal motion, especially for tsunami and earthquake early warning (Chapter 7, What Do New Approaches Promise for Hazard Forecasting, Warning, and Rapid Response?).
4. Developing seafloor geodesy instrumentation and deploying instrument networks on the seafloor.

Community-building Challenges

Earthquake scientists are often asked by policy makers and the public, “When will the next big earthquake happen?” While we cannot predict earthquakes, earthquake science has been increasingly successful at forecasting the locations at highest risk for large earthquakes, which in turn has been used to inform building codes and engineering designs. However, there are only a few places (e.g. California) where geodetic information is used to improve these forecasts and hazard maps. Broader incorporation of geodetic information into hazard maps and other earthquake forecasts will require improvements in the available data and modeling, and a more complete understanding and description of the uncertainties in fault slip rates or other data-derived quantities. A hazard map needs not just the “best” tectonic model that fits a geodetic data set, but rather a broad suite of models that are properly weighted based on how well they explain the data. This suite of models should incorporate variations in fault locations, connectivity, and other factors. The process of producing hazard maps commonly uses this approach, but focused research products do not.

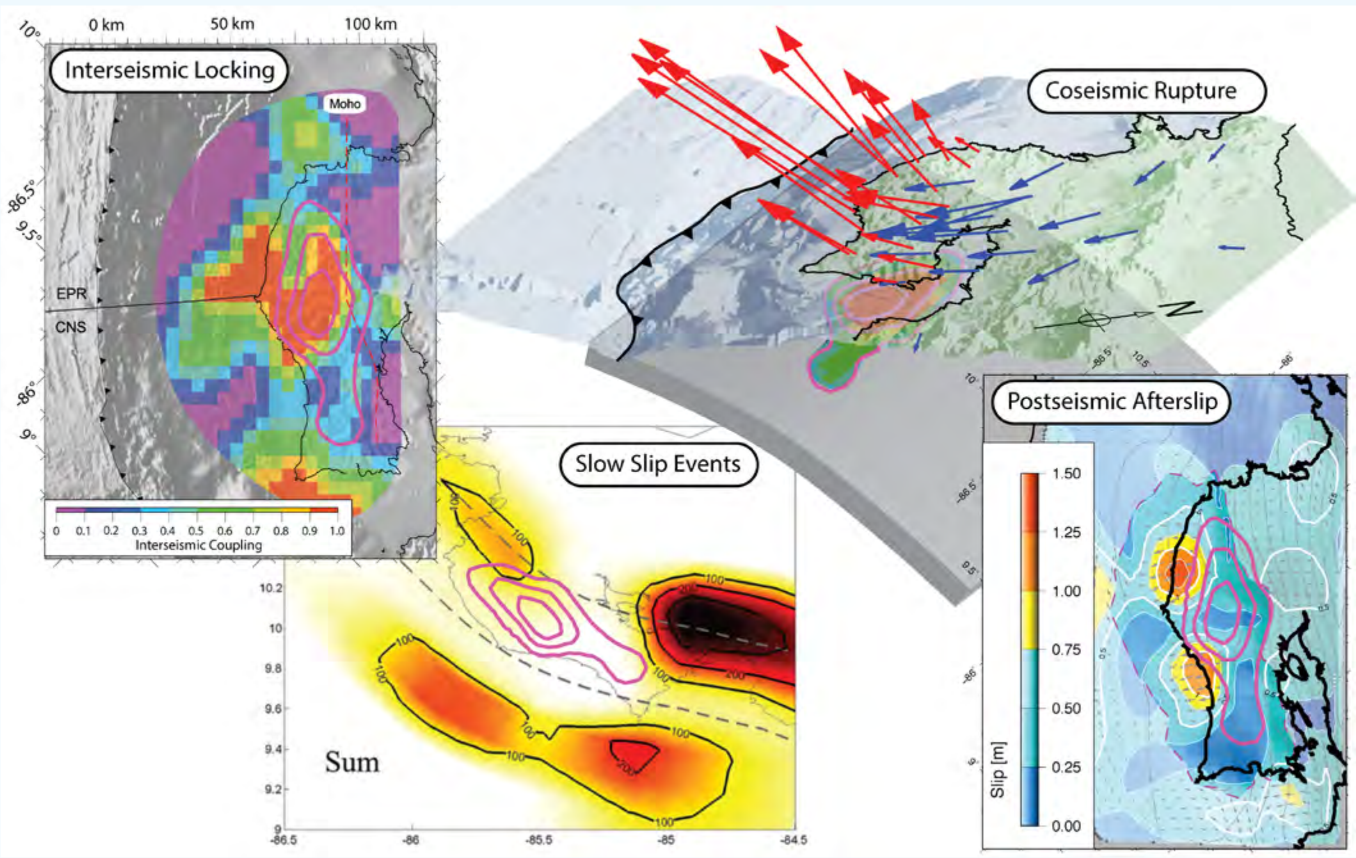
Geodetic data may also contribute information about the likelihood of extreme events, such as extremely infrequent, but devastating earthquakes that are missed by hazard assessments focused on seismicity catalogs. Geodetic observations can help to constrain the overall slip budget of faults, so that we can assess how often large-slip events should occur on average. This can be especially helpful in slowly deforming areas, such as plate interiors, where the historical earthquake record is far too short to represent the true seismic risk. The 2008 Wenchuan earthquake in China is a good example of this kind of risk, where earthquakes have a recurrence period of 2500-3000 years, but feature very large slip. In the Wenchuan case, the pre-earthquake contraction rate across the region was low, which is a cautionary reminder that strain rate by itself can tell us about the potential frequency of earthquakes, but not their ultimate size.

Geodesy also has the potential to contribute significantly to tsunami early warning systems. Kinematic GNSS displacements for very large near-shore earthquakes may provide an early estimate of magnitude without the high-frequency saturation that some seismic methods face. In addition, geodetic displacements can constrain the rupture length as soon as static displacements are available, something that has not worked yet with seismic data alone at a similar timeframe.

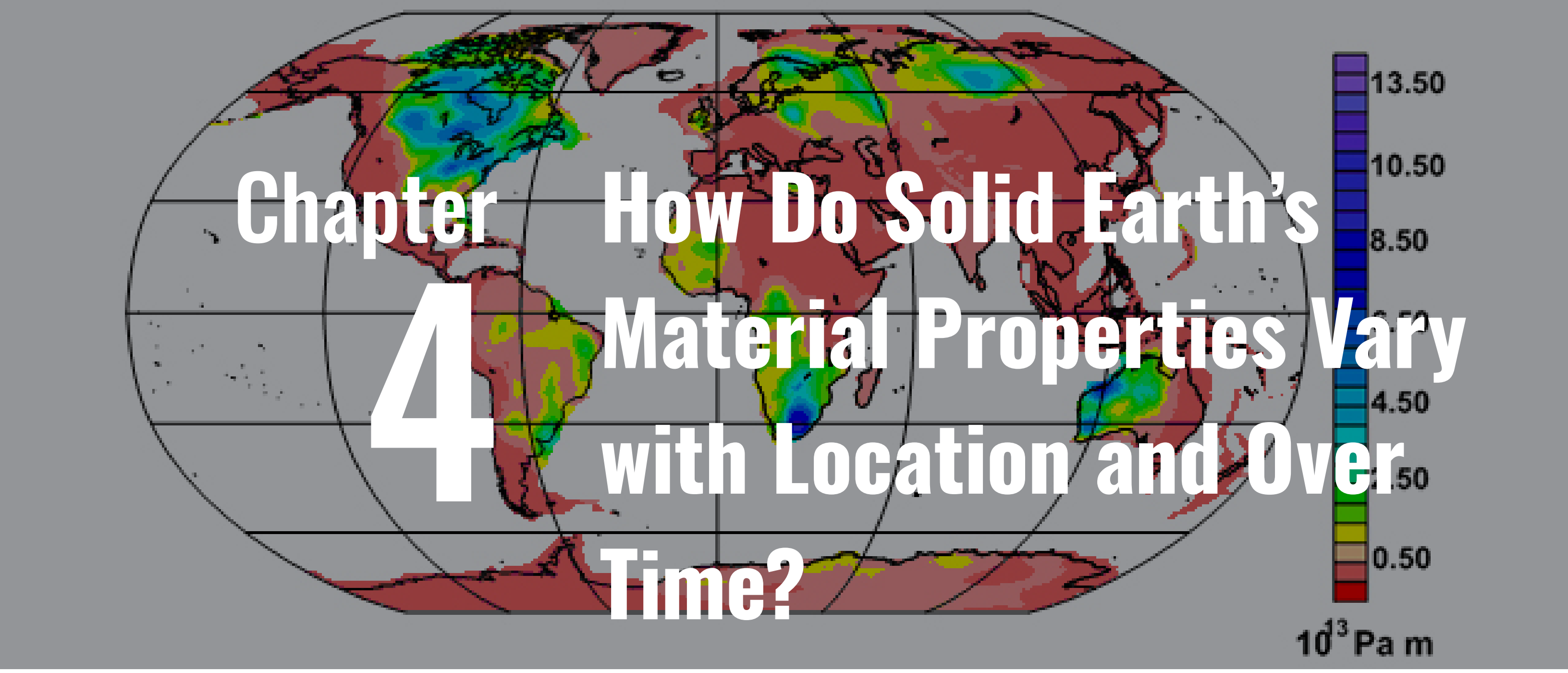
For earthquake early warning, the time horizon is much tighter, and the fact that geodetic data are not sensitive to small P-wave displacements is a limiting factor. However, rapid geodetic magnitude and fault model estimation can be used to confirm estimates of the earthquake size from seismology and can certainly be available soon enough for rapid situational awareness. Further work is required to operationalize this recent research.

Spotlight: Finite Fault Models from Geodetic Observations

With detailed imaging of a fault environment, particularly a low angle fault such as major plate boundary subduction megathrust like seen at the juncture between the downgoing Cocos and overriding Caribbean plates. Here, due to the rather unique proximity of land to the trench, on-land GNSS have been useful at creating some of the most detailed observations of seismogenic processes along the megathrust across the seismic cycle, highlighting the inter-relation between intereseismic locking, episodic slow slip events before, and coseismic rupture and afterslip processes following a major magnitude 7.6 earthquake in 2012. GNSS results have allowed for researchers to map the interrelationship between these processes across the seismic cycle at the interface here identifying strongly locked patches release in both coseismic rupture and afterslip, and that episodic slow slip, help to bound the region that ultimately rupture in the 2012 earthquake.



Shown are the differing published results for the megathrust behavior (color contours) beneath Nicoya Peninsula (dark contour) for four periods across the seismic cycle, including (top left) the late interseismic period [Feng et al., 2012], (bottom center) cumulative slip from several slow slip events between 2007 and 2012 [Dixon et al., 2014], (top right) coseismic rupture, also showing GPS vectors, and the down-going slab in perspective view, and (bottom right) 2.5 years of postseismic afterslip [Hobbs et al., 2017]. For reference, the coseismic rupture is overlaid across all panels (purple 1m slip contours).



Chapter 4 How Do Solid Earth's Material Properties Vary with Location and Over Time?

Key questions

1. What do geodetic observations reveal about Earth's material heterogeneity in space and time? What are the time constants for different mechanical approximations?
2. How can we combine geodetic data with other information to improve our knowledge of Earth's mechanical behavior, and what are the fundamental limitations of this knowledge?
3. How do complexities in material properties limit our understanding of Earth processes and dynamics?

Geodesy has always been an observational science, rooted in measurements of the shape and scale of the Earth and how they change over time. The most exciting advances in geodetic research come from linking these observations to underlying processes, from the force balance on lithospheric plates to the changing spatial distribution of hydrologic masses. The relationships between measurable deformations and their underlying causes are not always simple or linear, but instead require approximation of the material properties of the Earth. For example, the same surface mass load applied to an elastic solid, a viscous fluid, or a complicated layered material will produce very different outcomes. Thus, inverting displacement for load or for any applied stress requires a material model.

Qualitative or quantitative descriptions of the relationships between load and response for a continuous material are called constitutive or rheological relations. They enable us to predict deformation given a known stress or a stress inferred from an observed deformation field. Simple rheological approximations are appropriate when geodetic observations of deformation have low spatial and temporal resolution. For example, assuming perfect rigidity for lithospheric tectonic plates is sufficient for estimating general plate motion from observations of magnetic stripes on the seafloor. Similarly, coarse observations of postglacial rebound can be modeled using simple Newtonian flow within a constant-viscosity layer. However, as the spatial and temporal resolution of geodetic data improves, simple approximations become limitations. The solid Earth's real material properties increasingly appear to be highly nonlinear, with complicated time dependence and spatial variability. Many different emerging discoveries (Chapter 1, How are Ice, Oceans, and the Solid Earth Coupled in Space and Time?; Chapter 2, What Does Geodesy Reveal About the Terrestrial Water Cycle?; Chapter 3, How Do Fault Mechanics Influence Earthquakes and the Earthquake Cycle?; Chapter 6, What is the Connection Between Solid Earth Processes and Surface and Landscape Evolution?) depend on accurate knowledge of rheology, on sophisticated tools for handling nonlinear continuum mechanics, and on new methods for separating contributions from multiple processes.

Future advances in solid Earth rheology will require methods that deconvolve or extract signals of interest from an aggregate geodetic observation. For example, a vertical displacement time series from Yellowstone National Park combines a seasonal hydrologic signal from the snowpack, longer and shorter displacements related to changes in shallow and deep groundwater, episodic magmatic and hydrothermal events, elastic strain from magma pressure changes and fault loading cycles, and much longer time scale contributions from deglaciation, orogenesis, isostasy, and mantle dynamics. Each component of this time series is likely to be a valuable observational constraint for study of a subset of these processes, but few, if any, researchers study them in the aggregate. To fully capitalize on exciting new technical innovations in observational geodesy, we will require advances in continuum mechanics, signal processing, and our basic understanding of the relevant forcing processes to separate and interpret the various components of geodetic signals. These advances, in turn, require integrated data sets with high spatial and temporal resolution from many different geophysical and geological techniques. Data sets that span long length and time scales are also critical. These needs present major technical challenges in data handling, data integration, signal processing tools, and simulation techniques (Chapter 8, How Can Geodesy Meet the Challenge of Big Data?).

Scientific Challenges

There are two different kinds of scientific targets in the area of rheology. The first set of targets are fundamental inquiries into the rheological relations required to correctly and completely describe the solid Earth. These include the form of such relations, the extent to which they are nonlinear, the extent to which different rheological relations are required in different settings such as in continental vs. oceanic lithosphere, and the nature of vertical (radial) layering or zonation of the Earth and the nature of mechanical coupling between layers. The second set of targets are more applied results that can be used to facilitate research requiring mechanical models of Earth loading and response. These include stability analyses to determine which rheological approximations are appropriate for particular geodetically-constrained problems, as well as a better understanding of the uniqueness of particular inversions or other reductions of deformation observations for process constraints. Some specific scientific targets identified by the broad geodesy community include:

1. Providing complete rheological relations for different earth materials.
2. Determining approximate rheological relations for representative solid Earth architectures (e.g. "typical" continental lithosphere over average mantle, oceanic lithosphere over average mantle) and representative deviations of each (e.g. for continental cratons, lithosphere underplated by anomalous mantle, and mechanically thinned or thickened lithosphere). These relations must either be sufficiently complete to address a wide range of forcing periods, from seconds (e.g. seismic waves) to tens of millions of years (e.g. orogenesis), or they must have information about solution stability with respect to period in both length and time.
3. Performing quantitative sensitivity analyses for common mechanics approximations, with descriptions of the primary trade-offs among material properties, their arrangement in space, and force and torque balances.

Technological Challenges

Several methodological and technological advances are required to address the above scientific targets, spanning data handling, data collection, and advances in numerical computational. Data handling challenges include managing large and long-term data sets that feature increasingly higher spatiotemporal resolution and diverse metadata standards. Data collection challenges include the continuing acquisition of long time series and keeping pace with increasing data volumes and lower latencies of new high-rate and real-time observations. The computational challenge is primarily concerned with developing and benchmarking computational tools appropriate for diverse observations and complicated mechanics problems. Specific technological targets identified by the geodesy community include:

1. Providing single points of access to multiple data types and sources.
2. Standardizing metadata across datasets.
3. Building software tools and workflows for large low-latency data sets.

4. Maintaining instruments that are collecting very long time series.
5. Developing methods for combining multiple data sources to extend time series.
6. Developing adjoint inversion tools with robust error propagation.
7. Implementing Bayesian and other emerging statistical tools for geodetic data.
8. Benchmarking framework for model development and testing.
9. Sharing portals for numerical simulation and inversion algorithms.

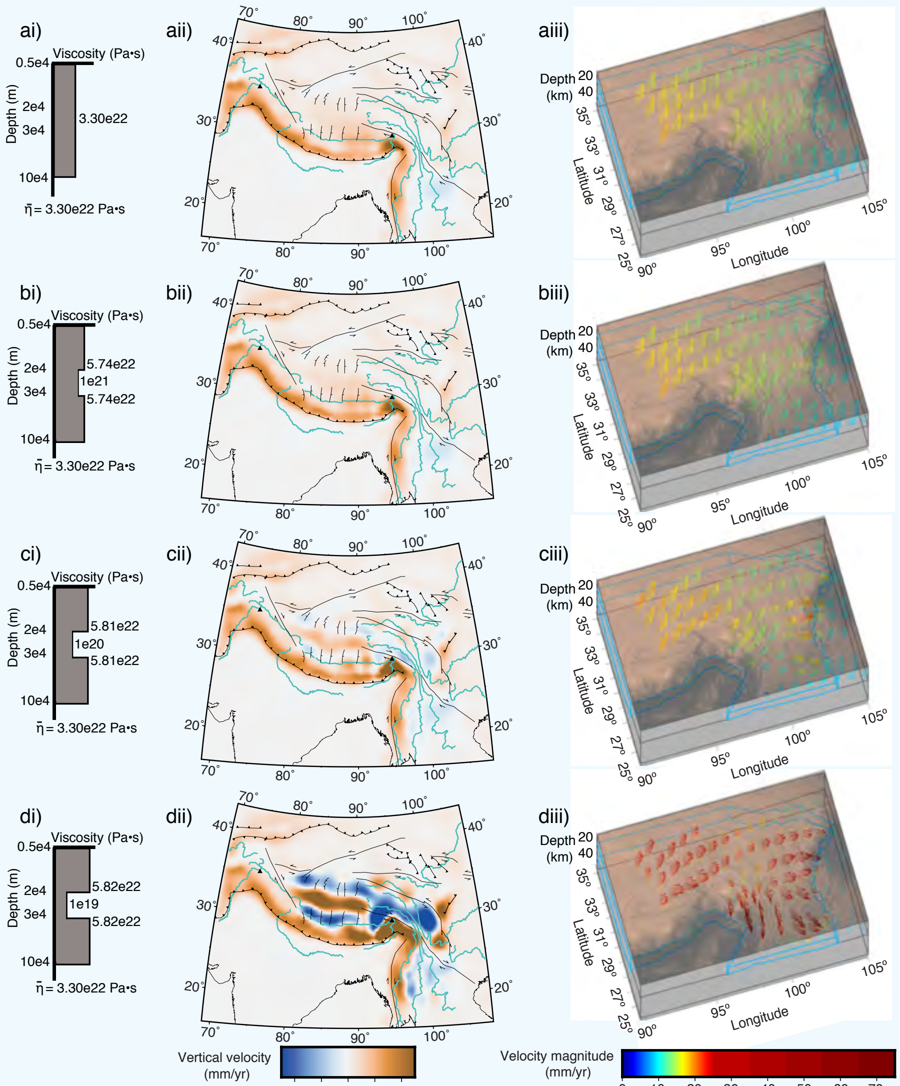
Community-building Challenges

Strengthening the cross-disciplinary user and practitioner community is required to better understand and utilize new results concerning the rheology and architecture of the solid Earth. For example, a research group seeking to use observations of landscape change to measure water mass or to calculate rates of local sea level rise will need to know how to use both observational data and rheological models. Infrastructure and best practices for sharing knowledge facilitates effective collaboration in this area. Specific targets include:

1. Digital infrastructure for information-sharing and collaboration.
2. Development and dissemination of dynamic reference frames and material models as community resources.
3. Education and outreach emphasizing the role of rheology and material models in geodetic research and applied problems.

Spotlight: Lateral mechanical heterogeneity in Asia

The same forces and torques when applied to different materials will produce markedly different responses. For example, squeezing a handful of modeling clay generates a very different style of deformation from squeezing a brick. This same basic principle applies to earth materials over a wide range of length and time scales, with the consequence that Earth's response to loading, whether from the precipitation dropped by a passing storm or the long-term, steady motion of lithospheric plates, depends on material properties as outlined in this chapter. In the Indian-Asian tectonic collision, vertically and laterally varying materials have a strong influence on the evolution of topography, the spatial distribution of seismic hazard, and the basic dynamics of the system.



Modeled solutions of vertical surface motion and lower crust velocity. i, Viscosity-depth profiles at 30°N, 99°E for test cases with lower crust characterized by a no weak lower crust, b 1021, c 1020, and d 1019 Pa·s. ii, Model solutions with color scale representing surface vertical velocity, teal lines/black symbols marking major rivers/faults, and black triangles denoting locations of Nanga Parbat and Namche Barwa peaks. iii, Model velocity solutions in weak lower crust of Southeast Tibet, with arrow color representing magnitude, blue/grey lines outlining weak lower crust/other domains, and semi-transparent copper color scale showing topography.

Chapter 5

What Can Observations of Surface Deformation Reveal About Magmatic Processes and Volcanic Hazard?

Key questions

1. What processes, over what timescales, can trigger volcanic eruptions, and how do volcanoes interact with nearby tectonic and magmatic systems?
2. What are the sizes, depths, and connections between deep and shallow magma reservoirs, and what fraction of magma intruded into the shallow crust is ultimately erupted?
3. Can we forecast the occurrence, type, and duration of large, globally-disruptive volcanic events on human-relevant timescales?

Magmatism is a vivid illustration of the heat engine that powers Earth's tectonics, and it plays a major role in the construction of Earth's crust. Volcanic eruptions can profoundly impact society through loss of human life and economic disruption. The past and potential dangers of large eruptions include lava flows, landslides, earthquakes, and lahars, regional impacts from tsunami and gas emissions, and far-reaching impacts on international airspace and changing climate patterns.

Because magma movement displaces and stresses the surrounding rock, surface displacement measurements can provide insight into the evolution of eruptions and warning signals for hazard forecasting. Similarly, because pressure changes within the magmatic plumbing system can impose high differential stress and strain rates on the environment, evaluating the evolution of the deformation signal illuminates rock and fault mechanics (Chapter 3, How Do Fault Mechanics Influence Earthquakes and the Earthquake Cycle?) and crust rheology (Chapter 4, How Do Solid Earth's Material Properties Vary with Location and Over Time?). For example, the eruption and dike intrusion in Miyakejima, Japan in 2000, and the 2005 Dabbahu rifting episode in East Africa have been used to test models of the relationship between stressing and seismicity rates and the tensile failure strength of the crust.

Magmatic systems are particularly dynamic, featuring processes that can vary on timescales of months to minutes. For that reason, studies of erupting magmatic systems have often made use of high-rate GPS positioning to augment daily GPS solutions. In addition, space-based InSAR has been an especially powerful tool given the number of volcanoes that lack in situ instrumentation. InSAR allows for a global survey of volcanoes, detecting activity in systems previously not considered to be at risk. This information can be used to plan additional ground-based equipment for research, monitoring, or response.

Magma may stall at various depths within the crust depending on its buoyancy, viscosity, and the surrounding medium. Quantifying the location of magma is challenging when more than one magma chamber is active at the same time, yet it is critical for understanding the mechanics of a magma reservoir and how likely it is to erupt. Through timely observations of our world's magmatic systems, geodesy can help constrain the spatial distribution and geometry of magma chambers and help answer the question of what fraction of magma is solidified at depth versus erupted.

Geodetic data are crucial for constraining pressure and mass changes within magmatic systems, but a full understanding of these systems requires integration with petrology, seismology, and other geologic and geophysical data, most notably temperature and gas fluxes. For example, two important processes by which magma and its rheology change during storage and ascent are gas exsolution/transport and melt crystallization. These processes can stabilize the magmatic system under certain conditions or can lead to catastrophic eruptions through nonlinear feedbacks. In particular, the release of gas within magma drives rapid magma ascent and changes in both viscosity and magma compressibility, whose interplay determine the dynamics of the system and affect the geodetic deformation signature observable at the surface.

Scientific Challenges

Eruption Dynamics and Magma System Mechanics: Magmatic system research incorporates both the highly nonlinear, dynamic processes that trigger and sustain eruptions and the slower thermomechanical processes that characterize crustal evolution as a magma plumbing system interacts with surrounding rock (Chapter 4, How Do Solid Earth's Material Properties Vary with Location and Over Time?; Chapter 7, What Do New Approaches Promise for Hazard Forecasting, Warning, and Rapid Response?). Both research areas are directly informed by geodetic observations of surface displacements and strains. Developing physically driven models for magmatic systems is both a considerable challenge and an opportunity to link geodesy, petrology, volcanic gas studies, and more. Critical targets in these areas include:

1. Characterizing complex magmatic plumbing systems and how magma moves between reservoirs as a possible indicator of eruption. Targets include the size and depth of magma reservoirs scaling relations for timescales of transport and storage; magma and gas fluxes; magma buoyancy, viscosity, temperature, and crystal content; and the nature of the surrounding medium.
2. Defining mechanisms that affect magma's dynamic behavior to help interpret pressure changes inferred from geodesy, accounting for compressibility and volatile content, the interrelation of varying magma types with differing volcanic structures, and tectonic environments.
3. Identifying early signals that indicate emergent changes within a magmatic system, driving it toward or away from instability and eruption. For example, reactivation of stalled magmas through contact with a fresher, hotter intrusion at arc volcanoes commonly triggers eruptions.
4. Numerical and analog modeling of the interaction between magma and surrounding medium (e.g. how magma bodies interact with and sometimes drive nearby tectonic systems, and how closely-spaced volcanoes can interact with each other).
5. Building useful theoretical or empirical eruption forecasting estimates and monitoring tools (Chapter 7, What Do New Approaches Promise for Hazard Forecasting, Warning, and Rapid Response?).

Technological Challenges

Several efforts are underway to integrate and model geodetic data in real-time for eruption monitoring and to describe the time-evolution of subsurface stress. Improved geodetic imaging of deformation and strain during volcano-tectonic interactions will come from denser deployments of high-rate GPS and borehole strainmenter measurements and more frequent InSAR estimates. Integrating these data sets with local microseismic recordings, geologic constraints, and degassing observations will enable comprehensive modeling of volcano systems, which has not previously been achievable. Efficient use of continuous high-rate GNSS and new InSAR observations requires technological advances, including:

1. Tools for joint analysis of complementary observations at different spatial and temporal resolutions. For example, GNSS provides daily or higher-rate point displacements in three dimensions, but its spatial sampling is sparse. InSAR, by contrast, provides a synoptic view, but its coherence is limited by loose materials, vegetation, and steep slopes, and it generally contains atmospheric noise that can mimic volcanic

or other signals. Fusion of these two data types often addresses the limitations of just one.

2. Improved methods for recognizing and modeling deformation within surficial deposits (e.g. cooling and compaction of flows, ash deposits, gravity-driven slumping). Volcanic deformation is often superposed with these signals, especially in InSAR data.
3. Consistent reference frames and inter-frame transformations for combining diverse data sets (Box 3, Reference Frame). GNSS data are easily referenced to a consistent global reference frame (ITRF), but in addition to volcanic signals, GNSS time series include tectonic plate motions and local tectonic deformation that can be challenging to remove when the number of nearby GNSS sites is small. InSAR time series are inherently relative motions and not always clearly documented, with tectonic and volcanic-signals still merged. Thus, separating volcanic signal from surrounding tectonic signal, and maintaining a suitable reference frame for localized volcanic studies, remain substantial observational challenges.
4. Low-cost, high-frequency, real-time telemetered GNSS sensors for dense deployments and high-risk deployments. GNSS hardware suitable for this likely exists in board or chipset form, but a systems engineering effort is needed to make a ready-to-deploy package. Telemetry is a particular challenge at many volcanoes because of the lack of access to wireless networks.
5. Methods for combining geodetic observations of deformation with other constraints, including changes in the gravity field, fluxes in gas chemistry, and petrologic thermodynamics. Developing physics-based models that link volcanic deformation and seismicity may well lead to improved eruption forecasting.
6. Tools for automatically creating, georeferencing, and sharing very large InSAR data sets.
7. Tools for automated identification of critical precursory signals in very large and noisy data streams, such as artificial intelligence/machine learning approaches (Chapter 8, How Can Geodesy Meet the Challenge of Big Data?).

Community-building Challenges

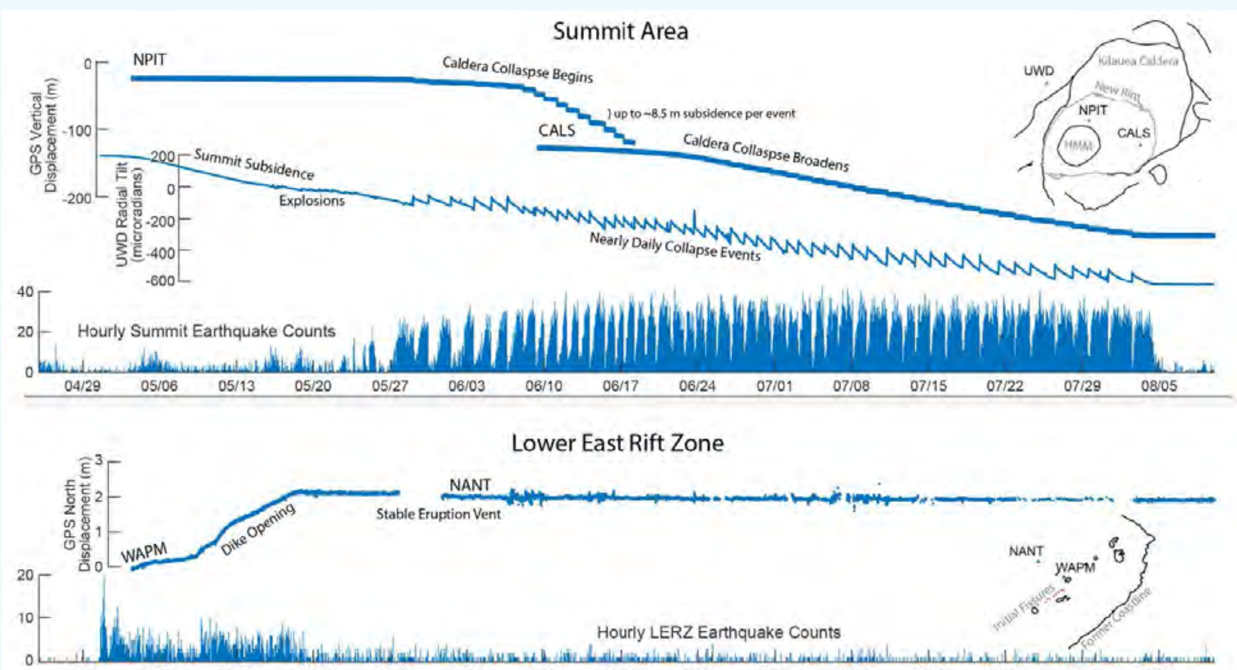
Addressing the challenges in this area will improve eruption forecasting and monitoring, safeguarding human and ecological communities. However, communicating hazard information and forecasts is a challenge. In many cases, existing volcano observatories are the natural conduits for this information, since communicating hazards to the public is part of their mandate. But while determining the probability of a volcanic eruption may be in the domain of science, what to do with that information is not. For example, should all forecasts above some confidence threshold be publicly communicated and, if so, who would set the threshold and how should uncertainties of the forecast be treated? Should at-risk communities be involved in real-time science and forecasting? How should mitigation and adaptation efforts be prioritized, and who pays for them? Because hazard forecasting combines physical science, societal, economic, and ethical considerations, some of the most urgent challenges include:

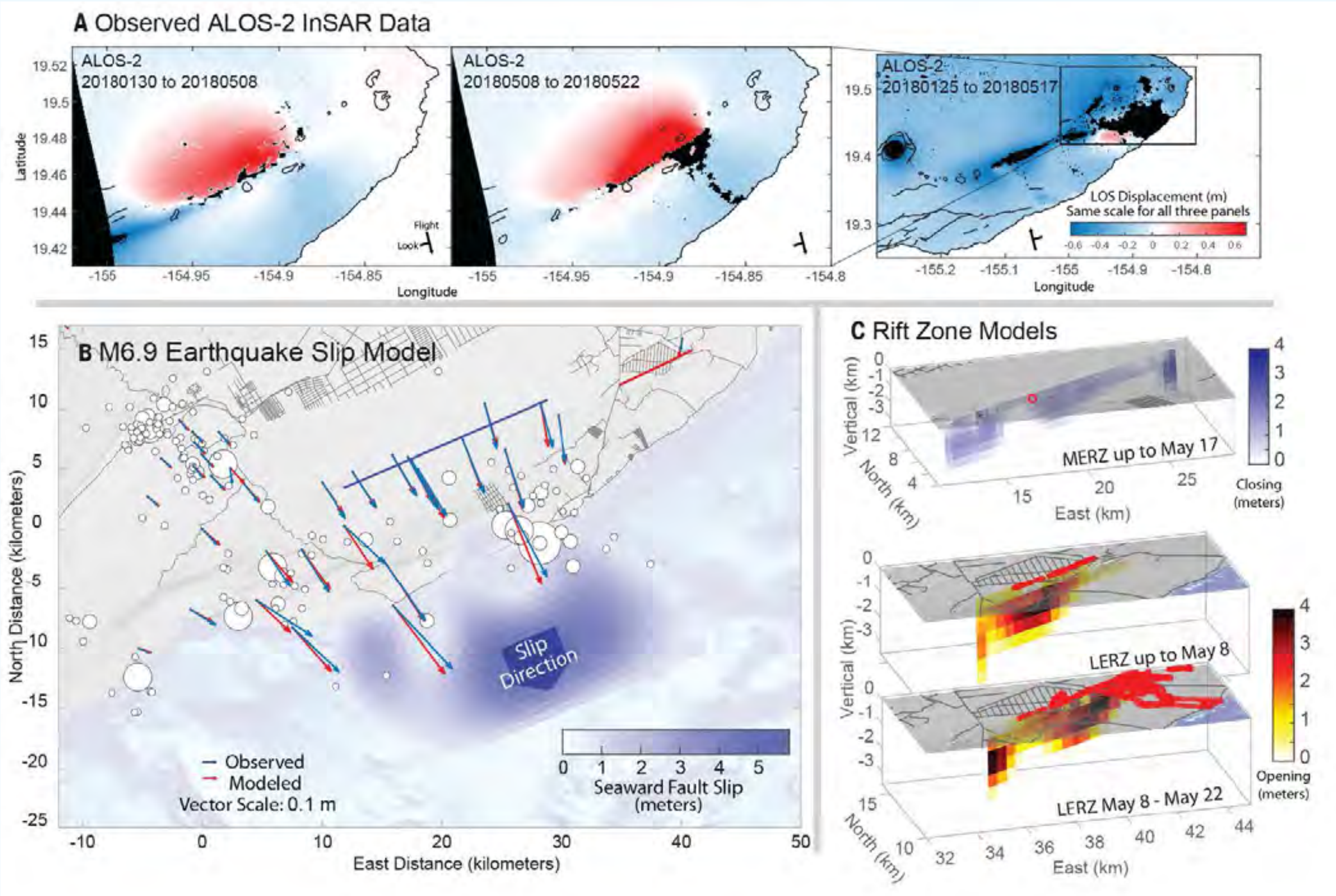
1. Communication of new scientific information through the agencies responsible for volcanic hazards, such as local volcano observatories, national geological surveys, etc.
2. Systematic tests of mitigation and adaptation practices.
3. Recommendations for preferred community engagement.
4. Clearly defined best practices for emergency response and communication.
5. Education and outreach tools to improve forecasting and probability literacy among non-experts.
6. Education and outreach tools for general volcano processes, including eruptions, lahars, gas explosions, and other hazards.

Spotlight: Geodesy and the 2018 eruption of Kilauea, Hawaii

Since 1983, Kilauea erupted from a series of vents at or near Pu'u 'O'o on the central Middle Rift Zone. Starting in 2008, there was an active lava lake in the Halemaumau crater within the summit caldera, and this (inside the "Overlook Crater") grew in size, with the lava level fluctuating over time as an effective pressure gauge on the main summit magma storage system. At the end of April 2018, the floor of Pu'u 'O'o collapsed and seismicity and deformation indicated that a dike was being intruded downrift into the populated Lower East Rift Zone. GNSS and InSAR data showed large amounts of extension associated with ~4m of extension at shallow depth within the lower East Rift Zone, and eruptive fissures began to open and erupt on May 3. On May 4 there was an MW 6.9 thrust earthquake, probably located on the basal decollement of the volcanic pile, and with ~5 m of seaward motion of the south flank. On May 18, hotter and less viscous magma began to erupt, and the dike under the Lower East Rift Zone continued opening until this time, and then neither opened nor closed significantly for the remainder of the eruption. By the end of the May, activity had concentrated at one location (Fissure 8), where it continued until August. Subsidence at the Kilauea summit began shortly after the onset of activity in the Rift Zone, and explosions associated with collapse events began by May 10. By the end of May, the summit caldera was undergoing rapid subsidence, including near-daily collapse events and explosions that dramatically enlarged the Halemaumau crater.

GNSS and InSAR data measured deflation and eventually collapse at the summit, along with deflation in the middle East Rift Zone, as magma left the higher elevation parts of the magma system en route to the eruptive vent. Parts of the rift zone either dilated or contracted, or both in sequence, as magma passed through the system to the vent at lower elevation. After the initial dike intrusion and earthquake in the Lower East Rift Zone, GNSS and InSAR data showed little ongoing deformation in that area. The lack of deformation indicated that the pressure in the magma system was not dropping despite the rapid extrusion of lava (ultimately, > 1 km3 erupted over 3 months, an extrusion rate 40-50 times higher than the average of the 35 year eruption from Pu'u 'O'o). Over much of the eruption, therefore, the erupted magma flux out of the vent in the Lower East Rift zone was matched almost exactly by the flux of magma out of the summit, upper and middle parts of the Rift Zone. Magma from the summit and Pu'u 'O'o accounted for ~2/3 of the total erupted volume; the remainder may have been stored in other parts of the Rift, or arrived freshly through the summit reservoir from the lower crust or mantle.





(Top) Eruption timeline illustrated through deformation observed at GNSS sites, and earthquake counts. The summit records show summit subsidence and eventually caldera collapse. The individual summit collapse events and explosions featured characteristic temporal patterns both in deformation and seismicity, which ultimately made them predictable.

(bottom) A. Interferograms for three key time intervals showing the changing pattern of deformation through the eruption. B. Earthquake slip model and GNSS displacements. The blue line shows the extent of contraction within the Middle East Rift Zone at this time, and the red line shows the extent of the dike injection. C. Models for the opening and closing of the Middle and Lower East Rift Zone over time, constrained by GNSS and InSAR data.

Chapter 6 What is the Connection Between Solid Earth Processes and Surface and Landscape Evolution?

Key questions

1. How does land surface morphology express the interaction between tectonic, hydrological, and gravitational processes?
2. How does topography evolve towards steady state, at steady state, and during/after extreme forcing events? What is the relative importance of timescales and processes in topographic evolution?
3. What causes landscape evolution to change state from quiescent, to steady, to catastrophic?

Earth's surface is continually reshaped by natural processes, both steady and catastrophic, which impact terrestrial water supply, ecosystems, landscape evolution, and the built environment. Geodetic data allow us to characterize these processes: from the tectonic forces that move the landscape, to the evolution of river networks, from the work done by erosion and sediment transport, to the impact of catastrophic events. These studies are enabled by precise and spatially-dense measurements of topography and topographic change from LIDAR (terrestrial, airborne, spaceborne), InSAR, Structure from Motion (SfM) photogrammetry, and other remote sensing techniques. High-resolution observations of topography can provide the means to disentangle overlapping signals and extract a better understanding of tectonic and climatic processes.

High-resolution images and three- and four-dimensional topographic maps inspire and facilitate field-based tests of a new generation of quantitative models of mass transport mechanisms. These models allow us to characterize Earth's surface at the appropriate spatial scales and to quantify land-forming processes. For example, innovative topographic metrics can help to characterize the interactions between tectonic and surface processes and the climatic modulation of process rates. 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.

High Resolution Topography (HRT), which features spatial resolutions better than 10 meters, has been essential to the impressive progress in characterizing Earth's surface evolution over the past decade. HRT is generated by newer InSAR missions (e.g. TanDEM-X), space-based photogrammetry from stereographic satellite images (e.g. ASTER), and aerial or ground-based LIDAR. Additionally, NSF investment in facilities such as NCALM, Open Topography, and UNAVCO has been critical to the collection, archiving, and dissemination of HRT data, as have projects such as the USGS 3D Elevation

Program. HRT has been used for: comparing predicted versus actual geomorphic transport in study areas such as Critical Zone Observatories, where complementary data sets have been collected; rapid response to events such as the historic Colorado Front Range floods, which served as a contemporary reminder of the importance of extreme forcing events for shaping Earth's surface; and repeated monitoring in support of physics-based investigations of processes such as landslides or post-fire alluvial fan building. The past decade has seen a further explosion of HRT due to mass adoption of imaging technology (e.g. LIDAR, photogrammetry) driven by commercial forces such as autonomous vehicle navigation.

Scientific Challenges

The study of Earth surface evolution requires a physical understanding of processes shaping Earth's surface over timescales ranging from seconds to millions of years. Often these processes involve complex, non-linear feedbacks and interactions, which complicates the interpretation of geodetic observations. Physics-based models with predictive power are increasingly relevant as human populations increase their impact on and dependence upon the actively evolving land surface. The 2010 Landscapes on the Edge report defined the Earth surface evolution community's current science goals. Here, we highlight the key geodetic needs essential to achieving these goals:

1. Measurements that capture the interaction between tectonic, hydrological, and gravitational processes, and their modulation by climatic variation.
2. Observations of topographic change during and immediately after an extreme forcing event, or from ongoing processes such as groundwater-related subsidence.
3. Physics-based models of processes such as landslides and debris flows.
4. Characterization of the coupling between the elastic earthquake cycle and mass wasting.
5. Measurements of biomass and biomass change in the context of land degradation, desertification, peatland oxidation, and tundra permafrost change using technologies such as LIDAR (space, air, and terrestrial), SAR, InSAR, and polarimetric InSAR.
6. Topographic metrics, such as slope-area, wavelet-based, and spatial power spectra, that can efficiently illuminate meaningful process signals in high-resolution topography.

Some of these objectives are closely linked to other problems in geodesy. For example, a better understanding of earthquake-related deformation of Earth's surface is required to interpret the paleoseismic record and define fault slip rates, which provide an essential long-term complement to present-day geodetic measurements of coseismic, postseismic, and interseismic deformation (Chapter 3, How Do Fault Mechanics Influence Earthquakes and the Earthquake Cycle?). The same tools used to measure changes in surface topography can measure volumes of erupted lava flows (Chapter 5, What Can Observations of Surface Deformation Reveal About Magmatic Processes and Volcanic Hazard?). Sudden changes in the landscape pose substantial risk to human populations (Chapter 7, What Do New Approaches Promise for Hazard Forecasting, Warning, and Rapid Response?), and high-resolution measurements of surface topography involve challenging, large data sets (Chapter 8, How Can Geodesy Meet the Challenge of Big Data?).

Technological Challenges

Addressing these questions requires quantitative measurements of topography at high-precision and high spatial resolution as a function of time. HRT can be measured using LIDAR, photogrammetry (including SfM), or similar tools, and requires precise geodetic control to ensure accuracy. Currently, many applications rely on terrestrial or airborne sensors since spaceborne measurements have limited spatial resolution, but large-scale spaceborne DEMs are becoming more detailed and accurate. For larger-scale problems, new scientific opportunities are enabled by spaceborne DEM measurements and four-dimensional DEMs such as the time-varying ArcticDEM and new reference DEMs for Antarctica and the Arctic.

Advances in change analysis techniques are also needed. Change analysis can include classical geodesy such as derivation of displacement fields, or estimates of bulk volume change. It can also depend on topographic metrics or their changes, as derived from digital landscape models. Finally, we need improved methods of geophysical inference using inverse methods, where geodetic data are compared to or assimilated into numerical models. This is a particular challenge because many observables are measured at different spatial and temporal sampling, but they are needed at similar scales to study underlying processes such as deformation, vegetation and soil moisture change, pore pressure variability, etc.

Spatial and Temporal Coverage: The first technological challenge is to get measurements where and when they are needed. Multiple platforms and tools are needed, and the data from all must be fused together. Imaging geodesy using LIDAR, InSAR, and photogrammetry is an extremely powerful tool, but the spatial resolution and error characteristics vary by technique. For example, SfM photogrammetry can be employed inexpensively from the ground, small aircraft, or drones, but without adequate ground control or precise geodetic positioning of the camera platform, it can accumulate large long-wavelength errors. Terrestrial or airborne tools require physical access to the study area, or the airspace above. This limits how often the measurements can be repeated and can be impossible for political or security reasons. Spaceborne tools avoid those limitations, but may lack the spatial resolution needed.

Imaging geodesy is not the only geodetic technique appropriate for land surface evolution. Individual ground-based sensors and networks (e.g. GPS/GNSS or strainmeters) can measure displacement and strain at high time resolution, which is critical for determining the dynamics of relevant processes and especially how they transition from steady to catastrophic change. The main technical challenges here are minimizing the cost of deployment and data retrieval, and developing low-cost sensors that can be deployed in a 'Large N' mode.

Topographic models cannot be limited to the sub-aerial land surface, as 70% of Earth's topography is under the oceans. Traditionally, mapping the seafloor has been separate from mapping the land surface, to the extent that datums (the reference coordinate systems for specifying position and/or elevation) for bathymetry and topography can be inconsistent at the level of a few meters. We need higher resolution bathymetric mapping, especially for shallow waters and the near-shore environment, and a unified reference system for topography and bathymetry that is accurate to the level of a few centimeters or better. This would not only enable cross-shoreline landscape studies, but it would also help address hazards such as tsunami runup.

Managing, Standardizing, and Merging Large Data Sets: Data that have been collected must be safely archived and served to users in useful ways. For example, the OpenTopography program and portal has been developed to archive and distribute high-resolution topography data at a variety of spatial resolutions, but long-term funding is uncertain. Other topographic data and products are distributed through specific projects (e.g. ArcticDEM, the MERIT DEM), facilities (e.g. NCALM), and agencies (e.g. SRTM or the USGS's National Map). Smaller-scale mapping efforts associated with individual studies may only exist in an individual research group's files. A key question is whether these data sources can and should be unified or regularized, and how data sets not associated with large governmental agencies can be most effectively be preserved, disseminated, and reused.

Processing Change with Geodetic Expertise: In some instances, simply collecting an HRT dataset enables comparison of predictive metrics between a process model and actual topography. For processes that evolve over timescales whereby repeat observations can be made, analysis requires change detection in one-dimension (e.g. comparison of vertical differences), two-dimensions (e.g. optical image correlation, particle imaging velocimetry), or three-dimensions (e.g. the Iterative Closest point algorithm for three-dimensional point clouds). With the advent and proliferation of geodetic imaging techniques such as InSAR, LIDAR, and SfM photogrammetry, change analysis now routinely involves meter to sub-meter level spatial resolution and displacements determined at the sub-centimeter to meter scale. These methods have been applied to study steady or abrupt landscape change, and to study processes such as landslides, earthquakes, or the deposits from volcanic eruptions using landscape change. However, quantifying some surface processes can be difficult, such as when displacements (e.g. debris flows, alluvial fans) are much larger than the slow solid-earth elastic displacements associated with much of the earthquake cycle.

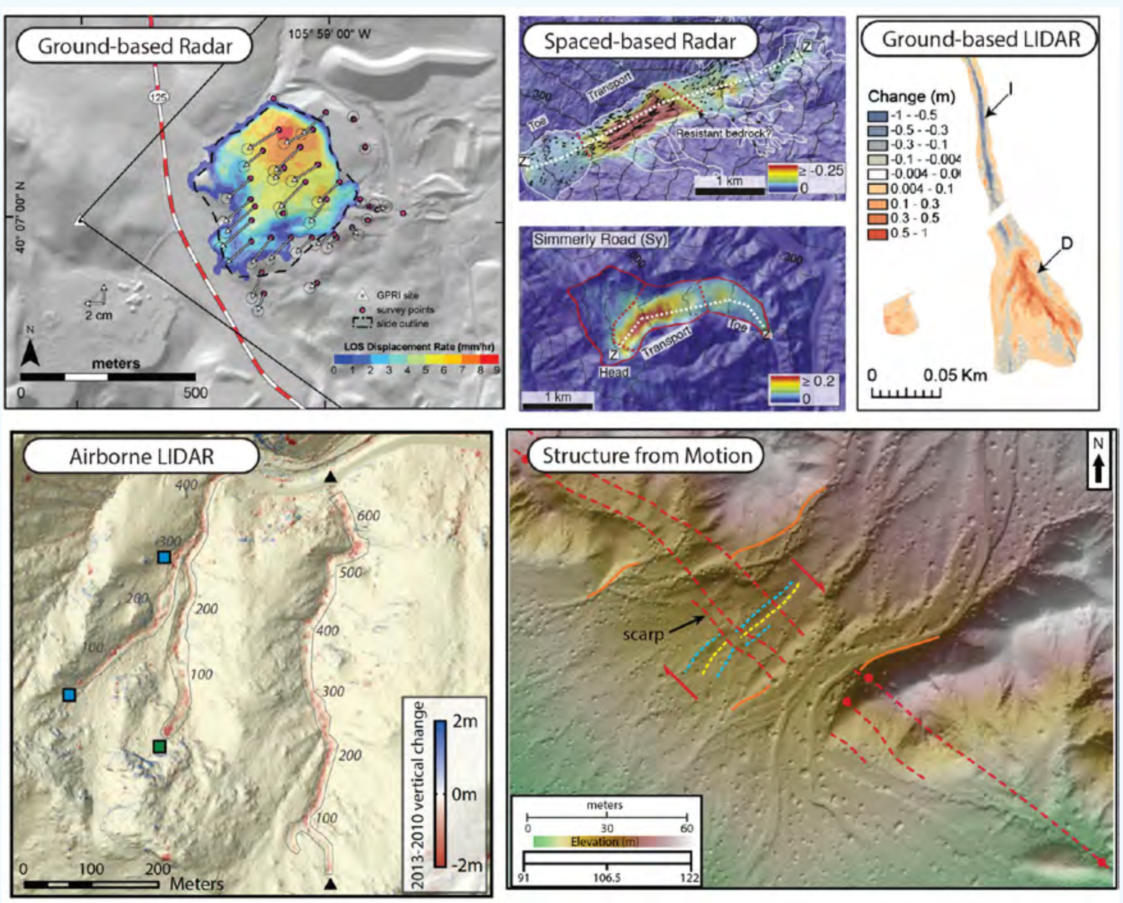
Geophysical Inversion: Inverting surface displacements to estimate parameters of an Earth model is at the heart of modern geodesy. The field has recently exploited the continuous accelerating of computational power to develop new approaches to modeling (e.g. Bayesian inversion, machine learning) that analyze exceptionally large suites of forward models. Adjoint inversion techniques are also increasingly used. A current area of interest in geophysical inversion, for instance, is in better assessment of model uncertainties in addition to data uncertainties. Improved inversion and geophysical inference tools are the critical 'last mile' in moving from one-off model explanations to more robust understanding.

Community-building Challenges

One of the biggest challenges is defining what various users and stakeholders actually want, so that scientific products and information will be useful to them. However, it is difficult to deliver scientific information that is technically correct, but distilled in a way that inspires understanding and trust among non-experts. Problems in landscape change and evolution are directly tied to problems in hazards, land use, and sustainability, which are relevant to policy and political choices. This increases the stakes of public engagement, and suggests that effective communication may benefit from an increased understanding of the social sciences.

Spotlight: High Resolution Landscapes

The past decade has seen the Surface and Landscape evolution community enthusiastically embrace and stimulate innovation of geodetic techniques. We now have the capability to make measurements at the joint spatial (meters to kilometers) and temporal (minutes to years) scales that are matched with the underlying physics of surface and landscape evolution processes. Platforms can be static or mobile and space-, aircraft-, vehicle-, or ground-based. They can be part of a routine data acquisition program or deployed rapidly to respond to crises or extreme events. Some of the techniques can quantify surface change from features that maintain radar frequency coherence during motion (such as ground- or space-based interferometric radar). When larger relative motions occur, high-resolution topographic data from laser scanning or photogrammetric data can be differenced along coordinate axes or combined with point-cloud displacement field techniques to create spatially complete 3-D displacement fields.



The figure highlights published results that use distinct geodetic techniques for illuminating surface and landscape evolution processes. Ground-based radar (Lowry et al., 2013) (top left) permits imaging of a spatially complete surface displacement field (~0.75-4 m pixel spacing) of an active landslide moving at rates of mms/hr. Space-based radar (Handwerger et al., 2015) (top center) detects active landsliding over survey regions on the order of 10s to 100s of kilometers. Ground-based LIDAR (Orem and Pelletier, 2015) (top right) maps topgraphic change of distinct alluvial fan building events. Airborne LIDAR (Anderson et al., 2015) (bottom left) documents debris flow mobilization for a regional extreme rainfall event. Structure from Motion photogrammetry (Johnson et al., 2014) (bottom right) allows individual researchers to create their own high-resolution topographic map of particular features such as a fault trace crossing an alluvial fan outlet.

Box 4: Emerging geodetic methods

Longstanding techniques for geodetic measurements are highlighted in box 2. However, more recent innovations, that either use existing data streams in new ways or develop new kinds of sensors, offer tremendous potential for advances the coming decade and beyond. Some examples include:

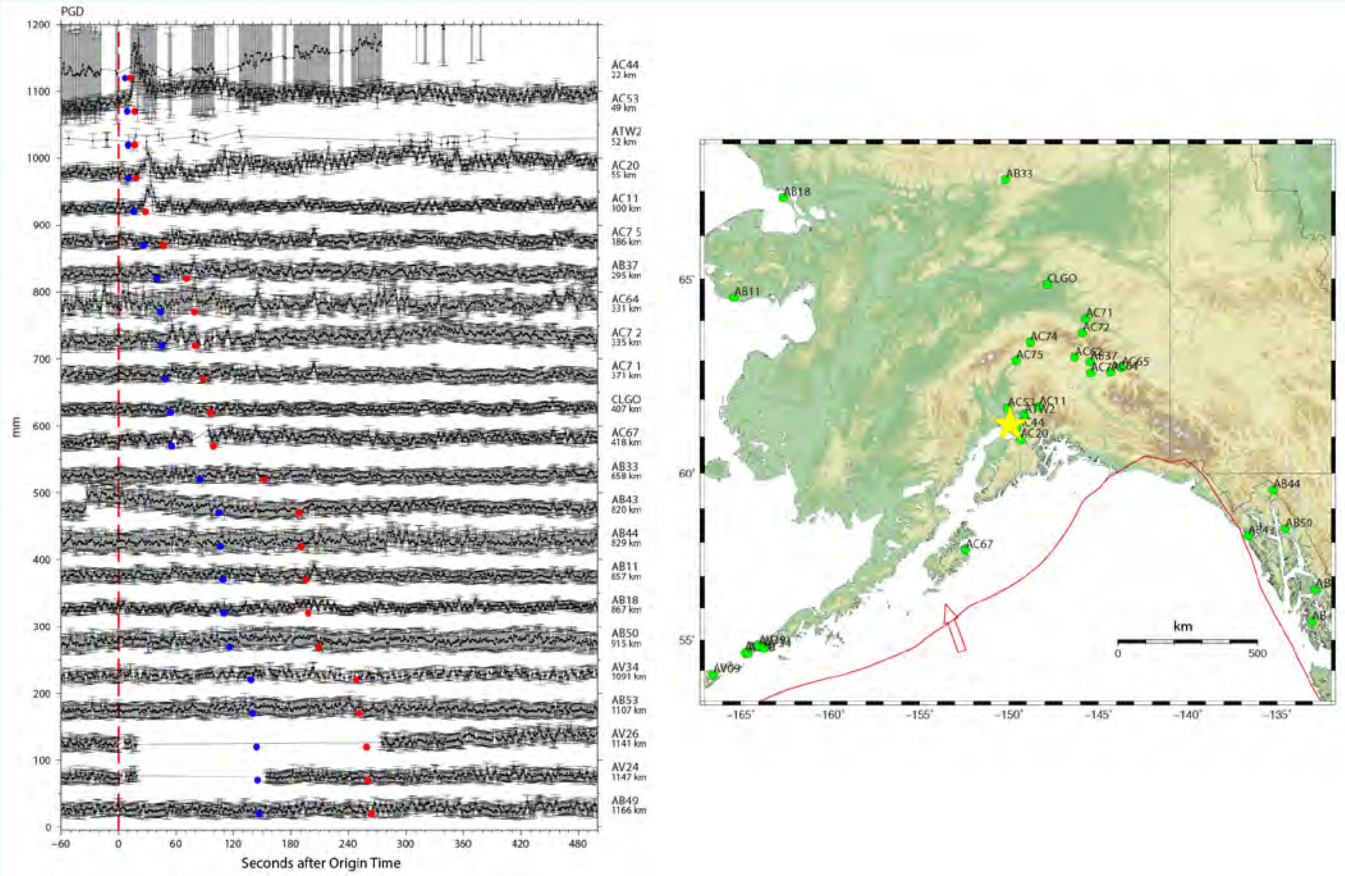
GNSS reflectometry: This method uses radio waves bouncing off the land, snow, or sea surface that are then recorded in a conventional GNSS receiver. The delay of the reflected phase compared to the direct arrival allows for estimation of changes in the land surface, such as from permafrost melting, snow surface, such as from snow accumulation or melting, or sea surface from tidal forcing, storm surges, or sea level change. Combinations of such sensors distributed globally on shorelines offer a unique measure of global sea level change.

High-rate GNSS: Geodetic observations collected at high rates (up to 100s of observations per second in some cases) combined with rapid transmission of observations, automated position estimation, and machine learning for identification of large motions can be used to identify and characterize major earthquakes in seconds to minutes. These data can be used to learn new things about the basic physics of earthquakes, tsunamis, and other rapid changes to the Earth, and to provide earthquake and tsunami early warning. Timely early warning and rapid event characterization have the potential to save lives and money, either by getting people out of harm's way or by optimizing rapid response to natural disasters.

Sea floor sensors: Many of the most dangerous tectonic features, such as major earthquake faults or volcanic systems, are located entirely or partially on the sea floor. Most current geodetic technologies only work on land, but newly mature approaches allow measurements of motion underwater, both to extend the basic research already done with geodesy onto the sea floor and to generate new understanding and new kinds of warnings from submarine data.

Rapid-repeat radar and optical sensing: New space-based sensors collecting optical and radar observations of the Earth's surface pass over every point once every six days or less. This means that changes to the surface can be identified very quickly with high spatial resolution. Such change detection combined with machine learning tools can map the damage from major natural disasters fast enough to assist with emergency response and recovery. For smaller changes, the huge amounts of data collected will allow much better resolution in time, capturing and quantifying the subtle and slow processes that shape the surface. Automation of complicated data processing, especially radar interferometry, will make change detection much more accessible for research questions beyond earthquake displacement and volcanic inflation or deflation.

Large-N sensors: The development of inexpensive kinds of sensors, combined with automated data processing algorithms promises to allow much higher spatial resolution of phenomena without high instrument costs. For example, large numbers of inexpensive GPS instruments could be deployed on volcanoes or on ice if the cost of losing some of them is negligible. Combined data from hundreds of thousands of sensors in mobile phones or other equipment with non-scientific uses can be co-opted for scientific research by leveraging the huge amount of data to reduce noise.



High-rate GPS sensors (data on the left) were used to correctly estimate the magnitude of the 2018-11-30 M 7.2 earthquake NNW of Anchorage, Alaska in less than two minutes using the stations shown in the map on the left. The magnitude determination from the global seismic network took more than 10 minutes.

Chapter 7 What Do New Approaches Promise for Hazard Forecasting, Warning, and Rapid Response?

Key questions

1. How can ubiquitous real-time data flow and processing enable science and early warning in the geodetic realm?
2. How can we use geodetic data to identify new high-risk zones, particularly in the built environment?
3. How do geodetic data inform forecasting, warning, rapid-response, recovery, and long-term consequences of natural hazards? How can geodesy be used to optimize hazard preparedness and mitigation?

Natural hazards are extreme manifestations of the ongoing processes that shape and govern our dynamic Earth. Drought, floods, extreme weather, landslides, earthquakes, and volcanic eruptions are outliers in the processes of normal water cycling, energy exchange between the atmosphere and oceans, erosion, and tectonic activity. Studying these processes helps us understand their associated hazards. Understanding and quantifying the processes that control Earth systems and their coupling improves our capacity to mitigate hazards, creating more resilient communities.

Geodetic research into hazards can be separated into three categories. First, the observation and study of underlying earth dynamics (Chapter 1, How are Ice, Oceans, and the Solid Earth Coupled in Space and Time?; Chapter 3, How Do Fault Mechanics Influence Earthquakes and the Earthquake Cycle?; Chapter 5, What Can Observations of Surface Deformation Reveal About Magmatic Processes and Volcanic Hazard?) informs decision making about the potential for event triggering and enables physics-based probabilities for event timing and magnitude. For example, studying the basic mechanics of masses under gravitational loads helps us estimate landslide frequency and how it can change over time. Second, the direct observation of extreme and hazardous events helps us better understand their nature and characteristics. Because natural hazards are often the consequence of strongly nonlinear feedbacks, it may be difficult to extrapolate from normal events to understand extreme hazards. For example, feedbacks among degassing, magma viscosity, and conduit pressure can substantially change the style of eruptions at a particular volcano. Finally, advances in identifying precursory signatures with real-time monitoring represent the most direct application of geodetic methods to hazards, with a focus on earthquake, tsunami, and volcanic early warning. These three themes broadly encompass the challenges for the future, with goals in basic research to illuminate the spatial and temporal distribution of hazards, goals in event observation to quantify and appreciate the details of catastrophic events, and goals in low-latency monitoring to issue timely warnings and facilitate the most-rapid response.

Providing science-based tools and solutions for hazard monitoring and mitigation encapsulates the 21st century role of science as a bridge between human communities and the natural environment. The better we understand basic Earth systems, the better informed our related ethical, cultural, and political decisions will be. Geodetic research and applications for hazard mitigation is cross-disciplinary and socially relevant, and can serve as a concrete example of how science improves the human condition.

Scientific Challenges

Basic research in natural hazards is basic research in Earth systems and processes. Looking at extreme events in power law distributions can be informative, but we often build our information with limited knowledge. How well are we prepared for "Black Swan" events, and what can we do through better science to illuminate their hazards and reduce risk? Pathways to improving our scientific understanding of hazards include:

1. Improvements in physics-based models for extreme events.
2. Characterization of critical parameters that influence transitions from "typical" to "extreme" events.
3. Characterization of interactions among processes, especially those that couple hazards leading to multi-hazard cascades. For example, we broadly know that drought influences wildfire, which in turn influences landslides, but the specific coupling across hazards is poorly understood and incompletely quantified.
4. Identification of useful precursory and forecasting signals.
5. Improvements in methods for handling observational uncertainty in both basic research and applied products.
6. Monitoring of slowly evolving hazards including coastal flooding due to sea level rise, coastal subsidence, and urban subsidence.

Technological Challenges

To achieve the goal of using geodetic observations for hazard early warning and forecasting, we need to overcome substantial technological challenges in data collection and handling. Data need to be freely and rapidly available in formats accessible for users from different fields and with various levels of experience. In particular we require:

1. Low latency tools and methods for delivering data from large, spatially distributed sensor networks.
2. Low latency tools and methods for automatic identification, discrimination, and verification of critical signals that indicate either increased risk or event occurrence.
3. Sensor placement in remote but critical regions, including the seafloor and parts of the cryosphere.
4. Full integration of data streams from many different kinds of sensors, including ground-based GNSS, GNSS-IR, seismometers, and space-based InSAR, gravity, and optical imagery.

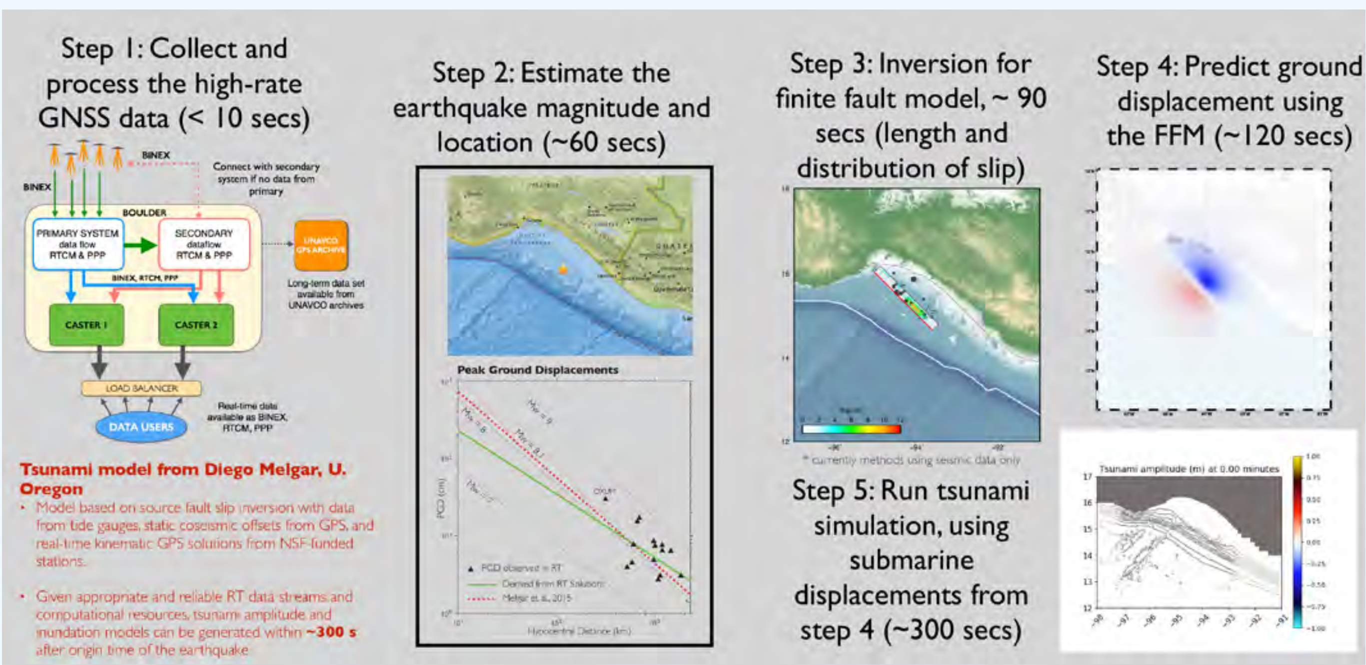
Community-building Challenges

This topic, perhaps more than any other, requires close interaction between the scientific community and many other stakeholders. Science-based hazard warnings and early response are useless if the public, public officials, and first responders do not know how to use them. Therefore, building community resilience to natural disasters requires:

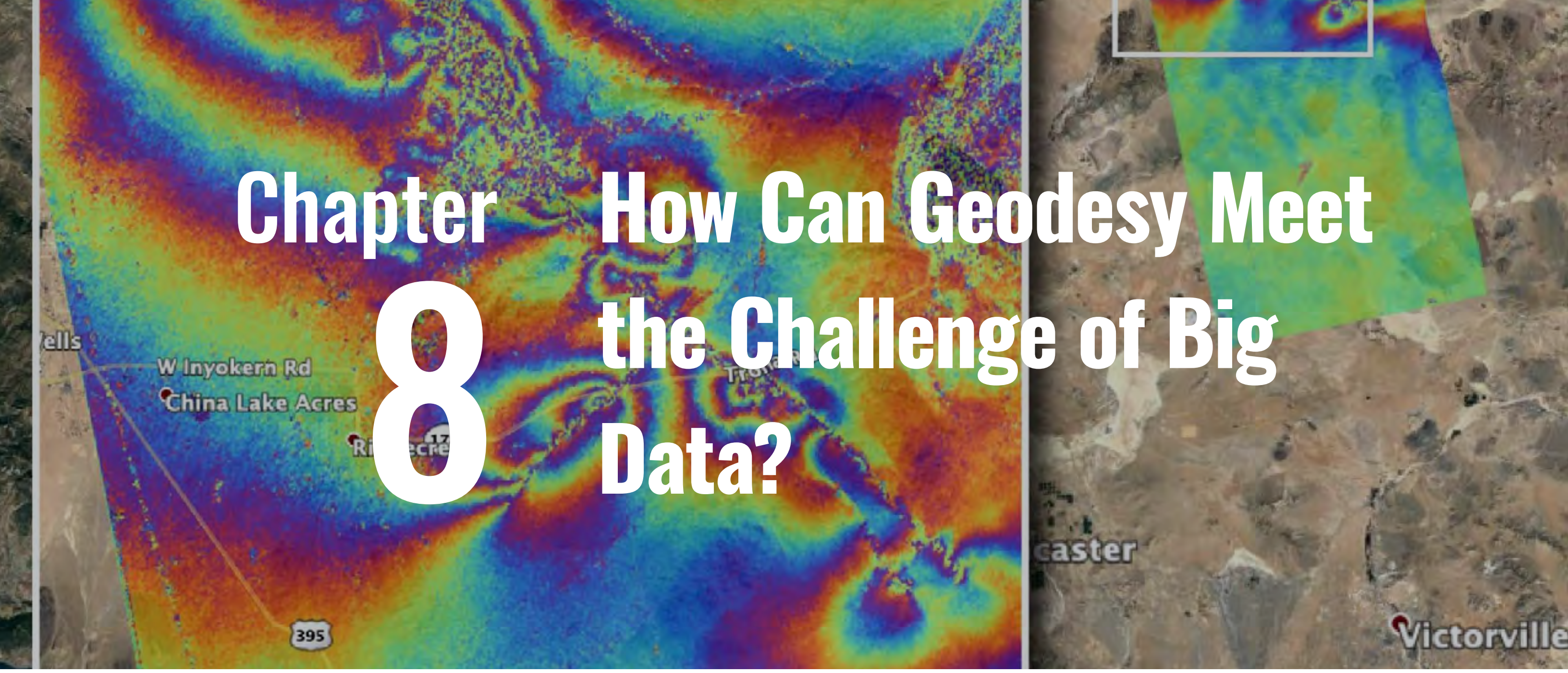
1. Communication of hazard science, preparedness, and mitigation strategies to many audiences with varied backgrounds and skills.
2. Clear integration of the best science into the risk governance cycle by: quantifying spatial and temporal risk, effectively disseminating warning information for accurate and timely characterization of changing risk, rapidly assessing hazard impact and aiding in efficient resource allocation, and identifying and quantifying follow-on cascading hazards.
3. Efficient support for the highest-risk communities through accurate classification of spatial and temporal risk.

Spotlight: Earthquake and Tsunami Early Warning

Although the global seismic network is designed to rapidly identify, locate, and quantify large earthquakes, two limitations on the speed of that determination exist. First, seismic waves must travel from the source to enough recording stations to precisely locate the event. These waves travel at velocities ranging from 2-13 km/s. Second, the early part of the seismic coda does not differ much, if at all, for events with a wide range of magnitudes. Therefore, event determination is fundamentally limited by seismic velocities and ambiguity in magnitude persists for at least several minutes. GPS and GNSS displacement observations from the epicentral region address both of these problems. First, information about events detected locally can travel at the speed of light through communication networks, speeding ahead of the seismic waves. Second, because of systematic scaling between displacement and magnitude for earthquakes, the near-instantaneous coseismic displacement is a robust indication of the event magnitude. Low-latency GNSS tsunami and earthquake early warning involves: 1. Collection and automated processing of high-rate GNSS data from the epicentral region (<10 s), 2. Estimation of earthquake magnitude and location from displacements (~60 s), 3. Inversion for a finite fault model (~90 s), 3. Prediction of ground displacement from the finite fault model (~120 s), and 5. Calculation of a tsunami simulation using the submarine displacements (300 s). In this sequence, an earthquake location and magnitude are available around a minute after rupture, a tsunami warning after 4.5 minutes, and a full tsunami forecast in less than 10 minutes, which is shorter than the arrival time for the tsunami for all but the closest shorelines. This gives threatened populations time to get out of harm's way.



Chapter 8 How Can Geodesy Meet the Challenge of Big Data?



Key questions

1. How will the geodetic community manage the growing volume and velocity of data in a big data future?
2. What are the implications of increasing demands by funding agencies and scientific journals for open data and open-source processing and analysis?
3. How do we enable joint access and analysis of complementary data from different sources?

Geodesy has become a data-rich field, with accelerating data volumes and availability driving expectations of open access to all data sources. Furthermore, as data sampling rates have increased, data latency has decreased. Although some parts of the world remain poorly sampled, we are approaching a future in which we have data everywhere, all the time. That future is already here in the case of current and planned InSAR satellites, and the experience of those missions in handling their data challenges provides a roadmap for thinking more broadly about impending changes in the field. In the case of InSAR, shorter sampling periods and broader coverage are resulting in the ever-faster accumulation of increasingly massive data files. Transmitting these files across the internet comes at a high price to data providers, and processing these files to recover information about surface change is beyond the expertise and computational reach of most users.

Similar challenges are afoot for other sensors and techniques, including in airborne and terrestrial LIDAR (up to billions of individual surface height measurements per survey), satellite laser altimetry (billions of measurements per day), and even legacy GNSS networks that are transitioning to high rate sampling (hundreds of millions of observations per day). Data are now available from more than 15,000 continuous GNSS stations around the world, and the number of installed instruments continues to grow. Multiple InSAR satellites already repeatedly image most of Earth's land surface on timescales of days to weeks. This firehose of data from a multitude of sources can easily overwhelm the physical resources and data management expertise of individual research groups, as can the data processing required to convert raw space geodetic observations into estimates of position and displacement.

Another significant change in geodesy has been the steady migration of academic research away from technical R&D and small-scale instrument deployments and toward the analysis and interpretation of geodetic network data. In the 1980s, most scientists working in geodesy were experts in all aspects of geodetic data collection, processing, and analysis. The emergence of continuous data acquisition and telemetry in late 1990s catalyzed the transition to operational geodetic networks, managed primarily by non-academic institutions (e.g. USGS and the SCIGN GPS network, UNAVCO and the Plate Boundary Observatory). Data processing techniques eventually matured, and today, geodetic network data processing is handled primarily by federally funded analysis centers that produce well-documented position data using best practices. Network data analysis and interpretation is still the domain of individual investigators, who are now free of the burden of keeping up with technical advances in processing algorithms and hardware.

Three fundamental challenges remain. First, even though terrestrial network processing is largely in the hands of experts, the flood of processed data is reaching levels that require the same data handling capabilities that used to be required only of technical domain experts. Additionally, airborne and satellite platforms are adding immense volumes of geodetic data at regional and global scales, multiplying the data challenge. Second, the value added from scientific research is now firmly in the domain of data analysis and interpretation, with many promising avenues requiring ease with observations outside the field of geodesy, an emphasis on big data approaches to analysis (e.g. data mining, machine learning), and facility with new numerical modeling codes that have rapidly democratized access to cutting-edge analysis. Finally, the paradigm of open data has spread to analysis, with journals and funding agencies increasingly requiring all code used to be open source. While this is a big step in the direction of transparency and reproducibility, it can be unpalatable to investigators who have built significant intellectual property in the form of code and workflows, and deeply disruptive to current practices.

Taken together, these changes represent a major challenge to the status quo in the geodetic sciences and beyond, but they are also a timely opportunity for greatly increasing our community's scientific throughput and impact.

Scientific Challenges

New Algorithms and Approaches: As data volumes and velocities increase, direct human input is becoming a smaller component of the data processing workflow. Similarly, increasingly voluminous data sets, often extending over continental or global scales, cannot be interpreted without resorting to new analytical tools and extensive automation. The recent boom in machine learning and Bayesian analysis in the Earth sciences is a direct response to this challenge, harnessing new theoretical techniques and greater computational firepower to tame big data problems. Applications that are poised to benefit from new approaches include detection of crustal motion transients on varying spatiotemporal scales in noisy data, identification of components of the earthquake cycle in extended geodetic time series, early warning of geophysical hazards from high-rate real-time data streams, and quality control of time series data.

Powerful and intuitive new data tools already exist, typically accessed via web interfaces. Examples include the NSF-funded OpenTopography service for accessing and processing geodetic point clouds and Google's Earth Engine for analyzing large raster data sets. NASA's future geodetic missions such as NISAR will rely on centralized, cloud-based processing to produce the higher-level data products that used to be the responsibility of individual investigators. These developments are fundamentally changing the emphasis of geodetic research, away from domain knowledge in details of instruments and processing, and toward high-level analysis of large data sets.

From an education perspective, change is driving a need for greater integration between data science and traditional geodesy and geophysics, and first movers will gain an advantage over peers and peer institutions. This is reflected in the recent increase in university investment in the data sciences on both research and teaching, with the goal of broadening campus efforts in fields such as statistics, data mining, programming, data management, geospatial analysis and visualization, and numerical modelling. Critical algorithm targets include:

1. Simple and economical tools for cloud computing.
2. Standardized metadata for large data sets.
3. Seamless, distributed data processing tools.

Open Data, Open Sourcing, and Community Processing: Recent trends are moving processing to where data are stored and giving individual researchers almost unlimited access to cyber resources at low cost (e.g. Google Earth Engine, OpenTopography, OpenAltimetry), even as traditional High Performance Computing resources at NSF and NASA are becoming more accessible. In return for access to computing and financial resources, funding agencies are increasingly expecting not only that newly collected data be openly available, but that processing code and analysis products be openly sourced. High-impact journals such as Nature and Science are leading the way in imposing these requirements on published products of scientific inquiry. These changes require community responses including:

1. Mechanisms for stakeholder engagement in development of computing resources.
2. Clear and transparent data and metadata formats and standards.
3. Centralized and highly-accessible repositories for data and derived products.
4. Enforceable standards of practice for use of data and derived products from open repositories.
5. Innovative multidata visualization and assimilation tools.
6. Pathways for training new users in data processing, as well as in understanding the strengths and weaknesses of multiple types of data, including both epistemic and aleatory uncertainties.

Technological Challenges

In the context of big data, technological challenges tend to be intertwined with the scientific challenges. However, a number of clear needs can be identified which need technological or legal solutions, or community standards. These include:

1. Continuous real-time geodetic data collection and low-latency telemetry.
2. Fusion of high- and low-quality sensors into single networks.
3. Scalable cyberinfrastructure.
4. Equality of access to data and tools, in response to agency/journal demands for open data and open source code.
5. Robust standards for data sharing and access across fields.
6. Security of intellectual property in the cloud.

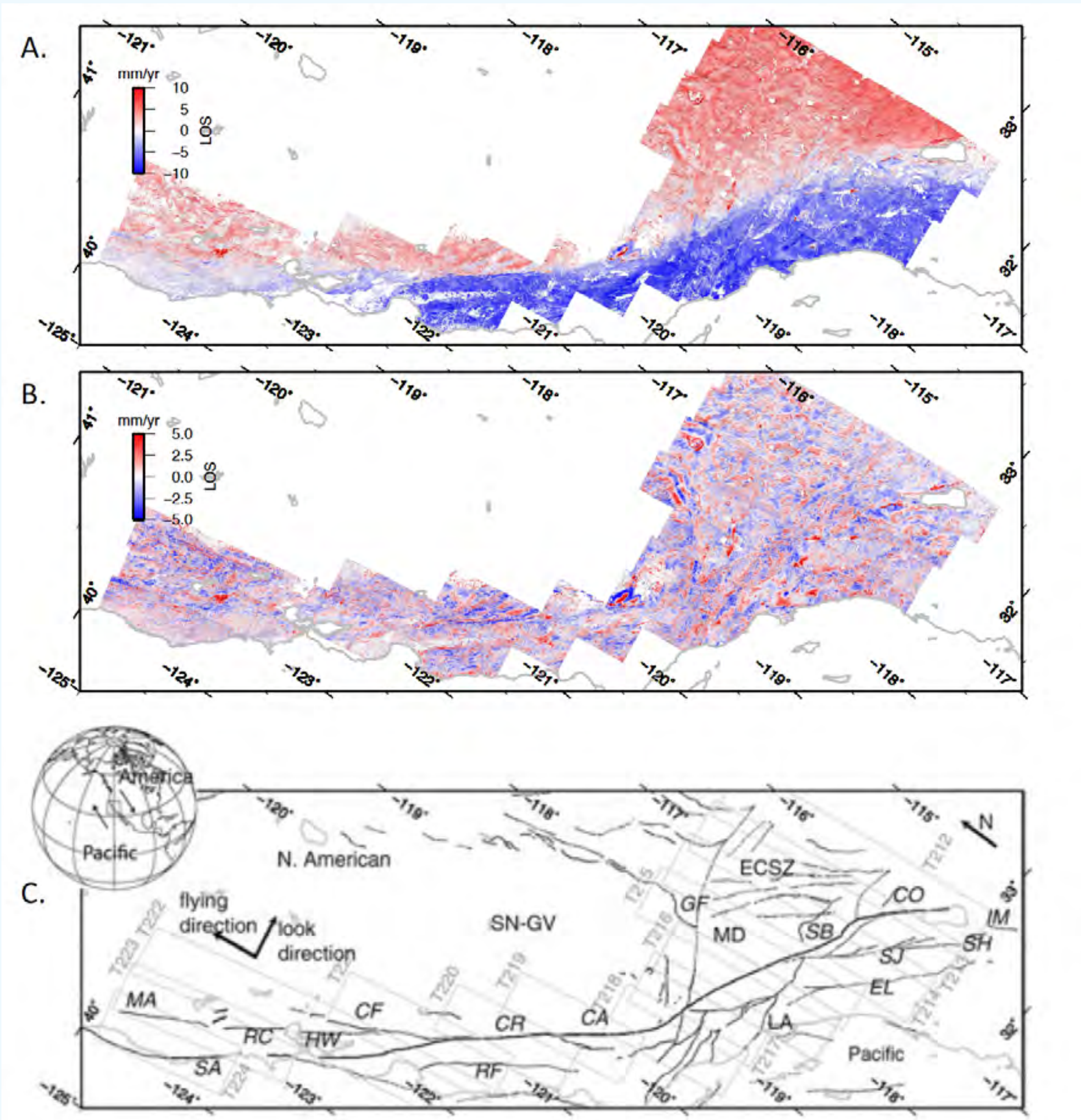
Community-building Challenges

With unprecedented access to potentially novel data and data products, the geodetic community must work with diverse stakeholders to make sure that they are used appropriately. For example, position outliers in a real-time, low-latency observation network could be indicative of a major natural disaster or simply a failing sensor. Expert interpretation of technical scientific observations remains critical, especially in hazard mitigation and response. At the same time, access to information about geodetic events at all length and time scales can inspire future scientists and can remind people of the basic value and relevance of scientific inquiry. Therefore, data-driven community challenges include:

1. Leveraging charismatic geodetic data sets (e.g. three-dimensional surveys of Mount St. Helens dome growth) to stimulate public interest in science.
2. Inspiring the next generation of data scientists with Earth processes and the next generation of geodesists with data challenges.
3. Making geodetic data broadly accessible to non-expert users.

Spotlight: InSAR and the challenge of big data

Satellite Interferometric Synthetic Aperture Radar (InSAR) is a technique for recovering mm-scale earth surface deformation from radar images taken from space. Processing the 1100 interferograms used to map the San Andreas Fault interseismic surface displacements shown below (Tong et al. 2013) was a computational challenge that is beyond the capability of most users. The latest SAR satellites image most of Earth's surface every 6 to 12 days and can generate tens of TB of data each day, posing both a challenge and opportunity for researchers investigating broad-scale deformation from processes such as tectonics and permafrost degradation.



High-rate GPS sensors (data on the left) were used to correctly estimate the magnitude of the 2018-11-30 M 7.2 earthquake NNW of Anchorage, Alaska in less than two minutes using the stations shown in the map on the left. The magnitude determination from the global seismic network took more than 10 minutes.

Box 5: Emerging geodetic results

Both well-established and new (Box 4) geodetic methods have produced major advances in Earth sciences in the past few years, with the promise of exciting additions to come. Some particular recent contributions from geodesy include:

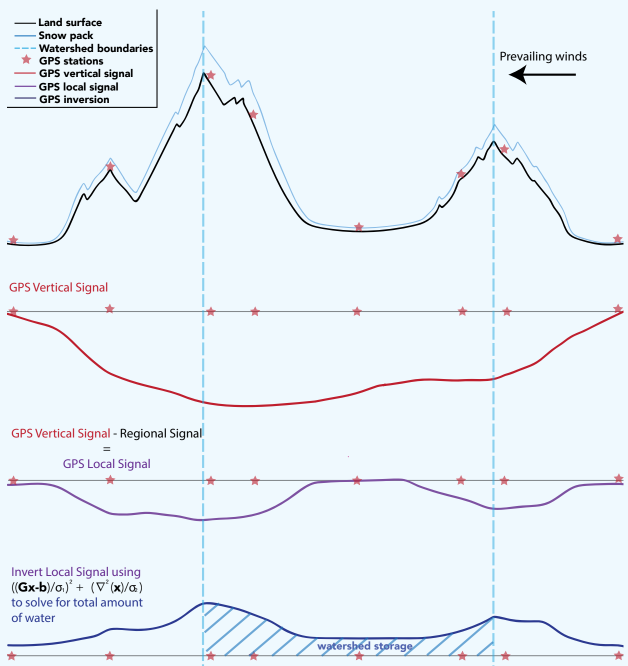
Hydrologic mass balance: GNSS displacement time series plus ground- and space-based gravity observations allow us to measure where and when water mass moves around on the planet. These techniques have been used to show the accumulation and runoff of water in seasonal snowpack, loss of water mass in extended droughts, the acceleration of ice mass loss in Antarctica and the Arctic, and the accumulation of water mass in major precipitation and flooding events such as Hurricane Harvey.

Broad-spectrum deformation: Geodetic observations were critical in first capturing evidence of a previously unknown mode of slow fault motion, episodic tremor and slip (ETS), in the early 21st century. These techniques and observations have now been extended over longer time scales and to different fault zones to show that deformation of the crust, especially around major faults, happens at many different rates and durations. We observe elastic loading and unloading of faults in the traditional "earthquake cycle", but these motions are modulated and complemented by multiple modes of fault slip. and changes in the shape of bulk materials. Some of these do not emit strong seismic waves, or that produce unique seismic signatures. Fault creep facilitates the interactions of fault systems over long distances, and impacts the energy budget that determines earthquake risk.

Adjoint inversion: The mapping from displacements of the Earth's surface to a source of deformation within Earth is nonunique, which means that many different causes can produce the same or similar observations. However, new inversion methods allow for statistically rigorous combinations of many different kinds of data with different precisions and different resolutions in space and time, and this helps us to find unique or the most appropriate solutions using multidata. This approach allows us to differentiate between competing hypotheses about the basic physical properties and behavior of the solid Earth.

Shallow-water bathymetry: Space-based laser scanning of the Earth's surface not only improves our mapping of dry land, but also of the shallow marine environment. High-resolution bathymetry opens a whole new world to detailed mapping and change detection to observe the processes of surface change in the near-shore marine environment. This area is where human impacts and climate change effects will be concentrated, so measuring and evaluating change is expected to yield important new results in the coming decade.

Ionosphere and troposphere mapping: GNSS signals are sensitive not only to changes in the position of ground-based receivers, but also to changes in the properties of the ionosphere and troposphere. GNSS data can therefore be used to map tropospheric wetness as a new set of observations for weather sensing and forecasting. They can also be used to capture ionospheric perturbations related to ground deformation, tsunami-related gravity waves, and space weather.



The total weight of water stored as mountain snow can be estimated from the vertical displacement of the Earth's surface bending under the load. Regional loading for a whole mountain range can be separated from the load in a single watershed with enough observations.

Summary and Recommendations

Geodesy has been evolving and advancing over the last several decades, as dramatic improvements in the precision and accuracy of measurements has enabled new areas of science. To take one example, from the 1970s to the early 2000s, positioning accuracy improved by approximately one order of magnitude per decade. Over the last decade or so, precision and accuracy gains have been slower, but the spatial and temporal coverage of measurements have improved dramatically (by orders of magnitude). Today, the absolute coordinate precision of a single epoch (e.g., 1 Hz) GNSS solution can be comparable to relative coordinate precision from a day of 1980s data. Furthermore, today's solution could be available in real time, rather than months after the fact. Many other areas of geodesy have seen similar improvements in measurement capability.

New technologies and the clever new use of features of existing data have opened up completely new areas of research. For example, making continuous global measurements of the changing gravity field is now the normal, although a few decades ago it was extraordinarily difficult to precisely measure gravity change at individual points. The development of GNSS reflectometry (GNSS-R) methods to do environmental sensing with existing sites is another example, along with the deployment of a GNSS-R satellite (CYGNSS) constellation into space. The next fundamental new development or breakthrough is not so easy to predict, but the history of geodesy tells us that it will come.

The opportunities for scientific study described in this report are thus based primarily on the present measurement capabilities and the advances that we can foresee for the next few years. To use the example of positioning again, one of those is likely to be the full maturity of multi-GNSS positioning, using all of the available constellations and not only or not primarily GPS. Research today is discovering system biases and systematic errors that have always been present in our data analysis; reducing those errors will then reveal some other process as the limiting error source, and work will then focus on improving models, and so on. A similar process of improvement will play out for other geodetic measuring systems.

The previous Grand Challenges report set out the long-term goal of geodesy as "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." The progress of the last decade has clearly moved us closer to that goal, and foreseeable advances over the next years will move us even closer. The recommendations that follow are provided in that context, informed by the scientific opportunities laid out in this report. Realizing these recommendations will bring us closer to truly global coverage, improved time resolution, and near-real time capabilities. The environmental sensing capabilities of geodesy, on the other hand, have already exceeded the forecast and expectations of the decade-old report, opening doors to entirely new science applications. The next spectacular innovation will do the same, likely in some different and new direction. The only constant in geodesy is that the pace of innovation never stops.

As representatives of a diverse and growing scientific community, the Grand Challenges writing team has identified overarching recommendations for investment:

1. Maintain and enhance continuous observations of the dynamic Earth and its environment.
2. 2Undertake geodetic missions recommended by the Decadal Survey, and develop future missions that will further enhance the time resolution and spatial coverage of critical geodetic observations.
3. Improve the accuracy and robustness of the global geodetic reference frame (International Terrestrial Reference Frame, or ITRF), continuing its evolution away from a description of a presumed linearly changing Earth, to fully and self-consistently incorporate the time variations associated with earthquakes, postseismic deformation, sea level monitoring, and mass transport.
4. Implement seafloor geodesy measurement systems and programs to enable study of the kinematics and dynamics of Earth in areas covered by water.
5. Implement real-time analysis systems to produce geodetic products for hazard early warning, situational awareness, and risk mitigation and rapid response.
6. Invest in our community's capacity to handle big data, and integrate data across disciplinary fields.
7. Invest in workforce recruitment and training, education at all levels, and communication of advances in geodesy and their application.

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Rainbow Ridge, Alaska. *J. C. Rollins, Michigan State University.*
Panorama of a POLENET site. *POLENET.org.*

Inside Cover:
Summer Miller surveying a campaign GPS site at Okmok volcano, Alaska.
J. T. Freymueller, Michigan State University.

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Xuankou Middle School, Yingxiu, Sichuan Province, which collapsed during the 2008 Wenchuan earthquake. *J. T. Freymueller, Michigan State University.*

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A continuous GPS site in Antarctica measures changes in the ice sheet. *POLENET.org.*
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Permanent subsidence from groundwater withdrawal in the California Central Valley. *CREDIT.*
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Fault scarp of the Wenchuan earthquake crossing an orchard in Gaoyuan village, near Hongkou, Sichuan Province. *J. T. Freymueller, Michigan State University.*
Chapter 4:
Integrated strength of the lithosphere, from
Tesauro, M., M. K. Kaban, and S. A. P. L. Cloetingh (2012), Global strength and elastic thickness of the lithosphere, Global Planet. Change, 90–91, 51–57, doi:10.1016/j.gloplacha.2011.12.003.
Chapter 5:
Continuous GPS site at Santorini volcano, Greece. *A. V. Newman, Georgia Tech.*
Chapter 6:
True color MODIS image from the NASA Terra spacecraft. NASA, 2001.
Chapter 7:
Network of the Americas (NOTA) site AC59 at Ursus Head, Alaska, with Augustine volcano in the background. *UNAVCO.org.*
Chapter 8:
InSAR deformation map for the 2011 M7.1 Ridgecrest, California earthquake and its M6.4 foreshock.
JPL ARIA Project, https://photojournal.jpl.nasa.gov/catalog/PIA23150

Summary:
Continuous GPS site at Santorini volcano, Greece. A. V. Newman, Georgia Tech.

Back Cover:
Dilational strain (colors) and residual motions relative to North America due to Glacial Isostatic Adjustment. *Kreemer, C., Hammond, W. C., & Blewitt, G. (2018). A robust estimation of the 3-D intraplate deformation of the North American plate from GPS. Journal of Geophysical Research: Solid Earth, 123, 4388–4412.*
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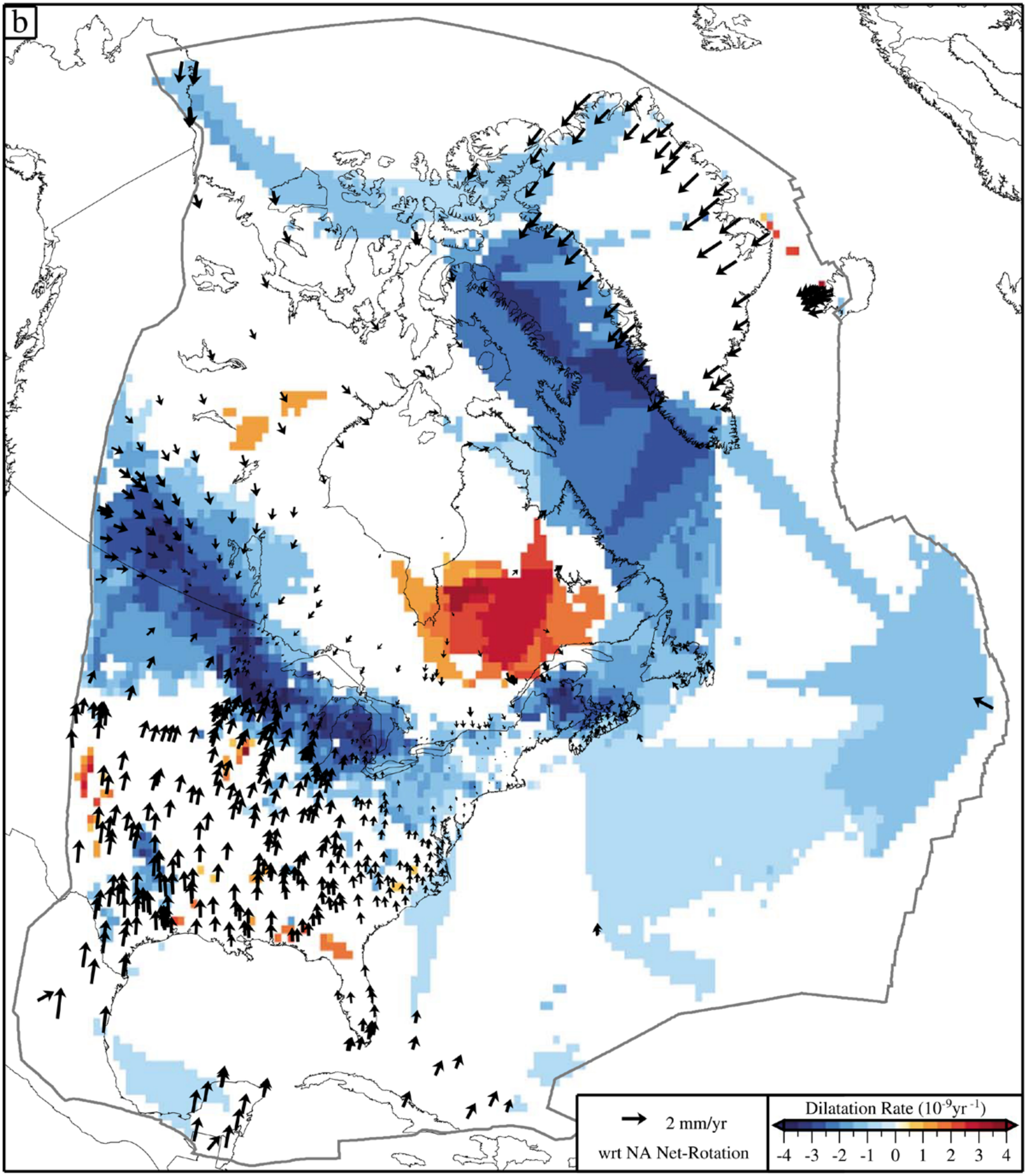
Peter LaFemina, *Penn State*
Noel Bartlow, *Uc Berkeley*
David Schmidt, *University of Washington*
Erik Fredrickson, *University of Washington*
Kristy Tiampo, *University of Colorado Boulder*
Xie Hu, *University of California, Berkeley*
Chris Rollins, *Michigan State University*
Estelle Chaussard, *University of Oregon*
Benjamin Phillips, *NASA*
John Weber, *Grand Valley State University*
C.K. Shum, *Ohio State University*
David Schmidt, *University of Washington*



Measuring the Restless Earth

Grand Challenges in Geodesy