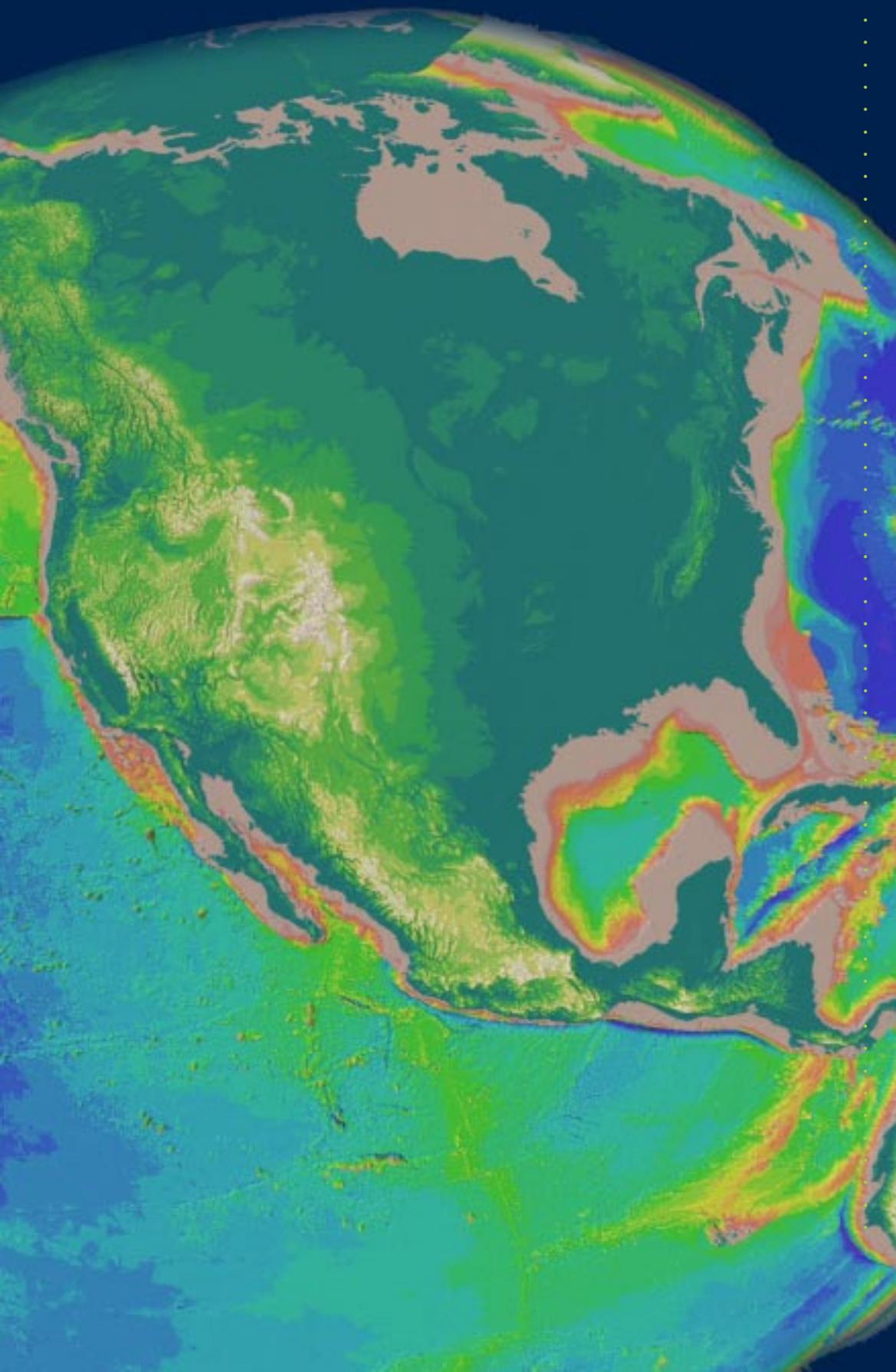


Living on a Restless Planet

**Solid Earth Science
Working Group
Report**



What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?

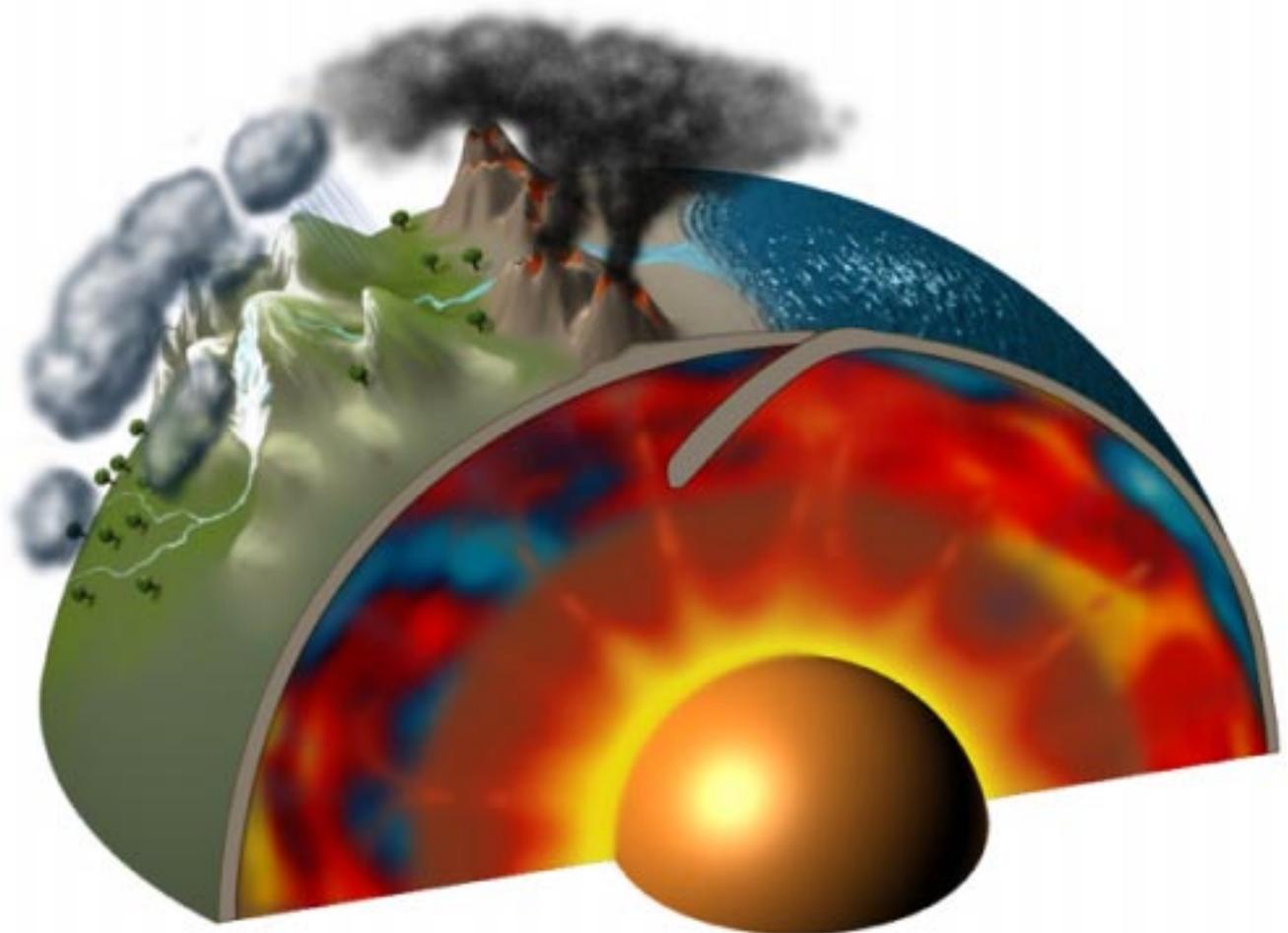
How do tectonics and climate interact to shape the Earth's surface and create natural hazards?

What are the interactions among ice masses, oceans, and the Solid Earth and their implications for sea-level change?

How do magmatic systems evolve and under what conditions do volcanoes erupt?

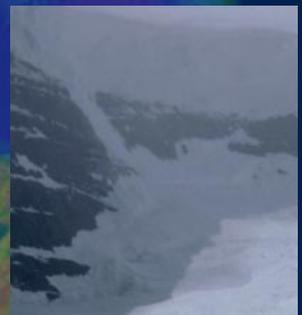
What are the dynamics of the mantle and crust and how does the Earth's surface respond?

What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?



Living on a Restless Planet

**Solid Earth Science
Working Group
Report
2002**



Web site: <http://solidearth.jpl.nasa.gov>

Cover: .
Topography of the Earth with the oceans .
drained reveals spreading ocean ridges .
(East Pacific Rise), subduction zones .
(Middle America Trench), and the .
transform fault boundary .
(San Andreas fault) between the Pacific .
and North American plates. .
Inset, top to bottom: A landslide that has .
destroyed a residential home; a massive .
section collapsed from the four-lane I-5 .
freeway — Northridge earthquake, 1994; .
catastrophic eruption of Mount .
St. Helens in 1980. .
Title page, top to bottom: Aerial view of .
the San Andreas fault slicing .
through the Carrizo Plain in the .
Temblor Range east of the city of San .
Luis Obispo, California. .
In Ice Fields Parkway, Alberta, Canada, .
glacial crevasses (deep cracks in the ice) .
open from the downslope movement .
of the glacier; as glaciers move, they .
quarry and pluck away at the lead sur- .
face on valley floors and along the sides. .
The confluence of the Mississippi, Mis- .
souri, and Illinois rivers are shown in this .
view of the St. Louis area from the .
Shuttle Radar Topography Mission. The .
rivers themselves appear black. The .
floodplains, colored green, are at .
particular risk during times of flooding. .
Color coding is directly related to topo- .
graphic height, with blue and green at .
the lower elevations, rising through .
yellow and brown to white at the .
highest elevations. .

To the Reader,

The surface of the Earth is where we live. Yet our planet is a restless home, subject to earthquakes, volcanic eruptions, destructive floods, landslides, and other natural hazards. The Earth's surface is always changing, in response to processes deep in the planet's interior as well as to a complex suite of interactions among the solid Earth, atmosphere, oceans, hydrosphere, and biosphere. Understanding these changes poses a deep scientific challenge, but meeting that challenge can reap enormous practical benefit.

NASA has an opportunity to make key observations that can revolutionize our ability to characterize, monitor, and forecast changes in our planet's surface. In recognition of that opportunity, Dr. Ghassem Asrar, the NASA Associate Administrator for the Office of Earth Science, appointed a Solid Earth Science Working Group (SESWG) in the summer of 2000. The SESWG was charged "to guide the science community in the development of a recommended long-term vision and strategy for solid-Earth science at NASA."

In the course of our deliberations, the working group sought the advice of experts both within NASA and from other organizations. We briefed our scientific colleagues at two national scientific meetings, and we maintained reports of our progress on an open Web site to invite comments and suggestions from the broad scientific community.

This report is the working group's response to our charge. We hope you agree that this "long-term vision and strategy for solid-Earth science at NASA" not only is scientifically compelling but offers the potential to improve humankind's ability to thrive on our restless planet.

Sincerely,

Sean C. Solomon
SESWG Chair
2002

Fragile Foundations

Over the past several decades, Earth science as a discipline has begun to recognize the dynamic, interconnected nature of the Earth as a system. Each component — oceans, atmosphere, biosphere, and solid Earth — interacts in fundamentally complex ways. Forcings from each component continually drive responses in the other components. Despite the familiar stability implied in “being on solid ground,” the solid Earth is actually a dynamic component of the Earth system. From core motions at the center, through mantle convection, plate tectonics, volcanic eruptions, and land surface evolution, the solid Earth is always changing. Measurements collected in the last decade have shown that it is now possible to study these fluctuations accurately and systematically from space across a wide range of time scales. Space-based technologies are revolutionizing our understanding of the solid Earth, as previously unrecognized subtle changes are revealed on regional to global scales.

Investigating the behavior of the solid Earth yields direct societal benefits. Combining space-based and terrestrial measurements has the potential to reduce significantly the losses due to inevitable natural disasters. NASA-sponsored activities will contribute substantially to our understanding of the processes leading to earthquakes, volcanic eruptions, sea-level rise, floods, landslides, and other hazards. NASA observations and analyses, integrated into ongoing hazards programs in federal, state, and international agencies, will reduce the loss of life and property through improved planning, improved response, and more efficient post-event recovery. In addition, by understanding the underlying forces, we can determine to what extent such natural hazards are predictable. Combining state-of-the-art measurements with advanced modeling techniques will lead to increasingly refined predictive capabilities for the entire Earth science community.

Collapsed apartment building in Van Nuys, California, after the 1994 Northridge earthquake, the costliest in U.S. history. The magnitude 6.7 quake raised nearby Oat Mountain, which overlooks the San Fernando Valley, by more than 30 cm. More than 3,000 homes were destroyed or damaged, and 57 people were killed. Estimates of damage exceed \$20 billion.



Understanding the Solid Earth and Mitigating Natural Hazards

A primary goal of solid-Earth science is the assessment and mitigation of natural hazards that seriously threaten health, safety, national security, and economic viability. Space-based data acquired by NASA and other cooperating federal agencies contribute heavily to our forecasting and understanding of these hazards. The 25-year vision of the Solid Earth Science Working Group (SESWG) is to understand natural and perturbed systems sufficiently well to predict outcomes, consequences, and impacts.



The 1995 Kobe, Japan, earthquake was a comparatively modest 6.9 magnitude event that nonetheless caused 5,480 deaths, over \$150 billion in damage, and a major disruption of Japan's economy with global impacts.

• **Earthquakes** — Earthquake hazards pose a serious risk to the health, safety, and economic viability of many parts of the United States and throughout the world. Recent urban earthquakes, such as Northridge, California; Kobe, Japan; and Izmit, Turkey, demonstrate the risks to modern industrial societies from consequent loss of life, infrastructure damage, and financial instability. Vulnerable populations and infrastructure in low-lying coastal regions are often subjected to amplified shaking, liquefaction, and tsunamis generated by submarine earthquakes and underwater landslides. Major earthquakes can be expected to occur adjacent to or within many metropolitan regions in the United States. How can we apply knowledge of surface deformation to aid in mitigation planning by highlighting regions of likely future earthquakes?

In 1991, Mount Pinatubo in the Philippines erupted with tremendous force, ejecting large amounts of ash and gas into the stratosphere. Strong winds spread the aerosol particles around the globe. The result was a measurable cooling of the Earth's surface for a period of almost two years.



• **Volcanic Eruptions** — Explosive volcanic eruptions pose both short-term and long-term hazards. Volcanic ash clouds can disrupt aircraft travel. Ash from a 1989 eruption in Alaska temporarily disabled all four jet engines on a commercial aircraft that barely managed to

return to Anchorage to land. On longer time scales, these eruptions can inject massive quantities of ash into the atmosphere, greatly reducing the solar heating of the Earth and potentially interrupting the global food supply for several years. Potential sources of massive eruptions in the Western United States include Long Valley caldera, Yellowstone, and the chains of volcanoes in the Cascade Mountains and in Alaska. What measurements can be made that will enable forecasting of eruptions?

• **Floods** — Flood hazards pose a major economic threat in many parts of the United States and the world. For example, the Yangtze River, China, flood in 1998 claimed 3,656 lives, displaced over 30 million people, and cost China \$38 billion. In the United States, the Mississippi River floods of 1993 displaced over 70,000 people, killed 52 individuals, and rendered temporarily useless over 30,000 square kilometers of productive farmland. Damage was estimated to cost \$15–20 billion. Can flood height determinations and floodwave modeling be used to predict inundation depths in near real-time and reduce damage from flooding?

• **Sea-Level Change** — Long-term variations in sea level relative to the solid Earth threaten major coastal cities worldwide. Along the eastern seaboard and Gulf Coast of the United States, sea-level rise combined with severe weather cause significant coastal inundation and erosion.



Shore erosion at Fire Island, New York, illustrates the combined effects of sea-level rise and severe storms on U.S. Atlantic coastal communities.

How do ongoing changes in global climate, ice masses, and land hydrology contribute to the rate of sea-level rise?

• **Landslides** — Throughout the western United States and indeed the world, wherever steep topography and urbanization meet (or are juxtaposed), landslides and debris flows pose a threat. Landslides cause nearly \$1.5 billion in damage in the U.S. each year. Can we provide real-time landslide likelihood by understanding geologic, climatic, and human controls on land surface change?

• **Forest and Wild Fires** — Wild fires destroy natural resources and habitations, accelerate erosion, and promote flooding. How



After excessive rainfall in the spring of 1995, the hillside above La Conchita, California, gave way; 600,000 tons of mud and silt partially buried the neighborhood.



can remote sensing of vegetation, soil moisture, topography, and climatic conditions serve to predict fire hazards and assist in planning fire-resistant communities?

The program described in this 25-year vision for solid-Earth science at NASA will vastly improve our nation's ability to respond to and prepare for natural

disasters. Space-based observations provide a unique capability to sample in detail catastrophic events that while locally rare are more common on a global scale and often occur in remote localities. Through partnerships with mission-oriented agencies, NASA data and models can be integrated with land-based observations to document fully the effects of each natural disaster both during and after an event. Through collaborative efforts, NASA can assist in defining, ahead of time, those regions most vulnerable to the disastrous effects of natural hazards.

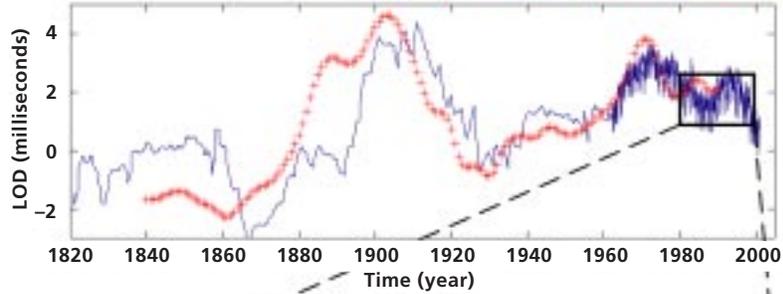
Wildland fires occur globally, the result of both natural and human causes, and are often a direct threat to human lives and property. Space-based monitoring and studies of post-burn areas are crucial to understanding and mitigating the negative effects of uncontrolled fires.

Global Perspectives

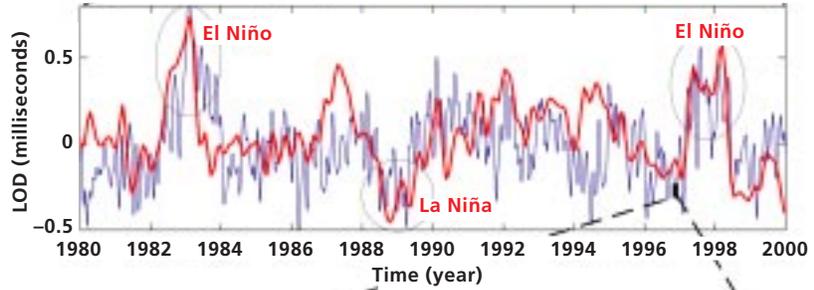
Variations in the Earth's length-of-day (LOD) are caused by many geophysical and climatic processes that transport large quantities of mass in the atmosphere, oceans, land, hydrosphere, solid mantle, and fluid core. Historical and precise modern data tell a fascinating story as shown in this sequence of "zoom-in" charts: The top panel demonstrates that the largest LOD variation is a result of material motions in the core; the middle panel zooms in on the interannual LOD variation caused by El Niño/Southern Oscillation in the tropical atmosphere-ocean system; the bottom panel zooms in yet further into sub-daily LOD variations, for which the ocean tidal motion is shown to be the cause.

Increasingly we recognize that our knowledge of the Earth will be incomplete until we can characterize, understand, and predict the interactions among the different components of the Earth system. The global nature of solid-Earth science requires a wide variety of observational strategies. Particularly critical is the comprehensive, synoptic perspective that is achievable only from space, a perspective that NASA is uniquely qualified to provide.

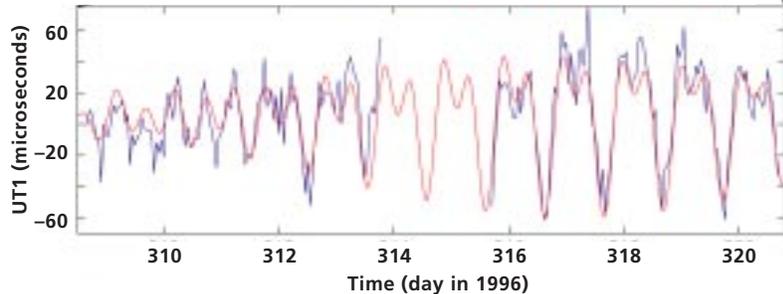
Excess Length-of-Day (LOD): Observed vs. Modeled Core Angular Momentum



Excess Length-of-Day (LOD): Observed vs. El Niño/Southern Oscillation (ENSO)



Universal Time (UT1): Observed vs. Ocean Tidal Angular Momentum



Interactions in the Earth System

The internal dynamics of the Earth are largely driven by the loss of heat from the deep interior. This heat engine drives the generation of the Earth's magnetic field in the fluid outer core. It is also responsible for convective flow in the mantle, which in turn drives the motions of the tectonic plates at the surface that result in mountain building, earthquakes, and volcanism. To understand the generation of the Earth's magnetic field, we must also understand the circulation in the outer core; and to understand convective flow in the mantle we must understand the flow of heat from the core to the mantle.

But the interactions extend beyond the Earth's interior. The Earth's magnetic field protects the atmosphere from space radiation and the solar wind. The interactions of high-energy particles with the atmosphere, mediated by the magnetic field, may play a role in climate change. Variations in the rotation rate of the Earth are coupled to changes not only in the circulation of the atmosphere and oceans but also to the circulation in the outer core and the rotation of the inner core. Large volcanic eruptions inject gasses and particulate matter high into the atmosphere, influencing climate for years.

Humankind's interactions with the Earth system are an increasingly important global component. Activities such as deforestation and excessive agricultural use wreak havoc on the natural processes shaping our landscape. In many cases these activities greatly disrupt the hydrological cycle and expose new areas to the risk of catastrophic fires, massive erosion, or flooding. Quantitatively predicting these impacts to the Earth system will require a fundamental understanding of the energy and mass fluxes in the natural processes shaping the landscape.

Role of Space Observations

Spaceborne data are uniquely suited to providing the synoptic perspective necessary to tie together sets of ground-based measurements on local spatial scales and variable temporal resolution to yield a truly global perspective on Earth processes. Space observations are therefore fully complementary to the often more intensive, local surface measurements that constitute the traditional core of solid-Earth studies. Understanding discrete events on and within the Earth, and from them building a complete picture of our planet's dynamics, requires views of the governing behavior at local, regional, and global scales. For many scientific issues — such as understanding the time-varying internal magnetic field, the deformation around great fault zones, or changing land-use patterns — satellite-based observations are the primary practical means to obtain an adequate density of coverage. Integrating these observations into comprehensive predictive models requires a new generation of satellite measurements at temporal and spatial resolutions substantially superior to those made in the past. Some examples illustrate the compelling opportunities:

• Space-based geodetic observations provide detailed information on the surface deformation adjacent to plate boundaries, both on land and on the seafloor. These observations are essential for understanding deformation of the tectonic plates and the fluid behavior of the mantle below.

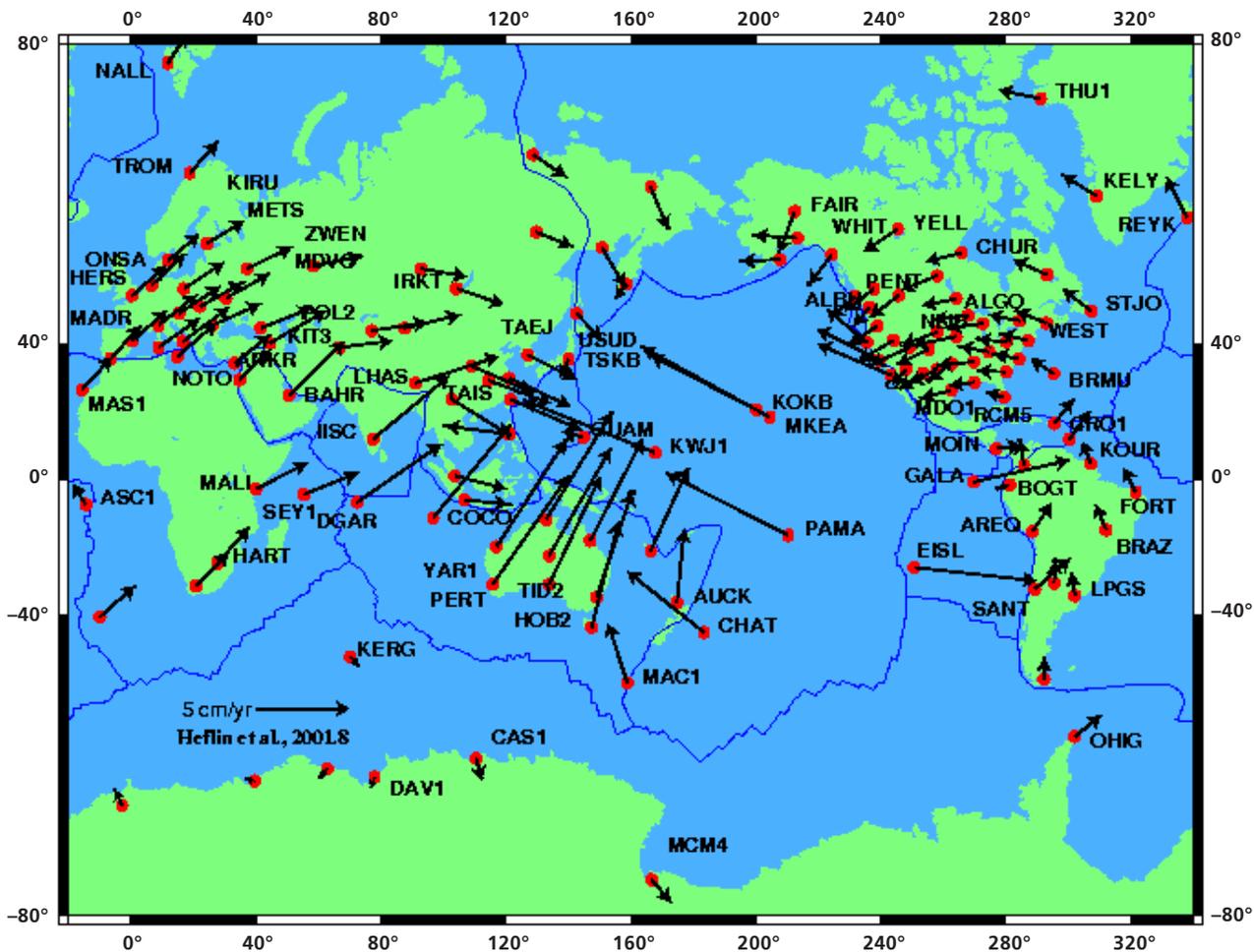
NASA's development of space-based geodetic techniques has revolutionized the science of geodesy. Today geodesy, along with seismology, provides primary data for understanding crustal and mantle dynamics and for evaluating and forecasting earthquakes and volcanic eruptions. Geodetic data include measurements made via satellite laser ranging (SLR), which provides a terrestrial reference frame essential for geophysical and astronomical observations. Very-long-baseline interferometry (VLBI) constrains an absolute reference for the Earth, which quantifies the Earth's rotation. The Global Positioning System (GPS), a constellation of 24 satellites used for navigation and precise geodetic position measurements, provides the position of any point on the Earth's surface with millimeter accuracy. GPS measurements can be made inexpensively, continuously in time, and with relatively dense land networks. Interferometric synthetic aperture radar (InSAR) measures spatially continuous deformation with sub-centimeter accuracy.

• Topographic data provide a record of past interactions among tectonic, hydrologic, oceanic, ice, and atmospheric processes. In modeling these processes, topographic data constitute the basis for predicting where and how hazardous events will impact the landscape and its human occupants. Radar and laser altimetry yield high-resolution topography and its temporal changes for ocean, land, and ice surfaces.

• Space-based measurements of rainfall, river heights, soil moisture, and vegetation change provide critical indices of the most commonly occurring hazards, floods and landslides.

• Space magnetic measurements are essential for mapping and understanding not only the main part of the Earth's magnetic field generated in the Earth's liquid outer core, but also the crustal field, the external field, and currents induced in the mantle by the external field. The combination of satellite-based measurements with numerical modeling promises to lead to a new level of understanding of the generation of Earth's magnetic field.

• Gravity maps provide critical constraints on the Earth's internal density distribution that is responsible for mantle flow. Time-dependent gravity changes monitor interior flow and near-surface deformation during the earthquake cycle, changes in the mass of ice sheets, and changes in the volume of water held in our aquifer systems.



Opportunities in Solid-Earth Science

The beginning of the 21st century is a time of unprecedented opportunity in solid-Earth science. The confluence of advances in satellite-based observing systems, high-performance computing and communications, and recent fundamental discoveries, all over the past few decades, promises an era in which many of the previously seemingly intractable problems in solid-Earth science are now ready to be solved. In the next two decades we will reach a new understanding of earthquakes, volcanic eruptions, wildfires, landslides, floods, and the dynamics of the Earth's core and mantle. NASA has unique approaches to contribute to seizing this scientific opportunity, as outlined in greater detail in this report.

- Horizontal velocities,
- primarily reflecting
- motions of the Earth's
- tectonic plates, are derived
- from daily position esti-
- mates determined from
- satellite signals
- recorded by receivers on
- the ground.

Scientific Imperatives

Scientific goals
and challenges
for the Solid
Earth Science
Program.

Six broad scientific challenges have been identified as highest in priority for NASA's Solid Earth Science Program for the next 25 years. These challenges have been chosen on the basis of four criteria:

- They are of fundamental scientific importance.
- They have strong implications for society.
- They are amenable to substantial progress through new observations.
- There are unique contributions that NASA can make to those observations.

The six challenges (highlighted in the blue table below) also build naturally on directions identified in the NASA Earth Science Enterprise (ESE) Strategic Plan (see the green table below), which was developed through a strong interaction with the broad Earth science community. The six challenges are guiding themes that should define the research objectives for solid-Earth science within NASA for the next two and a half decades.

Systematic observations of seafloor bathymetry, gravity, and the Earth's magnetic field in the 1940s–1960s provided the critical evidence that led to the development of the theory of plate tectonics, the greatest revolution in Earth science history. Over the past 30 years,

ESE Goal and Leading Solid Earth Science Questions

Observe, understand, and model the Earth system to learn how it is changing and the consequences for life on Earth.

- *How is the Earth's surface being transformed and how can such information be used to predict future changes?*
- *What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?*

Scientific Challenges for NASA's Solid Earth Science Program

1. What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?
2. How do tectonics and climate interact to shape the Earth's surface and create natural hazards?
3. What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea-level change?
4. How do magmatic systems evolve and under what conditions do volcanoes erupt?
5. What are the dynamics of the mantle and crust and how does the Earth's surface respond?
6. What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?



many details of plate tectonics have been worked out, although we have come to recognize that the Earth is a complex, interconnected system involving the solid Earth, the atmosphere, hydrosphere, cryosphere, and biosphere. We are still in the infancy stage of understanding this system.

Our focus now is understanding the processes that drive plate motions, deform the Earth's surface, and influence climate. Our goal is to construct predictive models that can forecast change or catastrophic events and predict the consequences of such changes and events through a concerted effort to address the defining challenges identified in this report.

All of these challenges, at least in part, address the processes that transform the Earth's surface. Nearly all of the changes to the Earth's surface are driven, in one manner or another, by the internal heat transport and dynamics of the Earth's interior.

Plate tectonic theory explains the large-scale motions of the outer surface of the Earth. In most cases these motions are associated with the cumulative displacement of earthquakes occurring along and near plate boundaries. What loading processes control the spatial and temporal patterns of earthquakes? How do fault systems interact and over what time scales? How broadly is plate "boundary" deformation distributed?

Earthquakes are just one of a number of natural processes that shape the landscape. Landslides, floods, tsunamis, debris flows, storm surges, and volcanic eruptions sculpt and deform the land as well. How do biologic and climatic inputs modulate the effects of tectonic processes acting on the Earth's surface? What properties should be monitored remotely to provide real-time prediction of natural hazards and their impacts?



• On May 4, 2000, a prescribed fire set at Bandelier National Monument, New Mexico, raged out of control due to high winds and dry conditions, threatening the nearby town of Los Alamos. In all, more than 20,000 people were evacuated and more than 200 houses were destroyed. Images acquired by the Enhanced Thematic Mapper Plus (ETM+) sensor aboard NASA's Landsat 7 satellite reveal the extent of the damage. Combining one visible and two infrared channels results in a false-color image where vegetation appears as bright to dark green. Rangeland appears pink to light purple. Areas with extensive pavement or urban development appear light blue or white to purple. The areas recently burned appear bright red.

• Lava flows are a constant presence on the Hawaiian Islands but still pose questions to scientists trying to understand the physical properties of magma systems, such as magma ascent rates, composition, and the connections between surface deformation and magma chamber activity.

The potential rise in sea level caused by melting of the Greenland ice sheets seriously jeopardizes low-lying areas such as the Florida coast. Red shows where land would be submerged for an estimated 5-m sea-level rise.



Global sea-level change has the potential for a devastating transformation of the Earth's surface worldwide. Sea level is the result of a delicate balance among competing geophysical processes within the solid Earth–atmosphere–hydrosphere–cryosphere system. Can we model the coupled processes that result in the natural variability in sea level? How can we recognize and model the effects of human activity amidst this natural variability? How do feedbacks affect the natural processes?

Processes occurring deep within the Earth drive much of the deformation and change that occurs at the Earth's surface. How does the mantle flow at depth? How do the forces in the mantle and crust cause surface changes? The connections between the core and the Earth's surface through the mantle and crust offer the keys to answering these questions.

The removal of heat from the core by the convecting mantle drives the geodynamo that generates the Earth's magnetic field. Much recent progress has been made in modeling the dynamo process, yet much remains to be understood. How is the magnetic field evolving on annual to decadal time scales? For how much longer will the current rate of decay of the field, sufficiently rapid to eliminate the dipole in 2000 years, be maintained? What role does the core play in the angular momentum balance of the Earth on decadal time scales? How important is the magnetic field in modulating the possible effects of space weather on the atmosphere, and hence on climate?

The goal of this report is to expand on the NASA Earth Science Research Strategy by recommending a long-term vision and strategy for solid-Earth science at NASA. The accompanying integrated program described in this report provides critical input for the next great revolution in Earth sciences, just as the military-driven data sets of the last century led to the theory of plate tectonics. This next revolution will involve development of predictive models of complex, interconnected Earth processes. For these models to be successful, particularly for an understanding of hazards, high-resolution, global observations with real-time or near-real-time data streams and processing will be required. Integrating the huge quantities of data and information being collected into forecast models will demand that information technology resources be developed in concert with advanced sensor and detection capabilities. Understanding the complex dynamics of the solid Earth will require sustained aggressive investments in science and technology over the next decades.

Essential Partnerships



The 25-year scientific program outlined in this report is extremely ambitious. The scientific challenges are broad, and they address goals common to the entire solid-Earth science community. Our success in meeting these challenges will depend on the close coordination and collaboration with other programs within NASA, with other federal agencies, and with international space agencies.

Partnering with Other NASA Programs

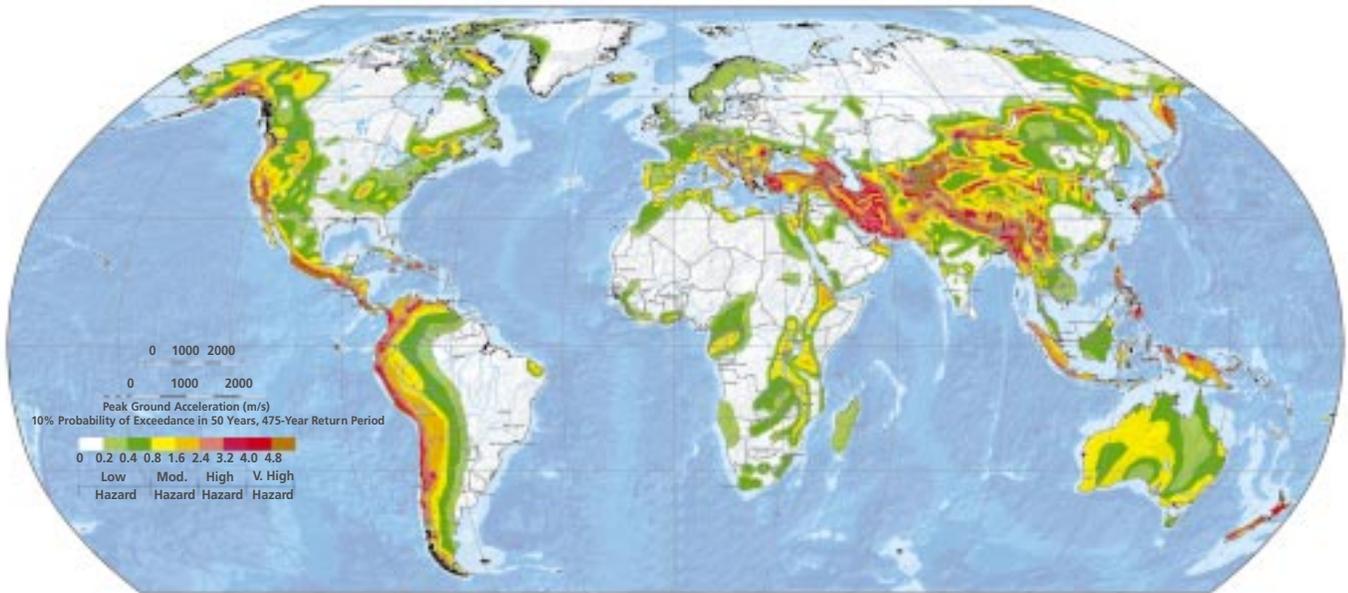
Within NASA there is a significant diversity of research and application programs. The Solid Earth Science Program works closely

with other agency programs to achieve common goals. For example, by combining research, observation, and modeling efforts with another ESE program, Cryospheric Sciences, we expect to make significant advances in our understanding of ice mass balance and sea-level change. Additional examples include the overlapping interests and capabilities of those programs addressing hydrologic and biogeochemical cycles, soil properties, and land cover and surface change. The breadth of NASA's research programs benefits especially those scientific challenges where cross-cutting interests focus attention and resources. Of no less importance is the role of the agency's Technology and Applications programs. The ESE Technology Program supports research by developing advanced technology and tools associated with orbital and suborbital missions using innovative remote-sensing technologies. The mission of the ESE Applications Program is to expand and accelerate the realization of societal and economic benefits from Earth science, information, and technology.

Partnering with Other Federal Agencies

Solid-Earth science initiatives sponsored by other federal agencies will enhance NASA's efforts to meet the scientific challenges outlined in this report and will allow the development of a predictive capability for our restless Earth. For example, NASA partners with the National Science Foundation (NSF), the U.S. Geological Survey (USGS), and the National Oceanic and Atmospheric Administration (NOAA) on a number of programs that address in a complementary fashion the goals of solid-Earth science at NASA. Interagency cooperation within these programs promises to advance significantly our understanding of the Earth's crust and mantle, earthquakes, and volcanoes. Among these programs are:

• *Despite benefits of space-based*
• *observations, crucial measure-*
• *ments often need to be made*
• *from the ground. Field geolo-*
• *gists from agencies such as the*
• *USGS complement NASA's*
• *solid-Earth program, and it is*
• *through such partnerships that*
• *many advances will be made.*



This seismic hazard map was produced by the Global Seismic Hazard Assessment Program (GSHAP). Launched in 1992, GSHAP promoted a regionally coordinated, homogeneous approach to seismic hazard evaluation, intended for national decision makers and engineers responsible for land-use planning and improved building design and construction. The coloring shows the hazard risk (from low in blue to very high in red), which is related to the probability that peak ground acceleration will exceed a given level within the next 50 years. The areas of highest risk are prime candidates for coordinated space and ground observations.

The NSF EarthScope initiative involves four integrated components: USArray, a moving array of broadband seismic instruments; the San Andreas Fault Observatory at Depth (SAFOD), involving deep drilling and instrumentation at depth; the Plate Boundary Observatory (PBO), primarily an array of continuous GPS stations and strainmeters to be deployed in the western U.S.; and a dedicated InSAR mission for obtaining synoptic information about crustal deformation globally. The first three components of EarthScope are expected to be led by NSF, but NASA can contribute to PBO through its accumulated expertise in space-based geodesy and GPS. NASA should be the lead for a dedicated InSAR mission.

The NSF seafloor observatory initiative, Dynamics of Earth and Ocean Systems (DEOS), includes as its largest component the North East Pacific Time-series Undersea Networked Experiments (NEPTUNE) project to instrument the Juan de Fuca plate offshore of the Pacific northwest. For this and other such initiatives, seafloor geodesy will be one of the technological and scientific frontiers.

NOAA's Geostationary Operational Environmental Satellites (GOES) provide the frequent (at least once per hour) spaceborne observations of the western hemisphere that are important for the detection of both volcanic plumes and lava flow hotspots. In addition, via agreements with foreign counterparts, NOAA provides NASA with prompt access to similar geostationary data covering most of the rest of the world. Sites of volcanic activity outside the field of view of GOES are also being monitored daily with the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA polar orbiting satellites. This capability is reinforced by NASA's own Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Moderate Resolution Imaging Spectrometer (MODIS) instruments on the

Terra and Aqua platforms. NASA relies as well on the NOAA AVHRR for sea-surface temperature measurements that are critical to our understanding of sea-level rise.

Providing ground truth and validating remote-sensing observations will require close collaboration between NASA and USGS scientists analyzing real-time, land-based hazard monitoring networks, including the Advanced National Seismic System (ANSS), high-resolution GPS and microearthquake networks, and the National Streamgaging Network. For example, volcanologists supported by NASA and USGS could work toward developing a remote predictive capability for volcanic eruptions. The documentation of surface deformation with InSAR and the integration of space-based remote sensing with infrared imaging and other tools by NASA could be combined with surface monitoring by others of microearthquake migration, harmonic tremor development, and borehole strain. On the basis of case studies with the full complement of measurements, behavior precursory to eruptions might be recognizable solely from space observations in remote areas where no land-based observations are available.

International Partnerships

International satellite partnerships — e.g., GRACE (Gravity Recovery and Climate Experiment, a joint NASA/German Earth system science pathfinder mission), Oersted (Danish magnetic mission), SAC-C (Argentine and Danish magnetic mission), CHAMP (Challenging Minisatellite Payload, a German gravity and magnetic mission), and the Radarsat series (Canadian SAR) — enable NASA to develop a broad range of observation types, to acquire rich data sets that are shared internationally, and to avoid high initial development costs. By designing a program architecture that schedules missions with respect to expected international developments (without wholly relying on them), NASA greatly improves the effectiveness of its scientific investment.

For example, the Canadian Radarsats employ C-band mapping, which is particularly useful for ice dynamics and topography, but that satellite series lacks an L-band frequency. By focusing on L-band InSAR development, NASA complements and addresses gaps left by existing and planned missions. Together with

more than 100 organizations worldwide, NASA supports international services that maintain the measurement, analysis, and archiving infrastructure of geodetic networks and serve as a forum for innovation, research, and standards. Space missions such as CHAMP and GRACE have been initiated in large part through the venue of international cooperation that these services provide.



The Shuttle Radar Topography Mission (SRTM), an extremely successful partnership between NASA and the National Imagery and Mapping Agency (NIMA), produced critical elevation data for 80% of Earth's landmass. This perspective view of a portion of the San Andreas fault was generated using SRTM data and an enhanced, true-color Landsat satellite image (vertical exaggeration 2:1). The view shown looks southeast along the San Andreas where it cuts along the base of the mountains in the Tumbler Range near Bakersfield. The fault is the distinctively linear feature to the right of the mountains.

What Is the Nature of Deformation at Plate Boundaries and What Are the Implications for Earthquake Hazards?



The San Andreas fault cuts through 1,200 km of California and is one of the most active fault systems in the world.

Expected Accomplishments

- Characterization of motions of the Earth's surface and their variability on a global scale
- Understanding of fault interactions and transfer of stress through the crust
- Models that predict the behavior of earthquake systems

Benefits for the Nation

- Enabling of rapid response to seismic disasters worldwide
- Enhanced global maps of natural hazards to support mitigation strategies
- Determination of the existence of local and regional precursors to earthquakes

The Challenge

Earthquakes are among nature's most complex phenomena, threatening many of the world's population centers. A great Pacific Rim earthquake near a major economic area might cause damages well in excess of one trillion dollars and tens of thousands of casualties. Reaching an understanding of earthquake fault systems is required in order to address the issue of their predictability, with the goal of mitigating their impact.

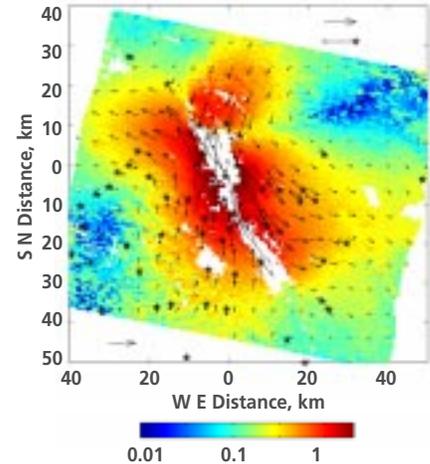
"The laws of nature are written deep in the folds and faults of the earth."

John Joseph Lynch, former president of the New York Academy of Sciences, 1963

Key questions include:

- How do individual faults behave and interact as part of an integrated system?
- What are the mechanical properties of the crust and mantle that control deformation?
- To what extent can earthquakes be forecast?

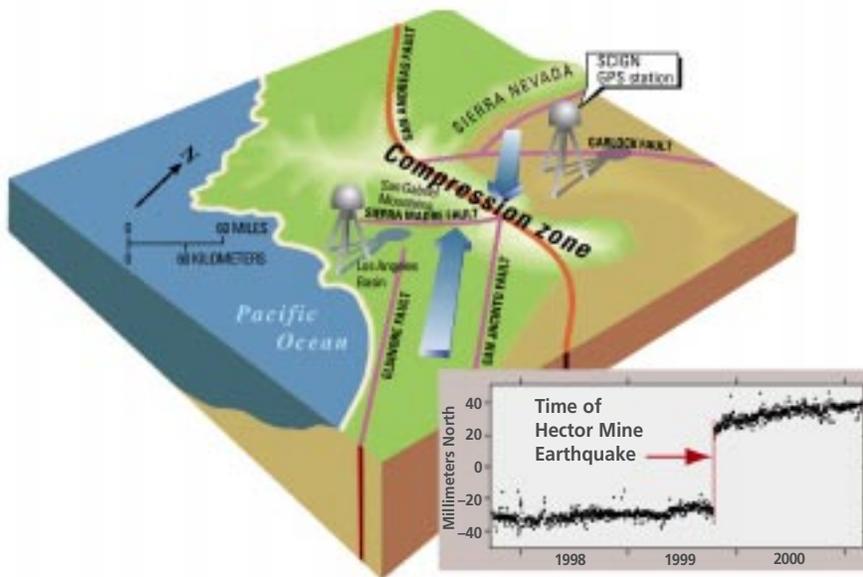
Investigations of surface deformation, plate-boundary motion, frictional properties of faults, and mechanical properties of the Earth's crust are necessary to determine what controls the spatial and temporal patterns of earthquakes. Space-based observations allow us to follow the entire earthquake cycle, including the aseismic accumulation of strain. These new measurements are providing insights into how stress is transferred between



Displacement from the 1999 magnitude 7.1 Hector Mine earthquake in California as measured using InSAR techniques. The radar echoes are reduced to interferograms by calculating the phase differences between images from multiple satellite passes. Color (using a logarithmic scale) represents horizontal displacement in units of meters. Arrows show both magnitude and direction.

faults, how much energy is released by earthquakes versus other modes of deformation, and how faults fail.

Fully modeling the earthquake system requires knowledge of both current and past motions and fault interactions. It is necessary to measure the ongoing deformation associated with plate tectonics and motion along faults. It is also necessary to obtain detailed topographic and geomorphic characteristics of faults in order to better understand earthquake history. Targeted measurements along plate-boundary zones can address how fault systems interact. Because we are discovering that such interactions may extend to hundreds of kilometers distance, explor-



Geodetic data from ~250 GPS stations primarily within the SCIGN array in Southern California provide a powerful tool for studying surface deformation and earthquakes, such as the slow strain buildup along the San Andreas and other faults. The inset shows the change in the north-south position of a SCIGN station near Palm Springs before and after the Hector Mine earthquake (about 50 miles from the epicenter).

atory large-scale measurements are also required until we understand these systems better. For example, by understanding the stress changes that occur after major earthquakes, it may be possible to determine more reliably the probability of future earthquakes occurring at other locations

in the system. Analyses of the transient changes and spatial complexity of deformation are likely to reveal previously unrecognized properties of the faults and of the Earth's crust. A complete program of study will integrate global-scale measurements and large-scale computing with laboratory and in situ measurements sponsored by other agencies to treat in an integrated fashion all aspects of the earthquake physics problem.

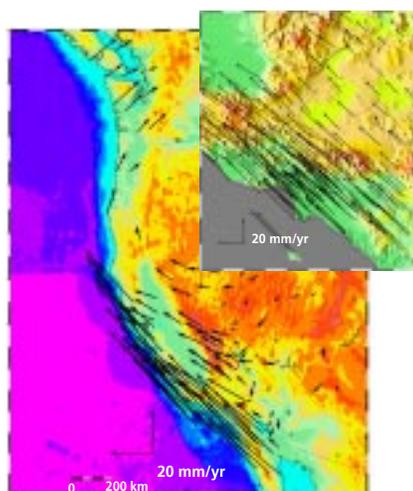
What We Know and Need to Learn about Deformation at Plate Boundaries and Earthquakes

Our knowledge of Earth surface deformation is discontinuous in both time and space. At global scales, plates move steadily relative to each other over long periods. Plate-boundary zones are typically broad on continents and narrow in oceanic regions. Plate boundary zones can be made up of many faults separated by

either rigid or deforming blocks. Elastic strain accumulates in a broad zone across a fault and is released suddenly during an earthquake. The crust continues to respond following earthquakes. Faults can continue to slip for years, and deformation propagates in the crustal layer and upper mantle as stresses are redistributed over decades or even centuries. Recent evidence indicates that faults interact, and earthquakes can influence faults up to several hundred kilometers away. This influence is probably determined by the structure and composition of crustal layers and frictional properties of faults and can best be understood by observing and simulating the motions of the Earth's surface throughout several seismic cycles.

Next Steps

To achieve a better understanding of the nature of deformation at plate boundaries requires information on the changes occurring at the Earth's surface, including the seafloor, and within the interior. Varying temporal and spatial sampling requirements and accuracies dictate specific observational approaches: GPS networks, InSAR constellations, and spaceborne laser altimetry and lidar will be needed to provide dense spatial and temporal sampling and high-accuracy observations of the changes on the Earth's surface. These data will complement information obtained from seismic networks, seafloor geodesy, borehole arrays, and highly accurate gravity measurements. The ensemble of data combined with advanced geophysical modeling will allow quantitative prediction of many aspects of fault zone deformation.



The surface velocity field of western North America, and the Los Angeles basin (inset), as observed by GPS.

How is the Land Surface Changing and Producing Natural Hazards?

Expected Accomplishments

- Development of a process-based understanding of the tectonic-climatic-biotic interactions that create landscapes
- Quantification of natural baselines and rates of change of the land surface
- Quantification of the causes, magnitude, and development in time and space of natural hazards
- Assessment of the relative roles of natural and human-induced changes

Benefits for the Nation

- Real-time prediction of the progression of floods, landslides, and coastal erosion
- Assessment of susceptibility to damage by natural hazards
- Quantification of watershed dynamics, hydrology, and landscape response
- Definition of the human role in influencing the landscape and abating and aggravating hazards



Prediction of hazardous processes such as floods or landslides requires quantification of both changing landscape characteristics and climatic inputs.

The Challenge

In order to lessen the impact of natural hazards, we need to characterize, understand, and predict the phenomena that cause them. The land surface is the dynamic interface between the lithosphere, hydrosphere, and biosphere. It is where interactions represent the most direct and commonly occurring impacts of solid-Earth science on humans. Landslides, floods, tsunamis, debris flows, storm surges, earthquakes, and volcanic eruptions sculpt and deform the land. The Earth's surface constitutes the geomorphic record of past tectonic-climatic interactions and is the topographic template upon which new natural hazards are generated. The challenge presented by the land surface is three-fold: to unravel the record of past interactions embedded in this surface, to determine the relative roles of natural and human-induced change, and to understand processes that act on this surface in order to predict and mitigate natural hazards. Reconstruction of past erosion, deformation, and deposition and quantification of tectonic, climatic, and biologic inputs to the evolving landscape will underpin the ability to develop a process-based understanding of the Earth's dynamic surface.

What We Know and Need to Learn about Land Surface Change and Natural Hazards

We know the land surface evolves as tectonic forces cause deformation and as transient hydrologic and biologic forces mediate erosion and deposition on the surface. The majority of the destructive

U.S. earthquakes of the last twenty years occurred on faults that did not rupture the surface, although they deformed the land surface above the fault and promoted new patterns of erosion. Interpretation of the deformed land surface allows us to construct rates of fault growth and past seismic activity. As large storms rain upon the land, topography, soils, vegetation, and rainfall intensity determine how floods and landslides are generated. We know that the amount of antecedent rainfall, soil cohesion and water content, recent fire history, water routing through the landscape, and hillslope angles all interact to determine where and when a landslide will occur. Similar interactions determine how flood waves will migrate through a catchment and how much sediment will be eroded, transported, and deposited during a storm.

Next Steps

Remotely sensed data play an integral role in reconstructing the recent history of the land surface and in predicting hazards due to events such as floods and landslides. Because land-surface properties change through time, remote sensing of such changes yields critical time control on landscape evolution. Remotely sensed data can determine properties of the surface and atmosphere in real time and with a high spatial resolution. Recognition that destructive floods or landslides can be launched by intense, short-lived storm cells a few kilometers in width pinpoints the need for higher spatial and temporal resolution of remotely sensed data. At present, even “well monitored” river catchments commonly have only a few gauges measuring precipitation and discharge. Few data exist on soil moisture,

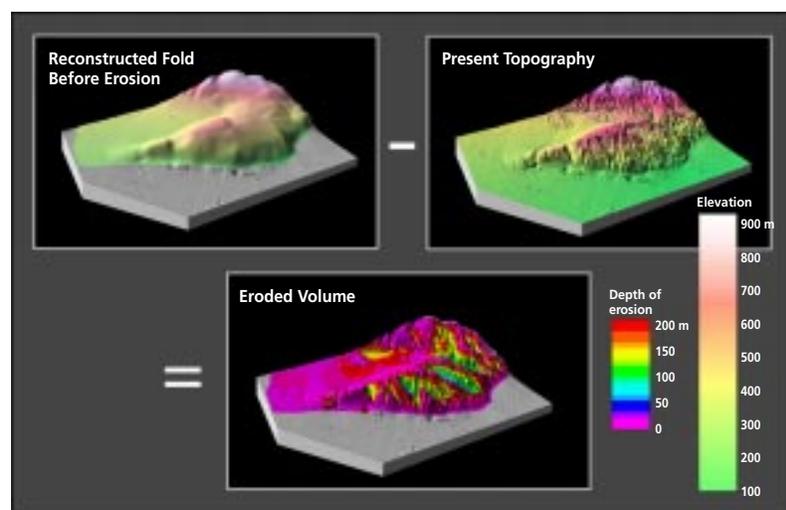
thickness, and strength, or on vegetation cover, fire history, or detailed topography. The only practical way to gather these data is through implementation of a broad-based remote-sensing program. The height and width of rivers, as well as rainfall intensity and amounts, need to be measured hourly during storms. Developing a process-based understanding of natural hazards depends on studies of the character of previous and ongoing events.

Information needed to address the challenges falls into the categories of surface, subsurface, and hydrologic characterization. These categories have diverse observational requirements. Those that change rapidly, such as river stage or precipitation, call for hourly measurements, whereas others, such as vegetation, com-

monly require seasonal measurements. Occasional (5–10 yr) quantification of soil composition and thickness would suffice in areas governed by gradual processes, but more frequent measurements will be needed in areas affected by such dynamic events as flooding or landsliding. The remote sensors that will provide these data include InSAR, GPS, visible and near infrared/thermal infrared (VNIR/TIR) imaging, multi-parameter SAR, laser altimetry, and microwave imaging. These observations will need to be augmented with extensive land-based measurements and data from existing and new hydrologic, seismologic, and geodetic arrays. By means of frequent, high-resolution remote sensing, a new capability will emerge for predicting hazards caused by tectonic–climate–land surface interactions.

“A man should examine for himself the great piles of superimposed strata, and watch the rivulets bringing down mud, and the waves wearing away the sea-cliffs, in order to comprehend something about the duration of past time, the monuments of which we see all around us.”

Charles Darwin, from the Origin of Species



Wheeler Ridge in Southern California is an example of a rapidly growing fold above a blind thrust. High-resolution topography defines uplift rates, erosion, and the interactions that produce natural hazards.

What Are the Interactions among Ice Masses, Oceans, and the Solid Earth, and the Implications for Sea-Level Change?



Coastal erosion, such as that shown above in Pacifica, California, is a pervasive problem that threatens many homeowners.

Expected Accomplishments

- Accurate estimation and prediction of global hydrological mass fluxes, including those of ice sheets and glaciers.
- Separation and prediction of steric (thermal and salinity) and mass-budget contributions in sea-level change.
- Separation of solid-Earth vertical motion (tectonic, post-glacial rebound, and environmental) from true sea-level change.

Benefits for the Nation

- Improved estimates of future sea-level rise
- Improved assessment of coastal erosion due to sea-level rise
- Long-term planning for coastal communities affected by sea-level rise

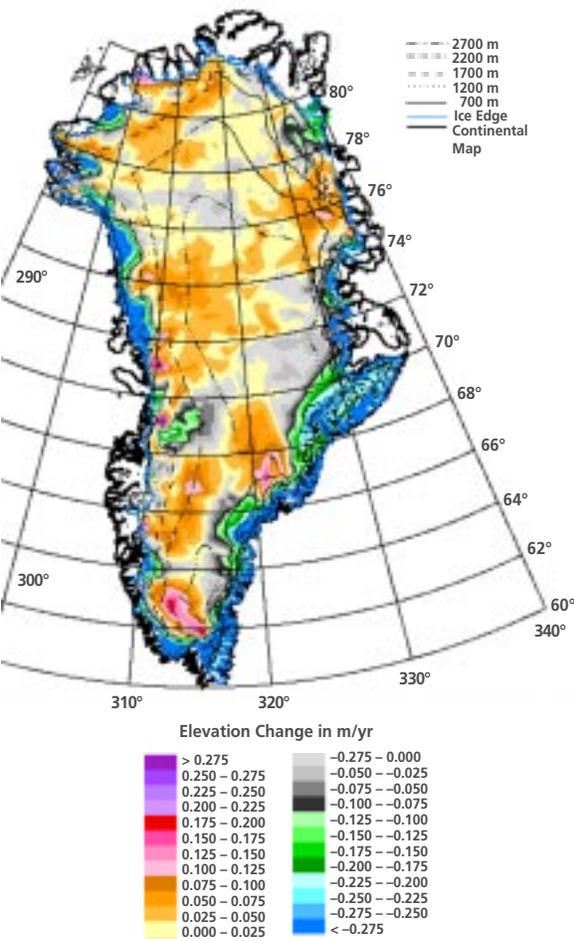
"Glaciers are delicate and individual things, like humans. Instability is built into them."

Will Harrison, glaciologist, 1986

The Challenge

Today more than 100 million people worldwide live on coastlines within one meter of mean sea level. Any short-term or long-term sea-level change relative to vertical ground motion is of great societal and economic concern. The very survival of many island states and deltaic coasts is threatened by sea-level rise. Inasmuch as paleo-environmental and historical data have clearly indicated the occurrence of such changes in the past, new scientific information on the nature and causes of sea-level change — and the development of a quantitative predictive capability — are of utmost importance for the future. This topic is inherently an interdisciplinary science problem addressed within NASA by the Cryospheric Science, Ocean Science, Hydrology, and Solid Earth Science Programs.

The 10–20 cm global sea-level rise recorded over the last century has been broadly attributed to two effects: the steric effect (thermal expansion and salinity-density compensation of sea water) of changes in global climate, and mass-budget changes due to a number of competing geophysical and hydrological processes in the solid Earth–atmosphere–hydrosphere–cryosphere system. While the steric effect is primarily a climatic issue, the Solid Earth Science Program is poised for a fundamental contribution by separating the two effects via a combined use of space geodetic measurements of sea-surface topography and time-variable gravity. The mass-budget changes include water exchange from polar ice sheets and mountain glaciers to the ocean, atmospheric water vapor and land hydrological variations, and human effects such as water impoundment in artificial reservoirs and extraction of groundwater. These exchanges are



Elevation changes in Greenland have been measured by airborne laser altimetry. The ice sheet appears to be in balance with snow accumulation at high elevation, but thinning predominates at low elevation. Overall, the Greenland Ice Sheet is estimated to lose mass to the ocean. Dramatic thinning occurs in largely understudied southeastern Greenland.

all superimposed on the vertical motions of the solid Earth due to tectonics, rebound of the lithosphere from past and present deglaciation, and other local ground motions. A number of space geodetic measurements of sea-surface topography, ice mass, gravity, and ground motions are directly relevant. A complete knowledge of sea-level change will then emerge and be used for the development of predictive global and regional models.

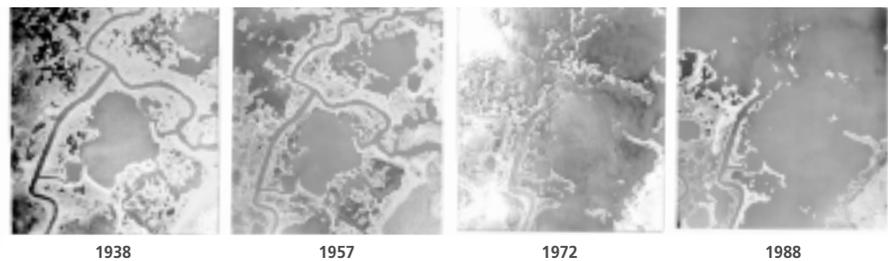
What We Know and Need to Learn about the Mass Balance of Earth's Ice Cover and Sea-Level Change

Globally sea level is estimated to rise by 1.5–2 mm/year, but few details are known. The relative contributions of the steric and mass-budget effects are under debate, as are their spatial and temporal variations. We are presently not certain whether Greenland and Antarctica are gaining or losing net ice mass. Estimates of mountain glacier melting are incomplete. The global land hydrological budget is not well known. Even the amount of artificial reservoir water impoundment is uncertain by perhaps a factor of two. If global warming continues, a most immediate and potentially dominant mass-budget contribution to sea-level change is likely to come from the melting of ice masses. The melting of temperate glaciers could raise sea level by a few tens of centimeters; the melting of the ice sheets in West Antarctica could raise sea level by several meters. Global and temporally continuous monitoring of sea-surface topography, ice mass, gravity, and ground motions is needed. Knowing how the present ocean “container” deforms is also necessary to predict the consequences of sea-level change. On a global

scale, that requirement calls for an accurate post-glacial rebound model incorporating knowledge of the Earth's internal mechanical properties and the history of past ice ages. At any given location along the coastline, additional tectonic motion and environmental impacts such as groundwater withdrawal need to be monitored and understood.

Next Steps

Measuring absolute as well as relative sea-level change is a geodetic endeavor. Further advances in geodetic measurement techniques must provide information on sea-level changes and consequences in a routine fashion, with enhanced geographical coverage, spatial and temporal resolution, and measurement accuracy. Research is needed to integrate the various relevant measurements — changes in sea- and ice-surface topography, time-variable gravity, deformation of the surface of the solid Earth (particularly along coastlines), all under a uniform terrestrial reference frame, together with in situ measurements from tide gauges and buoys, remote-sensing data such as sea-surface temperature and salinity, and global atmosphere–hydrosphere–cryosphere models that assimilate diverse climatic data types.



Aerial photo sequence spanning 50 years showing the progressive drowning and loss of coastal marshes in Blackwater National Wildlife Refuge near Cambridge, Maryland, in response to a rise in sea level relative to local land. The area shown is about 1 km across.

How Do Magmatic Systems Evolve and Under What Conditions Do Volcanoes Erupt?

Expected Accomplishments

- Up-to-date global inventory of active terrestrial volcanoes
- Further definition of the relationships among deformation, seismicity, intrusions, and eruptions
- Volcanic activity warning system
- Forecasting of volcanic activity on progressively longer time scales

Benefits for the Nation

- Detection of ash and plume products to provide warnings for air travel
- Hazard mitigation due to improved volcanic activity warnings
- Advanced planning for high-risk populations near volcanic regions

The Challenge

Volcanoes are direct links to the interior of the Earth, and their eruptive power and often-long intervals of quiet dormancy inspire fear and, in some societies, reverence. We are entering a period of rapid growth in our understanding of volcanoes, as diverse measurements are integrated and new observational tools are

“A cloud... shot up to a great height in the form of a very tall trunk, which spread itself out at the top into a sort of branches. This phenomenon seemed ... extraordinary, and worth further looking into.”

Pliny the Elder on the eruption of Mount Vesuvius, 79 AD

developed. Because eruptions are episodic and occur throughout the globe, we must rely on methods that give us observations of volcanic activity everywhere on the planet. Primary to our understanding of eruptive systems are the identification and characterization of active volcanoes. From the volcanoes rimming the Pacific to new eruptions on the ocean floor, there are thousands of volcanoes whose level of ac-

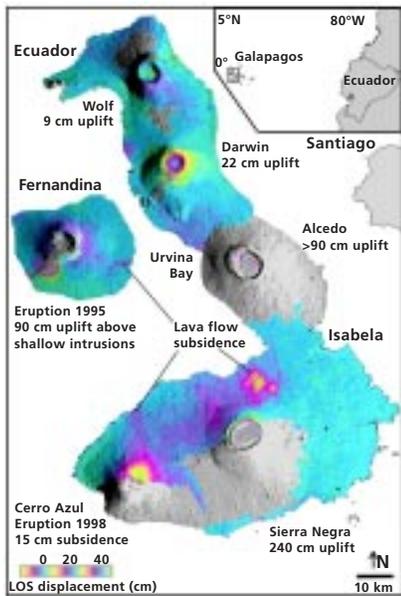


The 1980 eruption of Mount St. Helens, triggered by a magnitude 5.1 earthquake, dramatically affected the northwest U.S. Four hundred meters of the peak collapsed or blew outwards. As a result, 650 square kilometers of recreation, timber, and private lands were damaged by a lateral blast, and an estimated 150 million cubic meters of material were deposited directly by lahars (volcanic mudflows) into the river channels.

tivity is poorly known. Indicators of activity include surface deformation, seismicity, thermal emissions, changes in gravity, emission of gasses, and actual eruptions. We know little, however, about how these phenomena are interrelated. The physical mechanisms that cause surface deformation and those that control the rates and styles of eruptions are poorly understood. The ability to predict the timing, magnitude, and style of volcanic eruptions is an important but generally unmet goal.

What We Know and Need to Learn about Magmatic Systems and Volcanoes

Existing and foreseeable advances in technology allow us to consider a variety of questions critical to advancing our understanding of volcanic systems. Key observations already allow limited volcanic eruption forecasting. For example, under sim-



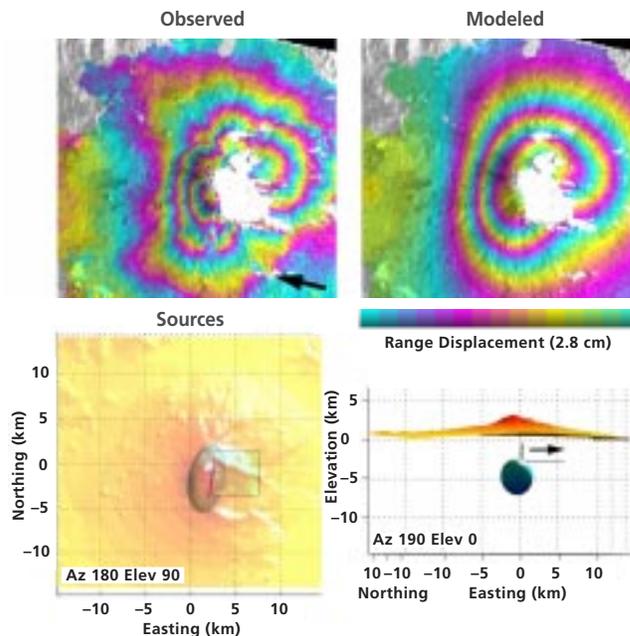
Deformation measured by InSAR at Isabela and Fernandina, islands in the Galápagos archipelago. Also shown is the maximum uplift at each volcano, assuming that displacements are vertical. Differences in the displacement patterns from volcano to volcano illustrate the complex range of deformation mechanisms that can occur.

plifying assumptions of an elastic crust and a limited range of possible magma chamber shapes, available measurements of surface deformation are routinely used to quantify the location and geometry of active magmatic bodies. Recent geodetic observations are also beginning to document a wide variety of complex sources of deformation, including flank instabilities, rift systems, and crater floor dynamics. Recent studies have also demonstrated the ability to measure thermal anomalies associated with volcanic plumes and degassing of SO_2 and CO_2 . Many challenges remain, however. We must assess the geometry of the volcanic plumbing system, the physical properties of the magma (composition, volatile content), magma ascent rates, and the location and mechanisms of volatile exsolution. A key question is how we determine a volcano's level of activity,

whether by surface deformation, variations in gravity, heat flux, mass transports, seismicity, or gas emissions. At any given time, only one of these manifestations of activity may be present. The extent to which we can currently predict eruptions is largely limited by a lack of observations.

Next Steps

To make significant progress addressing these volcanological challenges, we need a globally comprehensive compilation of observations of all major land volcanoes. This inventory will rely principally on geodetic and spectroscopic observations. From the geodetic standpoint, full vector deformation maps are required to reduce ambiguities in inferences of magma chamber geometry. Given the sporadic nature of volcanic activity, a global archive updated on weekly time intervals is required. Such time intervals would also permit us to gain sensitivity to low-level but more nearly continuous processes. In the event of an eruption, shorter time intervals are desired, with updating several times per day. However, in these cases, only a spotlight view of a targeted area of the globe is needed. A similar rationale holds for the timing of spectroscopic measurements. Such measurements provide sensitivity to heat flux and gas emissions (e.g., SO_2 and CO_2). Given the proper temporal resolution, temperature changes on the order of 0.5 K and accurate measurements of gas emissions, along with surface deformation maps, may allow forecasting of eruptions.



Satellite radar interferometry observations and models of surface deformation of Italy's Mt. Etna volcano prior to eruption shows inflation of the central magma chamber that induced movement of its unstable eastern flank. Bottom row shows a physical model of the magma chamber and fault dislocation solution: left, map view looking through the topography; right, side view, with the sense of flank motion indicated by the arrow.

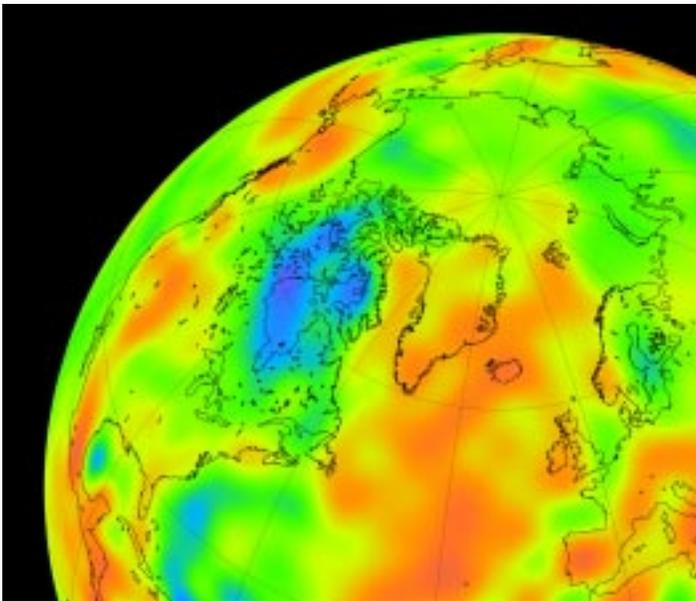
What Are the Dynamics of the Mantle and Crust, and How Does the Earth's Surface Respond?

Expected Accomplishments

- Global measurement of vertical intraplate deformation at mm/yr accuracy
- Measurement of global seafloor topography at 50-m vertical accuracy and 5-km horizontal resolution
- Improved measurements of the Earth's rotation and length of day (LOD)
- Integration of space-based geodetic observations with complementary seismic imaging studies

Benefits for the Nation

- Understanding the nature of mantle and crustal dynamics that give rise to earthquakes and volcanoes
- Better prediction of sea-level change from post-glacial rebound

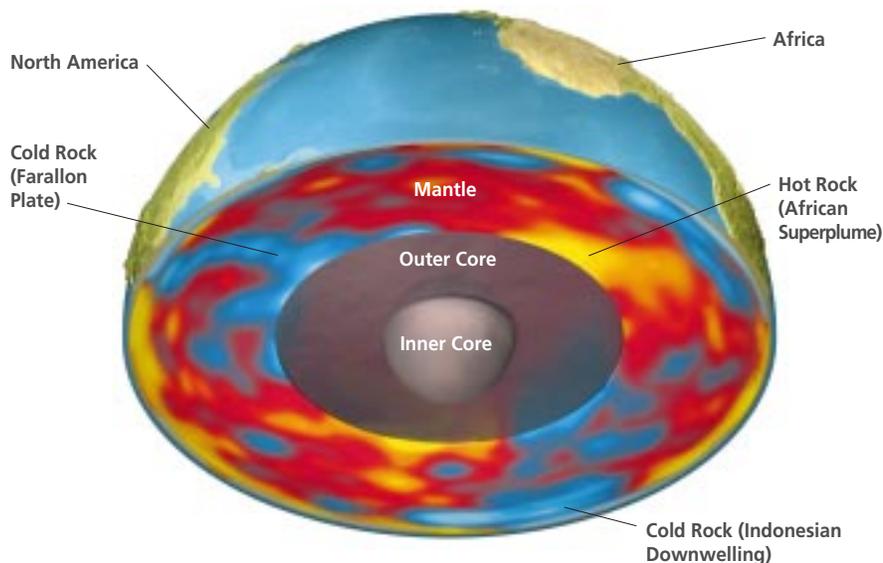


The free air gravity field of North America and the North Atlantic. Negative anomalies are indicated by cool colors and are associated with incomplete glacial rebound; positive anomalies are indicated by warm colors and are primarily associated with ocean ridge structure and western North America.

The Challenge

Tectonic processes in the mantle and crust are the engine responsible for seismicity, volcanism, and mountain building. Mantle convection converts thermal energy from radioactive decay and the cooling of the Earth into the continuous displacements responsible for plate tectonics. The deformation of the Earth's surface required to accommodate plate tectonics occurs primarily on plate boundary faults and relatively broad zones of deformation adjacent to the plate boundaries in the continents. The forces that drive the motions of the plates, however, are not well quantified. What are the relative roles of slab "pull," ridge "push," and basal tractions?

Mantle convection has been studied through computer simulations and laboratory analogue experiments, but models to date are limited in their ability to approximate Earth conditions at high resolution. Mantle seismic tomography is producing three-dimensional images of seismic velocity anomalies of increasingly sharper resolution, and studies of seismic wave anisotropy offer the promise of constraining the signature of alignment of mantle mineral grains by convective flow. The extent to which the seismic velocity anomalies seen in tomographic images are correlatable to the density anomalies that drive convective motions, however, is far from clear. The global gravity field and long-wavelength topography provide key integrative measures of these mantle density anomalies, although their interpretation requires information on the structure of the tectonic plates and the variation of viscosity within the mantle. Improved information on plate characteristics and mantle viscosity can come, in turn, from measurements of the time-dependent response of global gravity, topography, and Earth rotation to loading and unloading by glaciers, oceans, and other forcings.



Mantle cross section integrates measurements of seismic waves that have traveled through the planet. Regions where wave velocity is anomalously high (blue) are thought to denote cold, dense rock. Regions where wave velocity is anomalously low (yellow) are thought to correspond to hot, less-dense rock.

“Set the foot down with distrust on the crust of the world — it is thin.”

*Edna St. Vincent Millay, from her poem, Huntsman,
What Quarry?*

Understanding mantle convection, and its coupling to the motions of the crust and lithosphere, will require a combination of approaches. Improved definition of the time-dependent gravity field and long-wavelength shape of the Earth must be combined with sharpened images of seismic wave speeds and their direction dependence as well as continued measurement of variations in Earth rotation parameters. Sophisticated models of three-dimensional, time-dependent mantle flow must ultimately be capable of predicting the full suite of observable quantities.

What We Know and Need to Learn about the Mantle and Crust

Plate tectonics is a consequence of mantle convection. Mantle processes also influence surface deformation, internal mass redistribu-

tion, and changes in Earth’s length of day (LOD).

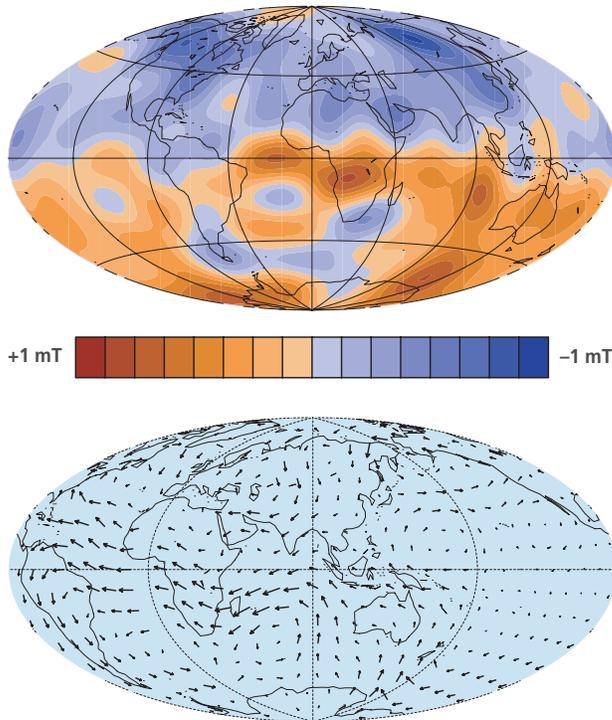
While we have determined the relative velocities among plates from surface geodetic observations, we do not know how mantle flow is coupled to the motions of the tectonic plates. There are major uncertainties concerning the geometry of mantle flow at depth. We do not know, for instance, whether the pattern of mantle convection is simple or complex. We have a relatively poor understanding of the dynamics of subduction at ocean trenches, or the mechanism for initiation of new subduction zones. While we generally understand the large-scale thermal structure of mid-ocean ridges and oceanic plates with ages less than about 50 million years, there are still questions about structure at small spatial scales as well as for older oceanic plates and continental plates. We lack information

on the deep structure and distribution of mantle plumes. We do not understand in detail the mechanisms that lead to island volcanism adjacent to ocean trenches. While oceanic crust is thought to be formed by partial melting of mantle rock at depth beneath an ocean ridge, we don’t understand how continental crust is formed or whether recycling of the lower continental crust into the mantle is an important process.

Next Steps

The observational approaches over the next 25 years must cover a broad range to answer these questions. Global gravity measurements will illuminate the time-varying gravity signal, which holds keys to understanding post-glacial unloading and ocean loading, and the mechanics of subduction. InSAR and GPS measurements of vertical deformation at millimeter/year accuracy and tens of kilometers resolution are needed both in the near term and over longer time scales to complement time-dependent gravity measurements. High-resolution radar altimeters will reveal the small-scale gravity signals of plate boundary and volcanic processes beneath the oceans. Terrestrial reference frame measurements using GPS, SLR, and VLBI will further enhance an understanding of the mechanisms of core-mantle and mantle-crust coupling. Changes in the Earth’s length of day and long-wavelength gravity field provide important information about mass movements throughout the Earth’s mantle. Through diverse observational opportunities and high-performance computer modeling, the critical connections of the mantle and crust to other components of the Earth system can be characterized and better understood.

What Are the Dynamics of the Earth's Magnetic Field and Its Interactions with the Earth System?



The top plot shows the radial component of the magnetic field at the core–mantle boundary (CMB) determined from Oersted observations. The bottom plot shows the fluid flow immediately beneath the CMB determined from maps of the magnetic field at the CMB.

Expected Accomplishments

- Understanding the dynamo that generates the Earth's magnetic field
- Separation of the external field from the internal field on a wide range of temporal and spatial scales
- Determining whether it is possible to predict changes in the Earth's magnetic field
- Measurement of the core's contribution to the Earth's rotation
- Understanding the 3-D electrical conductivity structure of the mantle

- Map of magnetization of the Earth's crust

Benefits for the Nation

- Forecasts of the magnetic field on decadal time scales, important for evaluation of the effects of space weather on communications and satellite operations
- Estimation of interannual and longer changes in mean atmospheric and oceanic zonal circulation from length-of-day observations and calculations of core circulation

The Challenge

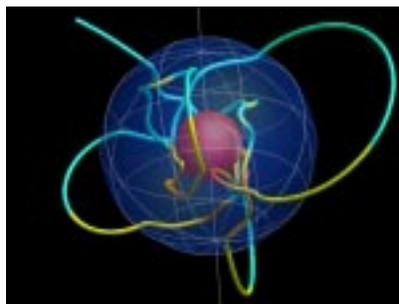
The problem of explaining the origin of the Earth's magnetic field was once ranked by Albert Einstein as among the three most important unsolved problems in physics. Although today it is widely recognized that the Earth's magnetic field is generated by a dynamo that operates in the fluid outer core, the details of how that dynamo works remain far from understood.

Over the past 150 years, the main (axial dipole) component of the Earth's magnetic field has decayed by nearly 10%, a rate ten times faster than if the dynamo were simply switched off. To that extent, the dynamo today is operating more as an anti-dynamo, a destroyer of the dipole part of the field. Intriguingly, this decay rate is characteristic of magnetic reversals, which paleomagnetic observations have shown occur on average, though with great variability, about once every half million years. Geographically, the recent dipole decay is largely due to changes in the field beneath the South Atlantic Ocean. This pattern is connected to the growth of the South Atlantic Magnetic Anomaly, an area in which the field at the Earth's surface is now about 35% weaker than would be expected. This hole in the field has serious implications for low-Earth-orbit satellite operations since it impacts the radiation dosage at these altitudes. How much longer will the South Atlantic Magnetic Anomaly continue to grow? How large will it become? Is the

field reversing? These questions currently cannot be answered because the mechanism by which the Earth's magnetic field is generated is only partially understood. But long-term satellite observations combined with numerical dynamo modeling will advance our understanding and allow us to model the evolution of this anomaly. In addition, satellite observations will enable mapping the three-dimensional electrical conductivity structure of the Earth, providing important constraints on the distribution of volatiles within the Earth. Other important contributions include mapping the magnetization of the Earth's crust and advancing our understanding of the core's contribution to the Earth's angular momentum budget.

What We Know and Need to Learn about the Earth's Magnetic Field and Core

The Earth's magnetic field originates in the fluid outer core, where self-regenerating dynamo action maintains the field against decay. This field gives rise to both permanent and induced magnetization in crustal rocks and also interacts with current systems in the ionosphere and magnetosphere (space weather). These interactions give rise to fluctuating external electromagnetic fields that in turn induce electric currents in the Earth's conducting interior. The induced electric currents produce time-variable electromagnetic fields at and above the Earth's surface, and the field measured at any point represents the vector sum of contributions from the core field, the crustal field, the external field, and the induced electromagnetic field. The separation of these different



Progress in modeling of the geodynamo and new satellite observations promise to advance greatly our understanding of the origin of the Earth's magnetic field. In this simulation, the outer spherical surface with the latitude-longitude grid is the core-mantle boundary; the inner red surface is the inner core. The magnetic field line is color-coded. Yellow and blue signify positive and negative radial components, respectively.

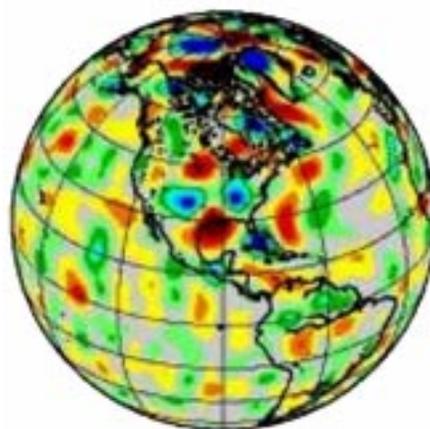
"I believe that there is a subtle magnetism in Nature, which, if we unconsciously yield to it, will direct us aright. It is not indifferent to us which way we walk."

Henry David Thoreau

signals is the greatest challenge for observational geomagnetism, yet the benefits from doing so will be great. It would then be possible to study short-period changes in the field originating in the core; these changes would enable estimation of the core's contribution to the Earth's rotational angular momentum balance on sub-decadal periods. The other main contributions to the Earth's angular momentum balance on these time scales are atmospheric and oceanic in origin, so estimating the core's contribution would enable these other contributions to be determined.

Next Steps

Multiple observation types and scales are required to address the challenges laid out to study the Earth's magnetic field. Foremost is a magnetic constellation in low-Earth orbit (LEO) that would allow measurements of the time-varying external field at a few nT accuracy. Each of the components of the field needs to be mapped out using methods such as a LEO gradiometer and a dense, ground-based electric and magnetic observation network. Accurate reference-frame measurements will assist in determining the core's contribution to the angular momentum budget. Continued active modeling efforts will contribute greatly to advances in understanding.



A combination of MAGSAT data and modeling that removes the dominant main magnetic field shows the variations in the magnetic field of lithospheric origin at the satellite altitude of 400 km.

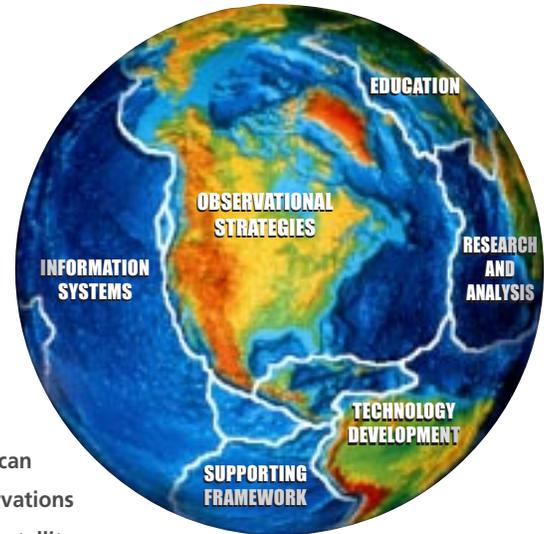
Recommendations for an Integrated Program for Solid Earth Science

To make substantial progress toward answering each of the six challenges for solid-Earth science, NASA must formulate a broadly conceived program with both near-term goals and clear steps toward longer-term objectives. A fully realized program contains elements that encompass all of the following aspects:

- Observational Strategies
- Research and Analysis
- Information Systems
- Technology Development
- Supporting Framework
- Education

By weaving each of these essential elements into an integrated program architecture, the long-term goals of understanding the solid Earth and achieving predictive capabilities can be attained. NASA's role in observations is primarily the development of satellite missions, but such projects cannot be as effective as possible without complementary terrestrial observations and the requisite partnerships with other programs and agencies. A dedicated research and analysis program is a critically important core activity, to ensure that newly acquired data are fully analyzed, to provide the new ideas for instrument and mission development, and to foster unexpected scientific discoveries. This effort should include significant investments in computation and modeling for testing theories and predictions. A number of observations needed over the next two and a half decades require a continuing investment in advanced technology development. This modular yet broadly interlinked program architecture offers flexibility to change as scientific discoveries and programmatic requirements dictate.

This strategy builds on current capabilities and resources. It requires data from missions and instruments that have recently flown, that are currently flying, and that are planned to be launched in the very near future (e.g., ASTER, SRTM, SAC-C, CHAMP, GRACE). It also relies on data from missions that are currently supported by other scientific disciplines such as the Global Precipitation Mission and the River Discharge and Cold Regions Exploratory Missions. This strategy leverages collaborations and partnerships to the largest extent possible with other government agencies, the private sector, and the international community. The focus in the following section is largely on new observational requirements that have been identified by the SESWG and on the implications for required technology investments.



Observational Strategies

Understanding the solid Earth and moving toward predictive capabilities where appropriate requires a broad observational strategy, incorporating numerous methodologies (including spaceborne and ground measurements), technological advances, and complementarity among observations. The SESWG recommends the following seven observational strategies to address the fundamental solid-Earth questions that frame this report.

Recommended Observational Strategies

- | | |
|---|---|
| 1. <i>Surface Deformation</i> | 5. <i>Imaging Spectroscopy of Earth's Changing Surface</i> |
| 2. <i>High-Resolution Topography</i> | 6. <i>Space Geodetic Networks and the International Terrestrial Reference Frame</i> |
| 3. <i>Variability of Earth's Magnetic Field</i> | 7. <i>Promising Techniques and Observations</i> |
| 4. <i>Variability of Earth's Gravity Field</i> | |

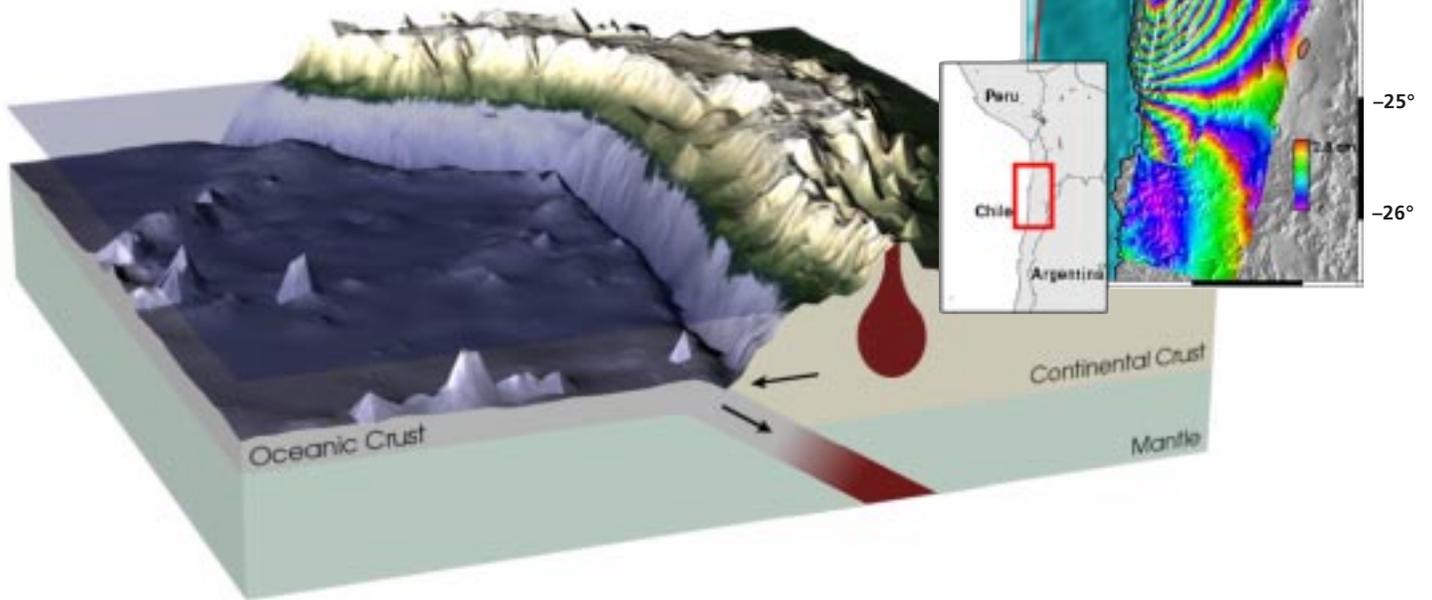
1. Surface Deformation

The land surface deforms both vertically and horizontally as a result of a number of geological and geophysical processes, many of which have significant implications for natural hazards. Episodic deformations arise from earthquakes and volcanic activities whose measurements are essential to understanding and mitigating these natural hazards. Aseismic deformation before and after earthquakes can now be measured as a result of space technologies and are key to understanding earthquakes and the Earth's internal dynamics. Post-glacial rebound occurs by slow, large-scale deformation that provides great insight into the mechanical properties of the solid Earth. Local land subsidence due to groundwater withdrawal, river and coastal erosion and deposition, landslides, and debris flows all impact the land surface and affect human livelihood. Continuous perturbations arise from solid-Earth tides and loading by variations in atmospheric pressure, oceanic circulation, and the distribution of water and ice.

Centimeter to millimeter/year accuracies are necessary to make meaningful detection of these land changes. The space geodetic techniques of satellite laser ranging, very-long-baseline interferometry, and geodetic GPS have in the past decade successfully measured relative horizontal motions among tectonic plates, as well as differential crustal movements along many active plate boundaries. In recent years they have also detected the postglacial rebound signal and the coseismic and postseismic deformations associated with several large earthquakes.

(Below) Three-dimensional rendering of subduction of the Nazca plate beneath western South America. (Right) Coseismic surface deformation from the 1995 magnitude 8.1 Antofagasta, Chile, subduction zone earthquake determined by InSAR. Each

color cycle indicates 2.8 cm of motion in the satellite line-of-sight (LOS) direction. The horizontal projection of the LOS vector is indicated by the arrow at the top right. The red line indicates the boundary between the Nazca and South American Plates at the bottom of the oceanic trench.

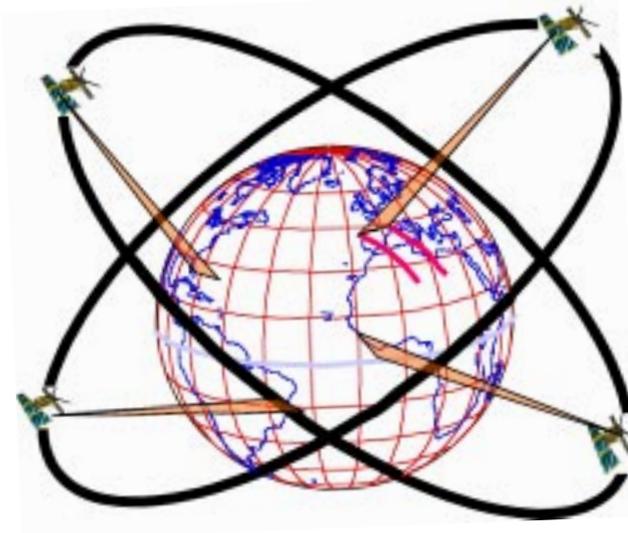


Complementary to the techniques described above, which are typically continuous in time but limited to specific locations, two new space geodetic techniques provide spatially continuous observations that are typically limited in temporal coverage: InSAR and laser altimetry (lidar). Both have proven successful in proof-of-concept airborne experiments, and InSAR has further demonstrated its great utility from space in detecting land surface changes caused by earthquakes, movement of magma at depth, ice-sheet motion, and land subsidence. InSAR measurements of surface deformation rely on repeated acquisitions of radar images, and satellite platforms permit a synoptic view of a host of geologic processes on a global basis.

The goal of the surface deformation observational strategy is to measure spatially continuous displacements of the Earth's surface on both temporally and globally comprehensive bases. Repeat observations must resolve rapid deformational processes such as earthquakes, volcanic eruptions, glacial flow, and regions of devastated infrastructure

due to fires and earthquakes in urban areas. The ability to map quickly these regions of devastation will substantially improve capabilities for rapid emergency response to these destructive forces. It is important as well to measure slow deformational processes such as interseismic strain accumulation, magma chamber pressurization, surface displacements from migration of crustal fluids (e.g., water and oil), and motions of the ice sheets.

Modeling to date indicates that accuracies of 1 mm/yr over 50-km horizontal scales are needed. Such a capability will permit an assessment of how slow transient events (e.g., modest strains over large areas) relate to earthquakes, distinguishing between strain accumulation on a single fault from strain on multiple faults, and accurate determination of the nucleation of earthquakes and the effects of fault asperities on earthquake slip.



Measurement requirements and suggested mission phasing are:

- *Immediate (1–5 years)*: A single dedicated InSAR satellite operating at L-band, with left/right-looking capability and weekly access to anywhere on the globe. Such a mission should include precise orbit determination and ionospheric correction capabilities. This mission should achieve accuracies of 1 mm/yr surface displacement over 50 km horizontal extents in selected areas. Displacement maps should cover 100-km-wide swaths. Continuous ground GPS observations will provide important complementary information.

Supporting research and analysis should include time-dependent modeling of local fault systems, including numerical mechanical models, pattern recognition, and visualization.

Studies show that, from a constellation of InSAR satellites, deformation maps can be made at daily intervals or better. One concept using four satellites in an enhanced low Earth orbit (1321 km altitude) would allow 100% of the Earth to be revisited every 16 hours. The long-term goal of hourly global access may be achieved by low-Earth or geosynchronous constellations of InSAR satellites.

The Nyiragongo volcano in the Congo erupted in early 2002 and subsequently sent streams of lava into the city of Goma (lower right, on the north shore of Lake Kivu). More than 100 people were killed, and hundreds of thousands were forced to flee. This computer-generated visualization combines Landsat and ASTER satellite images and an elevation model from SRTM.

• *Near Term (5–10 years):* A constellation of InSAR satellites capable of producing deformation maps at nearly daily intervals. Maps should extend several hundred kilometers in swath width and provide full vector surface displacements at accuracies of submillimeter per year over 100-km spatial extents and 1-m spatial resolution. Complementary ground and seafloor geodetic observations should continue.

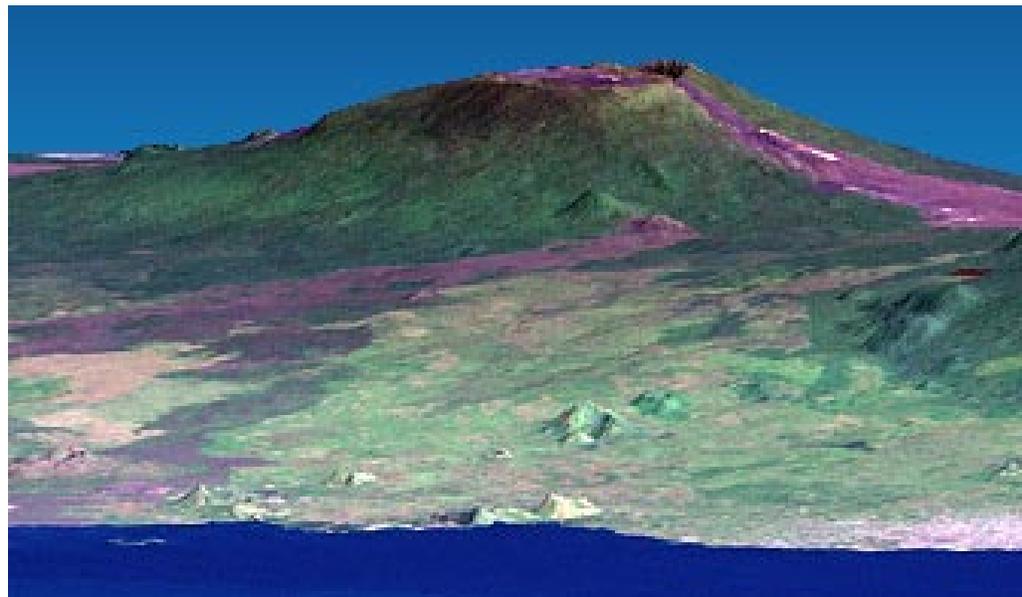
Supporting research and analysis should include assimilation in near-real time of observations into models of fault systems, volcanoes, and the crust–mantle system. The goal should be an understanding of time- and stress-dependent crustal and mantle properties.

• *Long term (10–25 years):* Hourly global access from a constellation of InSAR satellites in low Earth or geosynchronous orbits. There should be an increase in the density of continuous ground and seafloor geodetic observations.

Supporting research and analysis should target near-term forecasting of such natural hazards as earthquakes, volcanic eruptions, and landslides. Fully three-dimensional, nonlinear, spherical, time-dependent models of the solid-Earth system should be coupled to and able to assimilate continuous streams of new data.

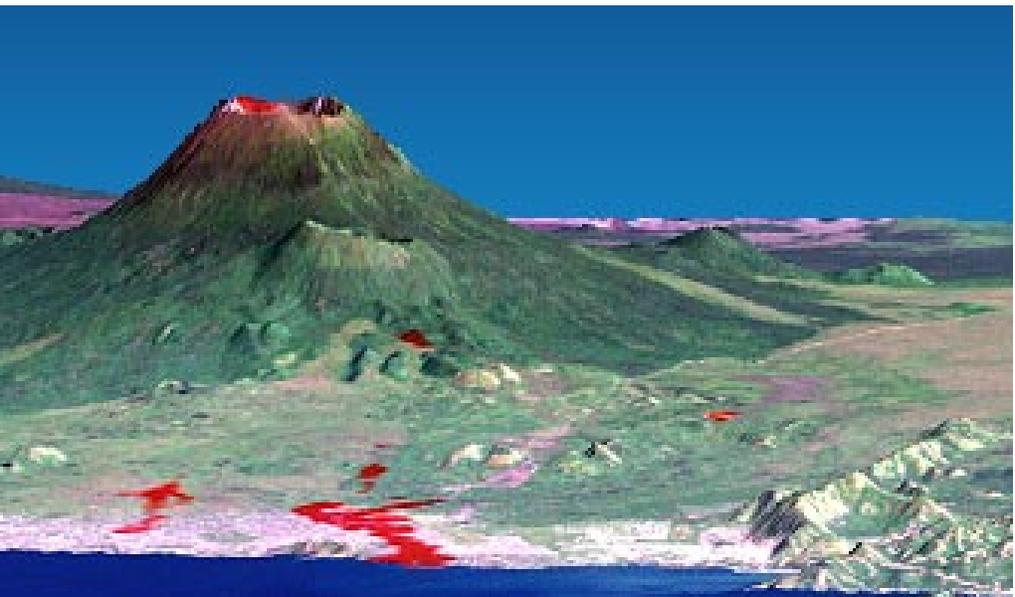
2. High-Resolution Topography

Accurate measurements of topography and topographic change are fundamental to most of the science themes addressed in this report. Topographic measurement capabilities have advanced significantly in recent years. Radar observations from the



Shuttle Radar Topography Mission (SRTM) acquired in early 2000, in cooperation with the National Imagery and Mapping Agency (NIMA), are being used to produce a nearly global digital topographic map with 30-m horizontal precision and 10-m vertical accuracy. A new generation of global digital elevation models with sub-meter-scale accuracy is needed to provide more accurate and frequently measured topography. Special attention must be paid to steep terrain (the sources of landslides and some floods), because such terrain was only partially imaged by SRTM. Measurement of transient topography, such as the surfaces of rivers in flood, is also a key need. Airborne scanning laser altimeter and InSAR techniques provide local to regional digital elevation models with meter- to tens-of-meters-scale resolution at decimeter- to meter-level vertical accuracy. The Shuttle Laser Altimeter (SLA) demonstrated spaceborne land surface altimetry at meter-level vertical accuracy, and the upcoming Ice, Cloud, and Land Elevation Satellite (ICESat) missions will provide comprehensive profile sampling of the Earth's land and ice elevations at decimeter- to meter-level accuracy. SLA and ICESat are profiling systems with along-track resolutions of 700 and 175 m, respectively.

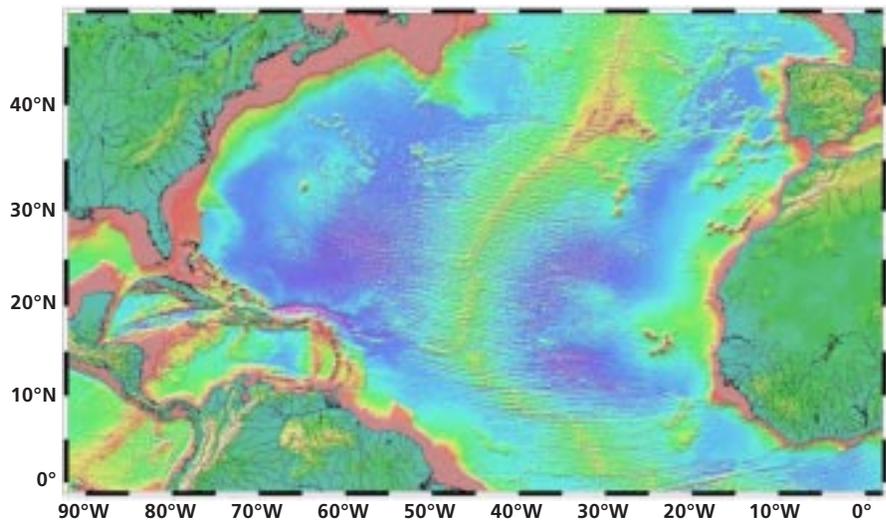
Because direct remote sensing of seafloor topography is not feasible, our historical understanding of the morphology of the 70% of Earth's solid surface that lies beneath the oceans comes from observations made with single- and multi-beam echo sounders mounted on oceanographic research vessels. The resulting data coverage is highly variable in coverage and resolution. To date, only 0.1% of the oceans has been surveyed at 100-m horizontal resolution, and large tracts of the seafloor (such as most of the southern oceans) have not been mapped at all. Seafloor topography can be inferred indirectly at lower (~10 km horizontal) resolution, however, from satellite altimeter mea-



Additionally, ASTER image data were used to supply a partial map of the recent lava flows (red), including a mapping of their intrusion into Goma. Topographic expression has been exaggerated vertically by a factor of 1.5 for this visualization. Nyiragongo and other nearby volcanoes sit within the East African Rift Valley, a zone where tectonic processes are faulting, stretching, and lowering the Earth's crust. Volcanic activity is common here, and older but geologically recent lava flows (magenta in this depiction) are particularly apparent on the flanks of the Nyamuragira volcano (left background).

Topography of the ocean floor derived from sparse ship soundings and dense satellite altimeter measurements of ocean surface height (i.e., geoid height). The 10-km resolution topography reveals the broad features of seafloor spreading such as the median valley along the ridge axis, the transform faults, and the thermal subsidence of the cooling oceanic lithosphere. Higher-resolution topography can be obtained by additional ship soundings and/or a new higher-resolution satellite altimeter mission.

surements of the sea surface (i.e., from the marine geoid). Recent global seafloor maps produced from spaceborne altimetry provide a large-scale view of Earth that is lacking from traditional sources and, in fact, has provided substantial new insight into the seafloor structure and geological history of remote parts of the globe. Forthcoming developments in radar and laser altimeters, constrained by selected higher-resolution shipborne measurements, could improve the resolution of global seafloor topography and morphology to a point that would substantially advance our understanding of volcanism, faulting, sedimentation, and plate evolution in oceanic regions.

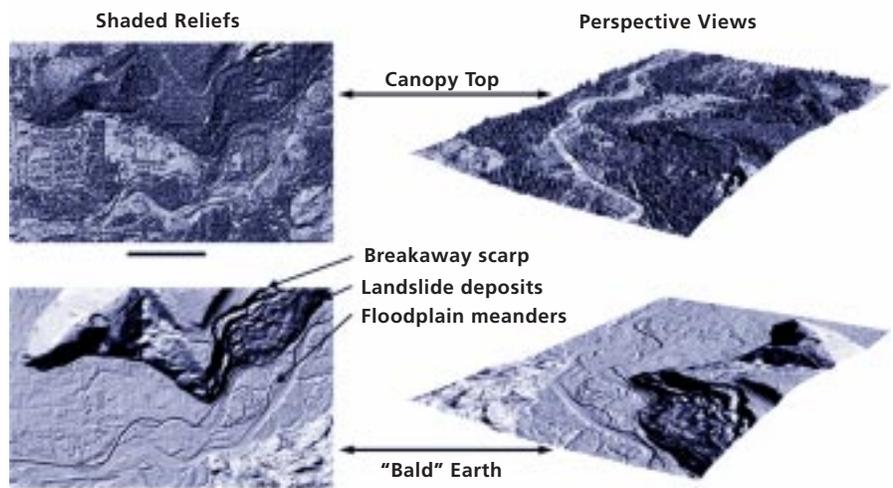


A specific new application of topographic measurements of the land surface is to obtain landslide inventories. Landslides are primarily associated with triggering events, such as rainfall, snowmelt, or earthquakes. The statistics of these events, however, are poorly documented. Since large landslide events are rare, it is essential to obtain inventories on a worldwide basis. One goal is to automate the measurement of landslide areas and volumes using differences in topographic observations prior to and after each landslide event.

Topographic measurements can also be used to quantify sediment deposition in arid areas during a flood. Analyses of the topography of alluvial fans before and after a flood will give the volume of sediment deposited.

Despite these advances in both methodology and analysis, topographic measurements necessary to achieve solid-Earth science goals remain inadequate due to limits in spatial resolution, vertical accuracy, extent of coverage, and frequency of repeat observations. Because topographic data and their temporal changes are fundamental to diverse solid-Earth disciplines, the observational requirements are discipline specific. Three classes of observations encompass the diversity of requirements: improvements in vertical accuracy to 0.1 m in targeted regions (with frequent repeats), one-time global mapping at 0.5-m vertical accuracy to define the present topographic template which surface processes and tectonics modify, and improved mapping of ice sheets and glaciers. Attainment of a process-based understanding and prediction of natural hazards is critically dependent on the determination of highly resolved and accurate topography.

Vertical accuracy refers to the ground or water surface whether or not vegetation cover is present (i.e., the “bald” Earth). For some applications, such as those dependent on local slope or landform shape, the vertical accuracy need be only relative (elevation with respect to an adjacent elevation). For others, such as those requiring regional elevation correlations or change detection, the vertical accuracy must be absolute (with respect to a reference frame).



Vegetation cover and underlying ground topography imaged by high-resolution airborne scanning laser altimetry. Terrapoint ALTMS (Airborne Lidar Topographic Mapping System) data obtained for the Puget Sound Lidar Consortium have 1.8-m horizontal resolution and ~20-cm vertical accuracy (no vertical exaggeration).

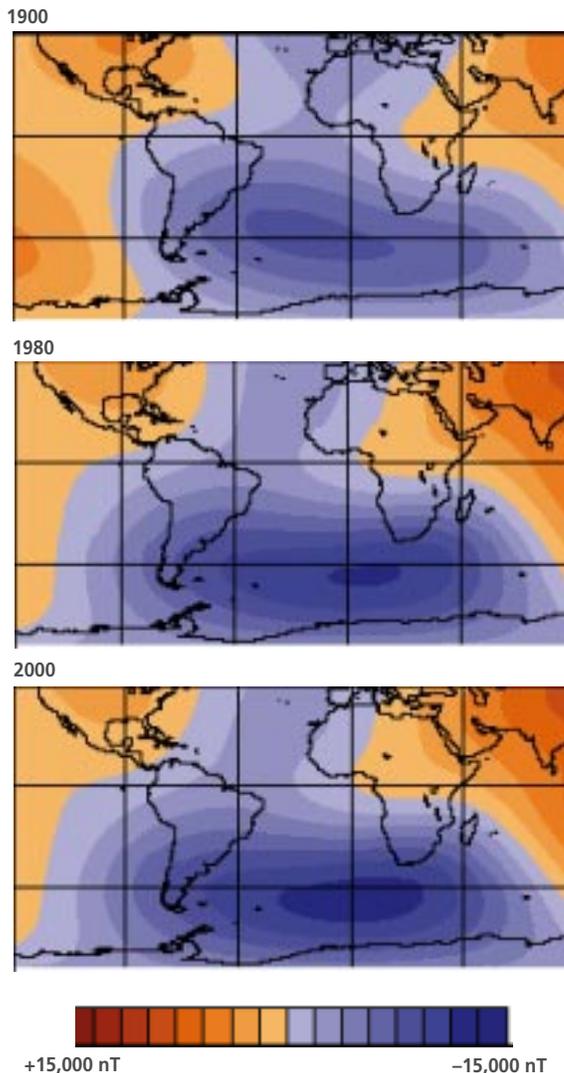
Spaceborne swath-mapping laser altimetry (imaging lidar) and dual-frequency interferometric SAR technologies, potentially in combination, hold the greatest promise for achieving these goals. Cross-track InSAR with precision antenna spacing can map topography with centimeter-level resolution. Lidar can measure topographic change over land, rivers, and oceans. The combined use of lidar and InSAR can provide comprehensive characterization of vegetation height and topography of high resolution and accuracy for the “bald” Earth. Considering the readiness level of these technologies and the current status of topographic mapping activities, measurement requirements and suggested mission phasing are:

- *Immediate (1–5 years):* Production and public distribution of global topographic data from the radar observations acquired by SRTM, launch the ICESat altimeter mission, and demonstrate imaging lidar capabilities in Earth orbit on the Shuttle or International Space Station.
- *Near term (5–10 years):* Global mapping to supercede the SRTM data set. One-time global mapping of the ground surface should be at 2- to 5-m resolution and 0.5-m vertical accuracy. Ice-sheet mapping, to enable data continuity with the ICESat mission, should be at 1-km horizontal resolution, 1-cm vertical accuracy for the ice or snow surface, and a repeat interval of months (for annual changes) to years (for long-term changes).
- *Long term (10–25 years):* Beginning of a continuously operating, targeted, high-resolution topographic mapping and change detection capability. Targeted local to regional mapping, with global access, at 1-m resolution, 0.1-m vertical accuracy for the ground and water surfaces, and a repeat frequency of hours to years depending on the rate of topographic change.

In addition to these mission activities, an active research and analysis program should establish methods to integrate laser and InSAR observations and to incorporate these new sources of topographic data into studies that unravel the past history of landscape evolution, reveal the interactions of geomorphic processes, and improve preparations for and predictions of natural hazard events. Emphasis must also be placed on the calibration and validation of these new satellite-based sources of topographic data, to ensure that they are appropriately used in landscape studies and modeling, through comparisons to detailed ground-based and airborne measurements of topography and vegetation cover.

3. Variability of Earth's Magnetic Field

Geomagnetism provides one of three space-based techniques to probe the Earth's interior. (The other two are gravity and Earth rotation.) Geomagnetic studies are currently limited by a paucity of observations and attendant difficulty in their interpretation. Recent advances in nanosatellite technology hold the promise for cost-effective geomagnetic constellation operations. The International Decade of Geopotential Research endorsed by the International Association of Geomagnetism and Aeronomy (IAGA) and the International Association of Geodesy (IAG) has played a major role in encouraging programs that have led to the launch of Oersted, Sunsat, CHAMP, and SAC-C over the last five years.



The South Atlantic Magnetic Anomaly strength at 500-km altitude has increased significantly over the last 100 years. In 2000, the magnetic field was about 35% weaker in the South Atlantic than would be expected from a dipole field. This weakness in the field has serious implications for low-Earth-orbit satellite operations, because it impacts the radiation dosage at these altitudes. How much longer will the South Atlantic Magnetic Anomaly continue to grow? How deep will it become? Long-term satellite observations will allow us to model the future evolution of this anomaly.

• Constellation measurements provide a number of advantages over single-satellite
• measurements, including improved tracking of external field variability with local time
• and latitude, by observing the field simultaneously at a range of local times; improved
• observation of the main field and short-period temporal variations; and magnetic gra-
• dient measurements for the determination of magnetospheric and ionospheric current
• systems and the determination of an accurate external field model.

• The density of the constellation is determined by the requirement to be able to sepa-
• rate spatial and temporal variability of the different components of the field, espe-
• cially variability of the external field. Furthermore, better measurements of the exter-
• nal field components will lead to higher resolution electromagnetic induction studies
• of the mid- to deep-mantle and facilitate studies of the relationship between space
• weather and the Earth's atmosphere. High-resolution main field observations will pro-
• vide an improved determination of core field secular variation.

• Measurement requirements and suggested mission phasing are:

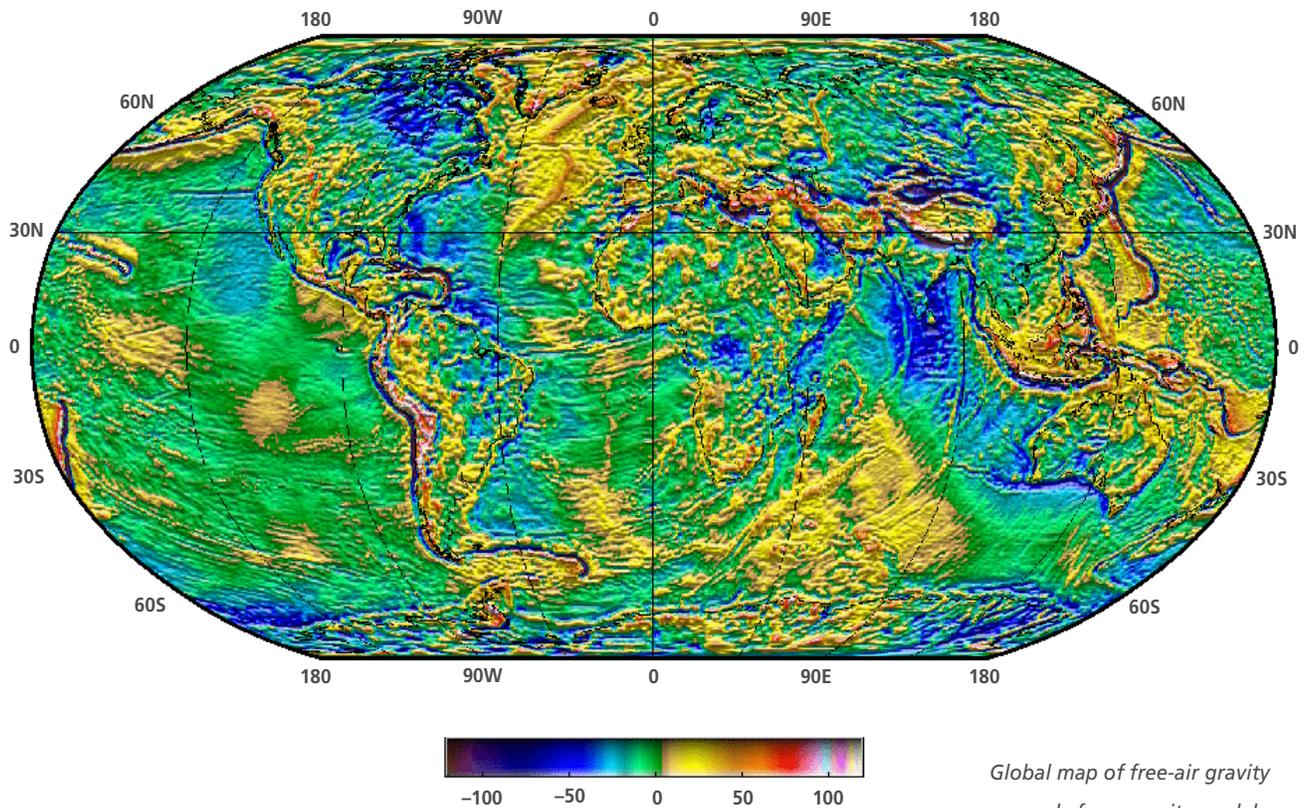
• • *Immediate (1–5 years):* Support of analysis of geomagnetic observations from current
• satellite missions. A modularized instrument package should be developed to facilitate
• taking advantage of missions of opportunity.

• • *Near term (5–10 years):* Constellation of 4–6 satellites at a range of local times in po-
• lar orbit at approximately 800-km altitude.

• • *Long term (10–25 years):* Establishment of a more complete, 12-satellite constellation
• by adding satellites at lower altitude (300 km) in polar orbits (to enhance study of the
• crustal field) and at 800 km in a low-inclination orbit (to enhance recovery of mantle
• electrical conductivity). Technological advancements should include the incorporation
• of star trackers on magnetometers and improved lifetimes at low altitudes.

• **4. Variability of Earth's Gravity Field**

• Satellite gravity measurements have demonstrated the clear importance of determin-
• ing the spatial and temporal variability of the Earth's global gravity field. The first
• measurements of spatial and seasonal gravity variability at scales of thousands of kilo-
• meters were obtained by laser-tracked geodetic satellites such as LAGEOS I and II.
• Seasat and subsequent ocean altimetry satellites provided the first high-resolution sat-
• ellite-derived gravity field over the oceans and yielded the most complete map yet of
• ocean floor bathymetry. There are now three dedicated high-resolution gravity mis-
• sions — GRACE, CHAMP, and the European Space Agency's Gravity Field and Steady
• State Ocean Circulation Explorer (GOCE) — either in orbit or planned. Each mission
• makes use of a different technique for gravity measurement. The 1997 National Re-
• search Council report "Satellite Gravity and the Geosphere" outlined in detail the com-



Global map of free-air gravity anomaly from gravity model EGM96, complete to spherical harmonic degree and order 360. Lighter shades denote higher gravity than average; darker shades, lower gravity than average. The unit is milligal, where 1 milligal ($10^{-5}ms^{-2}$) is about one-millionth of the Earth's average gravity. The pattern follows tectonic features and also reflects deeper density anomalies. Any time-variable gravity signal would be superimposed on this reference static field.

elling rationale for temporal measurements of the gravity field to the cryospheric, hydrological, atmospheric, oceanographic, and solid-Earth sciences.

GRACE, a collaboration between NASA and the German space agency, is the first satellite to measure temporal variability of the gravity field on a monthly basis at spatial scales as short as a few hundred kilometers. Although the strongest signals in the temporal variability of gravity are associated with mass transport in the atmosphere, oceans, and land hydrological systems, there are a number of measurements relevant to solid-Earth properties and processes, including lithospheric and mantle structure and glacial and oceanic loading and unloading of the lithosphere. Careful modeling of atmospheric, oceanic, and hydrological contributions will be necessary to resolve the signature of solid-Earth phenomena, as will calibration and validation with ground measurements. In situ ocean-bottom pressure measurements are also a required component of a space-based gravity measurement program so that ocean contributions can be separated from solid-Earth signals. Gravity missions such as GRACE, when combined with high-resolution radar altimetry missions such as Jason, will allow for the identification of the steric component of sea-level variations and the partitioning of water storage among continents, oceans, and ice sheets and glaciers. Combined use of time-variable gravity data and ice-mass data (e.g., from ICESat) can help quantify the mantle

• response to past and present glaciation. Because Earth-rotation parameters and gravity
• anomaly measurements are both manifestations of mass redistribution, geodetic and
• gravity measurements are excellent examples of synergy, allowing a better under-
• standing of global mass transport in the Earth system.

• Future gravity missions using laser interferometric or other high-resolution
• gradiometry techniques should achieve a sensitivity 100 to 1000 times that of GRACE.
• With that sensitivity it will be possible to resolve crustal deformation signals, such as
• mass displacement due to undersea lithospheric strain, vertical motions associated with
• lithospheric loading and unloading, changes induced by earthquake and volcanic pro-
• cesses, and subsurface aquifer and oil reservoir withdrawal.

• Measurement requirements and suggested mission phasing are:

- *Immediate (1–5 years):* Monthly estimation to within 10 millimeters of surface water-
equivalent load at a few hundred kilometers spatial resolution using existing satellites
such as GRACE.
- *Near term (5–10 years):* GRACE follow-on mission demonstrating satellite-to-satellite
laser interferometry technology.
- *Long term (10–25 years):* Gravity measurement improved by 2–3 orders of magnitude
in sensitivity using satellite-to-satellite laser interferometry or spaceborne gradiometer
technology.

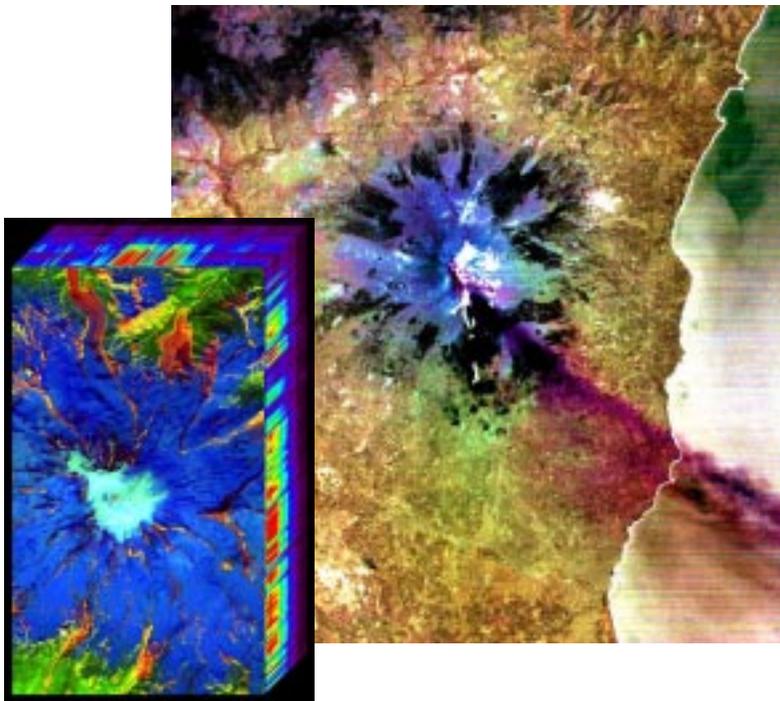
• **5. Imaging Spectroscopy of Earth’s Changing Surface**

• The Earth’s surface is the interface between the atmosphere, hydrosphere, and the
• solid Earth and is the interface of greatest importance to humankind. Imaging spectros-
• copy (or “hyperspectral” imaging) can resolve the surface attributes and expression of
• many of the processes related to natural and human-induced landscape change, volcan-
• ism, tectonics, and ice dynamics. Because near-surface materials and their properties of-
• ten determine a region’s susceptibility to such natural hazards as earthquakes, severe
• storms, wildfires, and volcanic activity, characterizing these materials will contribute
• significantly to global hazard mapping.

• Even in aerial photographs, which represent perhaps the simplest form of remote sens-
• ing, it is possible to recognize fire scars, landslides, old ice, and fresh lava. Imaging
• spectroscopy, in both the solar-reflected (0.4 to 2.5 μm) and thermal portions (3–5 μm
• and 8–12 μm) of the spectrum, raises this science to a new level because it permits the
• identification, separation, and measurement of subtle variations reflecting the overlap-
• ping molecular absorption and constituent scattering signatures of materials present
• on the Earth’s surface. Hundreds of spectral bands are sometimes required to resolve

and map the large number of materials present on the changing surface. In the face of the land surface's complexity, imaging spectroscopy provides a basis for the uniform compositional measurement of the exposed surface of the solid Earth for both basic science and hazards research.

As an example, measurements made by AVIRIS (Airborne Visible and InfraRed Imaging Spectrometer) are serving to define volcanic hazards and to aid in forecasting impending eruptions. AVIRIS data have been used to map subtle changes in near-surface rock chemistry and, thereby, to identify zones of volcanic-debris-flow susceptibility on the basis of rock strength inferred from specific mineralogical indicators of hydrothermal alteration. Debris-flow hazards to downstream communities represent the greatest volcanic threat for loss of life. Identification of susceptible zones could help to reduce this risk. Volcanic ash clouds pose a significant aviation hazard, as ash particles can and have destroyed jet engines. Real-time volcanic plume and ash detection and characterization in both the visible and thermal portions of the spectrum will reduce the risk posed by this hazard and will contribute significantly to our scientific understanding of eruptive processes. Identification of outgassed species near vents and craters provides information on subsurface activity and processes and may ultimately assist in forecasting eruptions. Thermal measurements of land surface temperature, together with simultaneous measurements of the changing emissivity, provide additional critical constraints on magmatic processes and volcanic activity.



(Right) Mt. Etna is one of the world's most active volcanoes and has been studied for centuries from the ground. This ASTER image was acquired during a recent eruption (July 29, 2001) and shows the sulfur dioxide plume (in purple) originating from the summit, drifting over the city of Catania, and continuing over the Ionian Sea. ASTER's unique combination of multiple thermal infrared channels and high spatial resolution allows the determination of the thickness and position of the SO₂ plume. The image covers an area of 24 x 30 km.

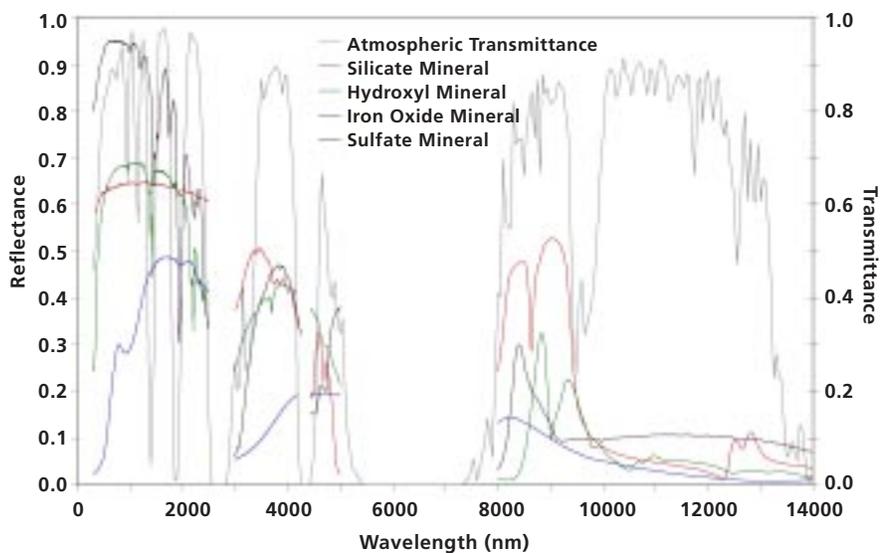
(Left) Mount Rainier, Washington, AVIRIS image cube. The top and right panel show the spectra from 400 to 2500 nm for the edge elements. The face panel (10 x 20 km) shows aspects of the composition of the surface, including frozen snow and ice (light blue), melting snow (dark blue), vegetation (green) and exposed rock and soil (red-brown). The AVIRIS spectra of this data set have been used to measure the snow and ice composition and melting status. The exposed rock composition and alteration has been determined for volcanic collapse hazard assessment.

• In arid environments, dust storms, sand storms, and migrating dunes pose hazards that
• can be effectively tracked via imaging spectroscopy. Although toxic chemicals can occur
• naturally, they can pose a hazard extending far beyond their source, if the weathering
• products become airborne, as is common in arid regions. For example, Owens Valley in
• eastern California is now recognized as the most significant source of toxic alkali dust
• in the western U.S. Understanding the spatial distribution of sources of naturally occur-
• ring toxins, the spread of contaminants from these source areas, and the correlation of
• contaminant distribution events with atmospheric winds and soil moisture (which con-
• trols susceptibility to wind shear) is possible through imaging spectroscopy.

• By combining determination of soil composition and moisture from imaging spectros-
• copy with other measurements, such as high-resolution topography and precipitation,
• we may be able to achieve real-time prediction of short-term surface-change events
• such as landsliding. Liquid water absorption in highly susceptible super-saturated soils,
• as well as seasonal, fire-induced, or human-induced changes in vegetation and related
• soil strength, are key determinants of landslide susceptibility that can be revealed via
• spectroscopy. In order to quantify snow accumulation, snowmelt, and surface runoff
• where winter snows persist, simultaneous, real-time measurement via imaging spec-
• troscopy of the three phases of water in melting snow and ice provides an otherwise
• unattainable window on the causative factors of major spring floods. Frequent obser-
• vations from space are required for such transient situations.

• The measurement of subtle differences in the mineralogy of surface rock and soil units
• serve to delineate the surface expression of earthquake faults. These same types of
• measurements can identify those naturally occurring minerals that acidify water and
• mobilize toxic heavy metals in water sources. Many materials in nature are harmful to
• man and often occur near population centers. The molecular absorption of a range of
• asbestos minerals, for instance, has been measured with AVIRIS in both natural and hu-
• man-altered environments. For asbestos and other spectrally unique materials, spatial
• concentrations of less than one percent of a pixel can be resolved. The key characteris-
• tics required to enable such results are a high signal-to-noise ratio, stability of the
• instrument's radiometric and spectral calibration, and orthogonal spatial and spectral
• characteristics (such that all wavelengths for a given spectrum come from the same
• area on the surface).

• In the solar-reflected spectrum, imaging spectroscopy of the solid Earth from space has
• taken an important first step with the Hyperion technology-demonstration sensor on
• the New Millennium Program Earth Observing (EO-1) spacecraft. Although Hyperion
• has a signal-to-noise ratio about one-fifth that of airborne AVIRIS, the success of its im-
• aging capabilities and analysis of its limitations will aid the development of the next-
• generation spaceborne imaging spectrometers.



• Much of the solar reflected, mid-wave infrared, and thermal infrared portions of the electromagnetic spectrum are transmitted through the atmosphere. Separating the molecular absorption and constituent scattering signatures in the spectra of surface rock and soil minerals, illustrated here for four common minerals, permits surface composition information to be recovered from high-resolution imaging spectroscopy.

The thermal portion of the spectrum includes important spectral signatures for Earth-surface materials. In addition to silicate mineralogy, changes in biota, soil water saturation, volcanic gas composition, and temperature can be discerned with appropriate spectroscopic measurements. Multispectral thermal-infrared measurements are being acquired by ASTER on the Terra platform. To address the challenges for solid-Earth science and hazards research with observations over this portion of the spectrum, substantially improved spectral sampling and high precision are required.

Acquisition of high-spatial-resolution panchromatic imagery in conjunction with imaging spectroscopy measurements will support the ability to measure and monitor small-scale surface displacements in a manner complementary to InSAR observations. Significant improvements in accuracy over what can be achieved with current NASA imagery require resolutions of 1–5 m/pixel.

The power of imaging spectroscopy is the ability for one technique to provide key data to solve a variety of problems, both within and outside of solid-Earth science. These data include ones that are relatively long lasting, such as images of zones of hydrothermally altered rocks or fault zones, and ones that are rapidly changing, such as measurements of soil saturation or airborne dust clouds. High spatial resolution is needed to delineate the persistent, but spatially complex, features of the Earth's surface, whereas high temporal resolution is required to predict, track, and mitigate most natural hazards. As the field advances and problems become more specific, imaging spectroscopy missions must evolve to meet the diverse requirements of a broad variety of scientific targets. NASA has guided the technique from the laboratory to airborne experiments and finally to space. Future spaceborne missions should focus on meeting science-specific requirements for signal-to-noise ratio, spectral and spatial resolution, and temporal sampling.

To address the challenges for solid-Earth science, measurement requirements and suggested mission phasing are:

- *Immediate (1–5 years):* Continued spaceborne and airborne imaging in the solar-reflected portion of the spectrum. An airborne capability in the thermal portion of the spectrum (3–5 μm and 8–12 μm with 30-nm spectral sampling) should be developed.
- *Near term (5–10 years):* An improved-precision solar-reflected spaceborne imaging spectrometer with a 100-km swath and 30-m spatial resolution. A high-spatial-resolution panchromatic capability should be included. A thermal imaging spectrometer (3–5 μm and 8–12 μm with 30-nm spectral sampling) having high signal-to-noise ratio, good calibration stability, and spectral–spatial orthogonality should be flown as a space demonstration project.
- *Long term (10–25 years):* Continuous spaceborne, wide-swath, full-spectrum, high-performance imaging spectroscopy. There should be a nested narrow-swath, high-spatial-resolution, full-spectrum capability to target transient events.

6. Space Geodetic Networks and the International Terrestrial Reference Frame

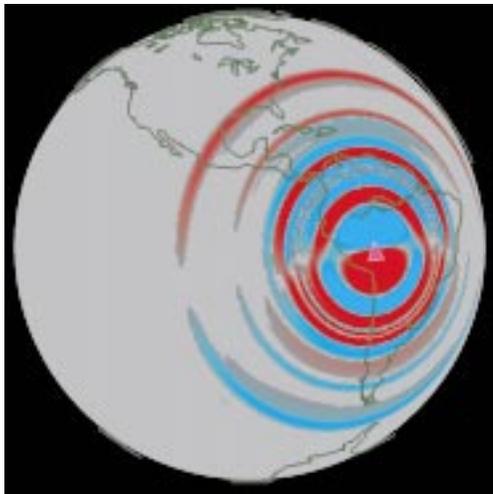
In cooperation with many international partners, NASA's Solid Earth Science Program plays a key role in establishing, maintaining, and operating global geodetic networks. Currently the networks include SLR, VLBI, and the GPS ground system. Relevant data products and valuable services are provided to the worldwide research community through the International Laser Ranging Service, the International VLBI Service, and the International GPS Service, respectively. Precise 3-D crustal motions are determined by all three networks, with dense GPS arrays particularly useful for regional tectonic and earthquake cycle studies. Beyond their scientific value, these data, together with precise determination of the 3-D geocenter motion by SLR and GPS, constitute the geodetic elements that define the International Terrestrial Reference Frame (ITRF), which is the basis for all geodetic measurements described in this report. The ITRF is geometrically connected to the Celestial Reference Frame via Earth Orientation Parameter (EOP) time series, which are determined primarily by the VLBI technique and contain a wealth of geophysical and climatic information. The ITRF and EOP, and hence the networks, should continue to be maintained and improved and their data routinely acquired at the best possible accuracy and temporal resolution.

7. Promising Techniques and Observations

A number of other promising observations that are either developing or expanding into the field of solid-Earth science offer additional methods to achieve the goals of the Solid Earth Science Program.

Seismology from Space

The SESWG is intrigued by the possibility of seismic imaging from space. Spaceborne seismology is a logical extension of spaceborne surface-change detection by SAR, radar, and GPS. The Southern California Integrated GPS Network (SCIGN) has observed near-field strain-wave propagation from the 1999 Hector Mine earthquake. It is likely that a continuously observing spaceborne system could image the occurrence of “silent” or “slow” earthquakes as well as the propagation of ground displacement by surface waves at scales of continents. The required technology, such as 30-m lightweight antennas, warrants early investment, and the specific data requirements for imaging from geosynchronous orbit should be defined. Another approach would be to use the ionosphere as a proxy for surface motion. It has been known for decades that the ionosphere responds to vertical motions of the Earth’s surface with an amplification of the vertical surface displacement on the order of ten thousand, although very limited in frequency content. Whether ionospheric tomography from GPS limb sounding and ground GPS networks, along with magnetic constellations, could image these surface-wave-induced ionospheric gravity waves should be explored.



Propagation of seismic waves from the deep, magnitude 8.2 Bolivia earthquake of June 9, 1994. The earthquake was so large that it produced a permanent displacement of the surface of the Earth of several millimeters near the epicenter in Bolivia.

The Solid Earth Beneath the Oceans

Over 70% of the solid Earth lies beneath the oceans, and many geologic processes of global significance occur on and beneath the ocean basins and margins. Some of these processes have analogues on land, but others are quite distinct. For example, at more than 50,000 km in length, the global mid-ocean ridge system is the dominant contributor to volcanic activity at the Earth’s solid surface. Mid-ocean ridges are the locus as well of pervasive hydrothermal systems that host unique biological communities not found at terrestrial volcanoes. Subduction zones, where great faults mark the sites of

• convergence between two tectonic plates, are found almost exclusively beneath the
• seafloor. Tsunamis, with their frequently devastating effects at coastal regions, origi-
• nate by motion at the Earth–ocean interface.

• Spaceborne observations have made significant contributions to the study of the solid
• Earth beneath the oceans. This generalization has been especially true in geodesy and
• seafloor mapping. Space geodetic techniques based on GPS combined with precise
• (centimeter-level) acoustic ranging provide the only means to place deep ocean bench-
• marks in an absolute reference frame, and hence integrate seafloor plate motions into
• the terrestrial (e.g., VLBI) deformation field. Satellite altimetry has been used to infer
• seafloor bathymetry from linear inversion of the global gravity field. While the result-
• ing product has lower spatial resolution than can be achieved with shipborne swath-
• mapping systems, it has provided the first global view of the shape of the ocean floor
• and the first comprehensive coverage in the remote southern oceans.

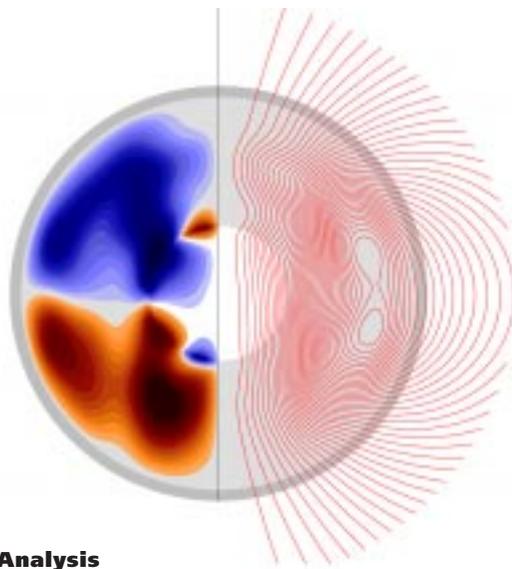
• Future satellite missions will extend observations of the solid Earth beneath the oceans
• to smaller spatial scales and will enhance global understanding of temporal variability.
• For example, high-accuracy gravity measurements from GRACE follow-on missions
• might be capable of observing intermediate-wavelength gravity anomalies generated
• by the accumulation of strain at locked convergent margins. Making such measure-
• ments in situ is costly and dependent on the serendipitous concurrence of seafloor in-
• strumentation with tectonic activity. Although some solid-Earth missions will have lim-
• ited application to submarine processes, NASA should be watchful for future opportu-
• nities to ensure that spaceborne measurements are utilized to their full capacity.

• Over the coming two and a half decades, the biological, chemical, and geological
• oceanography communities will increasingly focus on understanding episodic oceanic
• processes through the use of seafloor observatories. These will of necessity focus on
• the intensive study of relatively small regions, ranging from the scale of a mid-ocean
• ridge vent field up to that of the smallest (e.g., Juan de Fuca) tectonic plate.
• Spaceborne measurements that resolve temporal changes in the solid Earth beneath
• the seafloor will provide an essential global dimension to seafloor observatory efforts
• and should be coordinated with planned and future ocean observatory programs.

• **Subsurface Imaging**

• Spaceborne subsurface imaging was first demonstrated in radar images from the
• Spaceborne Imaging Radar (SIR-A and SIR-B) missions, from which sub-Saharan drain-
• age channels were identified beneath desert sands. Applications of this capability
• range from the estimation of ice cap thicknesses to the determination of subsurface
• properties such as geological structure, lithology, and soil moisture. Radar subsurface
• imaging combined with hyperspectral imaging could prove extremely valuable for re-
• motely mapping shallow subsurface characteristics that would make a region more vul-

nerable to natural hazards. For example, the capability to recognize areas of soft sediment or high moisture content could help delineate regions prone to strong shaking or possible liquefaction during earthquakes. Liquefaction effects after earthquakes have already been observed remotely in visual bands. Presently VHF or UHF sounding or SAR is the technology most often chosen as the means to achieve subsurface imaging. Advanced processing methods, improved hardware, airborne trials, and ground-truth procedures will need to be developed to capitalize on the promising potential that this approach offers for both basic and applied research.



Research and Analysis

Data analysis is an essential part of every NASA space mission. Not only are NASA data of greatest benefit when integrated with quantitative models, but the research leads to new ideas for how Earth processes operate, new ways of making measurements from space, and new concepts for missions. The solid-Earth system is inherently complex, and understanding it requires significant effort in the analysis of data and their comparison with models. Simulations must be carried out concurrently with data analysis so that the entire system can be studied and understood. Observational data can also be assimilated into computational models providing constraints on and verification of hypotheses.

A few examples of critical research and analysis programs for solid-Earth science at NASA include the following:

- Models of crustal deformation that incorporate InSAR and GPS measurements of surface deformation. The models for plate boundary zones should include the pre-, co-, and postseismic phases of the seismic cycle. Models must be developed for the many other sources of surface deformation including those associated with volcanic eruptions, water withdrawal, and loading and unloading by water and ice.

Numerical models of the geodynamo are now capable of reproducing many details of the geometry of the Earth's magnetic field. Shown is a cross section of a model for the axisymmetric part of the magnetic field through the Earth's core along the rotation axis. The white innermost region is the inner core, the light gray region is the outer core, and the thin dark-gray region is the lowermost part of the mantle. The left half of the image depicts the strength of the toroidal (east-west) part of the field, which is directed eastward in one hemisphere and westward in the other. The right half shows field lines of the poloidal part of the field, which displays a nearly dipolar structure. The dynamo maintains the Earth's magnetic field by converting poloidal field into toroidal field, and then converting toroidal field back into poloidal field.

• Models of landform evolution that account for time-dependent topography. The models should include the tectonic growth of topography as well as erosional processes.

• Models of time-dependent surface gravity. The models should account for tectonic, hydrological, surface loading and unloading, and mantle dynamical effects.

• Models of the Earth's magnetic field that account for observations.

Many solid-Earth science processes are associated with self-organizing complex systems and span time scales from seconds to tens of millions of years. A characteristic of these systems is that they satisfy self-similar, power-law statistics. Because this self-similarity extends over wide ranges of temporal and spatial scales, renormalization-group approaches are often required. These systems are generally chaotic, so they are statistical and intrinsically unpredictable. Examples include mantle convection, the outer core flow responsible for generating the Earth's magnetic field, the deformation of the Earth's crust responsible for earthquakes, and the evolution of land drainage systems.

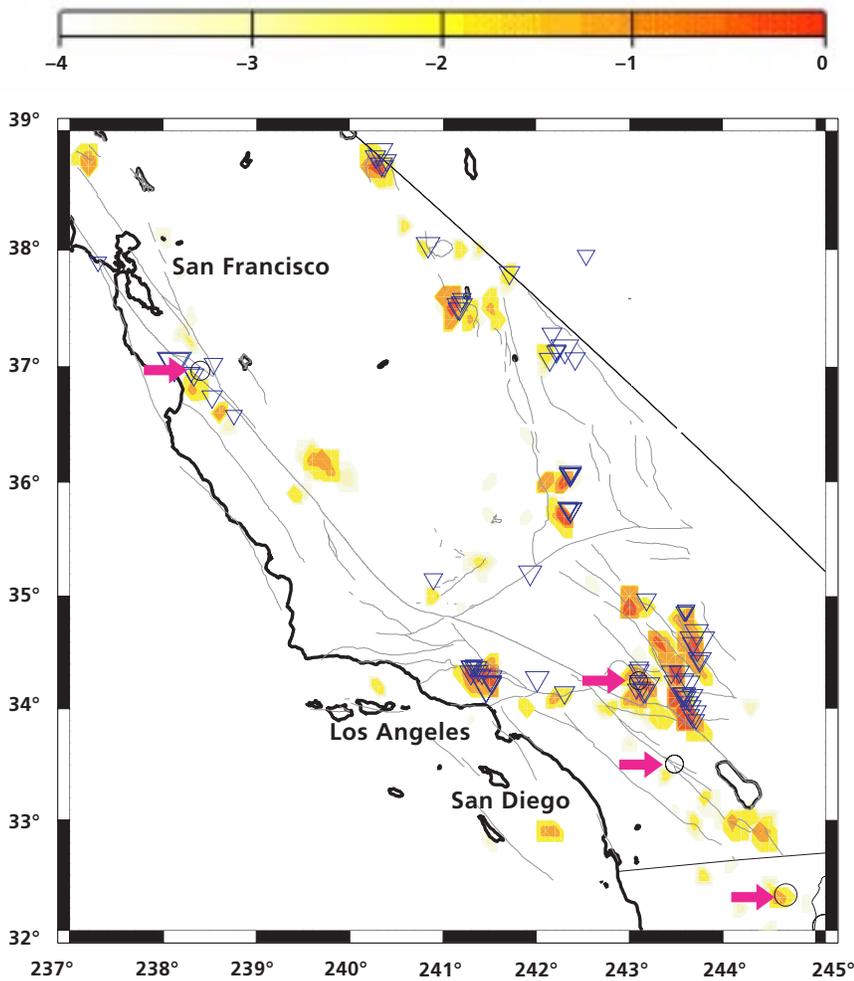
A number of natural hazards fall into this class of phenomena, including earthquakes, landslides, and forest and wild fires. Each of these natural hazards is characterized by a power-law distribution of severe "events." In order to explain this behavior, statistical physicists have introduced a number of simple cellular-automata models that yield power-law distributions of "avalanches." Three of these models can be directly associated with natural hazards: the slider-block model with earthquakes, the sandpile model with landslides, and the forest-fire model with large fires. The use of these models can provide a rationale for understanding and integrating a wide range of observational data on these systems.

Information Systems

1. Modeling and Computational Priorities

The broad range of spatial and temporal scales manifested by solid-Earth processes calls for a variety of modeling and data assimilation techniques. Advances in inversion methods, three-dimensional modeling, data assimilation, statistical analysis, and pattern recognition are all necessary for understanding these complex systems. High-performance computers are required for carrying out these approaches.

One of the major problems facing scientists today is that the scientific data volumes are increasing at a faster rate than computational power, challenging both the analysis and the modeling of observations. Resources must be put into improved algorithms to



simplify processing and to approximate complex phenomena to allow researchers to handle the large volumes of data as well as to find the dominant physics in a given data set. Another promising approach to handling large data volumes is to use pattern recognition to focus attention and point out subtle features in the data.

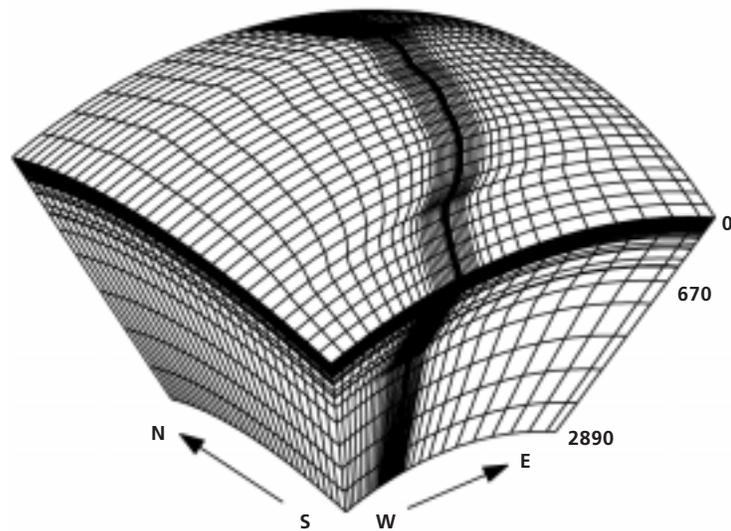
Because of the complexity of the solid-Earth system, high-performance computers are required for scientific progress. Computations of the systems being studied, from the geodynamo to interacting fault systems, take weeks to years to run on even the most capable of current workstations, making supercomputers the only means of modeling the systems. It is crucial to utilize the latest computational advances to make modeling an effective tool.

For example, numerical modeling of the geodynamo places extraordinary demands on currently available computational resources. Recent calculations have consumed

It is very difficult to forecast an earthquake. Yet advances in modeling and computational simulation methods, combined with increasing computational power, have suggested several methods for finding precursory space-time patterns hidden in existing data sets. One example is shown at left, where the colored anomalies are spots where future large earthquakes are likely to occur according to the analysis. More research is needed to quantify how well we can localize these occurrences in time. The red arrows point to four earthquakes of magnitude 5 or greater that have occurred since the forecast plot was made: the northernmost is the magnitude 5.2 Watsonville event that occurred on May 13, 2002; the middle earthquakes are the 5.1 February 10, 2001, Big Bear event, and farther south, the 5.1 October 31, 2001, Anza event; the southernmost is the 5.1 February 22, 2002, Baja California event. If the occurrence of moderate to large earthquakes were governed by statistical laws characterized by a uniform probability distribution in the space of seismically active crustal areas, then the probability that all four events fall within 11 km (the spatial resolution) of a colored anomaly can be computed to be about $P \sim .001$.

months to years of CPU time on supercomputers. Yet these numerical models operate far from the parameter regime of the Earth. There is the potential for great progress when computational resources reach the stage where data assimilation and sensitivity analysis become feasible. However, to achieve this goal will demand an entirely new approach to the provision of computational resources in the solid-Earth sciences, most likely with massive computational grids being made available.

A three-dimensional finite element grid for modeling mantle flow and crustal deformation along a subduction zone. Such modeling techniques are extremely computationally intensive.



2. Distributed Receiving and Processing Systems

An important aspect of data collection is to create distributed centers for processing and storing unique data sets. Developing the infrastructure to compare and use complementary data sets, such as ice topography and sea-level changes, opens the door to interdisciplinary research. It is also important to create the infrastructure to access other non-NASA datasets such as seismic and geologic data. These supporting data sets are critical for modeling and understanding the complete system. These distributed data centers are particularly important in the event of natural disasters, when not only can they support disaster management but they also enable real-time scientific experiments dependent on time-sensitive observations. Such centers will become more important as multiple data types are fused into integrated models. Characteristics of a system of centers should include distributed data at thousands of sites, each with data volumes of 1 TB–1 PB; multitier architecture for staging of the data; middleware to control integrity and versioning; support standards developed within the community; and high-performance user access of 100-GB files from 40-TB data sets within 5 minutes and program-to-program communication in milliseconds using staging, streaming, and advanced cache replication.

Technology Development

The ambitious research agenda of the solid-Earth community will provide unprecedented levels of highly accurate data. To achieve the accuracies and the spatial and temporal resolution needed to answer the highest-priority questions about the solid Earth, however, will require new advanced spaceborne technologies. Several promising technologies lie just beyond current capabilities. Systematic development of technologies through the Earth Science Technology Office (ESTO), Advanced Component Technology Program (ACT), the Instrument Incubator Program (IIP), and the New Millennium Program (NMP) will help reduce the risk, development time, and cost of the target missions.

The new technologies that will result in the highest science payoff are summarized in the illustration below. Other enabling technologies will be identified in coming years, but the figure serves to show the importance of investing in technology to meet the requirements for future science return.

An early investment in technologies will enable critical future observations.

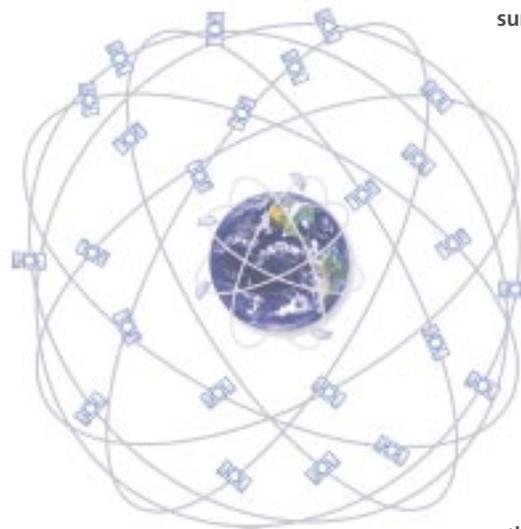


The Global Positioning System constellation is used for measuring surface position changes to millimeter accuracy. Applications range from plate tectonic velocity measurements to search-and-rescue operations in remote locations. GPS is a critical part of the supporting framework for solid-Earth science research but plays a dual role as an operational network relied upon by a broad range of military and civilian parties.

Supporting Framework

1. Maintenance of Global Geodetic Networks, Terrestrial Reference Frame, and Earth Orientation Parameters

The accuracy of global geodetic networks advances by about a factor 10 per decade, with submillimeter-scale reference-frame accuracy likely in the near future. Continued improvements in accuracy are critical to a number of the recommendations of this report, from the study of sea-level change and improved gravity-field measurements to



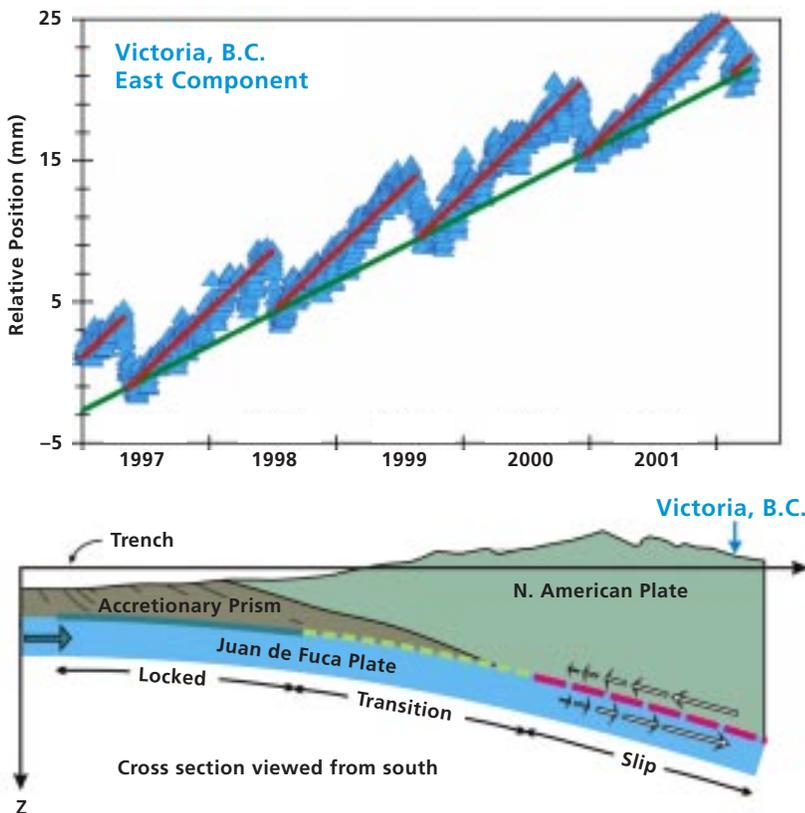
the detection and characterization of land surface change. The Internet and high-speed computing have recently been harnessed to provide near-real-time global GPS positioning and time transfer, of significant potential benefit to onboard satellite and airborne data reduction and natural hazards disaster management. For example, repeat-pass airborne InSAR is now possible given subdecimeter global navigation, a capability that can lead to real-time measurements of volcanic inflation and crustal deformation from an airborne platform.

Temporal changes in the gravity field and their links to Earth-orientation parameters are also an important focus of ongoing research. For instance, recent increases in the equatorial oblateness of the geoid may signal the migration of water from polar regions toward the equatorial seas.

Although initiated by NASA's Crustal Dynamics Program to measure crustal deformation and changes in Earth's angular momentum, the global geodetic networks now provide critical data products and valuable services to a multitude of scientific, government, commercial, and military users well outside the solid-Earth science community through the International GPS Service, the International Laser Ranging Service, and the International VLBI Service. A significant challenge for NASA is to identify a mechanism by which the support for these vital resources can be shared by all users within the agency, so that NASA's Solid Earth Science Program can turn its attention to the development and implementation of the strategic recommendations of this report.

2. Precise Orbit Determination (POD)

As is well-recognized by its international partners, NASA's Solid Earth Science Program supports the development, maintenance, and continuing refinement and enhancement of computer software for modeling and computing satellite orbits. This precise orbit determination (POD) capability is essential for the global space geodesy enterprise. Satellite-based geodetic techniques, such as SLR, GPS (including occultation and reflection experiments), microwave and laser altimetry, lidar, and SAR/InSAR all require continuous POD to accuracies within a decimeter to centimeter and better. These data also feed into the maintenance of the ITRF. Furthermore, the POD information constitutes primary data for solution of the Earth's gravity field. Single-satellite POD over the past four decades and recent spaceborne GPS satellite-to-satellite tracking have led to generations of steadily improving Earth gravity models used as a reference for a variety of civil, military, and research applications. POD is also a stringent requirement for planetary flights, space missions testing relativistic effects, and space VLBI. Relative POD from inter-satellite tracking (e.g., GRACE) provides improved measurement sensitivity and spatial resolution. Development of a "drag-free" system using onboard proof-mass technology will further POD and modeling capabilities.



GPS observations have documented that deformation across the Cascadia subduction zone in the Pacific northwest is governed by two processes acting on very different time scales.

Top: Change in relative east-west position between two GPS stations in British Columbia, one (Victoria) near the plate boundary marking the eastward subduction of the Juan de Fuca plate, and the other (Penticton) well inland on the stable North American plate. The long linear episodes of shortening (red lines) are interrupted at intervals of approximately 14 months by transients of opposite sign. The transients last 1–2 weeks and produce surface displacements of up to 5 mm. The average rate of shortening, the superposition of the two styles of deformation, is shown by the green line.

(Bottom) This deformation pattern has been modeled as the result of depth-dependent slip behavior along the interface between the two plates. The long-term shortening is attributed to the steady accumulation of stress across a shallow, locked portion of the subduction interface that lies off-shore. That stress appears to be released episodically by large thrust earthquakes at intervals of several centuries. The transient displacements are attributed to more frequent "silent earthquakes," episodes of slow slip that relieve stress along a deeper section of the plate interface but generate no seismic waves. The reason for the near periodicity of these transients is not known. Future space-based observations coupled with simulations involving models similar to that shown will aid in elucidating the underlying mechanics.

3. Coordination, Validation, and Calibration

While space-based measurements are inherently global in coverage, in many instances they are limited in their temporal or spatial sensitivity. For example, the spatial resolution of quantities derived from potential field measurements or their gradients will always be limited by the distance of a satellite from Earth's surface. The repeat times of satellites are often too long to resolve temporal variability at periods of hours to days, a problem that is worsened as orbit height is increased, e.g., in an effort to increase mission longevity.

In many instances, gaps in spatial and temporal coverage can be filled by utilizing other measurement platforms. Fine spatial resolution is often best achieved with land or seafloor arrays installed either semi-permanently or on a campaign basis. These arrays are typically focused on specific geologic features, e.g., the networks of seismic and GPS instruments along the San Andreas fault. Airborne SAR or imaging spectroscopy can provide smaller spatial and shorter temporal resolution of local features of special interest such as active volcanoes. Projects such as the Airborne Synthetic Aperture Radar (AIRSAR), AVIRIS, and the private industry GEOSAR illustrate the importance of airborne data collection. An important role for airborne programs is as technology testbeds for future radar techniques. Coordination of these efforts with space-based missions will yield a scientific return that exceeds the contribution from each measurement type and should be actively encouraged.



The atmosphere and oceans are a prominent source of signal for some space-based measurements. Examples include temporal gravity variations to be measured by GRACE and its follow-on missions or Earth rotation measurements to be made by future altimetric missions. Correction, validation, and calibration of these space-based observations will require in situ measurement of atmospheric and oceanic quantities before these data can be used to address solid Earth problems. Terrestrial-reference-frame measurements assist in separating out such signals. Removing the atmospheric and oceanic signals requires accurate models of the general circulation of the atmo-

This three-dimensional perspective view of the volcanic island of Manam, Papua, New Guinea, was obtained by AIRSAR operated in its topographic mode. The volcano, one of the most active in the Pacific "Ring of Fire," was in the midst of a large eruption when this image was acquired. Lava flows and hot clouds of rock, ash, and gas known as pyroclastic flows are emitted from craters at the summit of the volcano and race down the valleys. Deposits from earlier flows appear orange and blue; forested slopes of the volcano appear in pink.

sphere and ocean combined with assimilated global in situ measurements. Calibration and validation of GRACE-like missions requires the contemporaneous measurement of fluctuations of seafloor pressure. In the past, these supporting measurements have often been neglected or eliminated to accommodate budget shortfalls. Lack of such supporting data, however, reduces confidence in space-based measurements and in some instances can lead to incorrect inferences due to inherent measurement inaccuracy. Greater attention to validation and calibration is urged for all future mission planning.

Education

The discoveries and new knowledge gained from over 40 years of Earth remote sensing conducted by NASA have revolutionized our understanding of how the Earth functions as a system. This growing understanding is increasingly needed to inform political and economic decisions of local, national, and global impact.

The solid-Earth perspectives on life on a restless planet highlighted by this report offer exciting and engaging possibilities for education. To capitalize on these opportunities, the Solid Earth Science Program will collaborate with the NASA Earth Science Enterprise Education Program to stimulate broad public interest, appreciation, and understanding of Earth's interrelated systems, and encourage young scholars to consider careers in science and technology.

The Solid Earth Science Education Program (SESEP) will develop educational activities based on the three objectives identified by the ESE: informal education, formal education, and a work-force initiative in Earth Science Applications.

Informal education is considered an "out-of-classroom" educational opportunity such as those found in museums, science and technology centers, and similar nonprofit education organizations that provide significant educational activities for learners of all ages. Planned program components in this area include contributing new solid-Earth content and playing a consultative role for current and future development of exhibits, displays, and other non-classroom activities. For example, the California Science Center noticed that children's attendance in their Plate Tectonics area was down, likely because of a lack of appreciation among children (and probably their parents) that plate tectonics affects their lives. SESEP's remedy will be to develop hands-on activities to show the connection between plate tectonics and earthquakes and to create an enjoyable family learning experience. For existing NASA center partners, such as the interactive museum The Dynamic Earth, SESEP will arrange guest lecturers during Family Science nights and coordinate participatory demonstrations of topics such as earthquake simulation. SESEP will contribute to the NASA Earth Science Enterprise Museum Support workshops and conferences targeting the needs of informal educa-

Students make measurements of hidden magnets beneath a blue cloth in an analogy to the method GRACE uses to measure the gravity field of mass distributions in the Earth. Educational programs such as these are crucial in engaging the public in shaping and sharing NASA's experience in exploration and discovery and in appreciating how advances in solid-Earth science contributes to people's daily lives.

tors across the country. SESEP will also assist in the development of solid-Earth aspects of educational overviews and foster working relationships across the informal education network.

Formal education includes traditional classroom education from kindergarten through 12th grade, as well as undergraduate and graduate university programs. SESEP will support existing NASA and partner programs, such as the Global Learning and Observations to Benefit the Environment (GLOBE) program (field studies for students using GPS measurements), with the development of new resource materials for classroom teachers. SESEP will identify and supplement efforts for undergraduate and graduate research opportunities through NASA centers, universities having Memoranda of Understanding (MOUs) with NASA, and existing university programs that support solid-Earth education and research.



The Work Force Initiative in Earth Science Applications is a professional work-force development program aimed at identifying and addressing requirements for enhancing job skills in Earth science and technology fields. SESEP will establish a contact list of undergraduate and graduate students who are involved in solid-Earth science and are interested in participating in research programs. This list will be shared within NASA and with other government and private organizations that may have future opportunities for the students. SESEP partners and scientists will speak at specific engagements and professional conferences aimed toward industry to raise awareness of ongoing solid-Earth science efforts and to expand participation.

The Solid Earth Science Education Program is designed to exert a current, progressive, and informative influence that fulfills NASA's ESE objectives and leverages other ESE initiatives. SESEP will be an important element of NASA's contribution to the national socio-economic and educational agenda and will promote synergy among NASA and non-NASA activities while establishing its unique role and contributions to furthering solid-Earth education.

Summary

Earth science as a discipline now recognizes the dynamic, interconnected nature of the Earth as a system. Each component — oceans, atmosphere, biosphere, and solid Earth — interacts with the others in ways only partially understood and over a broad range of time scales. The solid Earth is a dynamic and essential component of the Earth system. From the motions in the core that generate the Earth’s magnetic field, through mantle convection, plate tectonics, volcanic eruptions, and land surface evolution, the solid Earth is always changing.

A primary goal of solid-Earth science is the assessment and mitigation of natural hazards that seriously threaten health, safety, national security, and economic viability. Space-based data acquired by NASA and other cooperating Federal agencies contribute heavily to our understanding and forecasting of volcanic eruptions, sea-level rise, floods, landslides, earthquakes, and other hazards. The 25-year vision of the Solid Earth Science Working Group (SESWG) is to understand natural and perturbed systems well enough to predict outcomes, consequences, and impacts.

Understanding the discrete events that shape the Earth, and from them building a complete picture of our planet’s dynamics, requires views of the governing behavior at local, regional, and global scales. For many scientific issues, satellite-based observations are the primary practical means to obtain an adequate density of coverage. Integrating the complementary and often more intensive, local ground-based measurements into comprehensive predictive models requires a new generation of satellite measurements at temporal and spatial resolutions substantially superior to those made in the past.

Six broad scientific challenges have been identified as the highest in priority for NASA’s Solid Earth Science Program for the next 25 years. These challenges are of fundamental scientific importance, have strong implications for society, are amenable to substantial progress through a concerted series of scientific observations from space, and build naturally on directions identified in the NASA Earth Science Enterprise Strategic Plan. The six science challenges are

- What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?
- How do tectonics and climate interact to shape the Earth’s surface and create natural hazards?
- What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea-level change?
- How do magmatic systems evolve and under what conditions do volcanoes erupt?
- What are the dynamics of the mantle and crust and how does the Earth’s surface respond?

- What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

These six challenges are guiding themes that should define the research objectives for solid-Earth science within NASA for the next two and a half decades. Each challenge, once met, offers a series of significant expected accomplishments and clear benefits to the nation. On the basis of current knowledge, the next steps needed to address each challenge can be readily defined.

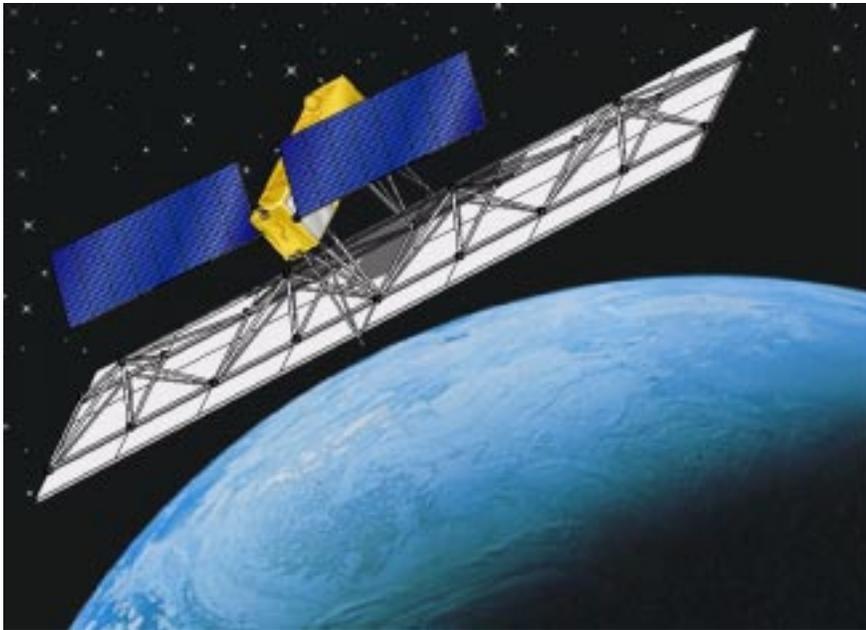
The six scientific challenges are also extremely ambitious and address goals common to the entire solid-Earth science community. Success in meeting these challenges will depend on the close coordination and collaboration with other NASA programs, with other federal agencies, and with international partners.

To make substantial progress toward answering each of the six challenges, NASA must formulate a broadly conceived program with both near-term goals and clear steps toward longer-term objectives. A fully realized program contains elements that encompass not only new observations, but also sustained investment in research and analysis, information systems, new technologies, supporting infrastructure, and education. While NASA's role in observations is primarily the development of satellite missions, such projects cannot be their most effective without complementary terrestrial observations and the requisite partnerships with other programs and agencies. A dedicated research and analysis program is critical to insure that newly acquired data are fully analyzed, to provide the new ideas for instrument and mission development, and to foster unexpected scientific discoveries. This effort should include significant investments in computation and modeling for testing theories and predictions. A number of observations needed over the next two decades require a continuing investment in advanced technology development. A modular yet broadly interlinked program architecture offers flexibility to change as scientific discoveries and programmatic requirements dictate.

The recommended plan for new observations from space to meet the scientific challenges for solid-Earth science builds on current capabilities and on data from missions and instruments that have recently flown, are currently flying, or are planned for the very near future. It also relies on data from missions currently supported by other scientific disciplines within NASA, and it leverages collaborations with federal, private, and international partners.

The plan is cast in terms of five observational campaigns or strategies, each of which addresses multiple scientific challenges. These strategies include

- deformation of the land surface,
- high-resolution topography and topographic change,



A dedicated InSAR satellite is the highest-priority objective for solid-Earth science at NASA in the next 5 years.

- variability of the Earth’s magnetic field,
- variability of the Earth’s gravity field, and
- imaging spectroscopy of Earth’s changing surface.

Specific recommendations for each strategy are divided by time horizon among the immediate time frame (1–5 years), the near term (5–10 years), and the long term (10–25 years). Supporting strategies are offered for space geodetic networks and the International Terrestrial Reference Frame, as well as for several promising directions where substantial technology development will be required.

The elements of these observational strategies, broken down by time frame, are illustrated in the table on page 60. The potential impact of each strategy on each of the six scientific challenges is also indicated.

In the next 5 years, the new space mission of highest priority for solid-Earth science is a satellite dedicated to Interferometric Synthetic Aperture Radar (InSAR) measurements of the land surface at L-band. Such a mission would address the most urgent objectives in the areas of plate-boundary deformation, land-surface evolution, ice and sea-level change, volcanism, and mantle dynamics.

Over the next 5–10 years, the scientific challenges facing solid-Earth science can be met by NASA leading or partnering in the flight of space missions involving constellations of satellites dedicated to InSAR and magnetic field measurements, new-generation instruments for mapping global topography and its temporal changes and for carrying

Timeline Observational Strategies	Immediate (1–5 Years)	Near Term (5–10 Years)	Long Term (10–25 Years)	Plate Boundaries	Land Surface Change	Ice and Ocean Dynamics	Magmatic Processes	Mantle Dynamics	Magnetic Field
	Surface deformation	<p>Single dedicated InSAR satellite</p> <ul style="list-style-type: none"> L-band, left/right looking capability, and weekly access to anywhere on the globe Precise orbit determination and ionospheric correction capabilities 1 mm/yr surface displacement over 50-km horizontal extents in selected areas 	<p>Constellation of InSAR satellites</p> <ul style="list-style-type: none"> Improved temporal frequency of deformation maps to daily intervals Maps at several-hundred-km width with full vector surface displacements at accuracies of submillimeter per year over 10-km spatial extents and 1-m spatial resolution Complementary ground and seafloor geodetic observations 	<p>Constellation of InSAR satellites in low-Earth or geosynchronous orbits</p> <ul style="list-style-type: none"> Hourly global access Increased density of continuous ground and seafloor geodetic observations 					
High-resolution topography	<p>Distribute all SRTM data, launch ICESat, and demonstrate imaging lidar capabilities in Earth orbit</p>	<p>Global mapping to supercede the SRTM data set</p> <ul style="list-style-type: none"> One-time global mapping at 2- to 5-m resolution and 0.5-m vertical accuracy for the ground surface Ice-sheet mapping with 1-km horizontal resolution, 1-cm vertical accuracy for the ice or snow surface, and a repeat interval of months (for annual changes) to years (for long-term changes) 	<p>Continuously operating, targeted, high-resolution topographic mapping and change-detection capability</p> <ul style="list-style-type: none"> Targeted local to regional mapping, with global access, at 1-m resolution, 0.1-m vertical accuracy for the ground and water surfaces Repeat frequency of hours to years depending on the rate of topographic change 						
Variability of Earth's magnetic field	<p>Support of analysis of geomagnetic observations from current satellites</p> <ul style="list-style-type: none"> Development of a modularized instrument package to facilitate taking advantage of missions of opportunity 	<p>Constellation of 4–6 satellites</p> <ul style="list-style-type: none"> At a range of local times Approximately 800-km altitude in polar orbit 	<p>Complete, 12-satellite constellation</p> <ul style="list-style-type: none"> Adding satellites at lower altitude (300 km) in polar orbit (to enhance study of the crustal field) At 800 km in a low-inclination orbit (to enhance recovery of mantle electrical conductivity) Technological advancements on incorporating star trackers on magnetometers and improved lifetimes at low altitudes 						
Variability of Earth's gravity field	<p>GRACE</p> <ul style="list-style-type: none"> Monthly estimation to within a few millimeters of surface water-equivalent load at a few-hundred-kilometers spatial resolution 	<p>GRACE follow-on mission</p> <ul style="list-style-type: none"> Demonstration of satellite-to-satellite laser interferometry technology 	<p>Gravity measurement improved by 2–3 orders of magnitude in sensitivity</p> <ul style="list-style-type: none"> Satellite-to-satellite laser interferometry, or Spaceborne quantum gradiometer 						
Imaging spectroscopy of Earth's changing surface	<p>Continued spaceborne and airborne imaging in the solar reflected spectrum</p> <ul style="list-style-type: none"> Develop airborne measurement capability in the TIR (3–5 and 8–12 micrometers) 	<p>Improved spaceborne imaging spectrometer</p> <ul style="list-style-type: none"> 100-km swath and 30-m spatial resolution in the VNIR Demonstration of spaceborne TIR imaging spectrometer: 30-km swath, 30-m spatial resolution 	<p>Continuous full-spectrum spaceborne imaging spectrometry</p> <ul style="list-style-type: none"> Targeted local to regional mapping, with global access, across multiple wavelengths Repeat frequency of hours to years, depending on the rate of change of the studied process 						

Scientific Challenges	Color Code	Examples of the Benefits to Society
What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?		Rapid response to seismic disasters
How do tectonics and climate interact to shape the Earth's surface and create natural hazards?		Floods, landslides, and coastal erosion risk assessment
What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea-level change?		Improved estimates of future sea-level rise
How do magmatic systems evolve and under what conditions do volcanoes erupt?		Advanced planning for high-risk populations near volcanoes
What are the dynamics of the mantle and crust and how does the Earth's surface respond?		Understanding mantle and crustal dynamics role in hazards
What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?		Forecasts of magnetic field for space weather effects on satellites

out imaging spectroscopy across a broad portion of the electromagnetic spectrum, and a GRACE follow-on to improve the resolution of temporal changes in Earth's gravity field. Several techniques and observations offer the promise to contribute in a major fashion to solid-Earth science but require substantial technology development. Among these are imaging of propagating seismic waves from space, linking space observations to processes occurring on and within the solid Earth beneath the oceans, and subsurface imaging from space with ground-penetrating radar.

The solid Earth is inherently complex, and understanding it requires significant effort in the analysis of data and their comparison with models. Simulations must be carried out concurrently with data analysis so that the entire system can be studied and understood. High-performance computers dedicated to solid-Earth science are required to carry out these calculations, as well as to manage the large volumes of scientific data that the recommended observational strategies will yield. Distributed centers are the preferred mode for processing, storing, and retrieving the needed data. Each observational strategy calls for new technologies, and the time frames when each new technology will be needed dictate the level and pace of required investment. All of the recommendations for solid-Earth science are predicated on maintaining NASA's special capabilities in updating the terrestrial reference frame, monitoring Earth orientation parameters, and carrying out precise orbit determination. Each recommendation also calls for ground-based validation and calibration measurements that are closely coordinated with the spaceborne observations. Finally, the expected new knowledge to be gained about the solid Earth and its natural hazards provides compelling material with which to inform and engage students at all educational levels.

The beginning of the 21st century is a time of unprecedented opportunity in solid-Earth science. The confluence of advances in satellite-based observing systems, high-performance computing and communications, and recent fundamental discoveries, all over the past few decades, promises an era in which many of the previously seemingly intractable problems in Earth science are now ready to be solved. In the next two decades we will be in a position to reach new insights into earthquakes, volcanic eruptions, wildfires, landslides and floods, and the dynamics of the Earth's core and mantle. NASA has a unique and essential role to play in seizing this opportunity to understand and manage the restless planet on which we all live.

Credits

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- Editor: Jeff Booth, JPL/Caltech
Design & production: JPL Design Services – David Hinkle, Adriane Jach, Marilyn Morgan, Audrey Steffan

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JPL 400-1040 11/02