Review of NASA's Solid-Earth Science Strategy

DETAILS

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Norman Sleep, Stanford University. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Preface

In 2000, Dr. Ghassem Asrar, associate administrator of the National Aeronautics and Space Administration's (NASA's) Office of Earth Science, established a Solid-Earth Science Working Group (SESWG) to prepare a 25-year vision and strategy for solid-earth science at NASA. This group, consisting of 16 members drawn from academia and federal agencies, met on three occasions between late 2000 and early 2002. In addition, "town hall" sessions were held at the 2000 fall and 2001 spring meetings of the American Geophysical Union to brief the broad scientific community and to seek additional input. The working group released *Living on a Restless Planet*[1] in late 2002. Dr. Asrar requested in 2003 that the National Research Council (NRC) provide an assessment of the strategy and vision presented in the SESWG document, and we report here the NRC response.

The charge to the NRC review committee is as follows:

An ad hoc committee will review NASA's 25-year vision for its solid-earth science program described in the report *Living on a Restless Planet*. The committee will evaluate the report with particular emphasis on answering the following questions:

1. Are the priorities of the report consistent with national priorities in the solid-earth sciences, as laid out in the strategic plans of relevant federal agencies and interagency organizations?
2. Does the report include all the major research foci for which NASA can make a unique contribution?

The review committee held one meeting on March 14–15, 2004, at the National Academies' Beckman Center in Irvine, California. In addition, the committee held teleconferences with Dr. Sean Solomon, chairman of SESWG, to discuss the background of the SESWG report, and with Dr. Asrar to discuss the motivation for the NRC review. Finally, the committee had access to a written review of the SESWG report prepared by the NRC Committee on Seismology and Geodynamics in September 2003 and to strategic planning documents produced by relevant agency and interagency groups. Our report is based on these inputs and on discussions among committee members at our meeting in Irvine.

[1] National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., 63 pp., 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

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Executive Summary

The centerpiece of the Solid-Earth Science Working Group's (SESWG's) strategic vision for the National Aeronautics and Space Administration (NASA) is an ambitious program of continuous measurements of the changing surface of the earth and its external fields. As explained in the SESWG report *Living on a Restless Planet*,[1] the justification of and motivation for this vision are the scientific and societal benefits that will be derived from NASA's undertaking this program and its unique role in mitigating a broad range of natural hazards.

In this report we review the recommendations in the SESWG report and answer the questions posed by Dr. Ghassem Asrar, associate administrator of NASA's Office of Earth Science:

1. Are the priorities of the report consistent with national priorities in the solid-earth sciences, as laid out in the strategic plans of relevant federal agencies and interagency organizations?
2. Does the report include all the major research foci for which NASA can make a unique contribution?

Consistency with National Priorities in the Solid-Earth Sciences

We find the priorities identified in the SESWG report to be consistent with the priorities of U.S. federal science agencies and organizations that sponsor significant programs in basic or applied solid-earth science. Implementing the recommended observational strategies in a timely manner will be important for major earth-science initiatives in many federal agencies, including:

- studying the structure, composition, and evolution of the solid earth (EarthScope, NASA, National Science Foundation [NSF], U.S. Geological Survey [USGS], Smithsonian);
- studying the dynamics at the interfaces of earth systems (NSF, NASA, Climate Change Science Program [CCSP], National Oceanic and Atmospheric Administration [NOAA]);
- studying the processes that cause natural hazards (NSF, NASA, USGS);
- measuring motions of the earth's surface (NASA, NOAA, NSF);
- analyzing watersheds, hydrological fluxes, or fluid flow in reservoirs (NOAA, USGS, Department of Energy [DOE]); and
- characterizing, monitoring, or managing the earth's surface (USGS, NSF, Environmental Protection Agency [EPA], U.S. Department of Agriculture [USDA]).

[1] National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., 63 pp., 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

Inclusiveness of Major Research Foci to Which NASA Can Make a Unique Contribution

The SESWG report identifies observational strategies in five primary areas: surface deformation, high-resolution topography, surface properties using imaging spectroscopy, variability of the earth's magnetic field, and variability of the earth's gravity field. We believe that these are the major solid-earth research themes for which NASA can make significant and unique contributions given reasonable assumptions regarding actual and proposed satellite-based observing systems. No other agency has the experience in developing, building, and launching instruments in these research areas, although many will use the data in their own applications. NASA's experience with IT will also be important for analyzing the large volumes of data produced by continuous, global monitoring and for disseminating information to the community quickly.

Analysis of SESWG Recommendations

The SESWG report makes recommendations for implementing each of the observational strategies in the short term (1–5 years), near term (5–10 years), and long term (10–25 years). Our analysis is as follows:

- ***Surface Deformation***. Interferometric synthetic aperture radar (InSAR) measurements are leading to significant advances in quantifying processes that deform the surface of the earth—including earthquakes, subsidence, the movement of magma beneath volcanoes, and the extraction of fluids—and their associated hazards. InSAR is also a key component of a number of agency programs, such as the USGS hazards mitigation program and EarthScope. *We strongly endorse the view expressed in the SESWG report that the new space mission of highest priority for solid-earth science is the launch of a satellite dedicated to L-band InSAR measurements of the land surface within the next five years*. However, we suggest that technological improvements to expand InSAR capabilities and/or reduce costs be considered when planning for future space-based missions.
- ***High-Resolution Topography***. We support the goals of releasing 30-meter data from the Shuttle Radar Topography Mission, acquiring global 2- to 5-meter-resolution land topography data in the near term, and developing the technology to collect targeted 1-meter-resolution data in the long term. Use of these data would advance studies of tectonic, geomorphic, climatic, and biotic processes and would improve the detection and forecasting of geologic hazards, as long as challenges in analyzing and distributing large volumes of data in near real time can be overcome. Advances in understanding ocean floor processes and mantle dynamics could be expected from the acquisition and use of 5-kilometer resolution bathymetric data, although collection of such data is not a stated goal of the SESWG report.
- ***Variability of the Earth's Magnetic Field***. We endorse the SESWG near- and long-term goals of collecting enhanced observations from increasingly dense constellations of satellites in coordinated orbits. Such instrument configurations are needed to separate out large-scale temporal and spatial variations in the external field, to study the effects of dynamo activity in the earth's liquid outer core and the electrical properties of the mantle, and to evaluate the impact of space weather on communications and satellite observations. Because geomagnetic missions are currently being flown by other countries, the SESWG report's immediate goal of analyzing observations from current missions is reasonable. The upcoming European Space Agency (ESA) Swarm mission would satisfy the SESWG report's 5–10 year goal for a small constellation of satellites, provided that NASA reaches a formal agreement with ESA for U.S. researchers to have timely and affordable access to Swarm data. To satisfy longer term goals NASA will have to initiate planning for larger constellations of satellites, exploiting opportunities for collaboration with other countries. This strategy should advance the science as well as help maintain U.S. expertise in geomagnetic instrument development, modeling, and analysis.
- ***Variability of the Earth's Gravity Field***. NASA's current time-variable gravity mission—Gravity Recovery and Climate Experiment (GRACE)—is functioning according to design, and we endorse the SESWG goal of spending the next five years using the data to study geophysical

processes such as postglacial rebound. ESA's Gravity Field and Steady-State Ocean Circulation Mission (GOCE) satellite will provide experience with satellite gravity gradiometry, and the proposed near-term NASA mission would test satellite-to-satellite interferometry. A careful analysis of these and perhaps other approaches will help NASA choose the most appropriate gravity measurement technology to replace GRACE in the long term.

- ***Surface Properties Using Imaging Spectroscopy***. We support implementation of the stated and implied SESWG recommendations, including continuation of the Airborne Visible/ Infrared Imaging Spectrometer (AVIRIS) and development of a hyperspectral (less than 10-nanometer bandwidth) visible-near-infrared spaceborne instrument. Rather than simply refining existing techniques, new sensor technologies will be required to enable identification of minerals, rocks, and soils and to monitor landscape change, volcanism, tectonics, and ice dynamics. In addition to airborne and spaceborne hyperspectral capabilities, continued operation of multi-spectral instruments would help meet a number of scientific objectives, although multispectral equivalent products could be derived from hyperspectral data if choices must be made.

Overall, we find that the observational strategies outlined in the SESWG report would take advantage of NASA's skills in sensor development and yield important data for addressing major earth-science challenges. Equally important to the success of NASA's solid-earth program will be the analysis of data from existing and planned instruments flown by NASA and space agencies in other countries, especially to meet the gravity and magnetics scientific objectives. Although adjustments might be necessary as new technology is developed, we believe that the observational strategies provide a sound basis for guiding NASA's solid-earth science program in the coming decades.

1

Introduction

OVERVIEW OF *LIVING ON A RESTLESS PLANET*

The premise of the Solid-Earth Science Working Group's (SESWG's) *Living on a Restless Planet*[1] is that data from National Aeronautics and Space Administration (NASA) satellites and aircraft and the advanced modeling techniques developed to interpret these data have a major role to play in detecting, quantifying, and understanding the dynamic processes affecting the solid earth and the interactions between the solid earth and its fluid envelopes. It is widely accepted that some of the most important scientific questions in earth and planetary science relate to defining and understanding these processes and that such knowledge is essential for establishing a baseline for exploration of other planets. The report emphasizes that these processes are of direct societal importance (and of value to federal, state, and local hazard-mitigation programs) since they underlie natural hazards such as earthquakes, volcanic eruptions, and landslides.

The report identifies six broad challenges that are of fundamental scientific importance, have strong implications for society, are amenable to substantial progress through new observations, and for which NASA can provide leadership by making possible critical and unique observations and analysis. These scientific challenges are:

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?

Based on these scientific challenges, the SESWG report defines five primary observational strategies, each of which, if implemented, would contribute to addressing two or more of the scientific challenges listed in the preceding paragraph:

1. surface deformation

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[1] National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., 63 pp., 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

2. high-resolution topography
3. variability of the earth's magnetic field
4. variability of the earth's gravity field and
5. imaging spectroscopy of the earth's changing surface.[2]

We note that imaging spectroscopy is the most practical way to measure certain surface properties remotely—it is not a fundamental scientific measurement. For consistency with the other observational strategies, we discuss it under the title "surface properties using imaging spectroscopy."

For each of the observational strategies, the SESWG report makes specific recommendations for implementation at short-term (1–5 years), near-term (5–10 years), and long-term (10–25 years) time scales. In addition to these five observational strategies, the report makes recommendations regarding space geodetic networks and the International Terrestrial Reference Frame, as well as promising techniques and observations. In general, priorities are not assigned to the recommendations, with the important exception that the launching of a satellite dedicated to interferometric synthetic aperture radar (InSAR) measurements of the land surface is identified as the single highest priority for NASA's solid-earth science program. The report concludes with a description of elements that complement the recommended observational strategy, including research and analysis, information systems, technology development, supporting framework, and education.

ORGANIZATION OF THIS REPORT

Our report covers the five observational strategies highlighted by the SESWG report and the specific recommendations related to each strategy. For each of the strategies, we

- provide a brief overview of its background;
- repeat the immediate, near-term, and long-term recommendations of the SESWG report;
- describe the scientific and societal benefits that would accrue from proceeding as recommended;
- summarize the relationship of the recommendations to national priorities in solid-earth science laid out in strategic plans of relevant federal agencies and interagency organizations (summarized and referenced in Appendix A);
- analyze whether the strategy as defined identifies ways in which NASA can make a unique contribution;
- analyze the strengths and weaknesses of the recommendations and highlight key technical challenges and advances that will be necessary to implement the strategies as described; and
- summarize our analysis.

After analyzing the observational strategies, we conclude with a summary of our evaluation, highlighting those aspects of the recommendations in the SESWG report that are of highest priority.

We note at the outset that there are aspects of the SESWG report that we have chosen not to review. For example, we do not evaluate explicitly the validity of the six broad scientific challenges that motivated the proposed observational strategies. Our reasoning is that these scientific challenges reflect classic, major issues in earth science.[3] Although considerable and

[2] National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., p. 29, 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

[3] For example, the scientific themes recommended to guide NASA's solid-earth program a decade ago were similar in scope, although somewhat different in focus, to the SESWG scientific challenges. They

interesting debate may arise about any aspect of these challenges, they are manifestly so important and largely uncontroversial that we chose not to invest our limited time in such debate. Likewise, we have chosen not to comment on the descriptions of supporting infrastructure (e.g., space geodetic networks, information systems) and education, except as they relate to the five main observational strategies. Again, these issues are not controversial at the level of detail given in the SESWG report. These decisions reflected our interpretation that our charge was to focus on the major initiatives proposed in the report.

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included (1) interactions of the earth's surface and interior with the oceans and atmosphere on time scales of hours to millions of years; (2) the evolving landscape as a record of tectonics, volcanism, and climate change during the last 2 million years; (3) the motions and deformations of the lithosphere within the plates and across plate boundaries; (4) the evolution of continents and the structure of the lithosphere; (5) the dynamics of the mantle including the driving mechanisms of plate motion; and (6) the dynamics of the core and the origin of the magnetic field. See National Aeronautics and Space Administration, *Solid Earth Science in the 1990s, Volume 1—Program Plan*, NASA Technical Memorandum 4256, Washington, D.C., 61 pp., 1991.

2

Analysis of SESWG Recommendations

This chapter presents our analysis of the recommendations in the Solid-Earth Science Working Group report, which focus on five observational strategies: surface deformation, high-resolution topography, variability of the earth's magnetic field, variability of the earth's gravity field, and surface properties using imaging spectroscopy.

SURFACE DEFORMATION

Interferometric Synthetic Aperture Radar makes it possible to measure deformation of the earth's land surface accurately (to 1 millimeter per year under favorable circumstances) and in great spatial detail (25-meter resolution or less) over wide areas. Surface deformation that occurs during the interval between the recording of two images results in changes in the radar signal, which can be transformed into a map of ground displacement. The first InSAR mapping of surface deformation associated with earthquakes and volcanoes used observations made by the European Space Agency's (ESA's) European Remote-Sensing Satellite (ERS) missions.[1] ERS InSAR data have since been used for a range of studies, including investigating the slow accumulation of crustal strain across fault zones; the motions that occur immediately following an earthquake (which allow the mechanical properties of the crust and uppermost mantle to be investigated); the inflation or deflation of volcanoes due to movement of magma at depth; subsidence in urban areas caused by the extraction of oil or water or the collapse of underground caverns; and the movement of Antarctic ice streams.[2] Despite their impressive successes, these

[1] Massonnet, D., M. Rossi, C. Carmona, F. Adragna, G. Peltzer, K. Feigl, and T. Rabaute, The displacement field of the Landers earthquake mapped by radar interferometry, *Nature*, **364**, 138–142, 1993.

[2] Alsdorf, D.E., J.M. Melack, T. Dunne, L.A.K. Mertes, L.L. Hess, and L.C. Smith, Interferometric radar measurements of water level changes on the Amazon floodplain, *Nature*, **404**, 174–177, 2000; Amelung, F., D.L. Galloway, J.W. Bell, H.A. Zebker, and R.J. Laczniak, Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation, *Geology*, **27**, 483–486, 1999; Amelung, F., S. Jonsson, H. Zebker, and P. Segal, Widespread uplift and "trapdoor" faulting on Galapagos volcanoes observed with radar interferometry, *Nature*, **407**, 993–996, 2000; Bawden, G., W. Thatcher, R.S. Stein, K.W. Hudnut, and G. Peltzer, Tectonic contraction across Los Angeles after removal of groundwater pumping effects, *Nature*, **412**, 812–815, 2001; Fialko, Y., M. Simons, and D. Agnew, The complete (3-D) surface displacement field in the epicentral area of the 1999 Mw 7.1 Hector Mine earthquake, California, from space geodetic observations, *Geophys. Res. Lett.*, **28**, 3036–3066, 2001; Gabriel, A.K., R.M. Goldstein, and H.A. Zebker, Mapping small elevation changes over large areas: Differential radar interferometry, *J. Geophys. Res.*, **94**, 9183–9191, 1989; Joughin, I., L. Gray, R.

observations were subject to limitations: (1) the 5.6-centimeter wavelength (C-band) of the ERS radars resulted in the radar coherence in vegetated areas decreasing rapidly with time; and (2) competing scheduling priorities for the ERS satellites resulted in the acquisition of images needed to observe crustal strain accumulation only in limited areas and at limited times.

SESWG Recommendations—Surface Deformation

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.

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.

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.

SOURCE: National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., pp. 31-32, 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

Scientific and Societal Benefits of the SESWG Recommendations

Scientific Benefits

Understanding of the processes governing deformation of the earth's surface at plate-boundary regions and the related problem of the physics of earthquakes is undergoing a revolution. Major advances have been made possible by the confluence of new observations of surface deformation using space geodesy, new theories of stress transfer and earthquake interaction in fault systems, and rapid growth in computational capability. In addition, the deformation fields before, during, and after several recent, large earthquakes have been characterized unusually well via both space geodesy and strong-ground-motion seismology. These observations have made it possible to constrain the kinematics of earthquake sources and the dynamics of stress and strain transfer after earthquakes in ways that were impossible previously.

InSAR has also influenced volcanology by improving measurements of ground deformation in systems ranging from small composite cones to the largest calderas. Measurements of volcano deformation have been available for some time, but before InSAR, they were time-

Bindschadler, S. Price, D. Morse, C. Hulbe, K. Mattar, and C. Werner, Tributaries of West Antarctic ice streams revealed by RADARSAT interferometry, *Science*, **286**, 283–286, 1999; Lyons, S., and D.T. Sandwell, Fault creep along the southern San Andreas from interferometric synthetic aperture radar, permanent scatterers, and stacking, *J. Geophys. Res.*, **108(B1)**, ETG11-1–ETG11-23, 2003; Massonnet, D., P. Briole, and A. Arnaud, Deflation of Mount Etna monitored by spaceborne radar interferometry, *Nature*, **375**, 567–570, 1995; Massonnet, D. and K.L. Feigl, Radar interferometry and its application to changes in the earth's surface, *Rev. Geophys.*, **36**, 441–500, 1998; Peltzer, G., P. Rosen, F. Rogez, and K. Hudnut, Postseismic rebound in fault step-overs caused by pore fluid flow, *Science*, **273**, 1202–1204, 1996.

consuming and incomplete. Moreover, most of the volcanoes of the world are not monitored in any way; it would be possible to monitor them all with a constellation of InSAR satellites.

Despite the advances made possible by InSAR, these observations have even greater potential for the future. For example, opportunities to observe the deformation associated with earthquakes have been missed because of insufficient space-based instrumentation. Although Global Positioning System (GPS) measurements provide high-accuracy determinations of displacements, these measurements are available only at a limited number of points. InSAR provides the capability for more complete spatial coverage, but available data have been limited in coverage (in space, time, and direction) and are limited to the shorter-wavelength C-band, where phase decorrelation may be more problematic. Moreover, these satellites have reached the end of their useful lifetimes.

The InSAR missions recommended in the SESWG report would provide observations superior to any that have previously been available. An InSAR satellite with orbital parameters and observation scheduling responsive to the needs of solid-earth scientists would provide global coverage at improved spatial and temporal resolution, and would potentially be poised to observe specific areas of interest. Because the earth deforms slowly and large earthquakes occur in any given region infrequently, the chance of obtaining the observations needed to understand the processes involved is substantially improved by global coverage. The proposed missions are L-band (~ 24-centimeter wavelength), which allows more robust phase correlation than previous C-band (~ 5.6-centimeter wavelength). Taking observations on both ascending and descending passes allows determination of multiple components of (vector) surface deformation. No active components are needed on the ground, making it possible to obtain observations quickly in remote and dangerous regions and without interfering with disaster response work.

Societal Benefits

Measuring surface deformation in regions of active fault systems, volcanoes, and landslides provides data for assessing the risk associated with these phenomena. For example, because volcanic eruptions are typically preceded by surface deformation, InSAR measurements could be used to make short-term predictions of volcanic eruptions. Measurements of surface motions associated with changes in pore fluids are relevant to hydrocarbon exploitation, water usage, and geothermal power production.

Consistency with National Priorities in the Solid-Earth Sciences

InSAR data are useful to agencies and organizations concerned with the deformation of the earth and associated natural hazards (see Appendix A and references therein). A National Research Council (NRC) review of the multiagency EarthScope initiative strongly endorsed the integrated approach proposed, including all four components: (1) the United States Seismic Array (USArray), (2) the Plate Boundary Observatory (PBO), (3) the San Andreas Fault Observatory at Depth (SAFOD), and (4) InSAR.[3] The report concluded that the scientific rationale for EarthScope is sound, that the scientific questions to be addressed are of significant importance, and that no necessary components have been omitted. It recommended that that all four components be implemented as rapidly as possible and that the National Science Foundation (NSF) and NASA collaborate to realize the InSAR goal at the earliest opportunity.

InSAR is of clear relevance to the NASA Earth Science Enterprise mission of predicting and mitigating natural hazards and also contributes to answering earth-science questions related to changes in ice cover and changes in the earth’s surface, and to understanding the coupling

[3] National Research Council, *Review of EarthScope Integrated Science*, National Academies Press, Washington, D.C., 61 pp., 2001.

between mantle motions and crustal motions. InSAR is also of significant importance to NSF programs in continental dynamics, geophysics, and tectonics and to Department of Energy (DOE) programs characterizing reservoir deformation associated with fluid flow. It is relevant to the National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey mission to improve observations and models for determining velocities of the earth's surface, as well as promoting innovative techniques. Finally, InSAR would provide extremely valuable data for seismic and volcanic hazard assessment for mitigation planning by the National Earthquake Hazards Reduction Program (NEHRP) and the U.S. Geological Survey (USGS).

Inclusiveness of Major Research Foci to Which NASA Can Make a Unique Contribution

NASA is the U.S. civilian agency uniquely qualified to develop, launch, and operate science satellites such as the proposed InSAR missions. NASA also supports information-technology (IT) development and is thus positioned to make important contributions to the modeling efforts needed to interpret physical processes from InSAR measurements. NASA has a track record in the kind of strong international collaborations that will be necessary to make advances as rapidly as possible.

Strengths and Weaknesses of the SESWG Recommendations

We believe that the immediate-term InSAR mission is correctly identified as the top priority for NASA's solid-earth program and agree that this proposed InSAR mission is timely, coinciding with the PBO component of the EarthScope project plan, of which it is a critical part. Furthermore, this InSAR mission would provide data that are important for understanding many scientific problems related to natural hazards, such as the physics of the earthquake cycle, the physics of magma movement and magma interaction with the upper crust, the mechanics of crustal deformation, and the processes that contribute to temporal changes of surface deformation and mountain building. The proposed InSAR mission would also make important contributions to other problems of societal import, such as assessing landslide hazards[4] and monitoring deformation caused by changes in ground water and hydrocarbon reservoirs and geothermal systems.

The recommendation to use L-band is sensible, given the advantages of robust phase correlation over a variety of surfaces and over long time scales. Also, acquiring data on ascending and descending passes is important in order to obtain vector displacements. Finally, the ability to look either to the left or to the right of the orbit plane is needed to mitigate loss of coverage caused by radar shadows behind rugged terrain. This capability will not be present on Japan's planned PALSAR mission, limiting the science that could be done with the data.

The main weakness of the part of the report addressing 1–5-year priorities is that the broad scope of science that would be enabled by InSAR is not well articulated (perhaps because of the space limitations). However, this science is clearly explained in a number of other studies,[5] so referring to these studies would be sufficient. Other minor weaknesses include the lack of discussion of the necessary IT component to cope with the InSAR data stream (including archiving and distribution of data and algorithms to the general research community), as well as insufficient discussion of coordination in development of observational strategies and research programs with NSF, USGS, and foreign partners. For example, collaboration with the Japan

[4] Hilley, G.E., R. Bürgmann, A. Ferretti, F. Novali, and F. Rocca, Dynamics of slow-moving landslides from permanent scatterer analysis, *Science*, **304**, 1951–1955, 2004.

[5] For example, National Research Council, *Review of EarthScope Integrated Science*, National Academies Press, Washington, D.C., 61 pp., 2001; National Research Council, *Living on an Active Earth: Perspectives on Earthquake Science*, National Academies Press, Washington, D.C., 418 pp., 2003; National Aeronautics and Space Administration, *Global Earthquake Satellite System: A 20-Year Plan to Enable Earthquake Prediction*, Pasadena, Calif., 100 pp., 2003.

Space Agency would be important for seamlessly integrating images from the proposed NASA instruments and the PALSAR instrument.

There are also some technological improvements that could be considered in planning missions in the near term and long term. For example, fully quadrature-polarimetric missions blended with InSAR capabilities could be used to characterize certain types of scenes (e.g., hard surface covered by vegetation) and would have application to both solid-earth and vegetation studies. Flying two satellites in tandem mode would offer the possibility of revisiting an area after a short interval (e.g., one day). The advantages of this configuration for glaciology applications were demonstrated by the ERS-1 and ERS-2 satellites from October 1995 to April 1996.[6] Finally, the long-term recommendations, including constellations and geostationary satellites, could be prohibitively expensive, so it may be necessary to explore more economical approaches to meeting the science objectives.

Summary

We strongly endorse the launch of an InSAR satellite as soon as possible as NASA's highest priority for solid-earth science. An immediate improvement in the U.S. capability for measuring surface deformation is consistent with national priorities laid out in the strategic plans of relevant federal agencies. NASA is unique among civilian federal agencies in having the capability to carry out this mission. As described in the SESWG report, the InSAR should be L-band, should collect data on both ascending and descending arcs, and should be able to look to both sides of its orbit plane. It should also be responsive to the needs of solid-earth scientists. In addition to providing a data stream, NASA should provide the necessary IT infrastructure for archiving and distributing these data, as well as for supporting the modeling needed to understand the dynamic processes that result in crustal deformation, earthquakes, and volcanic eruptions.

HIGH-RESOLUTION TOPOGRAPHY

Topography has traditionally been measured by triangulation and leveling methods, which require land-based crews to measure distances and elevation changes accurately.[7] Over the past several decades these ground determinations have been supplemented or even replaced by airborne photogrammetry, which enables the earth's surface to be mapped to a decimeter, and by geodetic networks, which enable points to be located on the order of millimeters. Bathymetry data are obtained from direct (e.g., acoustic) and indirect (e.g., radar altimetry) methods. The spatial resolution of topographic data varies, ranging from 30 meters to several kilometers over land areas and averaging about 25 kilometers over the oceans. By merging these measurements it is possible to produce global digital elevation models, such as ETOPO-2, which has a grid resolution of 2 minutes (or about 4 kilometers at the equator).[8] Such models have greatly enhanced analysis of surficial processes, topographic change, and the interaction of topography and climate.

NASA has recently launched two missions, which have further improved the resolution of global topography data:

1. The 2000 Shuttle Radar Topographic Mission (SRTM) was a joint NASA-National Geospatial Intelligence Agency (NGA) mission, which used radar interferometry to obtain topographic data at roughly 30-meter spacing (with about 16-meter vertical resolution) for about

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[6] First results from ERS tandem InSAR processing on Svalbard, <http://www.geo.unizh.ch/rsl/fringe96/papers/eldhuset-et-al/>.

[7] National Research Council, *Airborne Geophysics and Precise Positioning: Scientific Issues and Future Directions*, National Academy Press, Washington, D.C., 111 pp., 1995.

[8] <http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html>.

80 percent of the earth's landmass.[9] These data are at a much higher spatial resolution than previous surveys, particularly for regions outside the United States.

2. NASA's 2003 Ice, Cloud, and Land Elevation Satellite (ICESat) measures ice-sheet mass balance, cloud and aerosol heights, and land topography and vegetation characteristics. The Geoscience Laser Altimetry System (GLAS) instrument on ICESat provides data at 170-meter intervals along the earth's surface with a 70-meter-diameter footprint.[10]

"High-resolution topography," as conceived in the SESWG report, would move far beyond what the SRTM and ICESat currently produce, with surface elevation sampled at resolutions approaching 5- to 1-meter horizontal spacing and vertical errors as small as 0.1 meter.

SESWG Recommendations—High-Resolution Topography

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.

*NOTE: ICESat was launched in January 2003.
SOURCE: National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., p. 36, 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

Scientific and Societal Benefits of the SESWG Recommendations

Scientific Benefits

The topography of the land surface is an expression of competing processes of uplift, erosion, and deposition. Land surfaces interact with atmospheric circulation, affecting patterns of precipitation and directing runoff downslope. Land use further alters erosion and runoff, the magnitude and the resulting consequences of which are strongly dictated by topography. Local topography also influences the risks from natural hazards such as landslides, floods, and earth-quakes. Until recently, topographic data have been too coarse to allow mechanistic investigations of these linkages. Moreover, temporal variations have often gone undetected because of infrequent mapping and the crude nature of the maps. The ability to measure topographic change would permit mechanistic models to be tested and flux relationships to be quantified.

Presently, airborne LIght Detection And Ranging (LIDAR) can acquire high-resolution data for local landscapes, but although the technology to do this is evolving rapidly, surveys of large areas remain expensive and logistically challenging. Successful implementation of the SESWG recommendations would greatly improve what can be done, first enabling a global land

[9] <http://srtm.usgs.gov/mission.html>.
[10] <http://www.csr.utexas.edu/glas/>.

survey at 2- to 5-meter resolution and eventually enabling targeted areas throughout the world to be repeat-surveyed at 1-meter resolution. Global coverage would enable comparative studies of different tectonic, climatic, biotic, and topographic settings, even in areas that are inaccessible to aircraft or ground teams for geographic, economic, or political reasons. The areas selected for repeat surveys could be any place where events (e.g., rainstorms, volcanic eruptions, earthquakes) have led to a sudden change in topography, or where a time series would be especially useful to predict similar events.

Examples of important questions for which high-resolution topographic data and topographic-change data are needed include the following:

- What are the geomorphic transport laws responsible for shaping the earth's surface?
- How are tectonics, climate, erosion, and topography linked?
- What are the mass balances of ice sheets and how are they affected by climate change?
- What attributes of topography can be used to test landscape evolution models?
- Can the timing and location of landslides be forecast?
- What are the erosional responses to global climate change?
- How are active faults manifested in the landscape and what is their relation to plate-boundary strain?

Although the SESWG report focuses on the land surface, only 0.1 percent of the ocean floor has been surveyed at 100-meter horizontal resolution. Bathymetric mapping has revealed previously unknown submarine landslides along continental margins and volcanic islands, the architecture of the global mid-ocean ridge, and the location of large offshore faults.[11] Detailed seafloor bathymetry is also a useful tool for understanding ocean circulation and long-term climate change.[12] Satellite radar altimetry is the only economically feasible means of providing high-resolution bathymetry and gravity-field data on global scales.[13] Bathymetric data derived from GEOSAT flying in a non-repeat orbit have approximately 20-kilometer resolution. The exact-repeat orbits that are characteristic of altimeters designed for dynamic topography (e.g., Ocean TOPography EXperiment [TOPEX]) cannot yield useful bathymetry data. However, newer radar altimeter techniques combined with orbit patterns that eventually cover the ocean with more dense track spacing could improve bathymetric resolution to about 5 kilometers, a lower bound that is dictated by the underlying physics.

Societal Benefits

The use of high-resolution topographic data would improve the detection and forecasting of geologic hazards. Local topography influences hydrologic response, soil thickness patterns, susceptibility of land to failure, and flooding extent and susceptibility. Consequently, the ability of numerical models to predict the location and timing of landslides[14] and floods will depend on the quality of the topographic data. The proposed 2- to 5-meter global land survey would enable

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[11] Moore, J.G., D.A. Clague, R.T. Holcomb, P.W. Lipman, W.R. Normark, and M.E. Torresan, Prodigious submarine landslides on the Hawaiian Ridge, *J. Geophys. Res.*, **94**, 17,465–17,484, 1989; Pratson, L.F., and W.F. Haxby, Panoramas of the seafloor, *Sci. Am.*, **276**, 82–87, 1997.

[12] Cane, M.A., and P. Molnar, Closing of the Indonesian seaway as a precursor to east African aridification around 3-4 million years ago, *Nature*, **411**, 157–162, 2001.

[13] Smith, W.H.F., and D.T. Sandwell, Conventional bathymetry, bathymetry from space, and geodetic altimetry, *Oceanog.*, **17**, 8–23, 2004.

[14] Keefer, D.K., R.C. Wilson, R.K. Mark, E.E. Brabb, W. Brown, S.D. Ellen, E.L. Harp, G.F. Wieczorek, C.S. Alger, and R.S. Zatkin, Real-time landslide warning during heavy rainfall, *Science*, **238**, 921–925, 1987; Casadei, M., W.E. Dietrich, and N.L. Miller, Testing a model for predicting the timing and location of shallow landslide initiation in soil mantled landscapes, *Earth Surf. Proc. Landforms*, **28**, 925–950, 2003.

reliable landslide and flood hazard maps to be constructed at a sufficiently fine-scale resolution for making site-specific land-use decisions. Active fault detection and mapping of areas at risk from volcanic eruptions, pyroclastic flows, and mudflows would also be enhanced by high-resolution topographic data.

Fulfillment of the SESWG report's long-term recommendation—a satellite-based "continuously operating, targeted, high-resolution topographic mapping and change-detection capability"—would almost certainly radically alter the science of hazard detection and mitigation. Such a technology would permit researchers to document landsliding, flooding, earthquake, and volcanic eruption events around the world in nearly real time. Such near-real-time information could lead to continuously updating hazard-warning systems, enabling governments and other organizations to prepare for and respond quickly to hazard events.

High-resolution bathymetry data, while not a SESWG goal, have the potential to be used for a variety of societal applications. Detailed bathymetry data can be used to forecast where major underwater volcanic eruptions may occur and where large submarine hydrothermal fields are likely to be found.[15] The submarine hot springs support an exotic community of benthic animals whose tissues offer significant potential for pharmaceutical applications. High-resolution bathymetry data could also be used to identify the location of offshore faults which pose significant earthquake or tsunami risk.[16]

Consistency with National Priorities in the Solid-Earth Sciences

All federal agencies that use topographic data could benefit from the proposed satellite program (Appendix A). For example, high-resolution topographic data are useful in many different aspects of watershed management, including establishing limits on maximum sediment loads in waterways (Environmental Protection Agency [EPA]), assessing watershed and channel conditions where salmon spawn (NOAA's National Marine Fisheries Service), and monitoring soil erosion (U.S. Department of Agriculture [USDA]).

High-resolution topographic data are also important for agency programs aimed at understanding, predicting, or mitigating the consequences of physical processes. For example, such data are necessary inputs to DOE models that describe and predict physical systems and processes, especially land-surface-related processes. The USGS uses high-resolution topography data to support its goals of minimizing loss of life and property from natural disasters, assessing and mitigating geologic hazards, and modeling and predicting land-surface response to natural and human stimuli. NSF supports research in glaciology, hydrology, tectonics, geomorphology, and environmental engineering, all of which use topographic data. Topography is also an important feedback in climate-change models, which are supported by all of these agencies. Future programs that could benefit from high-resolution topographic data include the PBO component of EarthScope, which calls for the acquisition of such data to map active faults, and the USGS National Landslide Hazard Mitigation Program.

A number of federal programs also use bathymetry data for research or operations. For example, bathymetry data are used to study ocean circulation (NASA, NOAA, and NSF) and geophysical processes that occur on or below the seafloor (NSF), or to characterize the ocean environment for military purposes (Office of Naval Research).

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[15] MacDonald, K.C., and P.J. Fox, The mid-ocean ridge, *Sci. Am.*, **262**, 72–79, 1990.

[16] Polonia, A., M.-H. Cormier, M.N. Cagatay, G. Bortoluzzi, E. Bonatti, L. Gasperini, M. Ligi, L. Capotondi, L. Seeber, C.M.G. McHugh, W.B.F. Ryan, N. Görür, Ö. Emre, B. Tok, and the MARMARA2000 and MARMARA2001 scientific parties, Exploring submarine earthquake geology in the Marmara Sea, *EOS Trans. Am. Geophys. U.*, **82**, 229 and 235–235, 2002.

Inclusiveness of Major Research Foci to Which NASA Can Make a Unique Contribution

NASA is qualified to develop the technology to obtain satellite-based, global, high-resolution topographic coverage. Primary goals of this effort would be both to characterize surface elevation at a fine scale and to obtain repeat measurements to quantify elevation changes and hence solid-earth and ice mass fluxes. Although other agencies have the responsibility to address geologic hazards, only NASA can deliver the key next-generation topographic data needed to conduct this work. NASA-supported researchers could also contribute new models and theories that fully exploit the new topographic data. Finally, NASA's experience with remotely operated instruments and data transmission make it well qualified to explore and map the seafloor remotely.

Strengths and Weaknesses of the SESWG Recommendations

The SESWG report specifies topographic resolution goals of 2 to 5 meters for a first global land survey (the near-term goal) and 1 meter for its targeted change detection program (the long-term goal). These goals are well chosen. The 2- to 5-meter resolution data would signifycantly improve the analysis of topography and its use in numerical models. The 1-meter resolution data would enable detection of river channel migration, landslides, ground rupture from faults, ice-sheet flow, and many other sudden changes on the earth's surface. The report does not specify what technology might be used to obtain these data, but this is not necessarily a weakness because new technologies for measuring topography and new approaches for extracting topography information from instruments developed for other purposes are continually being introduced. For example, airborne laser-swath mapping technology is changing very rapidly and its full capabilities are not yet known. Just in the past few years, cross-swath sweep rate has jumped from 5 to 100 kilohertz, first- and last-return recording systems are being replaced with multiple-return systems (with plans for full waveform digitizing under way), and entirely new systems based on single-photon detectors are being explored. Moreover, instruments are being built that can survey both shallow water and land surfaces. These developments suggest that space-based LIDAR for high-resolution topography may ultimately be technologically feasible.

It may also be feasible to use existing SAR and commercial satellites such as Space Imaging's IKONOS or the French Systeme Probatoire pour l'Observation de la Terre (SPOT) 5 to obtain topography. Optical systems such as IKONOS and SPOT require daytime viewing and relatively cloud- and fog-free conditions. Under optimal conditions (i.e., clear visibility, bare soil, low relief) it may be possible to generate digital elevations with 1- to 2-meter horizontal accuracy and vertical accuracies of 1 to 2 meters (IKONOS) or 2 to 3 meters (SPOT 5).[17] However, even when these conditions are met, this approach may be practical only in selected areas because commercial imagery is expensive, it may not be available globally, and it may not be possible to assess its quality.

SAR techniques are well established for measuring topography as well as surface deformation. Indeed, surface-deformation determination requires a reference topographic surface, a source of which could be topography derived from InSAR. Although this dual capability might suggest that a single SAR mission could meet the objectives of both the topography and surface deformation missions, neither objective would be well satisfied because the mission requirements are different. For example, global topography requires a short revisit period (three days or less) by two spacecraft in slightly different orbits, whereas deformation studies require a revisit period sufficiently long (several days to several months) to capture the signal of physical change at the surface. Moreover, since SAR is strongly influenced by vegetation and soil moisture, the choice of an optimal system entails tradeoffs in fundamental parameters such as wavelength and polarization. InSAR determination of surface change requires coherence between observations,

[17] Toutin, Th., Comparison of stereo-extracted DTM from different high-resolution sensors: SPOT-5, EROS, IKONOS and QuickBird, *IEEE Trans. Geosci. Rem. Sens.*, **42**, in press, 2004.

which cannot be satisfied under all circumstances such as soil erosion. When the images are coherent it is possible to obtain surface-deformation rates on the order of 1 centimeter per year.

Finally, land topographic height resolution on the order of 10 meters is currently feasible from SAR techniques, but considerable development would be required to achieve 1- to 5-meter resolution. SAR is not currently capable of the centimeter-level precision required to estimate surface-elevation changes in ice sheets because of the geometry of the sensors (side-looking) and the absence of coherent permanent scatterers. The downward-looking IceSAT (NASA) and CryoSat (ESA) are specially designed for this application, using laser- and radar-altimetry, respectively.

The SESWG report also calls for the release of global land topographic data from the SRTM mission. Although the land surface between 60 degrees north and 56 degrees south was mapped at 30-meter resolution, under the agreement between NASA and NGA only 90-meter data are to be made available to the public because of national security concerns.[18] However, 30-meter data have been released for the United States and its territories. Moreover, much higher resolution elevation data over the United States are available from commercial satellite and aircraft vendors. Consequently, we see no reason why the NGA should not release the entire 30-meter data set.

Some issues of significance are not addressed in the SESWG report. For example, the report identifies the need for high-resolution bathymetric mapping, but does not make any recommendations for achieving this goal. Such data could fuel discoveries and new research, and if technological developments enable such measurements to be made from space, NASA could take a leading role in this work. Moreover, the management, analysis, and distribution of a new generation of high-resolution, time-dependent topographic data over much of the earth's surface will present extraordinary challenges. The community dealing with airborne laser-swath-mapping data is currently struggling with how to analyze and use these data in revised land-surface models, and these are very small efforts compared to what is envisioned in the SESWG report. It may be desirable for NASA to team with NSF and its IT program in meeting these challenges.

Summary

We support the SESWG goals of releasing 30-meter SRTM data, acquiring accurate global high-resolution land topography data, and developing the means to carry out targeted change-detection surveys. These actions would directly contribute to the aim of predicting and mitigating hazards caused by land-surface changes, particularly if change detection over large regions of the planet in near real time becomes possible. Although not a stated goal of the SESWG report, improved bathymetry data would help address scientific questions concerned with plate boundary deformation and mantle processes. The tools that will have to be developed to acquire, process, and analyze high-resolution topographic data sets would also benefit studies of surface processes on other terrestrial planets.

VARIABILITY OF THE EARTH'S MAGNETIC FIELD

Satellites provide a global perspective of the magnetic field that is not achievable from ground-based observatories and surveys. In 1980, NASA's six-month long Magnetic Field Satellite (Magsat) mission was the first to acquire global vector measurements.[19] These limited data generated intense activity in analysis and theory, directed primarily at understanding processes in the earth's core and mapping the lithosphere. They also highlighted the need for models that take account of the full range of internal and external physical processes on appropriate temporal and

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[18] Knight, J., Map data kept under wraps as Pentagon focuses on security, *Nature*, **414**, 831–832, 2001.

[19] Langel, R.A., G. Ousley, J. Berbert, J. Murphy, and M. Settle, The Magsat mission, *Geophys. Res. Lett.*, **9**, 243–245, 1982.

spatial scales. Following an almost 20-year hiatus, the Decade of Geopotential Research (1998-2008) ushered in a new era of satellite magnetic missions:

- Current missions include the Danish satellite, Ørsted, which was launched in 1998, and the Argentine-led Satelite de Aplicanciones Cientificas-C (SAC-C), and the German CHAllenging Minisatellite Payload (CHAMP) missions, both of which were launched in 2000. These missions are changing our view of the geomagnetic field. Surprisingly large changes have occurred in the geomagnetic field since the Magsat mission, including a significant decrease in the earth's dipole moment.[20] Substantial detail is now visible in the core field because increased mission length and improved instrumentation allow the construction of high-quality secular variation models that can test theories of the origin of secular variation.[21]
- Planned missions include the ESA initiative, Swarm, which is scheduled to be launched in 2009.[22] As currently envisaged, the Swarm configuration involves two satellites at low altitudes (450 kilometers), well designed for lithospheric and conductivity studies, with a single higher-altitude instrument (530 kilometers) that is better (but not optimally) positioned for core-field studies. To ensure adequate coverage with a small number of instruments, all of the proposed orbits are at high inclination.

Despite these advances, however, significant improvements are needed. For example, each satellite has been conceived as an independent entity with different orbits and instrumentation characteristics. As a result, it remains difficult to separate temporal and spatial variability of the different components of the magnetic field. A constellation of satellites, such as that envisioned in the SESWG report, would overcome this difficulty by providing denser sampling of the external magnetic field and improved accuracy and positioning of the moving instruments.

SESWG Recommendations—Variability of the Earth's Magnetic Field

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 polar 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.

SOURCE: National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., p. 38, 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

[20] Hulot, G., C. Eymin, B. Langlais, M. Mandea, and N. Olsen, Small-scale structure of the geodynamo inferred from Ørsted and Magsat satellite data, *Nature*, **416**, 620–623, 2002.

[21] Bloxham, J., S. Zatman, and M. Dumberry, The origin of geomagnetic jerks, *Nature*, **420**, 65–68, 2002; Jackson, A., Intense equatorial flux spots on the surface of the earth's core, *Nature*, **424**, 760–763, 2003.

[22] European Space Agency, *Swarm—The Earth's Magnetic Field and Environment Explorers*, ESA SP-1279(6), April 2004, <http://www.esa.int/export/esaLP/SEMANH57ESD_index_0.html>.

Scientific and Societal Benefits of the SESWG Recommendations

Scientific Benefits

Continuous monitoring of the geomagnetic field with high temporal and spatial resolution remains important for understanding why the earth has a magnetic field and the primary physical processes that control its variability. The largest part of the geomagnetic field derives from dynamo activity in the earth's liquid outer core and is driven by energy sources that reflect the thermal and chemical evolution of the planet. Although great advances have been made to numerically simulate the dynamo and the geomagnetic reversals that represent some of the longest-term changes in the magnetic field, these models do not yet capture temporal and spatial changes at sufficiently small scales to reliably represent processes in the deep earth. Improved understanding of decadal-scale dynamic processes is an important first step toward useful predictions of future changes in the geomagnetic field, as well as being important in its own right.

Secondary magnetic fields in the earth, which are induced by the time-varying external part of the field, are used to probe the electrical conductivity of the mantle,[23] which in turn provides information about the temperature, composition, and presence of volatiles in the deep earth. Improved data and models of the spatiotemporal magnetic field would lead to global estimates of three-dimensional electrical conductivity structure that cannot be secured from ground-based measurements. Deep-earth conductivity models, in conjunction with seismological and geochemical information, could also constrain poorly understood deep-earth processes.

The magnetization of the earth's lithosphere preserves a geological record of changes in the geomagnetic field and of large-scale surface tectonic activity. It is not possible to resolve long wavelengths of the lithospheric magnetic field from combined local or regional surveys collected at different elevations and times because the large-scale external magnetic field varies with time and there is no adequate reference model. However, satellite measurements, combined with aeromagnetic data, can be used to produce magnetic anomaly maps on a broad range of spatial scales. Such maps are used to study large-scale tectonics and the chemical and thermal evolution of the lithosphere.[24] An example of a map that would especially benefit from satellite data is the World Digital Magnetic Anomaly Map, which is suffering from large data gaps, hindering tectonic studies that cross national boundaries.

All of the applications above require a constellation of satellites to distinguish the separate contributions to the magnetic field.

Societal Benefits

The geomagnetic field directly affects the earth's electrodynamic environment, acting as a protective shield that prevents the solar wind from reaching the earth's atmosphere, thereby ameliorating many of the adverse effects of space weather. Space weather disrupts communications and satellite operations, especially over the expanding South Atlantic Anomaly,[25] so it is important to have reliable forecasts of the magnetic field on decadal time scales. The high-resolution satellite data envisioned in the SESWG report, combined with the use of data assimilation methods, would enable the development of the next generation of geomagnetic field models needed to provide these forecasts.

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[23] Constable, S.C., and C.G. Constable, Observing geomagnetic induction in magnetic satellite measurements and associated implications for mantle conductivity, *Geochem. Geophys. Geosyst.*, **5**, Q01006, DOI 10.1029.2003GC000634, 2004.

[24] Purucker, M., B. Langlais, N. Olsen, G. Hulot, and M. Mandea, The southern edge of cratonic North America: Evidence from new satellite magnetometer observations, *Geophys. Res. Lett.*, **29**, DOI 10.10292001GL013645, 2002.

[25] Olsen, N., and 25 coauthors, 2000 Ørsted initial field model, *Geophys. Res. Lett.*, **27**, 3607–3610, 2000.

Consistency with National Priorities in the Solid-Earth Sciences

Satellite magnetic measurements are important to federal agencies that directly or indirectly use geomagnetic data or magnetic field models (Appendix A). The USGS operates geomagnetic observatories and contributes data to the International Geomagnetic Reference Field (IGRF), a model based on a combination of observatory, survey, and satellite observations. Ground-based data remain critical for interpreting satellite magnetic data and for separating the various physical sources, especially fields within the ionospheric region.

The geomagnetic observations recommended in the SESWG report would complement NSF's priorities to study the structure and composition of the solid earth and dynamics at the interfaces of earth systems. A continued supply of high-quality global satellite measurements is also essential to planetary studies sponsored by other branches of NASA and NSF and by the Smithsonian Institution. Understanding the earth's magnetic field may reveal why some planets possess active magnetic dynamos, why some (such as Mars) had dynamos in the past that are no longer active, and why others carry no record of an intrinsic magnetic field.

Inclusiveness of Major Research Foci to Which NASA Can Make a Unique Contribution

NASA is the U.S. agency best suited to deliver global-scale satellite measurements of the geomagnetic field. At present NASA has no magnetic field missions, although it has contributed considerable expertise to all the current foreign missions and in some cases has provided the launch vehicle. For the past decade these missions—along with geomagnetism programs supported by Deutsche Forschungsgemeinschaft (DFG), Centre National de la Recherche Scientifique (CNRS), and the U.K. Geospace program—have provided excellent opportunities for training young European scientists, who are now well positioned to develop future missions and to exploit existing and forthcoming data collections. If the recommendations of the SESWG report are implemented, NASA would ensure that comparable opportunities are available for young scientists in the United States.

It would be redundant at this stage for NASA to carry out the SESWG report's 5–10-year recommendation to launch a constellation of 4–6 satellites. The planned Swarm mission would largely satisfy the same goals. However, it is now critical for NASA to strengthen collaboration with this ESA project so that U.S. researchers will have access to the data as they are collected. This would likely require that NASA make some significant contribution to the mission, perhaps in the form of an instrument (e.g., electric field or GPS). It would also be desirable for a broad range of U.S. scientists to become part of the data user group to ensure that the data products that are developed meet the needs of the U.S. research community.

Larger constellations of satellites, such as those envisaged by the SESWG report's 10–25 year goal, are within NASA's technological capability. Development of such a system would be important for meeting scientific goals (e.g., improved understanding of the large-scale structure of external fields) as well as for helping the U.S. regain critical expertise in magnetic instrument design, which has declined in the long hiatus of NASA magnetic satellites.

Strengths and Weaknesses of the SESWG Recommendations

The immediate SESWG goal is to sponsor comprehensive analysis of existing data sets. NASA has had a strong program in this area in the past, and it has provided a substantial benefit to the planetary exploration program; for example, theory and analysis tools developed for geomagnetic research have been applied to interpret the unexpectedly strong crustal magnetic fields discovered on Mars. The scientific benefits outlined above cannot be achieved without support for analysis of geomagnetic data. Such support should also foster the training of young scientists and allow the U.S. geomagnetic community to become a more active partner in the booming geomagnetic research currently centered in Europe. Funding for interpreting satellite magnetic data will be necessary as both a short- and a long-term goal if NASA is to retain a competitive role in international geomagnetic research.

The near- and long-term recommendations are for new observations of the magnetic field and constellations of satellites in coordinated orbits. Such instrument configurations are needed to determine large-scale temporal and spatial variations in the external field. All existing magnetic field models are limited by external field contamination because of the lack of simultaneous measurements at a range of local times and altitudes. The SESWG goal is to improve continually the spatial and temporal resolution of available data, using an initially sparse constellation of magnetometers in suitably coordinated orbits. A weakness is the lack of discussion about coordinating with other space programs to ensure a smooth follow-on from existing missions and to guarantee a continuous data supply throughout the current solar cycle. For example, the planned Swarm mission is scheduled to be launched one year after the CHAMP satellite ends in 2008, creating at least a one-year hiatus in magnetic field measurements. Although it is not worthwhile to launch a similar mission to close this data gap, an urgent priority is for NASA to negotiate a formal agreement with ESA to ensure that U.S. researchers have timely, affordable access to data from the Swarm mission.

Larger constellations than Swarm will be required in the future to ensure that the regions targeted for geomagnetic study are sampled adequately. There are benefits to sampling in more and different orbits and achieving better simultaneous coverage in local time. Such sampling should become part of the 10–15-year goal, and planning for future missions should be initiated now in collaboration with European or other foreign partners. Denser constellations of magnetometers may also require some innovative approaches to instrumentation, and the SESWG 1–5-year goal recommends developing a modularized instrument package to take advantage of missions of opportunity. The intention is to target more launch opportunities by adding low-mass instruments to existing missions or perhaps packaging a nanosatellite with other compatible satellites for a single launch. Given the need for magnetically clean spacecraft environments, the second of these options may be more fruitful. However, it remains unclear whether missions of opportunity can be exploited to deliver satellites designed to be part of a constellation with specific orbital configurations.

Summary

We endorse the SESWG goal of enhanced measurement of the geomagnetic field through increasingly dense sampling by a constellation of magnetometers, combined with an aggressive program to interpret observations from existing missions. The 5–10 year goals could be satisfied by the ESA Swarm mission provided that NASA takes immediate steps to negotiate a formal data access agreement for U.S. researchers. Such an agreement is essential to ensure that the United States is able to maintain expertise and to support data analysis and modeling in geomagnetism. To satisfy longer term goals NASA will have to initiate planning for future missions, exploiting opportunities for collaboration with other international efforts in satellite magnetometry.

VARIABILITY OF THE EARTH'S GRAVITY FIELD

Satellite measurements have revolutionized the study of the earth's external gravity field, beginning with the definitive determination of the oblateness (J_2) and the discovery of the "pear" shape (J_3) by tracking of the first artificial satellites in the late 1950s and early 1960s.[26] Recent technological developments have enabled the measurement of temporal gravity variations caused by a variety of dynamical processes that redistribute mass within the solid earth and its hydrological reservoirs on time scales ranging from weeks to decades. The strongest temporal gravity

[26] Kaula, W.M. *Theory of Satellite Geodesy: Applications of Satellites to Geodesy,* Blaisdell Publishing Company, Waltham, Mass., 124 pp., 1966.

signals are caused by mass transport in the atmosphere, oceans, and land hydrological systems and by postglacial rebound, but gravity data also benefit studies of solid-earth properties and processes, including structure and evolution of the crust and lithosphere and mantle dynamics.[27]

Two recently launched or planned satellite gravity missions provide the context for the recommendations in the SESWG report:

1. Gravity Recovery and Climate Experiment (GRACE), a collaboration between NASA and the German space agency, is the first mission with the capability to measure the time variability of the global gravity field. Launched in 2002, GRACE consists of two satellites in identical, nearly polar, low-altitude (485 kilometers) orbits; a microwave link is used to monitor the inter-satellite distance (nominally 220 kilometers) and, thus, the differential accelerations experienced by the two satellites. Temporal variations in geoid height over areas that are 300 square kilometers in extent can, in principle, be measured with an accuracy of ±1 centimeter on time scales of 30 days. Results to date have a spatial resolution of about 600 kilometers.[28]
2. Gravity Field and Steady-State Ocean Circulation Mission (GOCE) is a single satellite with a three-component gravity gradiometer that will be launched by the European Space Agency in 2006–2007. Its low-altitude orbit (250 kilometers) will give the mission an expected lifetime of only two years. The principal mission objective is a high-resolution (100 square kilometers), high-precision (±1 centimeter) determination of the geoid, which can be used in conjunction with altimetry measurements to deduce the dynamical topography of the oceans caused by geostrophic currents. The results from GOCE will also be useful for studies of mantle dynamics. Time-variable gravity is not a major focus of the mission, but GOCE should provide data that can be used to assess the potential of gravity gradiometer technology for future, higher-orbit (and therefore longer-lived) gravity missions.

SESWG Recommendations—Variability of the Earth's Gravity Field

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.

SOURCE: National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., p. 40, 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

Scientific and Societal Benefits of the SESWG Recommendations

Scientific Benefits

Time-variable gravity missions are inherently interdisciplinary. On time scales of months to decades, the gravity signal is dominated by changes in snowmass and the storage of surface water in soils and aquifers. These measurements are providing a new perspective on the field of continental hydrology—which has thus far relied on sparse surface measurements and modeling—

[27] National Research Council, *Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Envelopes*, National Academy Press, Washington, D.C., 112 pp., 1997.

[28] Tapley, B., C. Reigber, S. Bettadpur, and M. Watkins, The GRACE mission, its status and early results, European Geosciences Union, Nice, France, April 25–30, 2004.

and on climate research. Understanding the hydrological contributions to time-variable gravity is also necessary for detecting and studying the smaller contributions of solid-earth processes.

The largest purely solid-earth signal that is expected to be present in the time-varying gravity field is the influence of postglacial rebound.[29] Time-variable gravity measurements will help to differentiate between the effects of postglacial rebound and other processes with similar geographical patterns, such as changes in present-day ice sheets. Measurements of postglacial rebound will also lead to significant improvements in the knowledge of mantle rheology and its lateral variations.

Other weaker geodynamic signals can be recognized in time-variable gravity data because of their global extent. Examples include elastic mantle deformations caused by dynamical pressure variations on the core-mantle boundary; vertical crustal motions caused by surface uplift, exhumation, and mass redistribution via erosion and sedimentation; and long-term variations in earth rotation caused by surficial and interior mass distributions. Global variations in gravity are even useful for constraining the rotation of the aspherical inner core with respect to the mantle, which is caused by torques from the geodynamo.

Satellite gravity measurements are also needed to validate and adjust observations from surface gravimetry and to calibrate existing terrestrial and marine gravity measurements.[30] Improving the continuity of these measurements across shorelines and political boundaries will be important for understanding the structure of continental margins, the dynamics of active continental deformation, and seafloor tectonics. Resolving all of these geodynamic signals will require that gravity data be combined with ancillary data, including topography data at commensurate resolution.

Combining decade-long, time-variable gravity observations of surface water-mass redistributions with satellite altimetry will enable an improved understanding of the causes of observed sea-level variations, particularly the relative contributions of water-column thermal expansion and continent-ocean water-mass exchange, which are still poorly understood. Sea-level research has grown into a multidisciplinary enterprise, with the associated elastic loading and unloading effects directly linked to the solid-earth sciences. Other promising interdisciplinary research applications include the effects of surface water-mass redistribution on a number of geodetic variations such as geocenter motion, earth rotation, vertical crustal motion, and sea-level change.

Societal Benefits

The rate of change of mean sea level, measured by satellite altimetry (TOPEX/Poseidon and Jason-1) over the last decade, is 2.8 ± 0.4 millimeters per year.[31] Tide gauge measurements show a slightly lower average rate of sea-level rise over the past century, 1.0 to 2.0 millimeters per year.[32] The geographical variation of sea-level change is highly variable, with some regions rising and others falling at a rate up to ten times higher than in the past decade. Understanding the causes of these geographical variations will be important in planning for the societal consequences of future sea-level rise. Some regions, such as the U.S. Gulf Coast, will be affected more than other regions.

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[29] Velicogna, I., and J. Wahr, Post-glacial rebound and the earth's viscosity structure from GRACE, *J. Geophys. Res.*, **107**, 2376, DOI 10.1029/2001JB001735.

[30] National Research Council, *Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Envelopes*, National Academy Press, Washington, D.C., 112 pp., 1997.

[31] Cazenave, A., and R.S. Nerem, Present-day sea level change: Observations and causes, *Rev. Geophys.*, **42**, RG3001, DOI 10.1029/2003RG000139, 2004.

[32] Douglas, B.C., Sea level change in the era of the recording tide gauge, in Douglas, B.C., M.S. Kearney, and S.P. Leatherman, eds., *Sea Level Rise, History and Consequences*, International Geophysics Series, 75, Academic Press, San Diego, Calif., pp. 37–64, 2001.

Consistency with National Priorities in the Solid-Earth Sciences

Many of the scientific and societal benefits of time-variable gravity measurements are climate related. Those of direct interest to the solid-earth community focus on improved understanding of postglacial rebound, which will lead to an improved understanding of mantle rheology, a research goal supported by both NASA and NSF (Appendix A). Understanding the contribution of postglacial rebound to sea level is also of interest to non-solid-earth programs within NASA's Earth Science Enterprise, as well as to NOAA, NSF, and the Climate Change Science Program. Improved gravity measurements would also further the research goals of agencies interested in the structure and evolution of the crust and lithosphere, including NSF and USGS. Finally, the calibration of terrestrial and marine gravity measurements would help address a NOAA mandate for a geodetic reference frame for measuring motions in the earth system.

Inclusiveness of Major Research Foci to Which NASA Can Make a Unique Contribution

Global measurements of time-variable gravity can be made only from space. Time-variable gravity measurements are most valuable when combined with other global data, particularly high-resolution altimetry and topography data, being acquired by NASA. NASA is the only U.S. agency with the technical expertise needed to develop new methods of measuring time-variable gravity, such as high-altitude gravity gradiometry or laser-interferometric ranging. Gravity gradiometry may offer better precision and resolution than GRACE or GOCE for studying shorter-wavelength features such as regional tectonics, and laser-interferometric ranging could yield an order-of-magnitude improvement in performance over the microwave differential tracking of GRACE.[33]

Strengths and Weaknesses of the SESWG Recommendations

The study of many different geophysical processes will be significantly advanced by time-variable gravity measurements: the waxing and waning of Antarctic and Greenland ice sheets, continental water storage, sea-level rise (particularly the separation of steric and nonsteric components), dynamical topography of the oceans and seafloor pressure variations (which induce deformations of the solid earth), and postglacial rebound. The time scales of space-measurable gravity variations are months to decades—or even longer. For this reason, we consider the long-term (10–25 years) view of the SESWG report to be one of its major strengths. The report succinctly but clearly articulates the synergy of combining time-variable gravity measurements with radar or laser altimetric measurements, and the need for "careful modeling of atmospheric, oceanic and hydrological contributions . . . to resolve the signature of solid-earth phenomena."[34]

The recommendation to focus on a satellite-to-satellite interferometric ranging mission in the near term (5–10 years) is not very well justified in the SESWG report. The forthcoming GOCE mission will provide data that can be used to test the capabilities of satellite gravity gradiometry technology over the next five years. This may be one reason—although it is not a reason articulated in the SESWG report—for NASA to focus on a mission to demonstrate satellite-to-satellite interferometry technology in the near term. We feel that it may be premature, in the absence of a more extensive error budget analysis, to decide upon the most appropriate post-GRACE time-variable gravity measurement technology at this time.

[33] National Research Council, *Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Envelopes*, National Academy Press, Washington, D.C., 112 pp., 1997.

[34] National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., p. 39, 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

Summary

GRACE is functioning according to design, and we strongly endorse the SESWG short-term recommendation to spend the next five years taking full advantage of its measurement capabilities. The European Space Agency's GOCE mission will provide experience with satellite gravity gradiometry, and this is probably the best justification for NASA to adopt the SESWG recommendation to test the technology of satellite-to-satellite interferometry in the near term (5–10 years). Any such post-GRACE mission should be preceded by a careful error analysis of both interferometric ranging and high-altitude gravity gradiometry to determine the limiting factors.

SURFACE PROPERTIES USING IMAGING SPECTROSCOPY

The properties of surface materials caused by biological processes, pollution, and weathering of rocks and soils hold information relevant to many scientific and societal problems. The most practical way to measure spatial and temporal changes in surface properties is through imaging spectroscopy (IS) or "hyperspectral" imaging. The reflectance and emittance spectra of most materials on the earth's surface contain characteristic absorption features that allow them to be identified remotely. Imaging-spectroscopy data collected over the solar-reflected and thermal-emitted portions of the electromagnetic spectrum are used to identify minerals, rocks and soils, forest tree species, and invasive weeds and to monitor temporally variable phenomena such as landscape and vegetation change, water quality, volcanism, tectonics, and ice dynamics.

Imaging spectroscopy was developed in the early 1980s to counter the shortcomings of multispectral-imaging systems such as the Landsat Multispectral Scanner and later the Thematic Mapper, which could not be used to identify materials because of the poor spectral resolution afforded by 4 to 7 spectral bands.[35] The modern field of IS was born with the development of instruments that acquired spectral data in hundreds of narrow, registered, contiguous spectral bands.[36]

NASA has more than three decades of experience collecting high-quality multispectral and hyperspectral data from aircraft and satellites. Current hyperspectral instruments imaging the earth include the following:[37]

- Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) has been operational since 1987.[38] It uses a scanning mirror and 4 spectrometers to collect information in 224 contiguous bands in the 0.4 to 2.5 micrometer region and provides a spatial resolution of 20 meters. This resolution is sufficient for studying a wide range of processes, such as biomass burning, desertification, mapping the distribution of minerals at the earth's surface, and assessing the environmental impact of mining.

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[35] Modern multispectral instruments generally collect data in more spectral bands. Examples include the Landsat 7 Enhanced Thematic Mapper (8 spectral bands), the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) (14 spectral bands), and the Moderate Resolution Imaging Spectroradiometer (MODIS) (36 spectral bands). See <http://landsat.gsfc.nasa.gov/>, <http://asterweb.jpl.nasa.gov/APAA/ASTER.htm>, and <http://modis.gsfc.nasa.gov/>.

[36] Goetz, A.F.H., G. Vane, J. Solomon, and B.N. Rock, Imaging spectrometry for earth remote sensing, *Science*, **228**, 1147–1153, 1985.

[37] In addition to these NASA missions, spaceborne IS instruments are being flown by other federal agencies in the United States (e.g., Naval Research Laboratory's Hyperspectral Digital Imagery Collection Experiment) and by other countries (e.g., ESA's Medium Resolution Imaging Spectrometer). A number of private companies (e.g., HyVista [Australia], ITRES [Canada], SpecTIR [United States]) manufacture IS instruments and also provide airborne data collection services.

[38] <http://ariris.jpl.nasa.gov/html>.

- Hyperion, launched in 2000, was the first satellite instrument with contiguous spectral channels to become operational.[39] It collects data in 220 bands (0.4 to 2.5 micrometer range) and provides a spatial resolution of 30 meters. This technology-demonstration mission was designed to map rocks and soils and to monitor small-scale processes—including vegetation growth, deforestation, land use, erosion and other forms of land degradation, and urbanization—seasonally and on a global scale.

SESWG Recommendations—Surface Properties Using Imaging Spectroscopy

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.

SOURCE: National Aeronautics and Space Administration, *Living on a Restless Planet*, Solid Earth Science Working Group Report, Pasadena, Calif., p. 44, 2002, <http://solidearth.jpl.nasa.gov/seswg.html>.

Scientific and Societal Benefits of the SESWG Recommendations

Scientific Benefits

Spectroscopy has long been a tool to aid geologic mapping, both on the earth and on other planets in the solar system. Whereas multispectral instruments can sometimes provide information about the lithology of exposed rock, hyperspectral instruments allow particular minerals to be identified and mapped.[40] On the earth, IS can be used to identify minerals in areas that would be too difficult, dangerous, or time-consuming to map on the ground, or to differentiate subtle mineralogical differences in visually uniform surface materials. Imaging Spectroscopy can also be used to test and validate remote-sensing instruments destined for other planets. Almost everything known about the surface mineralogy of other planets has resulted from reflectance spectroscopy, initially using ground-based telescopes[41] and subsequently using thermal-infrared instruments on satellites and landers. In recent years, for example, thermal-infrared data (hyperspectral at about 5 kilometers per pixel and multispectral at 100 meters per pixel) from instruments orbiting Mars have led to new discoveries such as identification of minerals (e.g., feldspar, high-silica glass, crystalline gray hematite), surface ices, and surface processes.[42] On the

[39] Unger, S.G., J.S. Pearlman, J. Mendenhall, and D. Reuter, 2003, Overview of the Earth Observing 1 (EO-1) mission, *IEEE Trans. Geosci. Rem. Sens.*, **41**, 1149–1159, 2003.

[40] Clark, R.N., G.A. Swayze, and A. Gallagher, *Mapping Minerals with Imaging Spectroscopy*, U.S. Geological Survey, Office of Mineral Resources Bulletin 2039, 141–150, 1993.

[41] McCord, T., ed., *Reflectance Spectroscopy in Planetary Science: Review and Strategy for the Future*, National Aeronautics and Space Administration, NASA SP-493, Washington, D.C., 40 pp., 1988.

[42] Christensen, P.R., and 25 coauthors, Mars Global Surveyor Thermal Emission Spectrometer experiment: Investigation description and surface science results, *J. Geophys. Res.*, **106**, 23,823–23,871, 2001.

ground, a miniaturized thermal imaging spectrometer aboard the Spirit and Opportunity rovers is currently providing additional surface-mineral identification information.

In addition to mapping, IS data are providing important inputs into climate, hazard prediction, and crop-growth models.[43] Multispectral instruments are also useful for these applications. For example, multispectral (5 bands) thermal-infrared data are being used to monitor growth and land-use or land-cover changes in and around cities.[44] Data from the same instrument are also being used to extract volcanological parameters such as sulfur-dioxide flux, small-scale thermal output, and changes in lava compositions and textures.[45] When combined with surface-deformation observations from InSAR, such data have the potential to more completely characterize changes in the activity state of hazardous volcanoes around the world.

Societal Benefits

Imaging spectroscopy is used to help delineate zones at risk from natural hazards such as volcanoes, landslides, floods, and wildfires. It could also be used for a variety of environmental and land management applications—such as rapidly detecting and mapping pollutants released into the environment as a consequence of mining, industrial processes, or accidents (e.g., oil spills)—as long as the spectral signal of the pollutant of interest can be differentiated from the spectral signal of the surrounding material. If the SESWG report's recommendations are implemented, the simultaneous high-temporal- and high-spatial-resolution data sets could permit monitoring of particulate plumes from volcanic eruptions, sand storms, dust storms, and toxic materials on a global basis. These have multiple uses, ranging from airline safety to public health and antiterrorism.

Consistency with National Priorities in the Solid-Earth Sciences

Agencies concerned with improved mapping and characterization of the land surface have a potential interest in the proposed imaging spectroscopy program (Appendix A). Geologic mapping provides the framework for many of NSF's solid-earth science programs—including tectonics, dynamics at the interfaces of earth systems, hydrologic science, and geology—and complements EarthScope programs to understand North America structure and evolution, the Pacific-North American plate boundary, fault systems, and magmatic systems. IS-enhanced mapping is also a fundamental component of USGS programs in mineral and energy resources, geologic hazards, and geologic controls of ground and surface water. Better characterization of the geologic framework of ecosystems through IS would benefit USDA's soil and vegetation surveys and USGS's studies of land surface response to natural and human-induced stimuli. Finally, IS is useful for EPA's programs in the remediation and treatment of the land surface, including contaminated soils.

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[43] Ustin, S.L., S. Jacquemoud, P. Zarco-Tejada, and G. Asner, Remote sensing of the environment: State of the science and new directions, in S.L. Ustin, ed., *Manual of Remote Sensing, Remote Sensing for Natural Resource Management and Environmental Monitoring*, American Society Photogrammetry and Remote Sensing, Third ed., Vol. 4, John Wiley & Sons, New York, pp. 679–729, 2004.

[44] Ramsey, M.S., Mapping the city landscape from space: The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) Urban Environmental Monitoring Program, in Heiken, G., R. Fakundiny, and J. Sutter, eds., *Earth Science in the City*, American Geophysical Union, Washington, D.C., pp. 337–361, 2003.

[45] Ramsey, M.S., and J. Dehn, Spaceborne observations of the 2000 Bezymianny, Kamchatka eruption: The integration of high-resolution ASTER data into near real-time monitoring using AVHRR, *J. Volc. Geotherm. Res.*, (in review), 2004.

Inclusiveness of Major Research Foci to Which NASA Can Make a Unique Contribution

NASA is a proven leader in the development of imaging spectroscopy and is the U.S. civilian agency best suited to lead efforts for improved spaceborne IS. NASA's strengths in developing new analytical techniques (e.g., to map subpixel compositional and temperature variations); processing terabytes of data rapidly; integrating derived data sets into numerical and statistical models; and distributing data, tools, and models to the community will also help the agency develop a capability to resolve spectral signals of interest and to monitor environmental changes continuously.

Strengths and Weaknesses of the SESWG Recommendations

The SESWG report recommends improving the precision and resolution of solar-reflected IS in the near term and continuous full-spectrum IS in the long term. However, the recommenddations are worded vaguely. We assume that the immediate objective includes continuation of the AVIRIS instrument, which is the only research-caliber aircraft system available. We also assume that the long-term mission is for a hyperspectral (less than 10-nanometer bandwidth) visible-near-infrared spaceborne IS. If these assumptions are true, implementation of the SESWG recommendations would yield the high spectral and high spatial resolution needed to address a wide range of applications. For example, doubling the spectral resolution to 5 nanometers in the solar-reflected part of the spectrum while maintaining a high signal-to-noise ratio (e.g., 1000) at other visible-near-infrared wavelengths could help detect constituents (e.g., organic material) or differentiate between mineral forms (e.g., fibrous versus nonfibrous) that are important for environmental monitoring and geologic mapping.[46] Of course, improving spectral, spatial, or radiometric resolution would increase data volumes, so NASA will have to ensure that adequate resources are available to analyze these data.

On the other hand, not all science applications require high-spatial-resolution and high-spectral-resolution data. With 50 spectral bands MASTER (Moderate Resolution Imaging Spectroradiometer [MODIS]/Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER] Airborne Simulator)[47] can meet at least some of the scientific objectives driving the immediate SESWG goal of an airborne capability in the thermal portion of the spectrum. Multispectral, moderate- to high-spatial-resolution instruments such as 30-meter Landsat are useful for broadly characterizing the land surface and for monitoring long-term trends on a global basis. A new Landsat mission would fall within the 1–5 year SESWG goal, yet NASA has no plans for continuing this capability in the immediate future.[48] These instruments and the instruments proposed in the SESWG report would each meet different scientific objectives. However, if for financial reasons only one instrument could be flown, a hyperspectral instrument is the obvious choice because multispectral equivalent products can be extracted from hyperspectral data.

Another weakness of the SESWG report is the lack of specific recommendations for new technology and sensors; most of the discussion refers to refining existing techniques. For example, the thermal imaging spectrometer demonstration project recommended in the near term would require an order of magnitude improvement in spectral resolution. It is unrealistic to expect that the new sensor technologies needed for this mission will become available over the next five to ten years. Moreover, a technology demonstration mission could be expanded to include other technologies, such as microbolometer detectors that require no active cooling or constellation

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[46] Clark, R.N., T.M. Hoefen, G.A. Swayze, K.E. Livo, G.P. Meeker, S.J. Sutley, S. Wilson, I.K. Brownfield, and J.S. Vance, Reflectance spectroscopy as a rapid assessment tool for the detection of amphiboles from the Libby, Montana Region, U.S. Geological Survey Open File Report 03-128, 2003, <http://pubs.usgs.gov/of/2003/ofr-03-128/ofr-03-128.html>.

[47] <http://masterweb.jpl.nasa.gov>.

[48] NASA cancelled its request for proposals for a Landsat data continuity mission, which will lead to a data gap. See <http://ldcm.nasa.gov/>.

flying or unique orbits that allow both the high temporal and the high spatial resolutions required for mapping changes related to dynamic processes such as deforestation. The instruments NASA has flown to Mars provide precedents for this technology. Data from this wavelength region could serve both the surface-composition and surface-change (derived emissivity) as well as the natural hazards (surface kinetic temperature) communities.

Summary

We support implementation of the stated and implied SESWG recommendations, including continuation of AVIRIS and development of a hyperspectral (less than 10-nanometer bandwidth) visible-near-infrared spaceborne instrument. Rather than simply refining existing techniques, new sensor technologies will be required to achieve the stated scientific goals. In addition to airborne and spaceborne hyperspectral capabilities, continued operation of multispectral instruments would help ensure an uninterrupted record of environmental change, although hyperspectral data could be used to derive multispectral products if budgets are tight.

3

Conclusions

The centerpiece of the Solid-Earth Science Working Group strategic vision for NASA is the creation of a constellation of satellites that will provide continuous, global coverage of the continuously changing surface (and interior) of the earth. The title of the SESWG report, *Living on a Restless Planet,* emphasizes three underlying themes. “Living” refers to the need to gather the best possible information to help us anticipate and deal with the natural hazards of living on a dynamic planet. “Restless” conveys the idea that many of the geologic changes of greatest societal importance are rapid, even on human time scales. “Planet” emphasizes that the topics focus on spaceborne techniques that view the entire earth. Tackling these themes will require both basic and applied research.

We believe that the observational strategies outlined in the SESWG report provide a sound basis for guiding NASA’s solid-earth science program over the next few decades. The immediate goals (1–5 years) focus on launching an L-band InSAR satellite and continuing to collect, analyze, and distribute data from existing instruments. We endorse all of these goals, especially the InSAR satellite, which is identified as the top priority of the SESWG report.

Longer-term goals focus on new instruments that would capture information about solid-earth processes, and how they are changing over time, with sufficient spatial and temporal resolution to guide mechanistic models useful for making reliable natural hazard forecasts. Many of the new instruments (e.g., spaceborne LIDAR, thermal imaging spectroscopy, satellite-satellite interferometry for measuring time-variable gravity) would first be tested as technology demonstration missions over the next decade. We support this strategy as well as the goal of flying increasingly high-resolution instruments or constellations of instruments to measure surface deformation, topography, magnetic field, time-variable gravity, and land-surface characteristics. However, the specific technologies recommended at this early stage will not necessarily be the ones implemented in the long term (10–25 years). Although a long-term strategy is essential for planning, continued experience with new technologies at NASA and other space agencies will affect the optimal mission schedule and the choice of instrument to be flown. The goal should be to complement, not reproduce, instruments flown by other countries. Coordinating with other agencies (especially NSF) and with other parts of NASA might also help the Solid-Earth Division cope with the computational challenges that will arise from analyzing large volumes of data generated by the proposed observing program and from distributing some of the data in nearly real time. Without proper data analysis the instruments will be ineffective in meeting scientific objectives.

Appendixes

Appendix A

National Priorities in Solid-Earth Science

Agency	Geoscience Programs and Priorities
DOE[a]	• Characterization of oil and gas reservoirs and geothermal systems • Contaminant transport in aquifers • Chemical cycles of greenhouse gases and carbon sequestration • Advanced computation for the description and prediction of physical systems and processes
EPA[b]	• Pollution and suspended sediment in water • Remediation and treatment of the land surface, including soil contamination • Science (including geoscience) aimed at monitoring and regulation
NASA[c]	• Prediction and mitigation of natural hazards • Climate change
NOAA[d]	• National reference for latitude, longitude, height, velocity, and gravity • National data centers for climate (including paleoclimate) and geophysics (including solid-earth and marine geophysics) • Climate change
NSF[e]	• Structure and composition of the solid earth • Evolution of the deep earth • Tectonics • Continental dynamics • Interactions between the planetary interior and exterior • Biogeochemical cycles • Dynamics at the interfaces of various earth systems • Hydrologic sciences • Geology, paleontology, petrology, and geochemistry • Biocomplexity in the environment
Smithsonian[f]	• Formation and evolution of the earth and similar planets
USDA[g]	• Geologic component of the biosphere (ecosystems and watersheds) • Soil geography, surveys, and assessments

Agency	Geoscience Programs and Priorities
USGS[h]	• Geologic hazards • Energy and mineral resources • Climate change • Geologic framework of ecosystems • Geology and human health • Land surface response • Geologic controls of ground and surface water • Integration of earth- and life-science data
CCSP[i]	• Biogeochemical cycles and carbon sequestration • Geochemical tracers in water • Geological records of paleoclimate • Climate system (including a geological component) models
EarthScope[j]	• Continental structure and evolution • Pacific-North American plate boundary system • Fault systems and seismic hazards • Magmatic systems and volcanic hazards • Earth's interior

NOTE: CCSP = Climate Change Science Program; DOE = Department of Energy; EPA = Environmental Protection Agency; NASA = National Aeronautics and Space Administration; NOAA = National Oceanic and Atmospheric Administration; NSF = National Science Foundation; USDA = U.S. Department of Agriculture; USGS = U.S. Geological Survey.

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[b] Environmental Protection Agency, *2003-2008 EPA Strategic Plan: Direction for the Future*, Prepublication Copy, Washington, D.C., 276 pp., 2003, <http://www.epa.gov/ocfo/plan/2003sp.pdf>; Environmental Protection Agency, *Office of Research and Development Strategic Plan*, EPA/600/R-01/003, Washington, D.C., 35 pp., 2001, <www.epa.gov/ORD/SP>; Environmental Protection Agency, *Research Strategy, Environmental Monitoring and Assessment Program*, Research Triangle Park, N.C., 62 pp., 2002, <http://www.epa.gov/emap/html/pubs/docs/ resdocs/EMAP_Research_Strategy.pdf>.

[c] National Aeronautics and Space Administration, *Earth Science Enterprise Strategy*, Washington, D.C., 74 pp., 2003, <http://earth.nasa.gov>.

[d] National Oceanic and Atmospheric Administration, *New Priorities for the 21st Century: NOAA's Strategic Plan for FY 2003-FY 2008 and Beyond*, Washington, D.C., 19 pp., 2003, <http://www.osp.noaa.gov/ pdfs/ FinalMarch31st.pdf>; National Oceanic and Atmospheric Administration, *NOAA Research Strategic Plan for FY 2003-FY 2008 and Beyond: Understanding Threats to Society and the Environment from the Bottom of the Ocean to the Surface of the Sun*, Washington, D.C., 23 pp., 2003, <http:// www.spo.noaa.gov/ pdfs/FinalMarch31st.pdf>; National Oceanic and Atmospheric Administration, *Priorities for the 21st Century: A Strategic Plan for NOAA's Satellite and Information Service for FY 2003-2008 and Beyond*, 12 pp., 2003, <http://www.osp.noaa.gov/pdfs/LO%20Strat%20Plans%202003%20Final/ 1_NESDIS%20Strategic%20Plan%20Oct2.pdf>; National Oceanic and Atmospheric Administration, *NGS Vision, Mission and Goals*, 4 pp., 2000, <http://geodesy.noaa.gov/INFO/ NGSStratPlan98.html>.

[e] National Science Foundation, *National Science Foundation Strategic Plan FY 2003-2008*, Alexandria, Va., 34 pp., 2003, <http://www.nsf.gov/od/stratplan_03-08/draft-stratplan-FY2003-2008.pdf>; National Science Foundation, *NSF Geosciences Beyond 2000: Understanding and Predicting Earth's Environment and Habitability, Summary*, Alexandria, Va., 26 pp., 2000, <http://www.geo.nsf.gov/adgeo/ geo2000/geo_2000_full_report.htm>.

[f] Smithsonian Institution, *Building a Smithsonian for the Future: Smithsonian Institution Strategic Plan 2004-2008*, Washington, D.C., 26 pp., 2003, <http://www.si.edu/opanda/stgplan/StratPlan.031903.pdf>.

[g] U.S. Department of Agriculture, *Natural Resources Conservation Service Strategic Plan, 2003 Update*, Washington, D.C., 38 pp., 2003, <http://www.nrcs.usda.gov/about/spa/2003-NRCS_Plan.pdf>; U.S. Department of Agriculture, *USDA Forest Service Strategic Plan (2000 Revision). Integrity and Accountability: A Framework for Natural Resource Management*, Washington, D.C., 73 pp., 2000,

<http://www2.srs.fs.fed.us/strategicplan/ sp2000.pdf>; U.S. Department of Agriculture, *USDA Strategic Plan for FY 2002-2007*, Washington, D.C., 37 pp., 2002, <http://www.usda.gov/ocfo/pm/sp2002.htm>.

[h] Bohlen, S.R., R.B. Halley, S.H. Hickman, S.Y. Johnson, J.B. Lowenstern, D.R. Muhs, G.S. Plumlee, G.A. Thompson, D.L. Trauger, and M.L. Zoback, *Geology for a Changing World: A Science Strategy for the Geologic Division of the U.S. Geological Survey, 2000-2010*, U.S. Geological Survey Circular 1172, Reston, Va., 59 pp., 1998, <http://pubs.usgs.gov/circ/c1172/>; U.S. Geological Survey, *Biological Resources Division Strategic Science Plan*, 1996, <http://biology.usgs.gov/science/strategicplan.html>; U.S. Geological Survey, *Strategic Directions for the Water Resources Division, 1998-2008*, U.S. Geological Survey Open File Report 99-249, Reston, Va., 19 pp., 1999, <http://water.usgs.gov/pubs/ of/ofr99-249/pdf/ofr99-249.pdf>; U.S. Geological Survey, *Strategic Plan for the National Mapping Division of the U.S. Geological Survey*, 1999, <http://mapping.usgs.gov/ misc/strategic.html>; U.S. Geological Survey, *U.S. Geological Survey Strategic Plan: 2000-2005*, Reston, Va., 20 pp., 2000, <http://www.usgs.gov/stratplan/ stratplan_rev.pdf>.

[i] Climate Change Science Program and the Subcommittee on Global Change Research, *Strategic Plan for the U.S. Climate Change Science Program*, Washington, D.C., 202 pp., 2003, <http:// www.climatescience.gov/Library/ stratplan2003/final/ccspstratplan2003-all.pdf>.

[j] EarthScope Working Group, *EarthScope: A New View into Earth, Project Plan*, 36 pp., 2001, <http://www.earthscope.org/assets/es_proj_plan_hi.pdf>.

Appendix B

Biographical Sketches of Committee Members

Edward M. Stolper (chair) is William E. Leonhard Professor of Geology at the California Institute of Technology. His research focuses on experimental, analytical, theoretical, and computational studies aimed at understanding the origin and evolution of igneous rocks on the earth and other planets. Dr. Stolper has participated in a number of committees aimed at examining broad science issues, including the Committee on Grand Challenges in the Environmental Sciences, the Board on Earth Sciences and Resources, and the Space Studies Board. He is a recipient of the Meteoritical Society's Nininger Meteorite Award, the American Geophysical Unions' James B. Macelwane Award, the European Union of Geosciences' Arthur Holmes Medal, and the American Association for the Advancement of Science's Newcomb Cleve Prize. He is a member of the American Academy of Arts and Sciences and the National Academy of Sciences.

Anny Cazenave is a senior scientist at the Centre National d'Etudes Spatiales and deputy director of the Laboratory for Space Studies in Geophysics and Oceanography at Toulouse University in France. Her major areas of interest include satellite geodesy applied to the earth's gravity field and mantle dynamics, seafloor topography, the earth's rotation and polar motion, crustal motions, and the temporal change of the gravity field. Dr. Cazenave is a member of several French committees evaluating research, including the National Committee for Scientific Research Assessment, the French Academy of Sciences' Study Group in Geosciences, and the French Parliament's Scientific Council for Evaluating Science and Technology. She is a former president of the geodesy section of the European Geophysical Society and a recipient of that society's Vening-Meinesz Medal. She is also a fellow of the American Geophysical Union and its union international secretary. She is a member of the Academia Europaea and a corresponding member of the French Academy of Sciences.

Catherine G. Constable is a professor of geophysics at the Scripps Institution of Oceanography. Her research focuses on geomagnetism and paleomagnetism, variation in the geomagnetic field, the crustal magnetic field, and the electrical conductivity of the mantle. Dr. Constable chairs the steering committee for the Magnetics Information Consortium, which guides the development of databases for the magnetics community, and is a member of the advisory committee to the International Union of Geodesy and Geophysics' Committee on the Study of Earth's Deep Interior. She is a fellow of the American Geophysical Union and a recipient of the Royal Astronomical Society's Price Medal for geomagnetism and aeronomy.

Francis A. Dahlen, Jr., is department chair and a professor of geosciences at Princeton University. His research interests are in theoretical global seismology, seismic tomography, mechanics of earthquake sources, rotation of the earth, and the mechanics and thermodynamics of brittle frictional mountain building. Dr. Dahlen is a former member of the Committee on Seismology. He is a fellow of the American Geophysical Union and a recipient of its Inge Lehmann Medal for fundamental theoretical advances laying the foundations of modern global seismology. He is a fellow of the American Academy of Arts and Sciences and a member of the National Academy of Sciences.

William E. Dietrich is a professor of geomorphology at the University of California, Berkeley. He has appointments in the Earth and Planetary Science Department (where he is currently chair), the Department of Geography, and the Earth Sciences Division of Lawrence Berkeley National Laboratory. He uses fieldwork, radar altimetry, laboratory experiments, and numerical modeling to quantify and explore geomorphic processes and landscape evolution. Dr. Dietrich's current research includes mechanistic analysis of landscape processes and evolution, identifying linkages between ecological and geomorphic processes, and building tools to address practical environmental problems. He is a fellow of the American Geophysical Union and a member of the National Academy of Sciences.

Bradford H. Hager is Cecil and Ida Green Professor of Earth Sciences at the Massachusetts Institute of Technology. His research interests include the physics of geologic processes, mantle convection, crustal deformation, plate tectonics, and space-geodetic observations of surface deformation. Dr. Hager has chaired or been a member of several committees concerned with solid-earth science. These include the U.S. Geodynamics Committee, the Geodesy Committee, and the Committee to Review NASA's Earth Science Enterprise Research Strategy for 2000–2010. He is a fellow of the American Geophysical Union and he received that society's Macelwane Award in 1986. He also received the Woollard Award from the Geological Society of America.

Grant Heiken recently retired as a volcanologist in the Earth and Environmental Science Division at Los Alamos National Laboratory (LANL). Prior to joining LANL in 1975, he worked in NASA's Lunar Receiving Laboratory during the Apollo and Skylab programs. Dr. Heiken's research focuses on explosive volcanism, volcanic hazard analysis, geothermal exploration, and urban geoscience, and he has authored or coauthored books on all of these subjects. He was a Fullbright Scholar in 1999 and he studied the interaction between geology and history in Rome. He is a past president of the International Association of Volcanology and Chemistry of the Earth's Interior and a former member of the NRC Committee on Future Roles, Challenges, and Opportunities for the U.S. Geological Survey.

R. Keith Raney is a principal professional staff scientist at the Johns Hopkins University Applied Physics Laboratory (APL). Prior to joining the APL staff, he spent 18 years at the Canada Centre for Remote Sensing, where he was chief radar scientist and co-founder of RADARSAT, Canada's first remote sensing satellite program. He has contributed to the design of a variety of radar instruments and processing systems for NASA, the Canadian Space Agency, and the European Space Agency. Dr. Raney has served on numerous advisory committees related to remote sensing systems, and is currently a member of the science advisory group for ESA's CryoSat radar altimeter Earth Explorer mission. He is a life fellow of the Institute of Electrical and Electronics Engineers (IEEE) and a recipient of the IEEE's Millennium Medal, the Canadian Remote Sensing Society's Gold Medal, and the IEEE Geoscience and Remote Sensing Society's Outstanding Achievement Award.

Frank M. Richter is Sewell Avery Distinguished Service Professor at the University of Chicago. His research spans both geophysics and geochemistry, and includes investigations of mantle convection, thermal evolution of the earth, isotopic dating, pore-water chemistry in sediments, and melt segregation and chemical diffusion in molten rock systems. Both lines of research have led to professional society awards, including the American Geophysical Union's Bowen Award and the Geological Society of America's Wollard Award. Dr. Richter has served on numerous solid-earth science committees, including the Board on Earth Sciences and Resources, U.S. Geodynamics Committee, Committee on Seismology, and Committee on Basic Research Opportunities in the Earth Sciences. He is a member of the American Academy of Arts and Sciences and the National Academy of Sciences.

Mousumi Roy is an assistant professor of geophysics at the University of New Mexico. A modeler, her research focuses on tectonic deformation at different spatial and temporal scales, topographic evolution of tectonically active regions, and rheologic stratification in the lithosphere. Dr. Roy has convened or participated in a number of workshops related to large geophysical observation programs, including EarthScope and Continental Margins Research (MARGINS). She currently chairs the Geophysics Division of the Geological Society of America.

Lianxing Wen is an assistant professor of geophysics at the State University of New York, Stony Brook. His research focuses on the seismic structure of the earth's mantle and core, mantle rheology and dynamics, and seismic wave propagation. In 2003 he was awarded the American Geophysical Union's Macelwane Medal for significant contributions to the geophysical sciences by a young scientist and also became a fellow of the society. Dr. Wen is interested in both theoretical and observational methods and is currently a member of the Incorporated Research Institutions for Seismology's Standing Committee for the Global Seismic Network.

NRC Staff

Anne M. Linn is a senior program officer with the Board on Earth Sciences and Resources of the National Academies. She has been with the board since 1993, directing the USA World Data Center Coordination Office and staffing a wide variety of geophysical and data policy studies. In addition, she is the secretary of the International Council for Science's (ICSU's) Panel on World Data Centers, and a member of the ICSU Ad Hoc Committee on Data. Prior to joining the staff of the National Academies, Dr. Linn was a visiting scientist at the Carnegie Institution of Washington and a postdoctoral geochemist at the University of California, Berkeley. She received a Ph.D. in geology from the University of California, Los Angeles.

Acronyms and Abbreviations

ASTER	Advanced Spaceborne Thermal Emission and Reflectance Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
CCSP	Climate Change Science Program
CHAMP	CHAllenging Minisatellite Payload
CNRS	Centre National de la Recherche Scientifique
DFG	Deutsche Forschungsgemeinschaft
DOE	Department of Energy
EPA	Environmental Protection Agency
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
GLAS	Geoscience Laser Altimetry System
GOCE	Gravity Field and Steady-State Ocean Circulation Mission
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
ICESat	Ice, Cloud, and Land Elevation Satellite
IGRF	International Geomagnetic Reference Field
InSAR	interferometric synthetic aperture radar
IS	imaging spectroscopy
IT	information technology
LIDAR	LIght Detection And Ranging
Magsat	Magnetic Field Satellite
MASTER	MODIS/ASTER Airborne Simulator
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NEHRP	National Earthquake Hazards Reduction Program
NGA	National Geospatial-Intelligence Agency
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
PBO	Plate Boundary Observatory
SAC-C	Satelite de Aplicanciones Cientificas-C
SAFOD	San Andreas Fault Observatory at Depth
SESWG	Solid-Earth Science Working Group (NASA)
SPOT	Systeme Probatoire pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission

TOPEX	Ocean TOPography EXperiment
USArray	United States Seismic Array
USDA	United States Department of Agriculture
USGS	United States Geological Survey