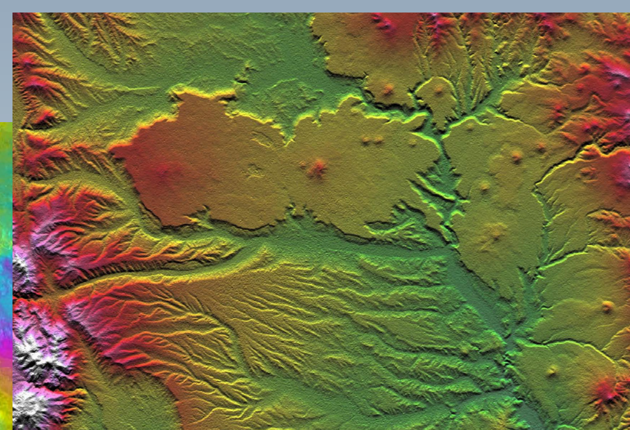
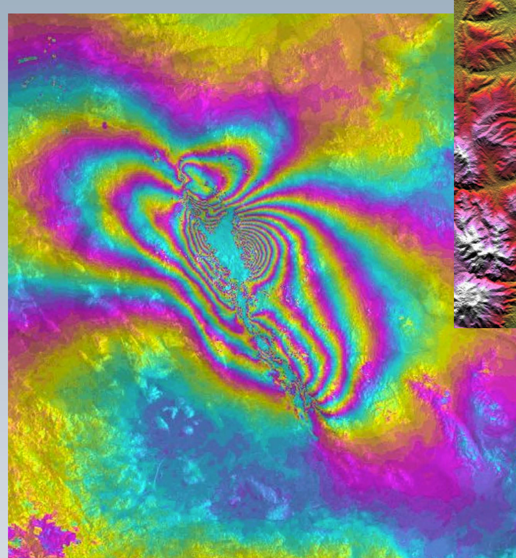
InSAR Workshop Summary Report

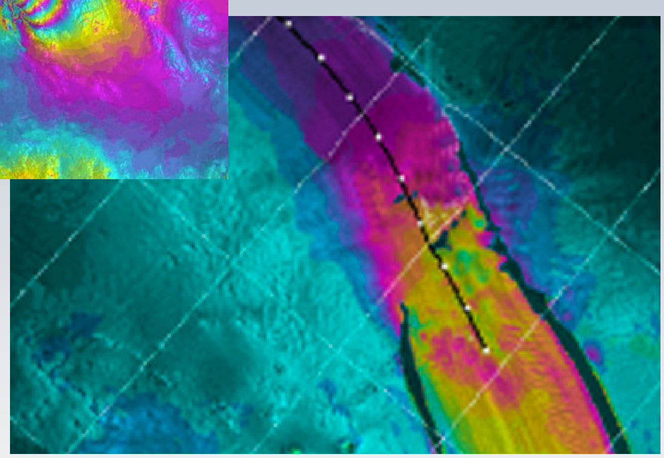
October 20–22, 2004

Oxnard, California

Sponsored by: National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), and United States Geological Survey (USGS)







Prepared by

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InSAR Working Group

On the cover — Coseismic deformation pattern of Hector Mine earthquake, from ERS (left, courtesy G. Peltzer, UCLA); high-resolution InSAR topographic map from SRTM mission (top right, courtesy JPL); flow rate of the Pine Island glacier, West Antarctic Ice Sheet, the largest discharger of ice in Antarctica, as derived from ERS satellite data (below right, courtesy E. Rignot, JPL).

This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Dear Reader,

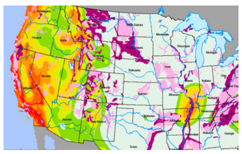
This report summarizes the major findings of a symposium attended by 260 scientists and engineers in an effort to guide U.S. efforts in Interferometric Synthetic Aperture Radar (InSAR), a critical tool for studying dynamic changes of the Earth's surface and natural hazards associated with these changes. InSAR observations provide critical and otherwise unavailable data enabling comprehensive, global measurements to better understand and predict changes in the Earth system. The InSAR Workshop was funded jointly by NASA's Earth Science program, the Geosciences Directorate of the National Science Foundation, and the U.S. Geological Survey. We hope that these and other agencies heed the call for a coordinated InSAR program to address these important research questions.

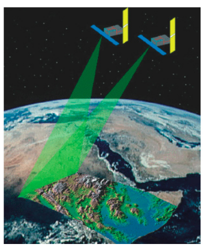
This report was assembled by the Reports Committee of the InSAR Working Group, namely Jill Andrews (Caltech), Andrea Donnellan (Jet Propulsion Laboratory, California Institute of Technology), Yuri Fialko (SIO), Maggi Glasscoe (Jet Propulsion Laboratory, California Institute of Technology), Ben Holt (Jet Propulsion Laboratory, California Institute of Technology), Ken Jezek (Ohio State University), Ian Joughin (U. Washington), Suzanne Lehner (U. Miami), Bernard Minster (SIO), Paul Rosen (Jet Propulsion Laboratory, California Institute of Technology), John Rundle (UC Davis), Jeanne Sauber (NASA GSFC), Mark Simons (Caltech), and Wayne Thatcher (USGS).

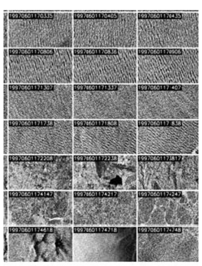
We especially would like to thank Andrea Donnellan and Maggi Glasscoe of JPL for assembling much of the background technical material and helping with the design of the report. We would also like to thank John McRaney for his many hours coordinating the meeting itself. We echo the call for "InSAR everywhere, all the time."

Cheers,
Howard Zebker
Editor

Contents







This report contains the efforts of many participants in the InSAR Workshop that convened on Oct. 20–22, 2004, in Oxnard, California. Contributions towards this written material have been included from, among others:

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Executive Summary

An "InSAR Workshop" convened at the Embassy Suites Hotel in Oxnard, California, from Oct. 20–22, 2004, jointly supported by the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the United States Geological Survey (USGS). The goal of this workshop was to define and codify the need for a scientific radar research program in the United States and internationally. Over 260 scientists, engineers, and educators around the world attended the Workshop.

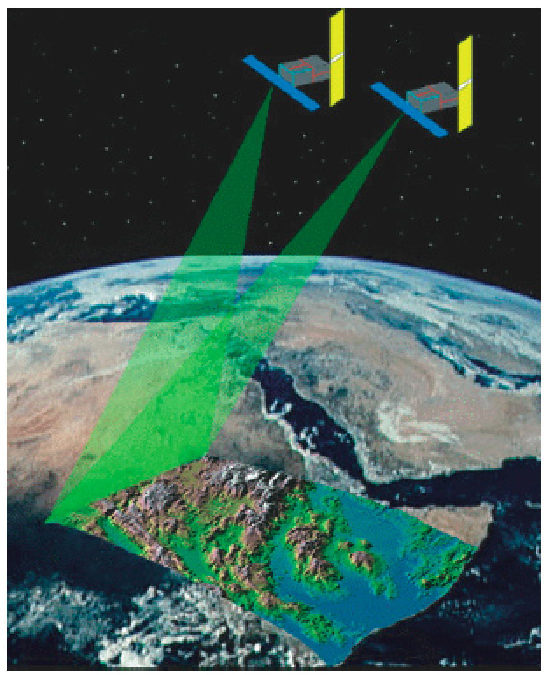
The workshop's purpose was twofold: to inform the community of the state of the art in InSAR/SAR and mission opportunities, and to receive from the community an assessment of science challenges and needs for InSAR. Six discipline groups formed, representing the crustal deformation, cryosphere, hydrology, land cover and land use, oceanography, and planetary science communities. A series of discipline-oriented breakout sessions addressed three major questions:

1. *What are the "grand challenges" in each science discipline area?*
2. *How can radar sensors help?*
3. *What is the role for existing data, sensors, and for new sensors?*

with specific instructions to

1. *Define the compelling science challenges for each discipline*
2. *Assess the utility/desirability of existing platforms/data to carry out science*
3. *Consider the advantages of a mission with "baseline" L-band InSAR technology*
4. *Ask how this system might be augmented or modified to attain science goals*

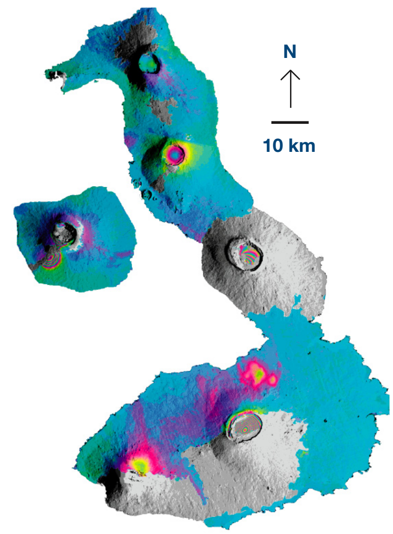
In addition, groups were asked specifically: *What new science is possible with additional frequencies or polarizations? What infrastructure needs development? What derived products are needed? And what is the role of "near-real-time" data?*



Interferometric Synthetic Aperture Radar (InSAR) is a satellite remote sensing method capable of measuring minute changes on the Earth's surface.

The group enthusiastically and definitively recommended the implementation of a comprehensive and coordinated U.S. InSAR program.

InSAR splashed upon the scene when Massonnet published this image of deformation resulting from the 1992 Landers earthquake. (Cover copyright *Nature*; used with permission.)



Deformation map of the western Galápagos Islands shows that most of the volcanoes are constantly in motion as magma moves beneath the surface.

They found that an interferometric radar mission is required to address important outstanding scientific questions in each discipline, including:

1. *Are there precursory deformation phenomena for either earthquakes or volcanos and can they be detected with InSAR observations?*

2. *What is the role of glaciers and ice sheets in sea level rise, and what do they tell us about possible changes in Earth's climate?*

3. *How do ground water, surface water, soil moisture, and snow pack contribute to the global fresh water budget and how do natural and anthropogenic processes redistribute water in both space and time?*

4. *What is the 3-dimensional structure of vegetation on the Earth's terrestrial surface, and how does it influence habitat, agricultural and timber resources, fire behavior, and economic value?*

5. *How does the ocean surface behave on a global, long-term scale and how does it drive the climate?*

6. *Where can we find water in the solar system to support human exploration?*

All of these science challenges can be met through the use of imaging radar remote sensing methods, especially InSAR. We therefore recommend a series of coordinated steps forming a U.S. InSAR Program that will:

1. Exploit existing radar resources such as international sensor missions and their data archives to further research

2. Plan and prepare for a U.S.-led satellite radar system optimized for these and other scientific and operational objectives

3. Educate and train future scientists who are able to continue the multidisciplinary research needed to solve many of these vexing problems

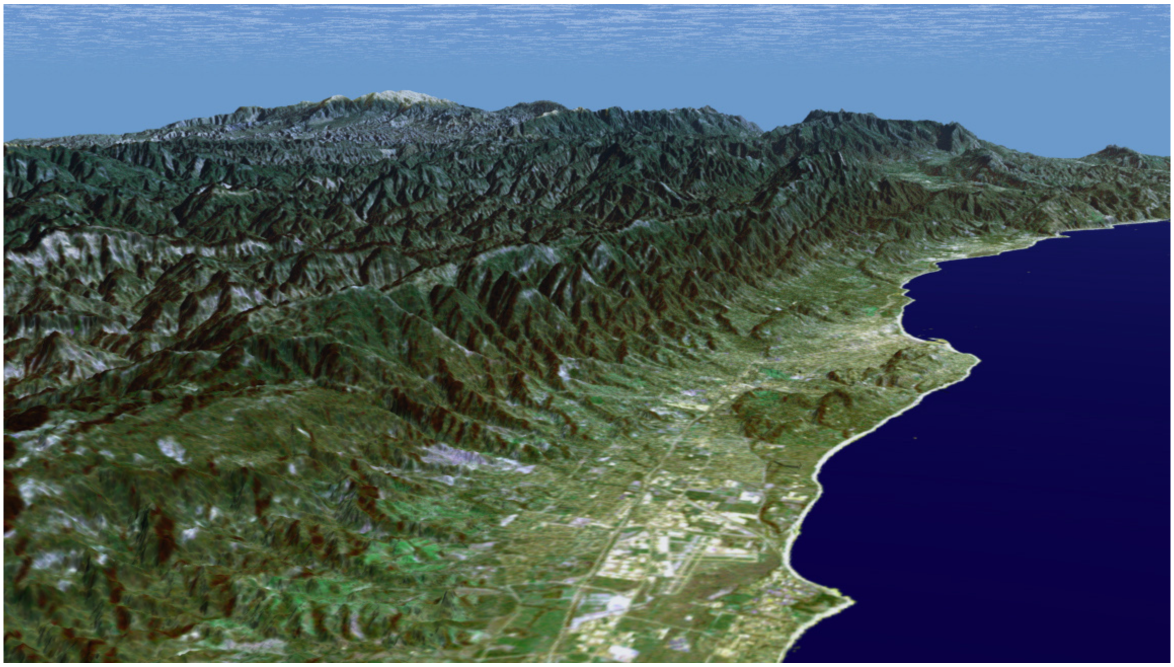
The technical requirements for a radar mission capable of meeting these goals are:

1. L-band wavelength

2. Approximate weekly repeat cycle

3. Millimeter-scale sensitivity

4. Tightly controlled orbit to maximize usable InSAR pairs



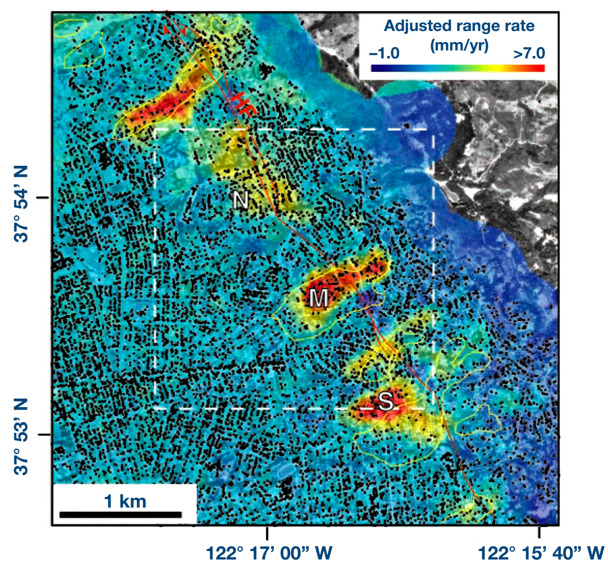
InSAR measures highly detailed topography of the Earth, as in this SRTM image of Santa Barbara, CA.

5. Both left and right looking for rapid access and more comprehensive coverage
6. Along-track interferometry for surface water velocity measurements

This mission would address major science objectives for each of the six disciplines, and provide coverage in areas where current/planned systems cannot. It would also provide frequent coverage for observing weekly or monthly timescale changes.

Some added objectives would be possible with the following technology enhancements:

1. ScanSAR operation for wide swaths
2. Increased power and storage to operate 20% of the orbit on average
3. Fully calibrated amplitude and phase data and polarimetry
4. C- and L-band imagery would provide the necessary control to map surface water elevation changes in a wide range of locations
5. Multiwavelength capabilities



Potential landslides are readily identified in this interferogram of the Berkeley hills in California. Rain causes slipping of the hillsides.

The results of the workshop can be summarized by a set of endorsed, community-wide recommendations.

We recommend opening negotiations between the U.S. and foreign space agencies to allow and encourage sharing of spaceborne remote sensing data fully among research scientists, with a goal of having all radar remote sensing data freely circulating among scientists.

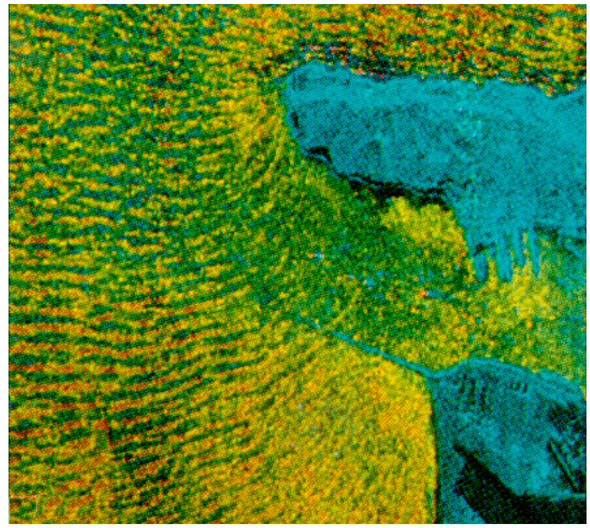
We recommend a series of workshops and negotiations to plan such experiments that would bring together scientists with common interests from around the world.

We recommend a research and analysis program with a goal of supporting undergraduate and graduate level research in InSAR studies, and also continuing technical workshops and summer schools for new students and young-thinking mature scientists.

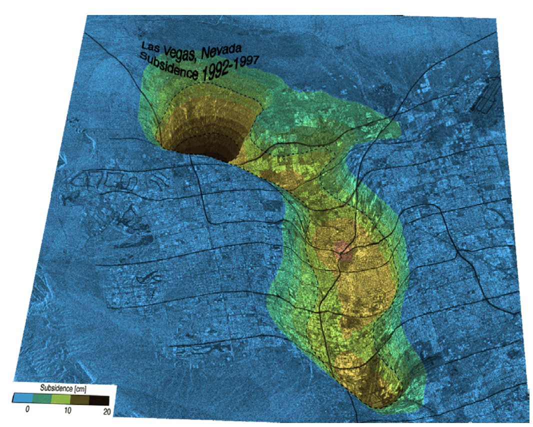
We therefore recommend that the U.S. orbit a new radar satellite capable of satisfying at least half of the objectives above by 2010, when most of the planned and existing systems will be reaching the end of their technical lifetimes.

We insist that any new radar remote sensing system developed by the U.S. or partner agencies put in place a free and open data access policy so that any researcher may obtain the data easily and cheaply.

This program is responsive to significant multi-agency needs, including those of NASA, NSF, USGS, and NOAA. InSAR is the fourth contribution to EarthScope, a broad interagency effort to understand and characterize the solid-Earth processes contributing to natural hazards and to provide policy relevant information to agencies such as FEMA for use in hazard assessment, mitigation, and response. The National Research Council 2001 "Review of EarthScope Integrated Science" characterized InSAR as "an essential component of the EarthScope Initiative." NASA's solid-Earth science strategic vision, *Living on a Restless Planet* (2002), documents a consensus view by the broad solid-Earth science community of distinguished scholars that InSAR is the highest priority mission for solid-Earth science. This workshop further reflects the community consensus of the importance of InSAR.



Another InSAR configuration yields images of ocean current and wave velocities, invaluable in oceanographic studies. Ocean currents are critical components of circulation and in the sustenance of hurricanes.



Many regions of the Earth are in motion, affecting the lives of millions of people. InSAR provides the only tool capable of mapping these changes globally, such as this subsidence near Las Vegas due to the withdrawal and recharge of groundwater.

Rationale and Context for Workshop

The National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the United States Geological Survey (USGS) jointly sponsored a workshop, titled simply "InSAR Workshop," at the Embassy Suites Hotel in Oxnard, California, from Oct. 20–22, 2004.The goal of this workshop was to define and codify the need for a scientific radar research program in the United States and internationally. This meeting, conceived by the InSAR Working Group, received over 350 applications from scientists, engineers, and educators around the world interested in radar, SAR, and InSAR (interferometric synthetic aperture radar); 260 members of the community attended the workshop.

The workshop's purpose was twofold: to inform the community of the state of the art in InSAR/SAR and mission opportunities, and to receive from the community an assessment of science challenges and needs for InSAR. The meeting lasted three days, and was organized around a series of discipline-oriented breakout sessions and a few informatory presentations. A three-part charge was given to the discipline groups:

1. *What are the "grand challenges" in each science discipline area?*
2. *How can radar sensors help?*
3. *What is the role for existing data, sensors, and for new sensors?*

with specific instructions to

1. *Define the compelling science challenges for each discipline*
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3. *Consider the advantages of a mission with "baseline" L-band InSAR technology*
4. *Ask how this system might be augmented or modified to attain science goals*

Most of the time was reserved for group discussions. The two breakout sessions on day 1 were aimed at

- defining truly grand and important challenges for each discipline, and
- refining the challenges by asking what science goals can be met with access to existing data archives, cooperative use of existing satellites, or only by new radar missions and sensors.

In addition, groups were asked specifically: *What new science is possible with additional frequencies/polarizations? What infrastructure needs development? What derived products are needed? And what is the role of "near-real-time" data?*

The second day began with a discussion of InSAR Working Group organization, followed by a Town Hall Panel Discussion where representatives of several U.S. and international space agencies presented views on SAR research and responded to questions from the community. The afternoon consisted of presentations from each discipline group from the previous breakout sessions.

Day 3 was reserved for summarizing results from the first two days and beginning to write this report.

Need for an InSAR Program

InSAR has proven to be an extraordinarily effective observation tool aiding many scientific studies of the Earth, and potentially other planets as well. Yet many important scientific questions addressable through InSAR methods remain, for example:

- *Are there precursory deformation phenomena for either earthquakes or volcanos and can they be detected with InSAR observations?*

- *What is the role of glaciers and ice sheets in sea-level rise, and what do they tell us about possible changes in Earth's climate?*
- *How do ground water, surface water, soil moisture, and snow pack contribute to the global fresh water budget and how do natural and anthropogenic processes redistribute water in both space and time?*
- *What is the three-dimensional structure of vegetation on the Earth's terrestrial surface, and how does it influence habitat, agricultural and timber resources, fire behavior, and economic value?*
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- Exploit existing radar resources such as international sensor missions and their data archives to further research
- Plan and prepare for a U.S.-led satellite radar system optimized for these and other scientific and operational objectives
- Educate and train future scientists who are able to continue the multidisciplinary research needed to solve many of these vexing problems

Identified Needs for Radar Remote Sensing

Many documents supporting the use of radar remote sensing to answer these scientific questions have appeared and we do not duplicate them here. This plan for SAR and InSAR applications should be viewed in the context of previous studies and also of ongoing national and international strategic planning for global Earth observations. Existing activities have produced, for example:

- "Strategic Plan for the U.S. Integrated Earth Observation System," Interagency Working Group on Earth Observations, of the Committee on Environment and Natural Resources, 2004.
- "Draft GEOSS 10-year Implementation Plan," Group on Earth Observations (GEO) Implementation Plan Task Team (IPTT), 2004.
- "Operational Use of Civil Space-based Synthetic Aperture Radar," Interagency Ad Hoc Working Group on SAR (R. Winokur, Chair), 1996.
- "Spaceborne Synthetic Aperture Radar: Current Status and Future Directions," A Report to the Committee on Earth Studies, Space Studies Board. NASA Tech Memo 4697, 1995.
- "Living on a Restless Planet," report of the Solid Earth Sciences Working Group (SESWG) (Sean Solomon, Chair), 2002.

Excerpts from the above reports detailing the need for SAR and SAR missions are given in Appendix 1.

From the perspective of the operational community, the 1996 Winokur report recommends that a U.S. SAR system be developed to acquire high-accuracy terrain elevation data and provide for change detection observations, permits characterization of vegetation, and supports geologic mapping. The report recommends, as one option, the development of a U.S. interferometric SAR satellite system that could be one element of an international SAR satellite constellation, comprising SAR systems with a diversity of frequencies and polarizations arranged in orbits that permit, with proper data registration, the extraction of multifrequency, multipolarization measurements.

These recommendations, which deal with international initiatives, are consonant with the Solid Earth Science Working Group (SESWG) report to NASA, which concentrates on solid-Earth science, and with a NASA-sponsored report on SAR research enabled by the Alaska SAR Facility data archive and downlink station (1998, "The Critical Role of SAR in Earth System Science, A White Paper by the Alaska SAR Facility User Working Group"). The SESWG report notes that the NSF EarthScope initiative incorporates "a dedicated InSAR mission for obtaining synoptic information about crustal deformation globally" in addition to the drilling component SAFOD, the seismic component USArray, and the geodetic component PBO. This was seconded by the National Research Council's re-

Table Key

- H = High level of importance to benefit area
- M = Medium level of importance to benefit area
- L = Low level of importance to benefit area

Earth Observations Note: This list of observations is not meant to be comprehensive	Societal Benefit Areas: Weather	Disasters	Oceans	Climate	Agriculture	Human Health	Ecology	Water	Energy	SAR Imagery	SAR Interferometry
Land Elevation/Topography	M	H	H	M	H	M	H	H	L	●	●
Land Use/Land Cover (Crops, Forests, Urban, etc.)	M	M	L	M	H	H	H	M	M	●	●
Ecosystem Parameters (Health, Diversity, etc.)	L	L	H	H	H	H	H	M	L		
Fire (Detection, Extent, Severity)	L	H	L	M	H	H	H	M	L	●	
Soil Moisture	M	M	L	H	H	H	M	H	L	●	●
Ice and Snow (Cover and Volume)	M	M	M	H	M	M	M	H	M	●	●
Land and Sea Surface Temperature	H	H	H	H	H	H	H	M	H		
River Runoff (Volume, Sediment, etc.)	L	H	H	H	H	H	H	H	H	●	●
Water Quality (Contamination, Spills, etc.)	L	H	H	M	H	H	H	H	L	●	
Sea Surface Height/Topography	L	M	H	H	L	M	H	L	L	●	●
Ocean Current and Circulation	M	L	H	H	L	L	H	L	L	●	●
Ocean Salinity	L	L	H	H	L	L	H	L	L		
Ocean Color (Chlorophyll, etc.)	L	L	H	M	L	H	H	L	L		
Atmospheric Constituents (Ozone, Greenhouse Gases, Black Carbon, Volcanic Ash, and Other Aerosols, etc.)	L	H	M	H	L	H	L	H	H		
Atmospheric Profiles (Temperature, Pressure, Water Vapor)	H	H	L	H	L	M	L	L	L		
Wind Speed and Direction (Surface, Tropospheric, Stratospheric)	H	H	H	H	M	H	M	L	L	●	
Cloud Cover (Properties, Type, Height)	H	M	M	H	M	L	L	L	L		
Total and Clear Sky Radiative Flux	H	L	M	H	H	H	M	M	H		
Solar Irradiance	L	L	L	H	L	H	M	L	L		
Space Weather	L	H	L	L	L	M	L	L	H		
Deformation/Subsidence/ Ground Failure	L	H	M	L	L	L	L	M	L	●	●
Earthquake and Volcanic Activity, Gravity, Magnetic Field Variations	L	H	L	M	L	L	L	L	L	●	
Geology/Bedrock and Surface Soils	L	H	L	L	M	L	M	H	M	●	
Species (Occurrences, Density, etc.)	L	M	H	H	H	H	H	M	L	●	

Table 1. Benefit Areas Related to Earth Observations.

views of EarthScope and of the SESWG report. The SESWG report states very simply that "A dedicated InSAR satellite is the highest-priority objective for solid-Earth science at NASA in the next 5 years." As we shall see in this report, the requirements for a SAR capability extend across a variety of disciplines and scientific and operational objectives. Table 1 is adapted from the IEOS report. It highlights a selection of Earth observations and their relative importance in the mitigation of various types of disasters. We have added two columns that suggest which Earth observations would benefit from SAR observations described in the main body of this report. These observations include:

- SAR image maps, where we do not distinguish between very different types of images, including simple amplitude images, multifrequency images, or polarimetric images.
- InSAR interferograms, where we do not distinguish between single-pass (dual antenna) interferometry, repeat-pass interferometry, or other modes such as along-track interferometry.

In some cases polarimetric, dual frequency, or along-track InSAR configurations are desired. Table 1 illustrates vividly the broad range of applications of imaging radar data, and their societal benefits, in very diverse areas. These and other SAR measurements were discussed and highlighted at the workshop. Note that these observations pertain to processes rather than individual events isolated in time. Consequently, the measurement requirements extend over time, and continuity is paramount.

Other major scientific endeavors will benefit from InSAR technology and, in fact, will be limited from a dearth of InSAR data if there is no viable InSAR program. For example, there will be an exceptional opportunity for interdisciplinary polar science in 2007–8 when the international science community will sponsor the International Polar Year (IPY). The IPY is a multinational program of coordinated research to explore the polar regions, further our understanding of polar interactions including their role in global climate, expand our ability to detect changes, and extend this knowledge to the public and decision makers (Bindschadler, 2004). The environmental changes in polar regions are significant, accelerating, and globally connected. IPY will build on the scientific heritage of the International Geophysical Year (1957) by incorporating observations of the icy parts of our planet from space. Hence, this is a unique opportunity to bridge in situ, airborne, and satellite observations, and to combine this data set with the latest models of polar variabilities. SAR will be critically important in IPY observations because of the ability to use SAR for making unique observations of ice sheet, glacier and sea ice motion.

Role of Exploration

Satellite-borne radar sensors continue the millennia-old tradition of human exploration of the Earth and the wider universe. Many unknowns remain even on our own planet and the launch of every new satellite technology reveals something about our world that was previously not known or not appreciated. Imaging sensors, and InSAR in particular, reveal, visually and viscerally, processes transpiring on the surface in a way that their extent and importance can be appreciated by scientists and non-scientists alike.

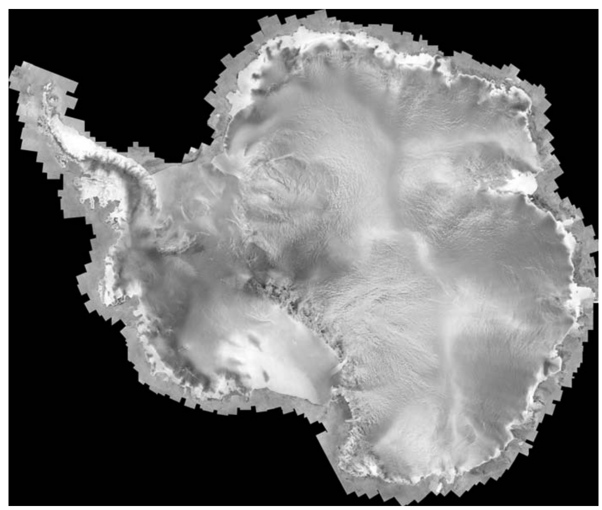


Figure 1. Radar mosaic of Antarctica from the RAMP cooperative mission between NASA and Canada.

SAR and InSAR provide high-resolution maps of surface features and velocity for Greenland and Antarctica, including the vast areas of these ice sheets where humans have yet to set foot. Figure 1 shows the first high-resolution radar map of Antarctica, prepared using data acquired in 1997. Analysis of the map and associated interferometric data resulted in the discovery of major ice streams draining the interior of East Antarctica into the sea.

InSAR observations of several large earthquakes, including the 1992 Landers and 1999 Hector Mine earthquakes in southern California, and the 1999 Izmit earthquake in Turkey, revealed unusual deformation on faults neighboring the earthquake ruptures. The high-resolution precise measurements provided by InSAR indicated that the earthquake faults may be associated with wide zones of heavily cracked and damaged rocks that have mechanical properties different from those of the surrounding crust. This discovery provides a new way for detecting potentially active seismogenic faults. Recent seismic studies of the fault damage zones also showed that the fault zone properties evolve in time. The observed spatial and temporal variations in the fault zone properties might provide valuable information about the fault evolution through the earthquake cycle.

What Have We Learned from InSAR?

InSAR is a relatively new development, and has been applied to geophysical studies of the Earth for barely 10 years. Yet in this time fundamental new knowledge about the Earth has been acquired. Some fields represented at the workshop have yet to take advantage of this technology fully as the proper sensor configurations have not been put into operational use. Still, many advances have been made.

Natural hazards. SAR interferometry has demonstrated valuable information for monitoring and predicting or forecasting a variety of hazards, from air, water, and earth. Large-scale hazards generated in the Earth include earthquakes and volcanic eruptions; each is driven by tectonic forces within the Earth's crust. Observation of deformation from subsurface flow of magma and of the accumulation of strain within the crust is needed to be able to understand these great forces of nature. More localized, but often intense, hazards include landslides, mud flows, and land subsidence or collapse due to natural or human removal of subsurface material or fluids and permafrost melting. Flooding is the most damaging hazard in most areas, from rainfall, snow, and ice melting, and natural or human-made dam collapse. In coastal regions, hurricanes, intense local wind events, shore erosion, and oil spills are major hazards. Finally, fire in forests and other vegetation is a major hazard in many areas. For each of these hazards, InSAR has proven a help in assessing damage after the events and evaluating the risk of future events by understanding and monitoring the processes involved.

Cryosphere studies. Recent observations reveal significant climatic changes in the polar regions. Analysis of satellite data shows unexpected linkages between both polar ice sheets and climate that are directly relevant to sea-level rise, on much shorter timescales than predicted by models. In the Antarctic Peninsula, ice shelves disintegrated over periods as short as several days (Doake and Vaughan, 1991; Rott et al., 1998), and is attributed to both increasing air and ocean temperatures that can increase the rate of surface and basal melt. The relevance of ice shelf retreat lies in the consequent release of upstream, grounded ice and the impact of that ice on sea level rise (Rignot 2004; Scambos and others, 2004). In the Arctic, changes include decadal reduction of sea ice thickness and extent, lengthening of the seasonal melt period with associated increase in open water, and increased melt and loss of ice around the margins of Greenland ice sheets. Some of the ice changes appear to be highly correlated with the North Atlantic Oscillation (NAO) and related Arctic Oscillation (AO); the associated sea-level pressure anomalies are linked to changes in the strength of the polar vortex. These patterns strongly affect the hydrography of the upper ocean and large-scale ice circulation.

There is a wealth of satellite and in situ observational capabilities that provide critical information on cryospheric processes, e.g., visible, infrared and microwave imagery, satellite radar, and laser altimetry. SAR complements these instruments through observations of backscatter, which is related to important geophysical parameters including sea-ice age, surface melt, and snow accumulation, and through the capability of InSAR/SAR to measure both ice-sheet and sea-ice motion. InSAR also possesses the extraordinary ability to measure the ensemble effect of short-term microscopic variations in the upper layers of the snow; these can be used to infer a variety of geophysical parameters from surface snow accumulation to the position of ice shelf grounding lines. SAR has unique capabilities that make it especially well-suited to high-latitude studies, including the ability to observe at fine resolution even during the long winter periods and in all weather conditions. plus rapid-repeat and broad coverage due to the convergence of orbits from a polar-orbiting system. When SAR observations are coupled with other fundamental observations from the present constellation of Earth-observing satellites, we can achieve an understanding of ice sheets, glaciers, and sea ice, at a level that is needed to predict their behavior in a changing environment.

Climate change. Decadal climate patterns in atmosphere–ocean circulation, such as El Niño/ Southern Oscillation (ENSO) and Arctic Oscillation, alter atmospheric circulation, temperature, and precipitation. Within the U.S., these climate patterns are directly tied to regional ocean warming, hazards (including flooding), and ecosystem health in both the coastal zones and on land. There are also recent observations of linkages of polar climate to extrapolar climate patterns (for example, ENSO), through alteration of mid-latitude storms and subsequent transport of heat and moisture, which may account for ice-related changes. SAR provides fundamental measurements of ice, ocean, and land parameters that are being used to understand the impact of climate change, including ice mass and melt, flooding, and freshwater discharge.

Hydrologic processes. Surface deformation caused by the flow of water through aquifer systems is apparent in InSAR images. The spatial extent of buried aquifers can be discerned from space, and provide visual data that readily shows the locations of buried, possibly unknown, fault systems that provide permeability barriers to the flow of water.

Natural resource management. InSAR analytical techniques are mature enough to be added to an existing panoply of geospatial tools currently in use in natural resource management. Applications include monitoring and modeling of baseline levels and rates of change in natural resource utilization and extraction, essential not only in enhancing the productivity and conservation of natural and human-made ecosystems, but also in mitigating and restoring areas affected by nonrenewable resource extraction (i.e., mining) and planning and guiding drastic land use change (e.g., urbanization), minimizing negative impacts. InSAR science and technology can also play a crucial role in the assessment, modeling, remediation, and mitigation of resource destruction processes, such as desertification, salinization, siltation, erosion, topographic alteration from the impact of unreclaimed/abandoned mined areas, flooding, deforestation, fire, wildlife habitat fragmentation, glacial recession, drainage pattern modification, and water body pollution.

Need for a New Mission

As is amply illustrated by the above, InSAR has enabled a wide variety of scientific investigations, and remains critical to the understanding of our Earth and solar system as the only way to provide many necessary observations. All groups who have studied the need for new sensor technologies conclude that InSAR is the major missing element in plans for continued research into evolving Earth processes, and our workshop joins the chorus repeating the urgent need for “InSAR everywhere all the time.”

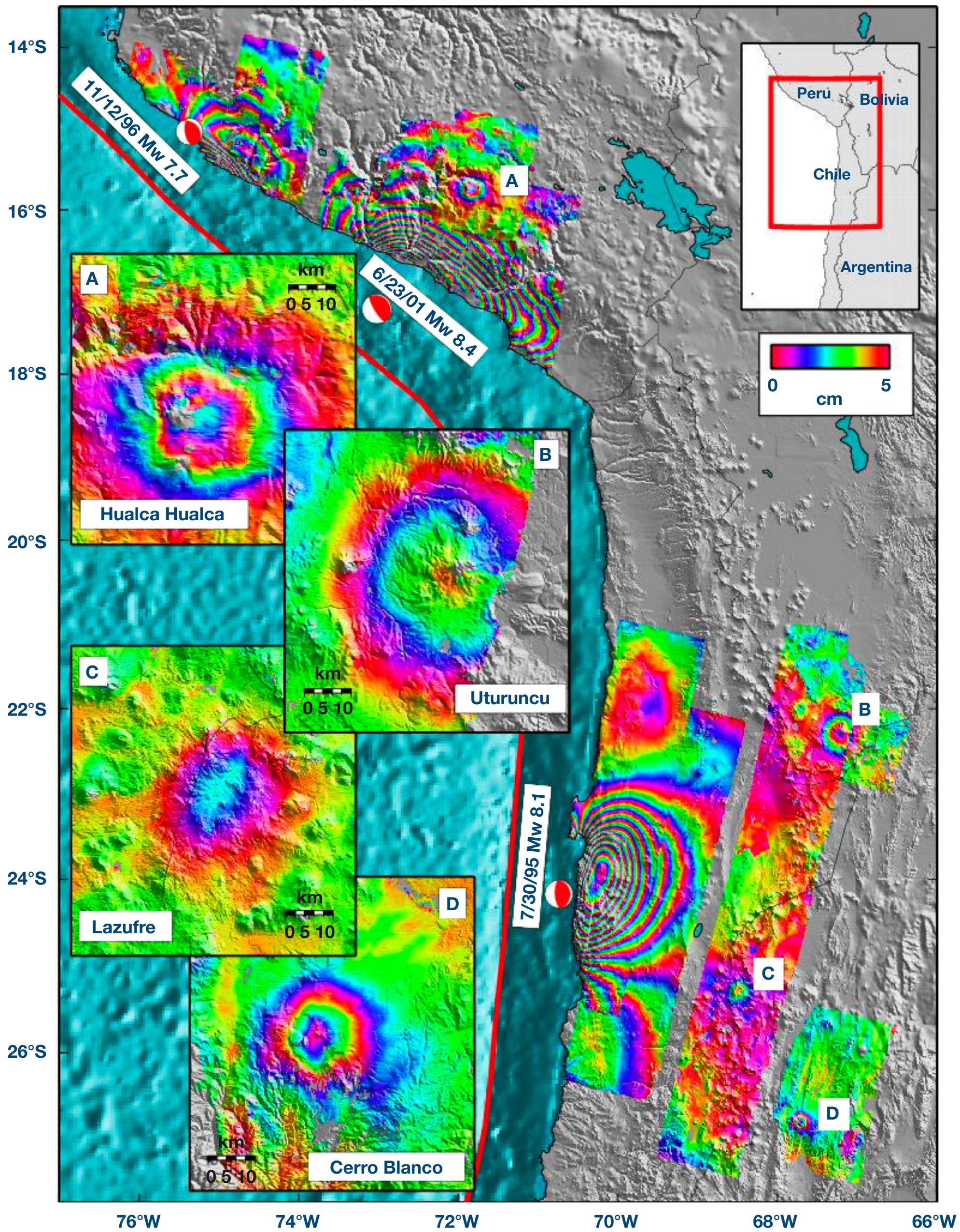


Figure 2. InSAR everywhere will illuminate unanticipated processes unfolding on our Earth. Observations from ERS-1/2 have revealed that four Andean volcanoes, thought to be inactive, are now known to be rapidly deforming. Each color cycle corresponds to 5 cm of deformation. The top three volcanoes are inflating and Robledo is deflating (Pritchard and Simons, 2002).

Workshop Summary Results

The InSAR Workshop on Oct. 20–22, 2004, provided a forum for many science discipline groups to come together and discuss an integrated and collaborative SAR program for the nation and the world. The 260 scientists, engineers, and educators who attended the meeting as representatives of this diverse group identified "big picture" grand science challenges, assessed each challenge in terms of how new SAR or InSAR data could enable the needed research, and finally focused on a set of recommendations for a radar program that benefits society through greater scientific understanding of the Earth and how it works.

A Large, Diverse Community

The workshop attendees were drawn from a broad cross section of scientists self-organized into several discipline groups. The groups, along with their self-definitions, were:

1. Crustal deformation — the study of surface expressions of deformation at depth responsible for earthquakes, volcanic activity, and isostatic adjustments in Earth's crust and mantle.
2. Cryospheric science — the study of ice on Earth, primarily in the polar regions, and its impact on climate, climate change, and habitability.
3. Hydrology — the study of the terrestrial water cycle and water budget.
4. Land cover and land-cover change — concerned with the terrestrial living component interfaces between the atmosphere, lithosphere, and hydrosphere components of terrestrial ecosystems.
5. Oceanography — dedicated to the study of processes that occur in the boundary layers of the atmosphere and ocean and how they interact at the ocean surface.
6. Planetary science — the study of planets other than the Earth, mainly within our own solar system.

In addition, two more groups, Education and Outreach and Information Technology, met as splinter sessions to assess what the needs were for a radar program in each of these areas. Material from these groups is reported below as well as the science summaries discussed above.

Grand Challenges for Each Discipline

Each discipline group defined the truly important and compelling science objectives within its field. The "grand challenge" science objectives for each are summarized in Table 2. In the remainder of this report, the workshop attendees evaluate these major objectives with respect to the expected contributions from InSAR and how future radar systems need to be configured to meet these challenges.

Recommended Studies

Each discipline group examined the major challenges in greater detail in order to describe exactly what investigations were needed and how these might be enabled and carried out by advancing capability and technology in radar remote sensing, especially InSAR. The following recommended studies were identified:

Crustal Deformation

1. What mechanisms control the occurrence of transient and steady-state aseismic fault slip?

Recent discovery of transient aseismic fault slip in the Cascadia and Japanese subduction zones has been a big surprise to Earth scientists and has raised compelling questions about the causes and effects of such transient events. Close association of these events with microseismic tremor activity is even more surprising and bewildering. While continuous GPS

Table 2. Grand Challenge Science Objectives by Discipline.

Crustal Deformation	1. What mechanisms control the occurrence of transient and steady-state aseismic fault slip? 2. What stress transfer processes are important in triggering seismic activity? Are long-range interactions important? 3. Are there precursory deformation phenomena for either earthquakes or volcanos and can they be detected with InSAR observations? 4. How does magma ascend from a source region to shallow reservoirs? What processes control the further ascent? 5. What processes cause/trigger flank instabilities on volcanoes? Are they related to eruption? 6. How are earthquake faulting and magmatism interrelated? Can an earthquake along the San Andreas fault trigger volcanism in the Cascades?
Cryosphere	1. What is the role of glaciers and ice sheets in sea-level rise? 2. What is the influence of sea ice on, and its response to, global climate change and biological processes? 3. How much water is stored as seasonal snow and what is its variability? 4. How much carbon is exchanged between the permafrost and the atmosphere? 5. How do changes in the cryosphere affect human activity? 6. What are the long-term impacts of a changing cryosphere on other components of the Earth system?
Hydrology	1. How do groundwater, surface water, soil moisture, and snow pack contribute to the global freshwater budget and how do natural and anthropogenic processes redistribute water in both space and time? 2. How does the land surface vary with time and how does it influence the dynamic water supply? 3. How can remote sensing technology improve water resource management and hydrological hazard mitigation associated with flooding and land subsidence?
Land Cover	1. What is the three-dimensional (3-D) structure of vegetation on the Earth's terrestrial surface that influences habitat, carbon, climate, agricultural and timber resources, fire behavior, and economic value? 2. How does land cover change over time and what are the mechanisms for human-driven land-use conversion between urban, forest, agriculture, and wildland? 3. How are biomass and carbon distributed over the surface of the Earth (global carbon cycle)? 4. What is the surface topography and change in surface topography under vegetation canopies? 5. How does land cover/vegetation control the cycling of carbon, nutrient, and water through ecosystems?
Ocean-ography	1. How does the ocean surface behave on a global, long-term scale and how does it drive the climate? 2. How can we better predict hazards at sea? 3. What is the nature of physical processes in coastal, frontal, and marginal ice zones and how do they affect biological processes?
Planetary Science	1. Where can we find water on Mars and the Moon to support human exploration? 2. How widespread is, and what is the role of, active tectonism/volcanism on Venus and Europa? 3. What is the potential habitability of Europa? 4. What is the fine-scale topography of the Moon, Mars, Venus, and the Galilean satellites for geomorphology studies and landing sites characterization?

networks and seismic arrays have played key roles in these discoveries, InSAR imaging has the potential to dramatically improve the spatial distribution of the 3-D deformation field of these events and image the causative deformation sources at depth on the interplate megathrust. InSAR has also imaged an aseismic slip event on an intraplate shallow thrust fault that was not otherwise detected.

2. *What stress transfer processes are important in triggering seismic activity? Are long-range interactions important?*

It has long been recognized that the static stress changes produced by earthquakes, glacial fluctuations, and magmatic unrest can either advance or retard the occurrence of subsequent seismic and volcanic activity. Current research is very actively elucidating the nature of the earthquake/earthquake interactions, rigorously quantifying the statistical likelihood of linkages, and beginning to shed light on time-dependent processes (e.g., post-seismic relaxation, state/rate fault friction) that influence triggered activity. However, emerging clues suggest longer-range interactions that are not mechanically understood. Any linkages should have deformation signatures, and synoptic InSAR imaging offers possibly the best means of detecting and elucidating the deformation causes and effects that may link regional earthquake events.

3. *Are there precursory deformation phenomena for either earthquakes or volcanoes and can they be detected with InSAR observations?*

This is the Holy Grail for solid-Earth natural hazards research. Current earthquake hazard maps are at a coarse resolution in both time and geography. Such maps depict probability of

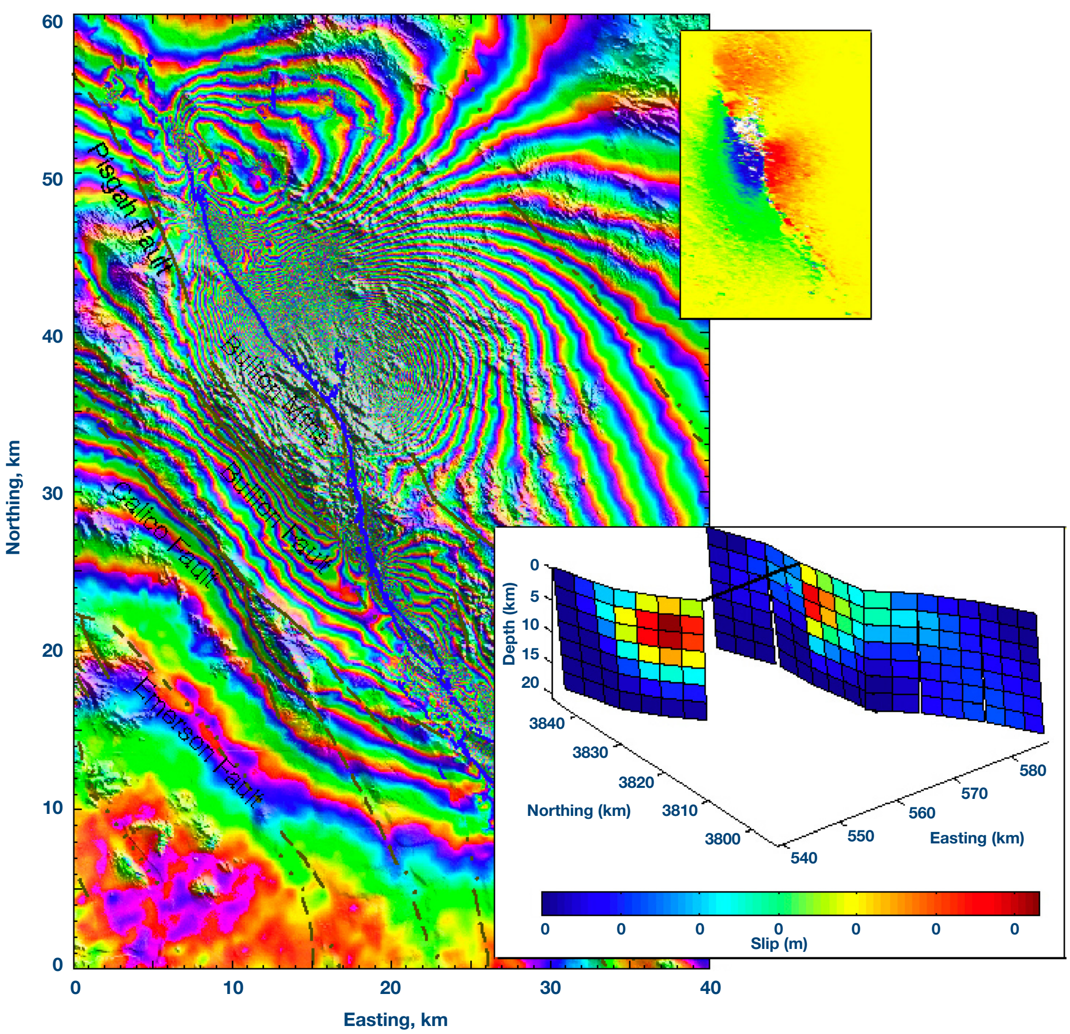


Figure 3. InSAR-derived coseismic displacements for the Hector Mine earthquake, with azimuth offsets in upper inset and a solution for slip on the fault at depth in the lower right. These slip distributions describe the earthquake physical process and help us understand the earthquake cycle.

exceeding a certain amount of shaking (generally that at which damage occurs) over the next 30 to 100 years, depending on the map. The spatial resolution is typically on the order of tens to hundreds of kilometers. These maps are based on information about past earthquakes observed in the geological or historical record. Measurement of crustal deformation, usually acquired using GPS, now provides information on strain rates; generally we find that earthquake rates are higher where strain rates are higher. The number of GPS stations that can be deployed on the ground limits the resolution of strain, and these stations can be expensive to install and maintain. InSAR can be deployed as a space-based imaging technique that will provide spatially smooth resolution of strain at 100 m, vastly improving resultant hazard estimates by two to three orders of magnitude in terms of spatial resolution. Furthermore, future science studies of crustal deformation will yield insights into earthquake behavior, whether high strain rates indicate the initiation of failure on a fault or quiet release of stress, and how stress is transferred to other faults. These studies will lead to science findings for improvement of earthquake hazard maps both spatially and temporally.

Similar studies employing InSAR to map deformation on volcanic terrain can reveal subsurface transport of magma, an important factor affecting eruption probabilities. Detailed maps of the shape of the magma trail give clues as to where pressure may accumulate and also may help constrain the explosiveness of the potential eruption. Global InSAR data will permit this mapping worldwide, covering all potentially active volcanoes. InSAR has clearly helped the discovery of unexpected processes in the post-seismic period. The continuous surveillance of seismic areas with a dedicated system will undoubtedly reveal the signature of precursory processes should the associated surface displacement be resolvable by InSAR. A lot of unknowns obviously exist in this field, but the quest for signal is worthy of pursuit.

4. How does magma ascend from a source region to shallow reservoirs? What processes control the further ascent?

The generation, migration, and emplacement of magmatic fluids are processes that play a fundamental role in the geological and geochemical evolution of the Earth's crust. These processes are also of paramount importance for our understanding of eruptive activity and mitigation of volcanic hazards. Significant progress toward unraveling the mechanics of magma transport from the source regions to the shallow crustal reservoirs has been made due to field studies of ancient eroded volcanic systems and theoretical models, but direct observational constraints on the style and dynamics of the magma ascent are still lacking. Such constraints are crucial for forecasting the replenishment and pressurization of shallow crustal magma chambers that may potentially feed volcanic eruptions. Because volcanic unrest episodes for any given magmatic system may be quite infrequent, and only a few volcanic systems around the world are closely monitored, a global observation system capable of detecting the ongoing magmatic unrest will result in dramatic improvements of our understanding of volcanic activity and the associated societal hazards.

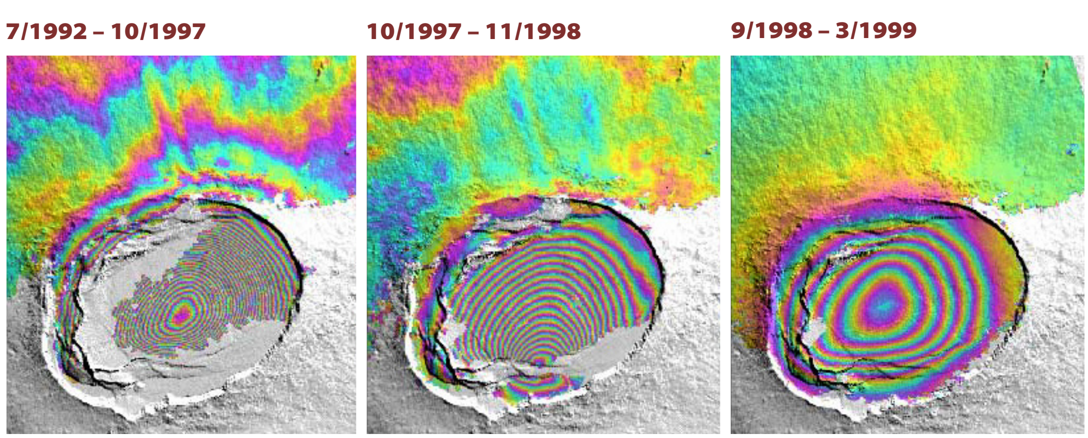


Figure 4. Time series of deformation at Sierra Negra volcano in the Galápagos Islands. Varying patterns imply several different mechanisms for magma accumulation and faulting under this volcano.

Existing observations of active magmatic systems worldwide indicate complex relationships between migration of magma at depth and the associated deformation measured at the Earth's surface. Current outstanding problems include the determination of the size and shape of magmatic reservoirs from geodetic, seismic, gravity, and other geophysical observations, the discrimination between the magmatic unrest associated with magma intrusion likely to give rise to eruptions, the existence and prevalence of detectable deformation prior to and following volcanic eruptions, and inferences about the volume and size of impending eruptive events. High-quality geodetic observations of active neovolcanic areas will provide important constraints on timescales and mechanisms of processes responsible for the initiation of magma withdrawal from the shallow magma reservoir to the Earth's surface, the magma transport through the upper crust, and the magma eruption.

InSAR observations of deformation at volcanoes indicate that shallow magma migration might be frequent, short-lived, and only rarely lead to eruption. A short timescale for intrusions is consistent with the fact that deformation at Mount Peulik, Alaska, is inferred to have occurred between 1996–1998 and the beginning or ending of periods of deformation was seen at South Sister in Oregon and Hualca Hualca and Lazufre in the central Andes. Even at volcanoes where inflation appears to be occurring more or less continuously, the specific rate of magma supply is time-dependent (e.g., Etna, Lazufre, Uturuncu, Okmok, Seguam). Geochemical evidence at other volcanoes suggests multiple timescales for intrusions and that there might be several small intrusions spanning the decades to centuries before an eruption. The durations of intrusive episodes can be governed by a combination of magma supply, the physics of transport, and potentially some external mechanism like earthquakes. More frequent observations of the precise timing of the beginning and ending of these intrusive events could constrain the rate of movement of the magmatic fluids and the physical processes involved.

5. What processes cause/trigger flank instabilities on volcanoes? Are they related to eruption?

Volcano flank instabilities and volcano spreading occur on a variety of spatial scales, from relatively small sector collapse on stratovolcanoes, through larger shield volcanoes such as Kilauea, to volcanoes on other planets such as Olympus Mons. The physical processes and mechanics of volcano flank instabilities are related to the gravitational potential of the volcanic edifice coupled with the structural mechanics of the various strata within the volcano and beneath it (Merle and Borgia, JGR, 1996). For large shield volcanoes such as Kilauea in Hawaii or Mt. Etna in Italy, for example, pre-depositional sediments are believed to form a basal dislocation plane that facilitates radial spreading of the edifice, and a link between volcanism and spreading is a subject of debate. In other cases, such as the flank sector collapse that triggered the explosion of Mount St. Helens in 1980, the instability of the flank was directly linked to its renewed activity. Recent examples from InSAR time series analysis in the case of Mt. Etna show that magma replenishment triggered renewed basal spreading, suggesting that magmatic/structural dynamics are closely linked (Lundgren et al., GRL, 2004). By understanding

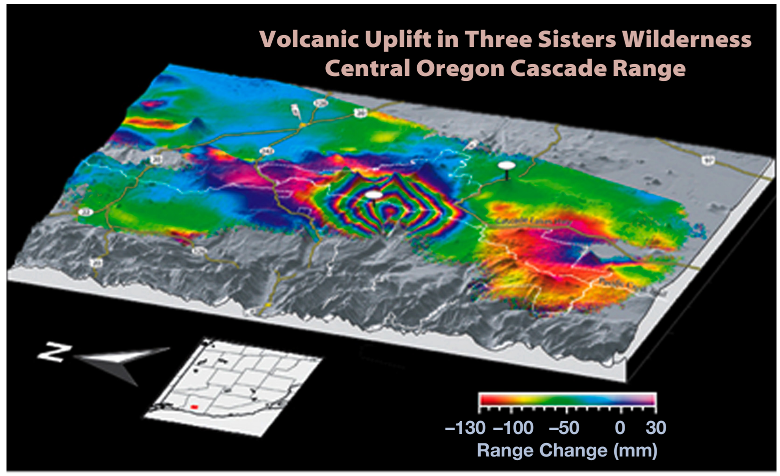


Figure 5. InSAR studies in the Cascade Ranges have found that observed uplift of 4 cm/yr is due to magma injection at a depth of 8 km. (Figures courtesy of W. Thatcher, USGS.)

the complete spatial/temporal evolution of a volcano deformation that is possible only through InSAR, we will be able to better understand both the physical mechanisms responsible for volcano flank instabilities and their hazard. The latter includes both the singular hazard they pose and their ability to focus the devastation of large volcanic eruptions.

6. *How are earthquake faulting and magmatism interrelated? For example, does an earthquake along the San Andreas fault trigger volcanism in the Cascades?*

Magmatism and earthquake activity are invariably linked, but the nature of the linkage, and in particular the cause and effect relations, are poorly understood. Ascent of magma through the brittle upper crust produces abundant seismicity, but longer-range linkages are uncertain and the subject of ongoing research. Anecdotal evidence relates large subduction zone earthquakes with subsequent eruption of arc volcanoes (and vice versa), but the correlations are hit-and-miss and the mechanistic linkage is obscure. Deformation measurements are key to connecting the operative seismic and magmatic processes but definitive observations are few. Synoptic InSAR coverage of coupled magmatic/tectonic regions worldwide would dramatically increase the inventory of case histories and lead to better understanding of the mutual interactions.

The Landers 1992 earthquake that occurred in the Eastern part of the Mojave Desert, California, was the first event captured by InSAR data acquired by the ERS-1 satellite.

The group raised several other items of current investigation in the area of crustal deformation. These tend to cross the specific disciplinary lines of the list of challenges but are related closely. The issues examined by the group were:

Post-seismic deformation and its variability. The Earth's crust and upper mantle is a mechanical system composed of layers of different composition with different structure, temperature, and confining pressure. These characteristics define their mechanical behavior and the way the system responds to stress changes imposed by earthquakes. Processes that have been advocated to explain observed post-seismic deformation include after-slip, visco-elastic relaxation, and poro-elastic relaxation. After-slip refers to continuous creep occurring on the deeper part of the fault, visco-elastic relaxation occurs in the deeper part of the crust and upper mantle, and poro-elastic relaxation involves the percolation of fluids (water) in the porous upper curst in response to the sudden pore pressure change produced by an earthquake. Each of these processes produces slow deformation and has its own temporal behavior (characteristic time). Each of them contributes to movements measurable at the surface using geodetic techniques. Understanding post-seismic processes is critical (1) to have a correct assessment of the aseismic part of the deformation in the overall budget of deformation in a given region, and (2) to estimate the way the stress evolves and is redistributed on adjacent faults or to other parts of the same fault.

Role of poro-elastic processes. The 1992 Landers earthquake that occurred in the eastern part of the Mojave Desert in California was the first event captured by InSAR data acquired by the ERS-1 satellite. In the years following the event, ERS continuously acquired images allowing scientists to observe the small movements of the ground produced by post-seismic deformation processes. Deformation patterns observed in the post-seismic interferograms could not be explained by classic after-slip models or visco-elastic relaxation in the lower crust. For example, the images showed the concentration of strain along the fault associated with upward movements in pull-apart structures and subsidence in compressive jog. This rebound of the ground highlighted for the first time with InSAR data was produced by poro-elastic relaxation of the stretched and compressed volume of crust in both extensive and compressive structures. Larger deformation patterns observed on both sides of the fault could not be explained by after-slip models and the contribution of poro-elastic deformation offered a way to explain the observed patterns.

These findings were made possible by the continuous view of the surface deformation provided by InSAR and by the high sensitivity of InSAR to vertical motions, a component that was not captured by triangulation surveys and captured poorly by campaign GPS surveys.

Strain and ground disturbance from dynamic earthquake rupture. Damage from earthquakes is primarily due to the stresses and strains associated with propagating seismic waves. The temporal and spatial variations of strain in regions around earthquakes are believed to be significantly larger during rupture propagation than the final integrated static strain change. While achieving temporal resolution on timescales of seconds is the realm of seismology, seismology suffers from an inherent trade-off between the spatial distribution of fault slip versus when slip occurs. By tightly constraining the final spatial distribution of slip, joint InSAR/seismic models are able to explore a larger space of model parameters such as rupture rise time, rupture velocity, and spatial resolution of the fault slip. Beyond taking advantage of the displacement data from InSAR, such highly resolved models make explicit predictions of ground accelerations and strains that can be compared with point measurements from local seismic recordings and decorrelation (damage) maps produced by routine InSAR processing. The link to seismic data and the use of damage maps become increasingly useful with increasing temporal resolution of the InSAR data.

Non-eruptive migration of magma and/or magmatic fluids. Volcanoes have different personalities — while some give notice of impending eruptions, it is often difficult to decipher what others will do next. Stratovolcanoes and some calderas are particularly elusive because they can erupt with little warning after centuries of quiescence. But satellite-based InSAR is revealing that these periods of apparent repose are not totally free of activity. Deformation at supposedly inactive volcanoes has been discovered with InSAR in the Galápagos Islands, Alaska, the Cascades, central Andes, and at calderas in the western U.S. and Alaska, the Andes, and Kamchatka. The hazard from these deformation episodes is unclear: will any magma accumulation result in an eruption, or is this a benign intrusion?

Furthermore, the physical cause of deformation is usually ambiguous — magma movements are a possible source, but so are other magmatic fluids like stream and brine, as well as volume changes caused by heating/cooling and phase changes from melting/freezing. However, InSAR observations provide some clues as to the physical source of the deformation. For example, if the inferred source of deformation is very deep, it is likely to be magmatic, because hydrothermal systems are typically less than 10 km deep.

Cryosphere

Cryospheric research encompasses all the frozen water and soil in the Earth system. This includes the role of land ice (ice sheets, caps, and glaciers) in current and future sea-level rise and the role of sea ice and associated feedbacks on the global climate system. It also includes studying the natural variability in the ice, ocean, and atmosphere systems for future predictions. Research also focuses on changes in permafrost and the seasonal snow cover. The latter is a contributor to important high-latitude feedback processes and the former is an important potential contributor to atmospheric carbon through the release of methane to the atmosphere. SAR is well-suited for use by this community because of its all-weather and day/night capability, fine resolution, and the ability to observe the motion of a dynamically changing ice cover over short timescales. Observations of the cryosphere and the changing polar climate are critical for the operational community, whose primary task is to reduce shipping hazards related to sea ice and iceberg tracking. Other climate-related changes in the cryosphere involve the impacts of a reduced ice cover on biological habitat and sea-level rise on coastal native communities.

1. *How is sea ice changing in response to a changing environment?*

Sea ice is a thin, snow-covered layer that is present at the boundary of the cold polar atmosphere and the comparatively warm ocean. As such, it influences, reacts to, and integrates fluctuations within the climate system, including surface heat and mass fluxes from its insulative properties and high albedo, and salt- and freshwater fluxes during ice formation and melt. In addition to the considerable seasonal and interannual variation in thickness and extent, sea ice is one of the fastest moving solid geophysical materials on the Earth's surface, which results in a highly dynamic and complex material responsive to a changing environment.

Measurements of the Arctic sea-ice cover from buoys, submarines, and satellites indicate that the thickness and the temporal and spatial distribution of the ice have changed over the last 30 years. The seasonal extent of the ice cover has decreased by approximately 3% per decade over the period of passive microwave satellite measurements, 1978 to 2003 (Comiso, 2003). The thickness of ice floes measured by submarine-based sonar (as indicated by under-ice draft) decreased from 3.1 m to 1.8 m between the periods of 1958–1979 and 1990–1994 (Rothrock et al., 1999). Ice thickness in the Beaufort Sea decreased by about 1.0 m over the shorter period of 1980 to 1994, with a distinct change after the 1987–88 winter (Tucker et al., 2001). The drift pattern measured by Arctic buoys appeared to shift in 1987–88 from a larger to a smaller anticyclonic Beaufort Gyre and with the transpolar drift stream shifted towards the western Arctic (Kwok ,2000; Tucker et al., 2001). These changes in the Arctic ice appear to be driven by changes in both thermodynamic and dynamic forcing. The changes in ice drift follow a similar shift in the sea-level pressure (SLP) pattern in 1987–88 that now shows lower SLP over the Arctic basin, a weaker Beaufort anticyclone, and lower pressure extending from the subarctic Atlantic Ocean into the Eurasian Basin (Walsh et al., 1996). This decrease in SLP is also represented by an increase in 1987–88 in the index of the Arctic Oscillation (AO), the dominant mode in the Northern Hemisphere SLP (Thompson and Wallace, 2000). The positive mode of the AO is also associated with higher surface air temperatures over the Arctic, as shown mostly by land-based stations. Increasing air temperatures imply an increase in the net surface energy over sea ice, which would reduce growth rates in winter and accelerate melting in summer. Measurement of the ice mass balance in the Beaufort Gyre during the year-long SHEBA field experiment in 1997–98 showed an average decrease in ice mass of 45 cm that resulted from 75 cm of growth and 120 cm of melt (Perovich et al., 1999).

Sea ice thickness and kinematics are the most important sea ice measurements in understanding, monitoring, and detecting change in polar climate, especially in the Arctic (ESE, 2000; SEARCH, 2002). Of key value for observing sea ice thickness as a climate indicator would be increased knowledge of the synoptic-scale perennial ice thickness distribution, needed to understand mass volume as well as which portion of the thickness regime might be changing. Sea ice thickness is not currently directly measured from space, but indirect measurements including freeboard, ice type, and both detailed and large-scale ice-motion fields provide information related to thickness and the estimation of sea ice mass balance.

The primary sea ice observable made by SAR is ice motion, whereby the detailed imagery enables tracking of ice features from day to day. On smaller scales of kilometers, motion fields show the detailed motion of individual floes, how ice moves as aggregates, the opening of leads, and the ridging process. Ice motion controls the abundance of thin ice and therefore the intensive heat flux from the ocean to the atmosphere, ice production, and salinity flux. On larger scales of several hundred kilometers, the general circulation of the ice cover provides the advective component of the ice mass balance as well as a velocity boundary condition on the ocean surface. Accurate measurements of ice motion and other key geophysical variables are being generated from the continuous, systematic, and rapid-repeat mapping of the Arctic Ocean using RADARSAT-1 that has been underway since 1996, termed the “Arctic Snapshot.” Key results include basin-wide estimates of ice age and ice production, detailed deformation fields (Figure 6) that have been compared to buoy and model estimates of deformation and ice production, and use of the SAR-derived motion both as a forcing field in ice models and for assimilation to improve ice trajectory predictions.

At the human scale, sea ice is a great impediment when navigating in polar waters or maintaining offshore structures. Sea ice is an important habitat for the smallest organisms that are at the base of the food chain in the southern ocean. In the Arctic, nutrient cycling along the ice margin nurtures one of the greatest seasonal explosions of life on the planet. Spaceborne SAR has been shown to provide the most detailed observations of ice type and conditions and the presence of open water within sea ice, as well as the observation of ocean circulation features, particularly within the coastal environment, that are critical to the above issues.

Extending the systematic sea ice coverage of the Arctic and Antarctic sea ice covers, from now and well into the future with RADARSAT-1, Envisat, and the InSAR mission, is crucial for maintaining an uninterrupted SAR sea ice data record suitable for assessment of climate change and global warming, the impacts from a rapidly changing environment on ocean circulation and radiative balance in the atmosphere, and the subsequent impact on humans.

2. What is the contribution of glaciers and ice sheets to sea-level change?

Glaciers and ice sheets are currently experiencing a global retreat, contributing to sea-level change. (*Report of Working Group I of the IPCC,* 2001). The precise reasons for the retreat are still unclear but must be associated with precipitation/melt change and/or by dynamic instability caused by a change in ice flow, which may or may not be climate-related. InSAR data are important in distinguishing the thinning caused by ice flow from that caused

Causes

Ocean Thermal Expansion

Coastal Uplift and Subsidence

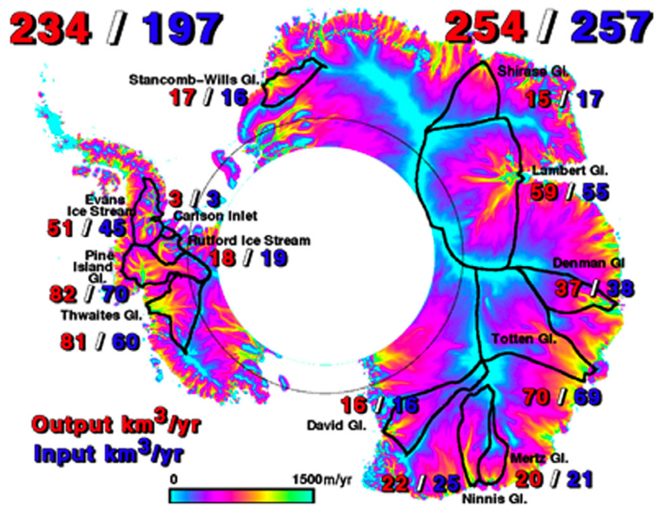
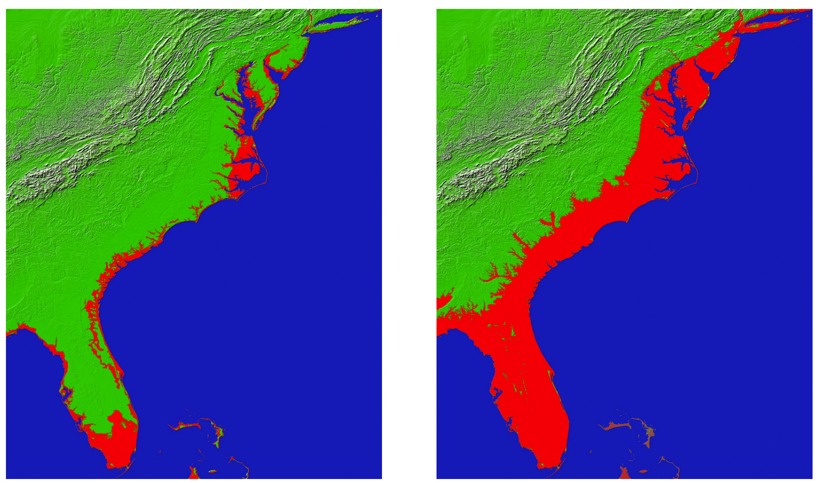


Figure 6. Mass balance estimates over Antarctica (top); maps of flooded areas resulting from the loss of ice over Greenland (below left) and Antarctica (below right).

Consequences



by accumulation and melt because it provides the crucial measurement of surface velocity (Goldstein et al., 1993) needed to relate estimates of ice mass change to ice dynamics.

InSAR data also provide direct estimates of ice sheet discharge and its variability. Until InSAR, ice sheets were assumed to evolve slowly with dynamic response times of centuries to millennia (Paterson, 1994). InSAR studies have radically altered this perception. Although only a subset of the Earth's ice streams and glaciers have been sampled interferometrically, examples of short-term (days to decades) change are abundant. In Greenland, observations of velocity change include a mini-surge (Joughin et al., 1996), a post-surge stagnation front (Mohr et al., 1998), and a near doubling of velocity of Greenland's largest outlet glacier, Jakobshavn Isbræ (Joughin et al., in press). Decadal-scale acceleration (Rignot et al., 2002) and deceleration (Joughin et al., 2002) have been observed in West Antarctica. InSAR also has been used to detect the migration of glacier grounding lines (Rignot, 1998), which is a sensitive indicator of thickness change. InSAR observations have also shown that loss of ice shelves often leads to dramatic acceleration of the grounded ice, which directly affects sea level (Rott et al., 2002; Rignot et al., 2004). These snapshots of temporal variation have been too infrequent to ascertain whether they constitute normal ice-sheet variability or indicate long-term change. Thus, a new InSAR mission must frequently (as often as every 8 days) monitor outlet glaciers in order to characterize and understand their short-term temporal variability. Comparison with archived ERS/RADARSAT data will facilitate detection of decadal-scale change.

The controls on fast ice flow are still the subject of active investigation and debate (Alley and Bindschadler, Eds., 2000). Understanding of ice-flow dynamics has been limited by a lack of data. The comprehensive velocity data provided by a new InSAR mission will validate existing models and motivate the development of new ones. In conjunction with ice-sheet models, these InSAR data will provide a powerful means to investigate controls on glacier flow. For example, inversion of an ice-stream model constrained by InSAR data was used to determine the location of a weak till bed in northeast Greenland (Joughin et al., 2001). Incorporation of this type of knowledge into full ice-sheet models will greatly improve predictions of ice-sheet evolution.

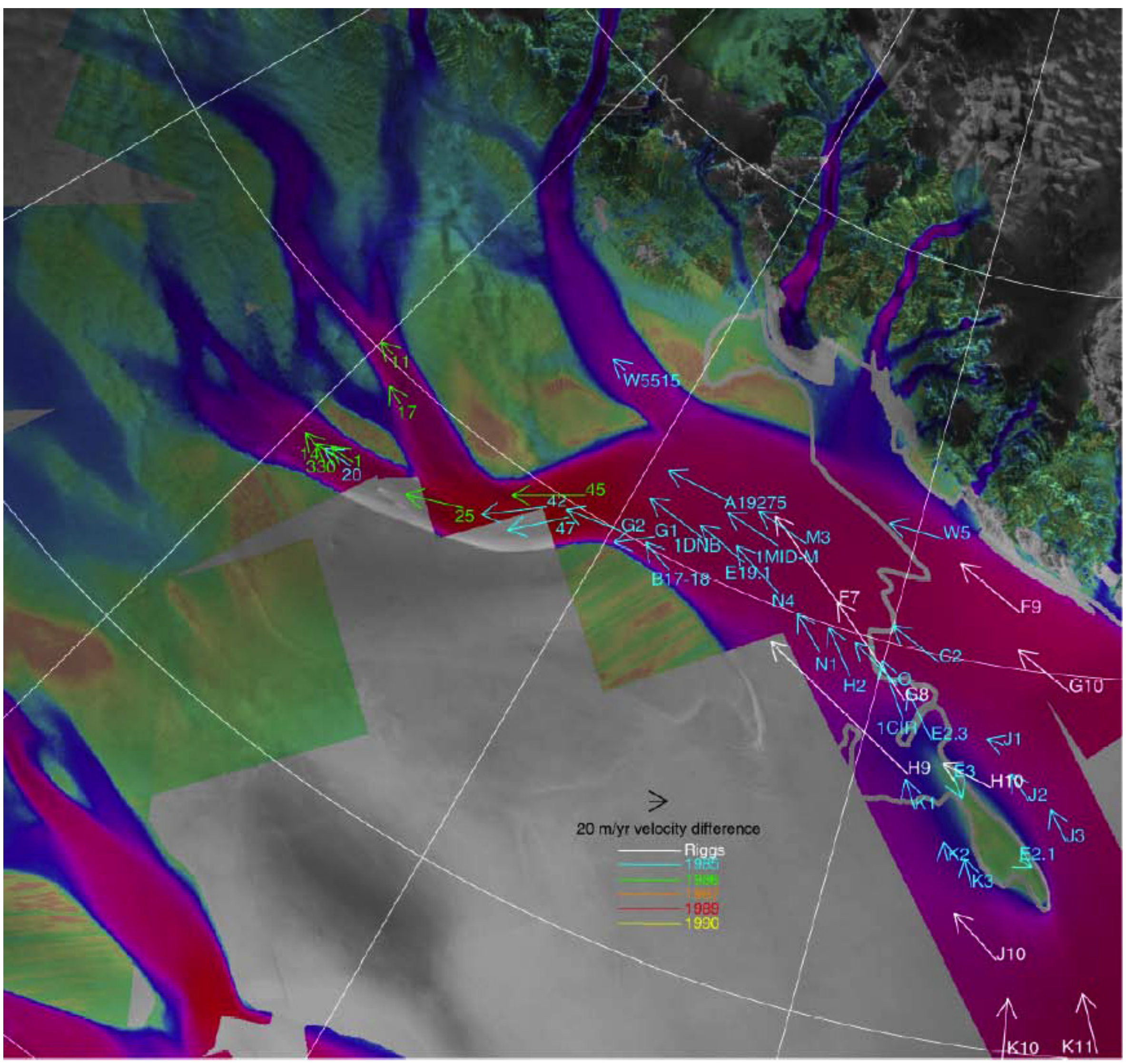
InSAR is an important tool to address the following science objectives pertinent to ice sheets and glaciers. We recommend specific studies to:

1. Determine ice velocity and discharge by ice streams and glaciers worldwide and quantify their contributions to sea-level rise.

2. Characterize the temporal variability in ice flow well enough to separate short-term fluctuations from long-term change.

3. Provide critical data to determine the fundamental forcings and feedbacks on ice stream and glacier flow to improve the predictive capabilities of ice-sheet models.

Figure 7. Ice-sheet velocities from InSAR over part of the West Antarctic Ice Sheet.



3. *What are the feedbacks between a changing cryosphere and other components of the Earth system?*

Seasonal snow covers a large portion of the Earth's surface, particularly in the northern hemisphere. This bright snow cover reflects most of the incoming energy from the Sun compared with the darker underlying surfaces. Therefore, the extent and timing of the snow has a great effect on the global surface energy balance. It is one of the physical components responsible for model predictions of amplified polar warming. Mapping snow-covered area, especially during the spring melt, is also needed for hydrologic applications of stream-flow modeling, flood prediction, and reservoir potential. SAR is the only instrument capable of mapping wet snow cover at the spatial resolution required in mountainous terrain, where the hydrology is dominated by a melting snow pack (e.g., the Sierra Nevada and the Rocky Mountains). In addition, promising results from current studies (Rott et al., 2004) indicate that InSAR is capable of measuring the snow-water equivalent (SWE) of the snowpack in complex terrain.

Hydrology

1. *How do groundwater, surface water, soil moisture, and snow pack contribute to the global freshwater budget and how do natural and anthropogenic processes redistribute water in both space and time?*

Groundwater. Groundwater currently provides 24% of the daily freshwater supply in the United States but remains a poorly characterized component of the terrestrial water budget. As drought conditions persist in the western U.S. and population continues to grow, new groundwater development will exacerbate the national subsidence problems that cost $168 million annually and have lead to coastal inundation, infrastructure damage, and new legislation.

Aquifer characterization: The characterization of how the land surface above aquifers responds to groundwater pumping provides important insights on the subsurface controls of the aquifer system, the location of groundwater barriers and conduits, the extent of the aquifer, and, when combined with groundwater level and pumping records, provides critical hydrodynamic properties of the aquifer systems that are necessary for measuring changes in the groundwater supply, modeling the aquifer system, and constraining the terrestrial water budget. An L-band InSAR mission with national coverage and routine imaging would significantly advance our ability to characterize both regional- and continental-scale aquifer systems and would provide the first uniform quantification of our national aquifer system.

Subsidence: Natural and human-induced land-surface subsidence across the United States has affected more than 44,000 square kilometers in 45 states and is estimated to cost $168 million annually from flooding and structural damage, with the actual cost significantly higher due to unquantifiable "hidden costs" (National Research Council, 1991). More than 80% of the identified subsidence in the United States is a consequence of the increasing development of land and water resources, which threatens to exacerbate existing land subsidence problems and initiate new ones (Galloway et al., 1999). Current C-band satellites are providing InSAR imagery of land subsidence in the western U.S. (see Figure 8 for an example). Increased access to these data would be beneficial. However, much of the central and eastern United States has been difficult to image because of dense vegetation. An L-band InSAR mission with national coverage and routine imaging would significantly advance our ability to map, characterize, and mitigate land subsidence.

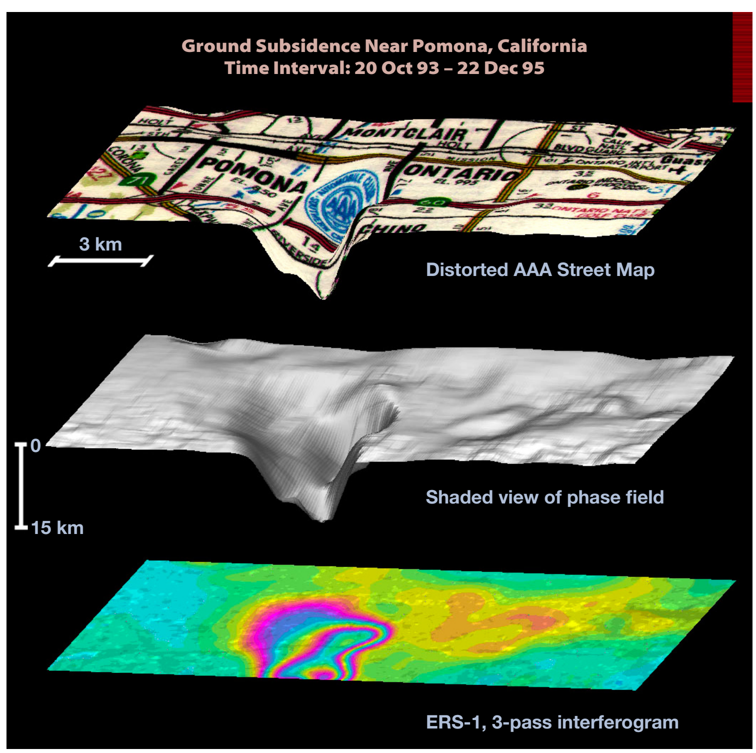


Figure 8. InSAR can readily detect land subsidence due to water withdrawal from space. An interferogram generated from multiple SAR observations can be transformed into a phase field that gives the vertical surface deformation over the observation period (courtesy Gilles Peltzer, JPL/UCLA).

Hydrotectonics: Surface deformation associated with natural processes and human activity is observed but difficult to separate in geodetic network data. For example, sediment compaction, tectonic extension, sinkhole collapse, groundwater pumping, hydrocarbon extraction, geothermal production and mining produce both vertical and horizontal surface motion. Consequently, characterizing and removing the hydrologic motion in EarthScope's Plate Boundary Observatory is essential to providing GPS time series that contain only tectonic motion. By combining geodetic and hydrologic time-series data with spatially-dense InSAR imagery, it is now possible to recognize, and in some cases separate, multiple land-surface deformation sources at a given location (e.g., Bawden et al., 2001). An L-band InSAR mission with national coverage and routine imaging would significantly advance our ability to understand and remove the contributions of human-induced surface motion on tectonic geodetic networks.

2. *How does the land surface vary with time and how does it influence the dynamic water supply?*

Surface Water. Surface water fluxes and storages in rivers, lakes, and wetlands are critical terms in the global water budget, carbon cycling, ecology, and the potable freshwater supply. Flooding events represent a major hazard to life and property, killing thousands worldwide and costing $2.41 billion annually in the U.S. alone (Myers, 1997).

Terrestrial surface water budget: Characterizing and monitoring how surface water (lakes, rivers, etc.) are naturally and anthropogenically redistributed in space and time is key to resolving the terrestrial water supply component of the water cycle. Resolving the aerial extent, volume, surface velocities, and circulation patterns in rivers and water bodies will significantly advance our understanding of the terrestrial water budget.

Flood, inundation, and hazard assessments: SAR and InSAR have provided significant advances in hydrology hazard assessments. Because SAR is an all-weather imaging tool, it is very effective at mapping and monitoring surface water extent during flooding events and tracking hydrocarbon spill events. The application of along-track interferometry during flooding events provides valuable velocity patterns and flood extent maps of the advancing floods such that informed decisions could be made to minimize the loss of life and property. InSAR has been applied to modeling and predicting ice-debris accumulations, failure locations, and the resulting flood levels. Estimates on the biogeochemical production in tropical regions can be obtained through mapping inundated regions, which correlate with methane production.

Wetlands: Double-bounce SAR interferometry has been shown to be a very effective way to measure surface-water elevation changes in wetlands. The radar pulse bounces off the water surface and is scattered back to the satellite with a second bounce from vegetation. Weekly InSAR imaging in both L- and C-bands would significantly advance wetland research, restoration projects, and management. It is anticipated that advances enabled by these data would result in automated procedures for data processing and assimilation in hydrologic models and management monitoring and mitigation tools.

Soil Moisture. Soil moisture is an essential parameter in measuring the global water budget, climate modeling, and forecasting drought, flood, landslides, and debris flow.

Detailed 4-D soil moisture maps: The soil moisture component of the water cycle is difficult to quantify but it is a part of the fragile interface between the hydrology and plant ecosystems. There are four key questions that can be addressed in part with 4-D soil moisture maps derived from SAR/InSAR imagery:

1. What is the state of the soil moisture water (permafrost, frozen, liquid, etc.)?
2. How do natural and anthropogenic processes impact the dynamic soil moisture supply?
3. What is the link between ecology, land-use, and soil moisture?
4. What is the depth distribution of soil moisture?

Snow Pack. Snow pack is a critical hydrologic reservoir that provides a large percentage of the national fresh water supply. Quantifying its extent and snow-water equivalence will advance water supply estimates, flood forecasts, climate modeling, and ecosystem monitoring.

The underlying question in snow-pack hydrology is "What is the extent and volume of water in the snow pack?" Recent publications have shown that L-band InSAR can be used to measure spatial extent of the snow pack and can resolve the snow-water equivalence. Measuring how much water is in the snow pack is essential for understanding the terrestrial water budget, managing our water resources, and mitigating flooding.

3. *How can remote sensing technology improve water resource management and hydrological hazard mitigation associated with flooding and land subsidence?*

Competing demands for water resources in the U.S. have underscored the importance of groundwater supplies and the role of groundwater in sustaining terrestrial ecosystems. More and more, groundwater systems are being used as a component of conjunctive-use strategies to optimize water availability by storing surplus water in subsurface reservoirs (aquifers) for use in peak demand periods. These aquifer storage and recovery (ASR) practices create large changes in storage and, in many places, concomitant deformation of the aquifer system. InSAR imagery is being used to provide valuable information about how aquifer systems respond to repeated stress conditions (seasonal pumping and recharge), thereby improving the scientific understanding of the mechanics of regional aquifer systems and improving the management methods necessary to mitigate further loss in aquifer storage and permanent land-surface subsidence.

Land Cover

1. *What is the three-dimensional (3-D) structure of vegetation on the Earth's terrestrial surface that influences habitat, carbon, climate, agricultural and timber resources, fire behavior, and economic value?*
2. *How does land cover change over time and what are the mechanisms, including the spatial distribution of change, regarding human-driven land-use conversion between urban, forest, agriculture, and wildland natural disturbance including fire, hurricanes/wind, insects/pathogens, landslides, and earthquakes/volcanoes?*
3. *How are biomass/carbon distributed over the surface of the Earth (global carbon cycle)?*
4. *What is the surface topography and change in surface topography under vegetation canopies?*
5. *How does land cover/vegetation control the cycling of carbon, nutrients, and water through ecosystems, and what is current the state the Earth system?*

The Earth's land surface is continuously reshaped by catastrophic hydrologic events, sea level rise, and collapses; all of which impact the terrestrial water supply, ecosystems, and infrastructure. Measuring and characterizing the paths that redistribute water and how the movement of water affects the land surface is key to understanding hydrologic processes and making links between hydrology, geology, and the biosphere. A repeat-pass InSAR mission configured to produce InSAR topography maps could map the Earth's surface on a monthly basis such that the following questions could be addressed:

- What is the source, path, deposition, and volume of material transported during large events?
  - Temporal and spatial SAR imaging will result in significant advances in the understanding of the mechanics, kinematics, monitoring, and prediction of mass movement.
  - An InSAR topography mission would mitigate a number of natural hazards, including landslides, sinkholes, mine collapse, and floods.
- What is the volume of material lost in coastal erosion?
- What is the relationship between hydrology and habitat stability in post-fire environments?
- How do hydrologic and ecosystem parameters vary with topographic change?

Oceanography

The main questions addressed by the oceanography group are:

1. *How does the ocean surface behave on a global, long-term scale and how does it drive the climate?*

In the vast bulk of oceanic flow, friction is small so that horizontal pressure gradients in slowly varying flows are balanced quite accurately by the Coriolis force. This is the geostrophic flow. At the ocean surface, the horizontal pressure gradient (expressed as the tilt of the surface) is now measured on a continuous, ocean-wide basis by the Topex/Poseidon and Jason-1 satellites. In a thin layer at the ocean surface, there is another component of flow in which friction is balanced against the Coriolis force. This "Ekman" current is not currently measured on an ocean-wide basis by satellite. It is however, the process by which the stress of the wind drives ocean currents. It is therefore a major element of the oceanic motion system. The proposed InSAR satellite, being able to measure surface currents if it includes an along-track mode, can remedy this situation by providing an adequate representation of the broad-scale, ocean-wide surface current, which is the combination of geostrophic plus Ekman flow (Graber et al., 1996; Marmarino et al., 1997). Measurements of this combined flow, even if not completely covering the ocean on a continuous basis, can be assimilated into ocean circulation models, thus contributing in an important way to the description and prediction of ocean circulation. This is a matter of importance for both operational purposes and for understanding climate change.

No other instrument can match the capabilities of a satellite-borne, along-track interferometric (ATI) SAR for these measurements. While NASA is currently considering the launch of the Wide Swath Ocean Altimeter, an interferometric radar for wide-swath, spatially dense measurements of sea-surface height, this cross-track interferometer, like the traditional nadir-looking altimeters Topex/Poseidon and Jason, will only provide the geostrophic component of the current.

At the air–sea interface, the action of the wind on the ocean creates surface waves with a wide range of wavelengths. Standard SAR is able to monitor the amplitudes, directions, and lengths of some waves on an ocean-wide basis to determine their spatial and temporal variability (Figure 9). Below a wavelength of about 100 m, however, standard SARs cannot detect surface waves traveling in some directions. An along-track InSAR will allow the measurement of waves down to tens of meters that are traveling in all directions. Such surface waves have long been suspected to influence the stress that the wind exerts on the ocean, but studies to date have been difficult to interpret. ATI SAR has the ability both to detect the presence of short waves that support much of the wind stress and determine radar reflectivity, and to image longer

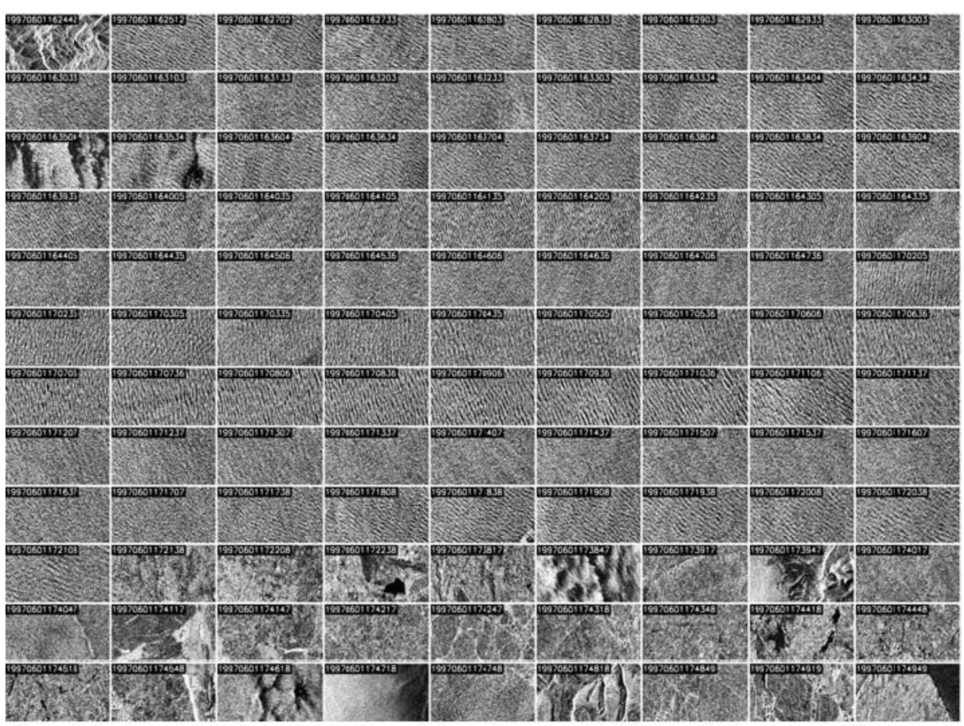


Figure 9. Time series (upper left to lower right) of SAR intensity imagettes from ERS-2 for a single orbit. These images are 5 by 10 km and are taken every 200 km. They illustrate the global capabilities of space-based SAR but, since these imagettes were not taken by an ATI SAR, they cannot show currents on a global scale.

waves. This unique capability will allow us to assess the effect of long waves on wind stress.

Spectra of surface waves, of course, do not tell the whole story of sea-surface displacements. Waves are observed to occur in groups and to break when they become sufficiently steep, characteristics that are not well studied with spectra. Because ATI SAR observes both the orbital currents of long surface waves and the modulation of short waves by them, it can be used to derive very detailed information of the spatial and temporal properties of surface displacements. Thus one can study the nonlinear processes that produce wave groups and breaking. With its high spatial resolution, ATI SAR offers the possibility of determining how these processes influence air–sea transfer of heat, momentum, and gases. Gas exchange across the sea surface depends on partial pressure of the gas in the atmosphere and ocean at the interface and the rapidity with which the surface diffusive skin is refurbished. This process of refreshment is greatly enhanced by the presence of ripples at the sea surface. SAR images are an effective way to detect the absence of ripples because in their absence, the backscatter to the radar is extinguished. Usually the absence of ripples is caused by a surfactant film at the sea surface (a slick); whether due to this cause or to the total absence of wind, we can expect gas exchange to be greatly inhibited. Thus, SAR imagery can provide an important insight into gas-exchange processes.

2. How can we better predict hazards at sea?

With its high spatial resolution and all-weather, day/night capabilities, SAR provides the opportunity to conduct detailed experiments on hurricanes (Figure 10). ATI SAR in particular opens many possibilities because of its ability to measure both sea-surface roughness and current vectors in a hurricane. Questions about hurricanes that can potentially be addressed by ATI SAR include the following: What is the morphology of hurricanes? What currents do hurricanes generate? Are boundary layer rolls important contributors to the energy balance of hurricanes? What is the size and shape of the eye? What is its location? What is the spatial distribution of waves in the eye wall region? What triggers eye wall replacement cycles? What are wind speeds at landfall? Answers to these and other questions will lead to better prediction of hurricane intensities and movement,

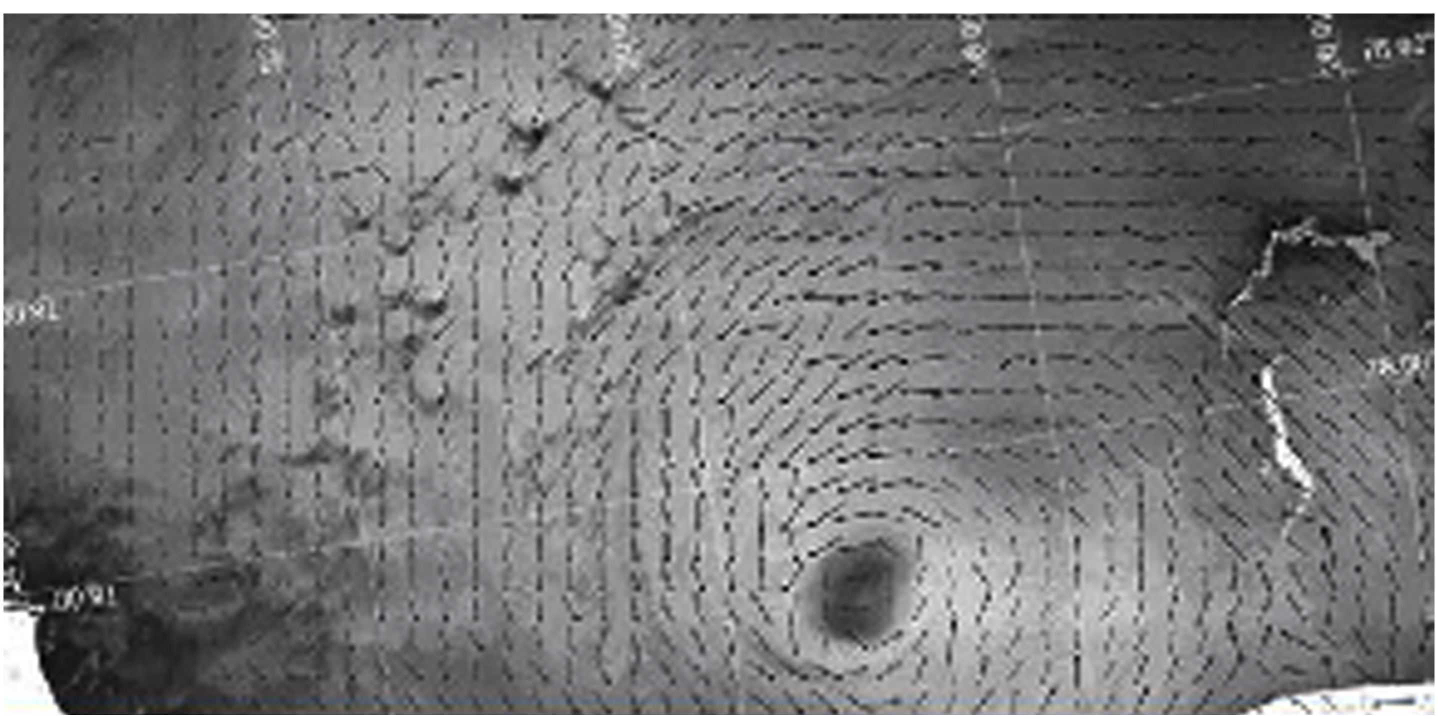


Figure 10. Hurricane Floyd imaged by RADARSAT-1 in the ScanSAR mode. The arrows are surface wind vectors; currents cannot be obtained by this non-interferometric SAR.

thus greatly benefiting coastal regions under the threat of hurricanes. Again, currents within hurricanes cannot be measured by any means other than ATI SAR.

A major hazard to navigation of the ocean is the occurrence of extreme waves associated with areas of high winds and locations where the normal propagation of high waves is suddenly interrupted by an opposing current. Such locations need to be accurately predicted in order that ships can be routed around them. The current capability to predict their occurrence reliably is inadequate; extreme waves are responsible for the loss of nearly a thousand seamen each year and for the sinking of an average of 130 commercial vessels per year. Some of these disasters are caused by the rogue waves of folklore, which are extremely high waves that appear unexpectedly under low wind conditions. Because they are so unexpected and so traumatic, their occurrence is not well documented. Without SAR, we are unable to accurately assess either their global distribution or the extent to which nonlinear processes are responsible for them. ATI SAR is the only instrument with the potential to fully address these problems. Winds in coastal regions can vary greatly in magnitude and direction in very short distances. Many times these extreme variations are not captured well by existing forecast models (Figure 11). Currents also can vary rapidly in short distances in coastal regions but at present are not regularly measured. The combination of winds, waves, and currents that ATI SAR measures has the potential to produce better information on hazardous coastal conditions and therefore improve the prediction of high coastal winds.

It is difficult to imagine an instrument more suitable than ATI SAR for monitoring oil spills and natural slicks and predicting their future motion. The slicks and spills make their presence evident by an extreme reduction in backscatter, resulting in very dark regions in the images. Standard SAR cannot determine currents around these features except by tracking them at closely spaced intervals, a procedure that is difficult to accomplish from space. ATI SAR, on the other hand, can measure currents in the vicinity of slicks and spills on a single pass, thus allowing prediction of the movement of the surfactant. This same ability makes ATI SAR very valuable for search and rescue operations at sea.

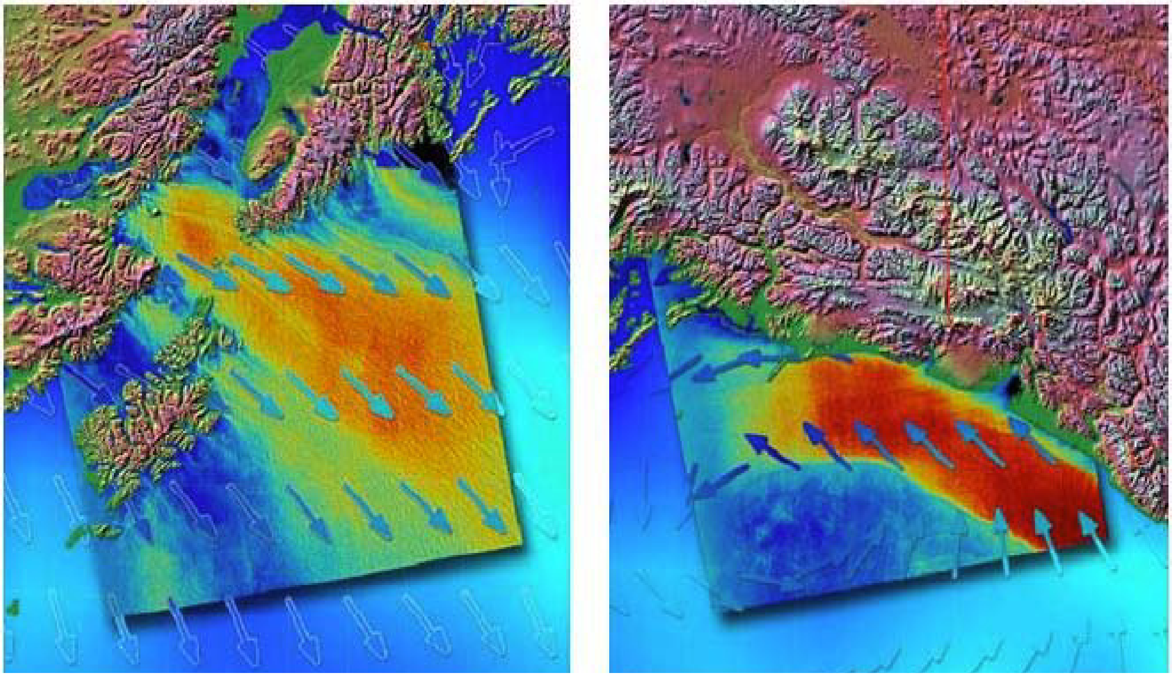
3. *What is the nature of physical processes in coastal, frontal, and marginal ice zones and how do they affect biological processes?*

The upwelling of nutrient-rich water influences the growth of algae in areas of rapid spatial change of physical conditions (Figure 12). The depth of the mixed layer plays a significant role in this process, but the exact mechanism remains to be elucidated. The same is true of the transport of harmful algal species and pollutants by the currents associated with these zones. Eddies of a wide range of scales are key components in many coastal regions and may also play key roles in enhancing primary productivity and transport of pollutants (DiGiacomo and Holt, 2001). Internal waves are another example of ocean regions where physical processes change rapidly and can impact nutrient availability through mixing as well as resuspension of pollutants contained in sediments. Systematic observations of these highly varying coastal circulation features are needed to understand their role in biological productivity.

Winds and currents are presently poorly monitored in regions of rapid spatial change in the coastal regions due to resolution limitations of most satellite-borne instruments. Currents associated with oceanic fronts and coastal bathymetry cannot be studied on a continuous, global scale. This limits our knowledge of the nature of these currents and their effect on other processes such as the transfer of heat, momentum, moisture, and other gases across the air–sea interface. In coastal regions, winds, waves, and currents strongly affect beach erosion, but our techniques for understanding these processes are usually very local and labor-intensive in nature. If long-term measurements of high-resolution winds, waves, and currents were available in coastal areas and marginal-ice zones, the prospect of improving the modeling of these regions would greatly increase.

Finally, within the United States, there is an increasing presence of human population near the coastal regions. This exacerbates the influence of human beings on coastal regions through wastewater discharge, perturbation of the natural process of erosion, and stormwater runoff and composition. The latter is further influenced by the increase in impervious surfaces, where reduced rain absorption back to the water table results in increased runoff that may be untreated. Conversely, the impact of episodic events including large storms and hurricanes, themselves related to seasonal and climatic pat-

Hazardous Coastal Winds



Gap Winds *Coastal Barrier Jets*

Figure 11. RADARSAT-1 ScanSAR images of the Alaska coastline with superimposed wind vectors (arrows) from the NoGaps coastal model. Colors in the offshore region indicate wind speeds, those in the arrows coming from NoGaps, those in the inserts coming from RADARSAT. Reds indicate high winds, blues indicate low winds. Clearly, the model is not capturing the hazardous, high coastal winds.

Coastal Upwelling and Associated Biological Activity

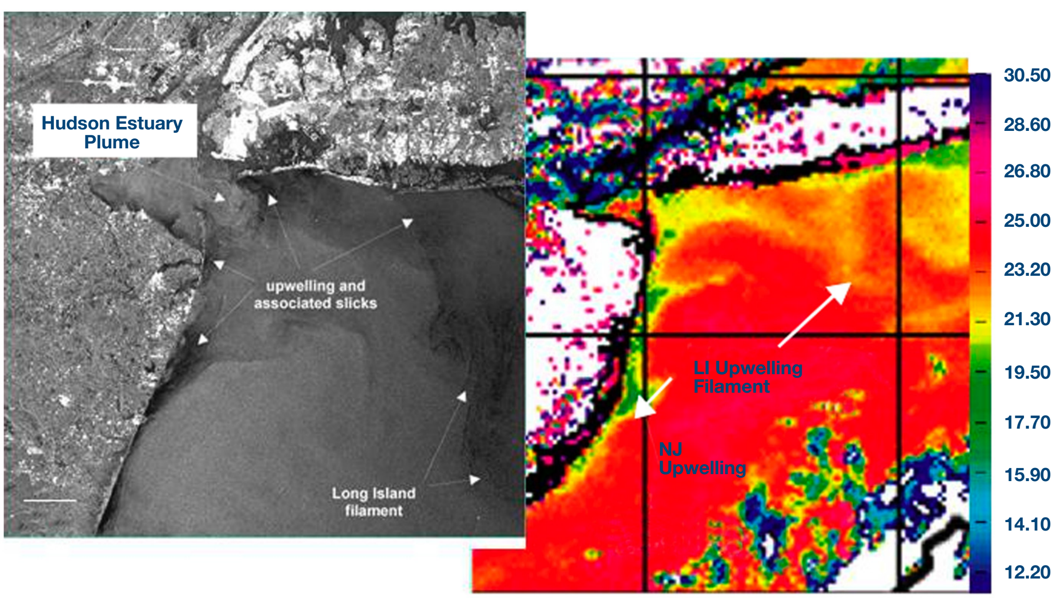


Figure 12. At left is a RADARSAT-1 ScanSAR image of the Hudson River Estuary and Long Island on July 30, 1998. At right is a near-coincident AVHRR image. Dark areas in the SAR image coincide with colder water in the AVHRR image. The filaments in the SAR image are slicks produced by biological activity.

terns, are often most intensive near the coasts and thus are hazardous. InSAR offers the possibility of monitoring the flux and transport of pollutant-laden fresh water into these regions and of more accurately assessing the anthropogenic impact on the water quality and productivity within the coastal zone (DiGiacomo et al., 2004).

Planetary Science

The major questions addressed by the planetary science group were:

1. *Where can we find water on Mars and the Moon to support human exploration?*

Moon: Investigate polar ices and possible polar landing sites. The primary focus for lunar studies is to explore the polar regions, where crater floors that are permanently in shadow may be the location of ice deposits. These deposits offer the potential of resources (fuel, air, water) for lunar landers and have intrinsic scientific value because they derive from comet impacts over lunar history. Radar imaging of these areas of permanent shadow at the poles, as well as the determination of the lighting geometry at the 10-m scale for rover power resources, are high priorities. The characterization of topography at potential landing sites at the meter-scale would facilitate planning for future rover missions.

Mars: Follow the water and investigate climate change. Radar could make a fundamental contribution to Mars science if it could detect present-day near-surface liquid water. This would be accomplished via the striking differences in dielectric properties of liquid and frozen water. InSAR offers the unique capability to study the surface motion, seasonal variability, and rates of change of the polar caps (Figure 13) and, via decorrelation of the image, the quantification of surface change (e.g., “swiss cheese” formations in the south polar cap). The potential to track the seasonal migration of the ice–water interface across the globe, as observed by Mars Odyssey and others, and the seasonal freeze/thaw phenomena (e.g., rock glaciers, crater gullies, polygons) would further characterize the response of the landscape to climate change. Mapping subsurface topography to search for buried drainage channels, and the search for evidence of rainfall, would change our model of paleoclimate on Mars. InSAR would also offer unique observations on surface change at lower latitudes (e.g., the movement of dunes and landslides). Topographic mapping for landing site characterization, and the quantitative analysis of landform geomorphology, would also contribute to our greater understanding of climate change on Mars.

2. *How widespread is, and what is the role of, active tectonism/volcanism on Venus and Europa? What is the potential habitability of Europa?*

Venus: Is the planet still active? The identification of ongoing tectonic and/or volcanic processes on Venus would initiate many fundamental comparisons with the geodynamics of Earth. Plate tectonics dominates crustal recycling on Earth and liquid water is believed to be an essential component of this process. But on Venus, where surface temperatures exceed 400 ºC, no liquid water can exist; thus, the way that heat is lost from the planet may be quite different from on Earth. The geographic location(s) of these tectonic and volcanic events on Venus are hard to predict, so frequent global InSAR coverage would be needed in order to detect such an event. Global topography mapping with resolution of ~75 m is required for rheological modeling of slopes. Radar penetration studies of the shallow subsurface structure are needed in order to resolve lithologic questions at landing sites (e.g., layering at the Venera 14 landing site). Resolution of the origin of anomalously high dielectric properties (e.g., the summit of the volcano Maat Mons) would place further constraints on how recent the last volcanic activity has been on Venus, as the weathering environment is so severe that high dielectric materials should weather rapidly on the surface.

Europa. The fundamental question that InSAR could resolve on Europa is the thickness of the icy crust. The subsurface ocean is a possible habitat for life beyond Earth. Determining the crust’s thickness would be achieved by searching for deformation along cracks (occurring on timescales of a few days for repeat imaging) in the crust and the identification of new fluids (brines) leaking to the surface (Sandwell et al., 2004). Detection of such phenomena would demonstrate that the crust is thin and that the subsurface ocean is in physical contact with the surface. Deformation studies with InSAR of other tectonic features, such as the prominent strange “cycloid” ridges, may be related to the large tides (amplitudes of ~30 m), on 1.8-Earth-day time periods. These cycloids may be formed from daily fracturing, again indicating a relatively thin crust.

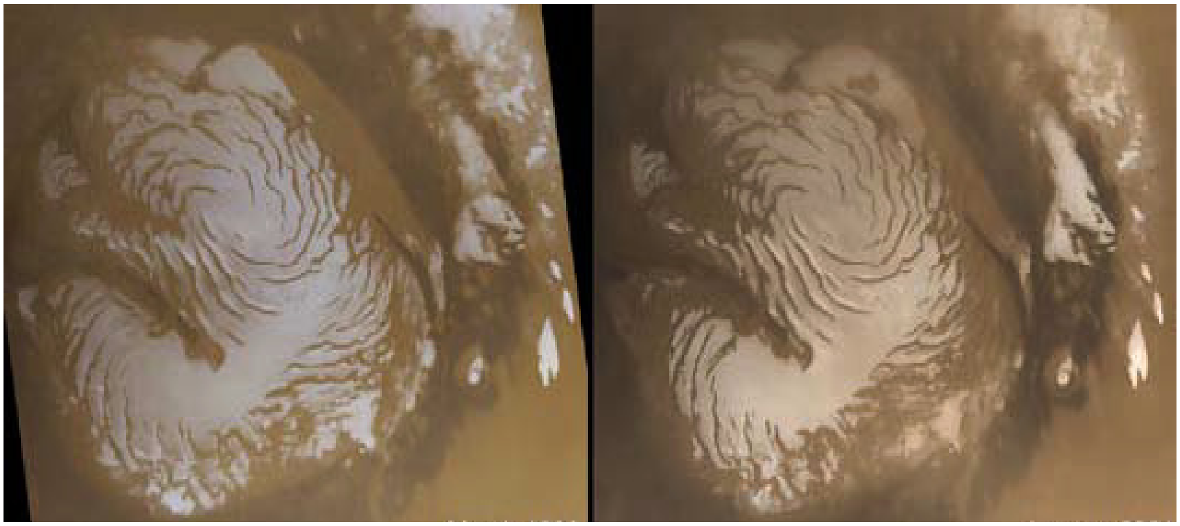


Figure 13. Images of Mars ice cap at two time intervals. InSAR could be used to monitor long-term and seasonal variation in the Martian ice caps.

March 1999 **January 2001**

3. *What is the fine-scale topography of the Moon, Mars, Venus, and the Galilean satellites for geomorphology studies and landing sites characterization?*

Current visions for human exploration of the cosmos begin with outposts on the Moon and Mars, and eventually beyond these to the Galilean satellites. It is necessary to assess the topographic conditions of any potential landing sites if we wish to emplace manned vehicles there. The details of the topography and surface shape give many clues as to the state of any ongoing geologic processes extant on the surface. While landings on Venus will be difficult for many reasons, understanding its evolution as compared with Earth and other planets will yield vital information for the planning and implementation of manned missions outward to the universe.

Societal Benefits

Our nation is at risk, not just from earthquake hazards, but also from landslides and other solid-Earth hazard events (Figure 14). The Administration's National Science and Technology Council report, *Reducing Disaster Vulnerability Through Science and Technology* (2003), documents significant risk in the United States from natural and technological disasters. Dramatic development along coastlines, near fault zones, and within flood plains puts an increasing number of our citizens and our infrastructure in harm's way — often unknowingly. The increased threat of international terrorism has added a new dimension to our security concerns and amplified the level of risk to our nation. The national imperative is to provide for a more robust information and prediction infrastructure to meet these challenges in order to protect and improve life in every American community.

Major categories of natural disaster and assessments of their economic costs are illustrated in Table 3, along with savings on the costs to society that are projected benefits from an InSAR program. Using an established benchmark of a 20% benefit factor, the annual savings derived from an InSAR mission are projected to be about $2.04 billion per year in the U.S., and $6.4 billion per year globally.

We also considered the impact to quality of life as well as the economic impact of InSAR.

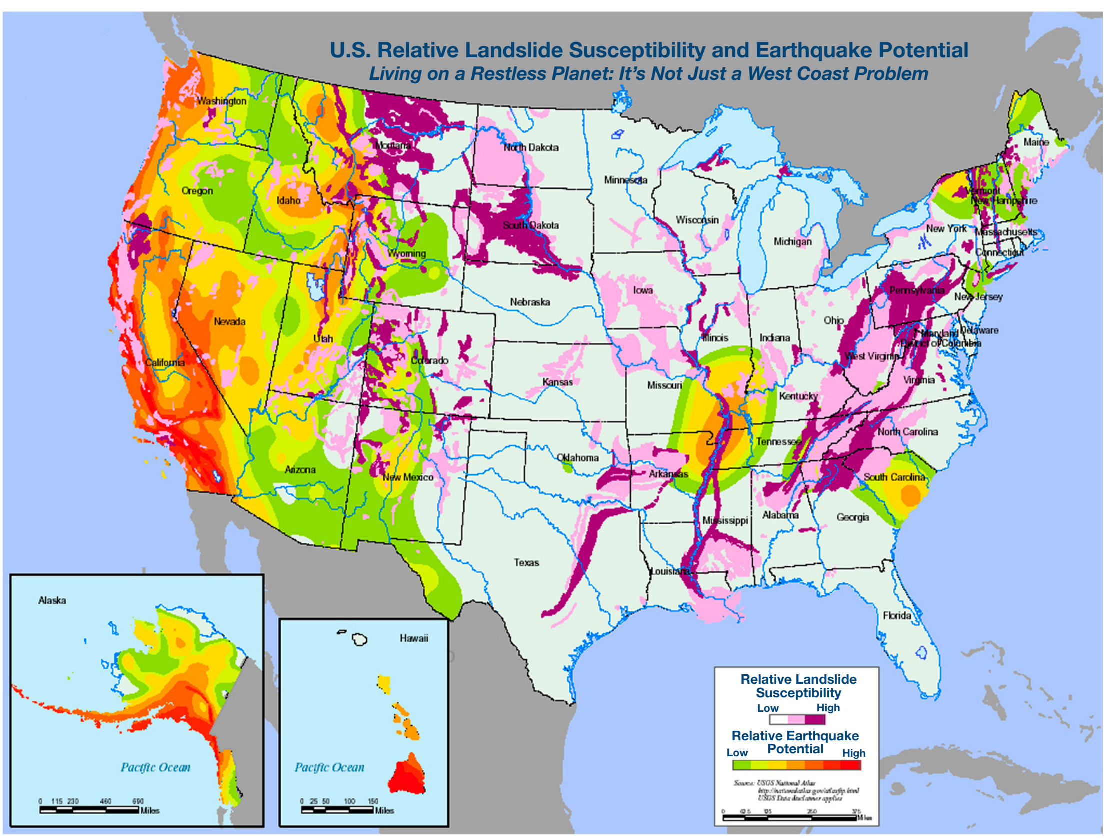


Figure 14. Relative landslide susceptibility and earthquake potential in the United States.

Table 3. Estimated Savings to Society Accruing from InSAR.

Natural Disasters, Effects	Industries, Government Services Potentially Affected	United States Impact (yr. 2000 USD)	Global Impact (yr. 2000 USD)	United States estimated savings	Global estimated savings
Earthquakes					
Infrastructure damage: buildings, bridges, roads, highways	Transportation, Transport-dependent businesses, buildings, housing	$4 billion	$12.5 billion	$800 million	$2.5 billion
Volcanoes					
Infrastructure damage: buildings, roads Airline damage	Transportation, construction, public health, housing	$30 million/yr (Mt. St. Helens: $1 billion)	$3 billion over 15 yrs (1994: $3.5 billion) $230 million/yr	$6 million	$0.05 billion
Flooding					
Disruption of transportation, damage to agriculture, housing, buildings	Transportation, agriculture, construction, housing	$4 billion	$12.5 billion	$800 million	$2.5 billion
Subsidence					
Damage to infrastructure: transportation, buildings, pipelines	Petroleum industry, water supply, transportation, construction	$159 million	$500 million	$31.7 million	$100 million
Landslides					
Damage to infrastructure: transportation, buildings	Recreation, transportation, construction, housing	$2 billion	$6.3 billion	$400 million	$1.3 billion
Total per year				**$2.04 billion**	**$6.4 billion**

Table 4 shows a list of the 40 worst catastrophes from 1970 to 2001. It is very clear that earthquakes, severe storms, flooding, and landslides have taken a very severe toll of human life during the past three decades. It is also clear that these natural disasters have taken their heaviest tolls in poor and developing countries. Poor and developing countries simply do not have the resources to carry out mitigation strategies without more directed and effective hazards information. For example, the Northridge earthquake claimed 60 unfortunate victims; the Great Hanshin earthquake (1995) claimed nearly 6500 lives, while a moderately larger Gujarat earthquake (2001) claimed 15,000 lives. The factor of 250 differences in lives lost reflects the preparedness of these earthquake-prone zones. More accurate warnings of impending hazards can be used effectively in developing countries to avoid substantial suffering by focusing resources upon preparedness as well as disaster response. InSAR is about the development of improved risk estimates.

A recent FEMA report, *Impact of a Magnitude 7.0 Earthquake on the Hayward Fault: Estimates of Socio-Economic Losses Using HAZUS (Hazards U.S.),* determined that economic losses associated with building damage from this sce-

Table 4. The 40 Worst Catastrophes in Terms of Victims, 1970–2001.

Victims	Starting Date	Event	Country
300,000	14.11.1970	Storm and flood catastrophe	Bangladesh
250,000	28.07.1976	Earthquake in Tangshen (magnitude 8.2)	China
138,000	29.04.1991	Tropical cyclone Gorky	Bangladesh
60,000	31.05.1970	Earthquake (magnitude 7.7)	Peru
50,000	21.06.1990	Earthquake in Gilan	Iran
25,000	16.09.1978	Earthquake in Tabas	Iran
25,000	07.12.1988	Earthquake in Armenia	Armenia
23,000	13.11.1985	Volcanic eruption on Nevada del Ruiz	Colombia
22,000	04.02.1976	Earthquake (magnitude 7.4)	Guatemala
19,118	17.08.1999	Earthquake in Izmit	Turkey
15,000	29.10.1999	Cyclone 05B devastates Orissa State	India, Bangladesh
15,000	26.01.2001	Earthquake in Gujarat (magnitude 7.7)	India, Pakistan
15,000	11.08.1979	Dike burst in Morvi	India
15,000	19.09.1985	Earthquake (magnitude 8.1)	Mexico
10,800	31.10.1971	Flooding in the Bay of Bengal and Orissa State	India
10,000	12.12.1999	Flooding, mudslides, landslides	Venezula, Colombia
10,000	25.05.1985	Tropical cyclone in the Bay of Bengal	Bangladesh
10,000	20.11.1977	Tropical cyclone in Andrah Pradesh and Bay of Bengal	India
9,500	30.09.1993	Earthquake (magnitude 6.4) in Maharashtra	India
9,000	22.10.1998	Hurricane Mitch, Central America	Honduras et al.
8,000	16.08.1976	Earthquake on Mindanao	Philippines
6,425	17.01.1995	Great Hanshin earthquake, Kobe	Japan
6,304	05.11.1991	Typhoons Thelma and Uring	Pakistan
5,300	28.12.1974	Earthquake (magnitude 6.3)	Pakistan
5,112	15.11.2001	Rainfall, flooding, landslides	Brazil
5,000	23.12.1972	Earthquake in Managua	Nicaragua
5,000	02.12.1984	Accident in a chemical plant in Bhopal	India
5,000	10.04.1972	Earthquake in Fars	Iran
5,000	30.06.1976	Earthquake in West Irian	Indonesia
5,000	05.03.1987	Earthquake	Ecuador
4,500	10.10.1980	Earthquake in El Asnam	Algeria
4,375	21.12.1987	Ferry Dona Paz collides with oil tanker Victor	Philippines
4,000	30.05.1998	Earthquake in Takhar	Afghanistan
4,000	24.11.1976	Earthquake in Van	Turkey
4,000	15.02.1972	Storms and snow in Ardekan	Iran
3,840	01.11.1997	Typhoon Linda	Vietnam et al.
3,800	08.09.1992	Flooding in Punjab	India, Pakistan
3,656	01.07.1998	Flooding along the Yangtze River	China
3,400	21.09.1999	Earthquake in Nantou	Taiwan
3,200	16.04.1978	Tropical cyclone	Reunion Island

nario earthquake are estimated to be nearly $37 billion (2000 dollars). Under a targeted rehabilitation program, major injuries and deaths could decrease by nearly 58%. If a comprehensive rehabilitation program were fully implemented, economic losses would be reduced by over 35% ($37 billion to $24 billion) and major injuries and deaths could drop by over 80%, from an estimated 1600 to 300 in a nighttime earthquake. Thus, better understanding of earthquake physics and the expected shaking from a given event will enable better targeted mitigation strategies such as building rehabilitation that can significantly reduce the risks to human life in the U.S. and even more so in less-developed regions where little or no mitigation strategies currently exist.

The goal of an InSAR mission is to provide sound science for sound decisions. The process of enabling new sources of knowledge to be used by decision-makers requires partnering from the inception of the project, thereby optimizing the capacity to transfer research results effectively between the technology agency (NASA), the science agency (NSF), and mission (USGS, FEMA, and international) agencies. Scientists from these agencies were present at this workshop and have an established track record of working closely together.

Non-solid-Earth hazards are important for the world as well. Ice plays an important role in daily human activities, from weather forecasting, to ship navigation, to high-latitude industries such as fishing and oil recovery from platforms located in ice-covered waters. SAR imagery is critical to operational sea-ice analysis in the U.S. and is the data source of choice for National Ice Center (NIC) ice analysts. In fact, when available, SAR is the primary data source used in their analyses. According to the National Weather Service in Alaska, SAR data and products have allowed for more accurate ice analyses and forecasts and their use has been linked to fewer deaths and fewer vessels lost in the Alaskan region. This is partly because of the ability of SAR to image through cloud cover. For example, in the case of the Arctic, 80% cloud cover is not unusual, making SAR vital in providing high-resolution observations for research and operational support. NIC and NOAA are responsible for iceberg detection and tracking, for which SAR is again an ideal sensor.

In the longer term, the impact of sea-level change on coastal populations is of great societal importance. Our work will inform the public on how the waning ice cover measured with SAR contributes to global sea-level rise. A greater understanding of Earth systems, including the ocean-ice-atmosphere system, is important to a society contemplating the responsibilities of stewardship of the planet as we move into the era of potentially profound effects from global change.

Specific New Data and Technology Needs

Each of the science disciplines represented at the workshop lacks data for advancement of its primary research objectives. While all communities can make good use of InSAR data, the specific needs vary by field of investigation. Each group assessed its own data needs in terms of which of its science goals could be met using existing and archived data sets, which could be met by creative and collaborative use of existing satellites, and which require new satellites with perhaps new technology. For example, during the past decade, the cryospheric community has benefited greatly from community involvement in ERS-1/2 and an effective SAR infrastructure through the development of the Alaska Satellite Facility and the McMurdo Ground Station. In parallel with those activities, NASA and the Canadian Space Agency negotiated a memorandum of understanding during the early 1980s that provided access to RADARSAT-1 data for the sea ice research and operational communities and provided access to the RADARSAT system for two high-resolution mappings of Antarctica.

The availability of SAR data enabled development of InSAR techniques for glaciers and ice sheets, to establish baseline ice-flow velocities for a number of areas, and to advance our understanding of many basic physical processes that control fast ice flow, systematic rapid repeat mapping of sea ice over the Arctic. Current and planned SAR instruments are limited spatially and temporally by sensor limitations (such as the repeat-cycle limitations and the ability to map Antarctic sea-ice cover). But most importantly, the cryosphere community now lacks a viable, comprehensive acquisition strategy for the next 5 to 10 years. Access to data from existing systems such as Envisat is limited by data restrictions placed by the spacecraft operators. At present, there are no plans for access to large volumes of data from RADARSAT-2 or to continue access to RADARSAT-1 data if available after 2005. Options for access to ALOS data are being negotiated but there are no firm funding commitments. ***In short, the U.S. research and operational communities must develop new partnerships and arrangements for data access.***

Access to data from existing archives and future acquisitions. Archives exist from multiple radar platforms and additional archives are expected from planned missions. For each existing satellite system, there have been specific calls for scientific involvement through AO processes. To facilitate further access to these archives, different disciplines self-organized and developed a variety of strategies. The U.S. crustal deformation community formed a consortium (WInSAR) that provides data over North American study areas. Currently, WInSAR holds limited data from ERS-1 and 2 and Envisat and will soon contain RADARSAT-1 data. ALOS data are also expected. This consortium functions by buying data using funds from NASA, NSF, and USGS. WInSAR has developed a prototype Web-based data ordering and distribution system that is open and freely available. As another example, the cryospheric community has a heritage in data dating back to the Seasat era. Through successful collaborations with international partners on programs such as the Program International for Polar Oceans Research (PIPOR), the RADARSAT Antarctic Mapping Project, the VECTRA Project, and the Arctic Snapshot, we have an established baseline of data for detecting changes in the polar environment. This important heritage should be considered in the further development of the SAR and InSAR programs as we attempt to extend our studies into the future. At this time, there are no firm commitments for such partnerships in the foreseeable future.

There is a useful distinction to be made between easily accessing archived data and tasking for new data. In terms of archived data, there is now much greater capability and a user base for dealing with large volumes of SAR and InSAR data. To satisfy emerging demands, we encourage a more systematic and open access to archived raw data for research purposes. In terms of future tasking, there is a need to intimately involve the science community with the spacecraft operators in a wholistic approach to acquiring new observations. Such an approach involves recognizing that each platform forms part of a constellation that in total provides a powerful scientific capability and a stepping stone to future mission designs. We encourage sponsors and stakeholders to reinvigorate the dialogue for fully pursuing and creating new collaborative opportunities for access to current and planned systems.

Each group examined its science priorities list and determined its current needs for new data and technological advance. These data needs define the fundamental requirements for advancement in the field, and hence the science needs for the InSAR program. These requirements are summarized in the following.

Crustal deformation. While there are many diverse subdisciplines within the full crustal deformation community, surprisingly strong consensus exists in the choice of configuration for a proposed InSAR mission. This follows because most application can be addressed with the availability of mm-scale crustal deformation data globally.

The major goal of the crustal deformation community is continuous, spatially comprehensive maps of deformation along major tectonic boundaries, and also over the world's 600 potentially active volcanoes. While C-band is a proven frequency for deformation research, we advocate the use of L-band to increase signal coherence over time. Many areas of interest decorrelate quickly at C-band, and L-band gives much longer coherence intervals. We prefer an 8-day period for both interferometric deformation measurements in order to capture month-scale processes, such as rapidly evolving volcanoes. With the 35-day repeat available in operating systems, we are not able to capture much useful information.

Coverage needs are the Earth's major tectonic boundaries plus a number of mid-plate volcanoes. The specific needs of the crustal deformation community include:

- L-band
- 8-day repeat cycle
- Millimeter-scale sensitivity
- Tightly controlled orbit to maximize usable InSAR pairs
- Both left and right looking for rapid access and more comprehensive coverage

This mission would address all major science objectives described above. It would provide coverage in areas where current/planned systems cannot. It would also provide frequent coverage for observing weekly or monthly timescale changes.

Some added objectives would be possible with the following technology enhancements:

- ScanSAR operation for wide swaths
- Increased power and storage to operate 20% of the orbit on average

Cryosphere. The primary requirement of the cryospheric community is the uninterrupted continuation of the systematic rapid repeat mapping of sea-ice and ice-sheet cover over the Arctic and Antarctic, and an increased mapping of Antarctic ice-covered waters to match that of the Arctic. C-band is a proven frequency for cryospheric research and operational needs. There can be some small advantages to choosing either HH or VV polarizations depending on the objective. Because sea ice and even glacier ice can move relatively quickly, a major requirement is to have repeat observations at about an 8-day period for both interferometric and feature retracking methods of deformation fields. Because of generally longer repeat cycles, current systems are not optimized for InSAR observations of important areas of Greenland and Antarctica.

Current and planned systems provide inadequate systematic coverage of the Arctic and the southern oceans. This limitation reduces sea-ice mapping, monitoring, and climate time series. Moreover, planned and existing systems are not optimized for InSAR observations of important areas of Greenland and Antarctica, restricting viable mountain glacier coverage to very limited areas.

Therefore, the specific needs of the cryospheric science discipline include:

- 8-day repeat cycle
- Polar orbit
- Tightly controlled orbit to maximize usable InSAR pairs
- L-band
- Both left and right looking for complete polar coverage

This mission would address all ice sheet and glacier objectives related to surface motion. It would provide coverage in areas where current/planned systems are problematic, some of which are the largest contributors to sea-level change. It would also provide frequent coverage for characterizing outlet glacier variability.

With the addition of

- fully calibrated amplitude and phase data,
- ScanSAR operation for wide swaths, and
- sufficient power and storage for full Arctic and southern ocean coverage,

a mission could also provide all of the sea ice objectives for ice cover, thickness, and motion.

Hydrology. Hydrology is a diverse field, with somewhat different requirements for each important process we wish to measure. Requirements for each major area of investigation are given below.

Surface water investigations:

- Rapid repeat times for interferometry. Daily imagery would be ideal for flood and other hazard assessments.
- Along-track interferometry for surface-water velocity measurements.
- Full polarization to exploit the water–vegetation interface.
- C- and L-band imagery would provide the necessary control to map surface-water elevation changes in a wide range of locations.

Soil moisture:

- Rapid repeat times for interferometry. Daily imagery would be ideal to map dynamic changes in the surface water content. A minimum requirement would be weekly coverage.
- Multiwavelength (L- and P-band) capabilities for imaging soil moisture content at varied penetration depths. Ideally, a multiwavelength mission(s) could image soil moisture at depths of about 10 cm and 1–2 m. The depth penetration would produce true 4-dimensional soil moisture maps that would provide the basis for hydrology and ecology studies.
- Full polarization
- 10-m postings

Snow pack hydrology:

- L-band primary wavelength
- Multiwavelength mission(s) preferred to allow various penetration depths, greater coherency, and more accurate snow-water equivalency measurements
- Full polarimetry provides snow structure control

Topography:

- Satellite mission optimized for topographic InSAR or a tandem mission to generate repeat global topography maps for land surface change.
- Z (vertical) relative error of 1 m is desired.
- X, Y (horizontal) resolution at a minimum of 20 m.
- Orbit/mission control optimized to generate monthly imagery.

Land cover. Land-cover biomes extend from tropical forests, subtropical woodlands, temperate forests, boreal and montane forests, and desert shrublands; to grasslands, savannas, tundra, wetlands/coastal, and agricultural lands; to complex urban and peri-urban lands. InSAR is particularly well-suited to characterizing land-cover ecosystems because it is an imaging active sensor that is not limited by darkness and weather (thus it can map areally, all-weather, all the time), it has unique capabilities for characterizing the 3-dimensional structure or volume of vegetation, something traditional optical sensors cannot do, and it has enhanced ability to detect both significant and subtle change over time, by both repeat orbiting missions and temporal decorrelation of interferometric signals.

Requirements for new measurements include:

- Zero baseline L-HH InSAR for estimating temporal decorrelation, which empirical models relate to vegetation characteristics.
- Non-zero baselines L-HH InSAR to obtain a topographic map, useful for both vegetation structure and permanent scatterer deformation measurement
- 1 to 4 (optimal) occurrences per year useful.
- Repeat period that minimizes temporal decorrelation, useful for both vegetation and deformation.
- Bandwidth from 15 MHz to 80 MHz.
- Fine spatial resolution — current 100 m is useful, 15–30 would aid some studies.
- Fully polarimetric capability.
- Pol-InSAR for improved vertical structure accuracy and land-cover type discrimination.
- Dual frequency — add X-band to L-band providing two height estimates used to expand observation.
- Single pass formation flying — two identical L-HH sensors solves the temporal decorrelation and choice of baseline(s) issues.
- Multibaseline interferometry for 3-D structure mapping.

Oceanography. Ocean research requires that all InSAR be acquired on a single pass (or by two very close-flying satellites) because the surface decorrelates on a timescale of tenths of a second. While many studies are enabled simply by frequent SAR amplitude image availability, for real advances in oceanography we require:

- L-band
- Single-pass, along track interferometric (ATI) SAR. This is absolutely essential. The desired wavelength of the system needs to be studied, trading science, performance, and system cost. Systems from X-band through L-band could provide a viable current mapping capability.
- Capability of squinting fore and aft for single-pass current vector calculation, and to allow wind direction to be determined and more accurate directional wave spectra.
- Long-term measurement of winds, waves, and currents, which are three of the most important oceanographic variables.

Planetary science. Currently there are no InSAR missions planned to any of the planets. Major initiatives to explore the Moon and Mars offer the potential for new U.S. or foreign partner missions. Fundamentally new questions — such as how thick and active is the ice cover of Europa or what are the characteristics and dynamics of the Mars polar ice caps — would be answered if an InSAR mission were flown to any of the solar system bodies.

Existing Tools and Algorithms and State of Maturity

In the context of assessing the need for new measurements, technology, and satellites, the groups found it useful to identify the state of each maturity for each discipline in terms of existing tools, analysis methods, and other interpretational tools. A summary of each follows.

Crustal deformation. We continue development of progressively more sophisticated Earth models and inverse methods for use in interpretations of crustal deformation data for fundamental geophysical parameters. One of our priorities has been exploring the sensitivity of inferred results to traditional modeling and inversion techniques, and improving techniques or refining conclusions when required. We have enhanced our understanding of the character of atmospheric signal and how inversions propagate the contribution from water vapor into the inferred results (including slip distributions and confidence limits on earthquake locations).

As a community, we have worked towards the creation of a global, geodetically located catalog of precisely located earthquakes and their rupture zones complementing existing teleseismically determined catalogs. Such a catalog can serve as a check against teleseismic location methods, which feed into studies such as the Comprehensive Nuclear Test Ban Treaty (CTBT). Precise earthquake locations are also inputs into tomographic models and can be used in tectonic studies based on the distribution and character of seismicity.

Cryosphere. Existing SARs have provided an important data set to develop InSAR techniques for glaciers and ice sheets, to establish baseline ice flow velocities for a number of areas, and to advance our understanding of many basic physical processes that control fast ice flow. Current and planned SAR instruments, however, have been restricted spatially and temporally by sensor limitations and the lack of a comprehensive acquisition strategy. In particular, access to data from planned systems (e.g., RADARSAT-2) is likely to be more limited than with current systems. Even if the data access issues were overcome, there still would be no viable interferometric coverage for important regions of the ice sheets and temperate glaciers.

Hydrology. The state of maturity of interferometry algorithms and InSAR hydrologic applications varies widely. Tools exist to generate several products relevant to hydrology for standard stripmap-mode SAR data collected to date. Several new approaches and modes of operation, e.g., Persistent Scatterer and ScanSAR interferometry, show promise in supporting hydrology. Yet hydrological problems vary from region to region and require region-specific studies. We are in the initial stages of interpreting InSAR hydrological observations and incorporating them with ground data. The input of InSAR measurements into hydrologic models and management tools is in its infancy and near-real-time capabilities beyond interferogram formation have not been developed with the current data latency. Near-real-time capabilities would significantly advance hydrologic hazard assessments.

Land cover. Past and current coordinated science efforts include the NASA Forest Structure Workshop, Airborne AIRSAR and GeoSAR instruments, shuttle-borne SIR-C, SRTM C-band and X-band acquisitions, and spaceborne Envisat and RADARSAT missions. The utility of these has been to answer specific but limited science questions and confirm desired InSAR parameters. Assessing these, we have found that C-band has some utility to vegetation science.

Identified limitations of these data sets are:

- Limited spatio-temporal coverage
- Data may have limited or difficult access
- Repeat-pass C-band has limited vegetation capabilities due to temporal decorrelation

Looking at near-future expected sensor systems, the ALOS-PALSAR L-band polarimetric data and UAV SAR airborne L-band polarimetric data will provide some needed data. PALSAR appears to be a good experimental platform with good parameters to contribute to change detection. The UAV L-band SAR will allow repeat-pass experiments and can be used to study temporal decorrelation and vegetation structure.

Yet these promised systems still have limitations that are not met by any currently planned systems. ALOS-PALSAR has long repeat times, leading to potentially large temporal decorrelation. The UAV system, being airborne, is somewhat limited in coverage and access, necessitating a more capable orbital radar.

Oceanography. Although ATI SAR imagery is not routinely collected either from the air or from space at this time, surface current extraction algorithms and techniques have been developed and are presently being refined (e.g., Romeiser and Thompson, 2000; Kim et al., 2003), including a technique to measure *vector s*urface currents with a single aircraft or spacecraft pass (Toporkov et al, 2004). Algorithms have been developed for retrieving high-resolution wind speeds in the coastal zone from standard SAR imagery (Monaldo et al., 2001). Algorithms are also in use at weather centers to derive two-dimensional ocean wave spectra from standard SAR imagery (Hasselmann and Hasselmann, 1991; Krogstad, 1992). These require a first-guess spectrum to derive information on waves shorter than SAR's cutoff wavelength. Mastenbroek and de Valk (2000) have developed an algorithm that avoids this by using SAR imagery combined with scatterometry to obtain information on the shorter wavelengths. ATI SAR could allow the determination of properties of short-wave spectra from the SAR image alone (Lyzenga, 1989).

Oceanographic measurements require long-term, global observation over the ocean, significantly increasing on-time and data storage. Many applications require near-real-time access to the data.

Oceanographic measurements require a low noise-equivalent cross section and large dynamic range that is not changed when the satellite passes from land to ocean. Radiometric calibration is essential for retrieving ocean winds from InSAR. L- and C-bands are most desirable for high-wind-speed response and for minimizing response to rainfall.

For retrieving wind speeds from SAR data, a model function like the CMOD function relating the normalized radar cross section (NRCS) of the ocean surface (σ^0) to the local near-surface wind speed (ν_0), wind direction versus antenna look direction (pointing direction of the radar), and incidence angle (angle from nadir to the pointing direction) is used. Thus for windspeed determination from SAR accurate calibration and a large dynamic range is crucial.

For applications at weather centers, an algorithm that works in real time has been developed to derive two-dimensional ocean wave spectra from SAR image spectra. The first algorithm solving this problem, taking nonlinear imaging effects into account, is the so called "first guess inversion" MPI-1 algorithm, developed by Hasselmann and Hasselmann in 1991 and redescribed by characteristic functions by Krogstad (1992). In adapted forms (MPI-2), the algorithm is still in use at the ECMWF for the inversion of ENVISAT ASAR data. To derive information on ocean waves shorter than the cutoff wavelength, a first guess from a wave model is used together with the SAR information to obtain the complete two-dimensional ocean wave spectrum.

Mastenbroek and de Valk (2000) developed a spectral inversion algorithm, the so-called SPRA scheme, that would use only the SAR image spectra as input. Instead of using a model wave spectrum as a first guess, the missing information on the wind sea is derived from the scatterometer wind vector measurement that is available simultaneously on the ERS satellites. The main advantage of the method is that wave measurements could be performed independent of a sophisticated wave model providing a first guess and global input wind fields as only available at weather centers.

Need for a New Mission

The limitations of existing and planned radar sensors for many of the scientific problems of interest imply that a new spaceborne radar is a top priority. Advances enabled by a new mission for each discipline include the following:

Crustal Deformation

An InSAR mission would make global crustal deformation data available. At that point, it would be possible for the first time to view the subtle, ongoing deformation of the Earth everywhere. This would allow production of worldwide maps of the accumulation of strain in the crust, so that connections between disparate parts of the world might be apparent. We would be able to address all objectives described in this report and begin to rethink many models of earthquake and volcanic evolution. The basic physics of important geophysical processes in the Earth would be better understood by scientists, and better communicated to the public. Improved forecasts and hazard assessments would be enabled, with immediate societal benefit.

Cryosphere

An L-band InSAR mission would address all ice-sheet and glacier objectives related to surface motion. It would provide coverage in areas where current/planned systems are problematic, some of which are the largest contributors to sea-level change. It would also provide frequent coverage for characterizing outlet glacier variability. These would greatly enhance our understanding of the role, both diagnostic and controlling, that ice plays in Earth's climate.

If a more capable mission, with fully calibrated amplitude and phase data, ScanSAR operation, and sufficient power and storage for full Arctic and southern ocean coverage were implemented, the mission could also provide all of the sea-ice objectives for ice cover, thickness, and motion.

Hydrology

InSAR would first allow the generation of subsidence maps over all of the world's many aquifer systems. These would quickly permit areal estimates of the size and change of aquifers, critically important in so many countries today. Monitoring subsidence along with wellhead data would facilitate planning and use of water storage systems over much of the planet. The techniques could easily be applied to regions with little infrastructure for water management, a very tangible benefit to the developing world.

Land Cover

L-band InSAR has already demonstrated strong capabilities in the area of land cover and land-cover change. With an appropriate satellite system, temporal decorrelation data can be used to relate empirical models to detailed vegetation characteristics. Repeat-pass analysis with fairly long baselines will yield a topographic map at much finer precision than that offered by SRTM, which we can use to both constrain vegetation structure and permit permanent scatterer deformation measurements at very fine detail. Polarimetric InSAR capability will lead to improved vertical structure accuracy and land-cover type discrimination. Dual-frequency X-band and L-band data provide two height estimates that better identify foliage canopies. If the system accommodates single-pass formation flying, then two identical L-HH sensors overcome the temporal decorrelation and baseline selection issues. This also makes it easier to implement multibaseline interferometry for 3-D structure mapping. This wider range of applications than is presently possible raises a number of significant impact areas:

- Vegetation height and canopy profiles
- Forest and timber management
- Carbon accounting
- Fire fuels mapping and fires modeling

- Biodiversity and habitat modeling, including wildlife management, invasive species, and endangered species study
- Agricultural health and productivity

The land-cover community's long-term needs include:

- Vegetation 4-D structure observatory with parameters and spatial and temporal resolutions ideal for vegetation structure and biomass
- Fusion of InSAR, multifrequency, polarimetric, and multibaseline radar data with lidar and hyperspectral data for canopy chemistry and fine-scale structure

Oceanography

For oceanography to derive maximum benefits from InSAR techniques, single-pass, along-track interferometric (ATI) SAR is absolutely essential. This ATI SAR should have the capability of squinting fore and aft for single-pass current vector calculation. These improvements also allow wind direction to be determined and more accurate directional wave spectra to be measured. Winds, waves, and currents are three of the most important oceanographic variables to be measured and a squinted ATI SAR can obtain all three. Their long-term measurement on a global basis via ATI SAR will produce a dramatic increase in oceanographic information that can be used to study climate impacts, marine hazards, and physical/biological processes in coastal regions of rapid spatial variation.

Supporting Information Technology Infrastructure

An InSAR mission and program will need supporting information technology. Rather than constructing only a data and software repository with limited functionality, we examined an InSAR data, analysis, and simulation environment based on a Web service portal architecture. In such an environment, data from satellites can be downloaded, accessed, validated, simulated, interpreted, fused with data from other sources, and visualized, all without leaving the Web-based portal environment. The general topics and requirements developed by the IT group are shown in Table 5.

Table 5. Information Technology Requirements for InSAR Missions.

Topic	Requirements
Technology Needs	Web access to data, software for data mining and data exploration, software for simulating, interpreting, visualizing data
Potential End Users	Engineering, education, government and policy decision makers, operational and hazards response, commercial users
Access Through Data Bases	Standards for domestic and international missions, security, quality and validation, bandwidth, interoperability, content addressable storage, near-real-time or real-time access, rapid response tasking of satellite
Software and Hardware	Data exploration and analysis: higher-level functionality, portal architecture, peer to peer, collaborative, error quantification, graduated authentication
Simulating, Interpreting, and Visualizing Data	Large-scale simulation and modeling capability is needed and should be part of mission plan, centralized and grid computing resources, code sharing (open source), code validation and curation, reliability and robustness

We envision a concept similar to the multitiered Solid Earth Research Virtual Observatory that was first proposed at the NASA Computational Technologies workshop held in Washington, D.C., on April 30–May 2, 2002. We consider applying distributed computing coupling technologies (services for managing distributed geophysical applications and data) to problems in data transmission and archival, data mining/pattern informatics, and multiscale geophysical simulation. Major topics for designing such a system include:

1. Data requirements for applications, including database/data file access as well as streaming data.
2. Service coupling scenarios: composing meta-applications out of several distributed components.
3. Limits and appropriate time-scales for this approach.
4. Data sources and characterizations.
5. Pattern informatics techniques.
6. Multi-scale modeling techniques
7. Coupling scenarios.

Recommended Plan

Elements of a Radar Program

A coherent, dedicated program is needed if we are to meet the challenges outlined by the science discipline groups. The program entails more than a space mission, although a new satellite would easily be the most expensive component. Many gains can be made through exploitation of existing data archives, collaboration with international partners who are already orbiting satellite systems, and supporting the U.S. science community in its pursuit of basic and applied research.

The main elements for a successful program must include:

- Access to existing data archives worldwide
- Negotiated collaborative use of existing satellites
- Education of new scientists
- Plans for a new InSAR satellite

Our specific recommendations follow:

Archives from many operating satellites exist; what is now lacking is full access to these historical data. ***We recommend opening negotiations between the U.S. and foreign space agencies to allow and encourage sharing of spaceborne remote sensing data fully among research scientists, with a goal of having all radar remote sensing data freely circulating among scientists by the end of 2005.***

Currently operating satellites such as Envisat and RADARSAT-1 provide much valuable data for InSAR research. If the U.S. community can collaborate fully with foreign providers of these satellites, and also providers of future satellites, very useful experiments can be undertaken that are well beyond the scale of individual investigators. These collaborations would include definition and exploitation of natural laboratories, coordinated satellite experiments such as the RADARSAT Antarctic Mapping Project (RAMP), and international emergency response efforts. ***We recommend a series of workshops and negotiations to plan such experiments that would bring together scientists with common interests from around the world.***

InSAR has been used to advance many scientific studies over the past dozen years. Yet it remains a non-traditionally-taught subject. We need to incorporate radar remote sensing methods into our curricula through courses and research in order to train a new generation of researchers. It is also necessary to refresh current scientists and update them on advances in the field. Traditional outreach activities would educate secondary school students of the exciting possibilities enabled by modern radar technology, and kindle more interest in the field. ***We recommend a research and analysis program with a goal of supporting undergraduate- and graduate-level research in InSAR studies, and also continuing technical workshops and summer schools for new students and young-thinking mature scientists, to be in place by summer 2005.***

The final plank of the program platform is a new spaceborne radar mission with sufficient capability to implement the science studies described in the previous section. We have seen that while we can expect to make great gains by more fully exploiting available resources, there are many problems that cannot be addressed with current systems. ***We therefore recommend that the U.S. orbit a new radar satellite capable of satisfying at least half of the objectives in Table 3 by 2010, when most of the planned and existing systems will be reaching the end of their technical lifetimes.***

Exactly which of the objectives should be met by the initial satellite system depends on the agencies sponsoring the sensor and their own priorities. For example, an oceanographic agency would be most interested in along-track InSAR configurations, while a solid-Earth science agency or program might prefer an initial emphasis on repeat-pass InSAR at long wavelengths. There are many valuable studies remaining to be done in all of our disciplines, and we would like to have progress begin in any and all of them. It is quite likely that any system that is arrived at by consensus would contribute across the board to our science goals.

Supporting data policy and information technology. Access to existing data is a critical barrier for today's radar scientist. ***Therefore we insist that any new radar remote sensing system developed by the U.S. or partner agencies put in place a free and open data access policy so that any researcher may obtain the data easily and cheaply.*** Elimination of the cost and nuisance barrier to the free flow of scientific information is in the best interests of the worldwide science community and for humanity. We advocate the development of an InSAR data, analysis, and simulation environment based on a Web service portal architecture to support any space mission. In such an environment, data from satellites would be freely downloaded, accessed, validated, simulated, interpreted, fused with data from other sources, and visualized, all without leaving the Web-based portal environment.

Value of satellite observations. Satellite-borne InSAR sensors support diverse and valuable research in many areas. Considerable effort has been expended on studying user requirements and reflecting them in the planning and coordination of satellite missions, but the current situation does not satisfy all the requirements of each benefit area. All-weather observation data and climate-related observations, as well as high temporal/spatial resolution data, are basic observation data and can be used across virtually all topics. SAR sensors, passive microwave observation, high-resolution optical observation systems, and geostationary observation systems should also be considered key observing systems.

Addressing disaster requirements includes the need for high spatial resolution and all-weather capability through technology such as optical and SAR satellites, as well as high temporal resolution observation from geostationary orbit for disaster monitoring of volcanic eruption, forest fires, aerosol and other hazards.

Continuity of SAR sensor data, including L-band and C-band, for interferometry and GPS capability is required to meet the needs of the disaster societal benefits area. The agriculture area needs continuity of a high-resolution satellite network (5–30 m) for monitoring selected hotspots in agriculture, rangelands, forestry, fresh water, and fisheries. Societal benefits in the water area could be served by development of a plan to institutionalize surface-flux measurements.

GEOSS will address Earth observation continuity, emphasized as a fundamental requirement across the range of societal benefit areas. Continuity is needed for both basic observation networks and intensive observation focused on select areas. Only with assured continuity can users invest confidently. The continuity of high- to moderate-resolution optical and SAR observations over land and other critical observations over oceans needs to be assured. Accordingly, contingency plans of observation system operators should be sensitive to how their user communities are affected by interruptions of data and services.

Discipline long-term science goals. InSAR techniques are applicable to many different research endeavors. Radar system requirements are thus becoming more uniform among disciplines, making it much easier to select among competing mission concepts. Land-cover and vegetation InSAR needs are converging with those of solid-Earth science goals in regards to operating wavelengths and resolution, and as we have seen, the L-band radar approach would permit advances in such differing applications as 3-D vegetation structure, ground disturbances from natural hazards, biomass and carbon cycle questions, crustal deformation from earthquakes, volcanoes, and landslides, and hydrologic concerns such as topography and groundwater flow.

If a new radar mission were created, either by the U.S. alone or involving foreign partnerships, radar scientists from all of our constituent groups would enthusiastically support it and contribute to the overall success of the mission, regardless of the discipline for the initial pool of support.

Role of the InSAR Working Group

The working group itself plans a number of future InSAR activities directed at advancing several objectives:

1. Develop an international InSAR community with broad discipline representation in Earth and planetary science to identify key science questions to be addressed with InSAR data.
2. Define and advocate an InSAR program that includes a U.S.-led InSAR mission.
3. Maximize the use of existing SAR data by increasing access to current and earlier mission and aircraft data sets.
4. Educate and support new InSAR scientists

In particular, we recommend convening workshops and special sessions at meetings that include presentations on new InSAR applications and technological advances. To increase the number of scientists using InSAR data, we recommend holding week-long workshops on processing of InSAR data. We expect that progress toward the four objectives above will require meetings of small working groups as well as broader workshops. Thus, in addition to convening workshops, we recommend the formation of an InSAR steering committee to organize and communicate with the SAR user and developer community. We recommend that this group work with mission teams in the early planning stages to develop science, software, and data requirements. To promote the access to new and historical SAR data, we recommend the formation of a W(orld) InSAR committee to expand the data acquisition approach developed by the WInSAR working group.

Education and Outreach

A U.S. InSAR program promises exciting new opportunities to pursue unanswered scientific questions related to Earth and space exploration. InSAR research, technologies, and data will also advance knowledge and enable efficient management of our natural resources from local to global scales. In order to achieve these goals, a comprehensive education and outreach plan is essential.

The community believes in and supports fully a broad Education and Outreach (E&O) effort that operates as an integral part of a national program. Our first step should be to create an E&O working group devoted to ensuring the success of the ongoing InSAR mission. The primary charge to the E&O Working Group will be to create a strategic plan that clearly states our goals for serving the InSAR scientific community and also includes broad audience participation in InSAR-related programs outside the context of specific missions.

Our current goal is to develop a plan that will describe how we and our partners will

- Articulate a vision and mission statement for InSAR E&O
- Set and prioritize E&O goals, based on the vision and mission statement

- Raise public awareness of InSAR
- Increase understanding of the uses and potential of InSAR
- Develop partnerships
- Seek funding as appropriate
- Identify appropriate target audiences
  - — informal education (museums, articles, media)
  - — formal education (K–16)
  - — knowledge transfer (industry and InSAR professionals)
- Evaluate the E&O effort

The broad goals of a successful E&O component include:

Awareness. We need to answer some very basic questions to raise public awareness, beginning with "Why InSAR? What can InSAR provide that other technologies cannot? What was life like before InSAR? How will life improve with InSAR?" In addition, we need to develop concrete examples linked to hooks such as "…single most valuable tool that Earth scientists can provide to world geological hazard mitigation." Goals include:

- Provide examples of products for the public sector according to audience types
- Create products to publicize the importance of InSAR (reports, brochures, news articles, TV/film/video production)

Understanding. Our goal to deepen understanding at all levels should result in programs that increase the widespread use of InSAR in both science and industry as well as inspiring the next generation of scientists by stimulating science learning. We seek to advance public understanding of the benefits of InSAR technology and uses and to promote understanding of the long-term benefits of InSAR (i.e., space exploration, including Earth and beyond).

Friends. "Friend-raising" is the first step toward creating truly beneficial partnerships with sustainable results. In our outreach effort, we should aim to recruit potential collaborators in all sectors, thereby increasing potential use of research results and data output. Partnerships also may lead to increased awareness, understanding and provide pathways to finding additional resources.

Developed with strong participation by representatives from all sectors of the science, industry, education, and public communities, the E&O strategic plan will support and increase the use of radar imaging while providing innovative educational opportunities intended to inspire the next generation of Earth explorers.

Summary

On October 20–22, 2004, a community workshop convened in Oxnard, California, to guide U.S. efforts in Interferometric Synthetic Aperture Radar (InSAR), a type of space-based radar observation that allows ground displacements from earthquakes and other sources to be measured over many millions of pixels (each representing a resolution of about 10–30 meters) to a displacement accuracy of several millimeters. The potential of a robust InSAR observational capability has generated strong interest among the research and applications communities. The workshop addressed a broad spectrum of end uses, including crustal deformation science related to earthquakes, ice sheet and glacier variability, volcanoes, hydrologic processes, vegetation structure, and disaster management. Long-term access to InSAR data will greatly advance our understanding of how these basic processes affect life on Earth.

This workshop helped to devise a long-term strategy for U.S. InSAR activities, including the funding of dedicated U.S. InSAR satellites, access to foreign SAR data, and continued education and advocacy for InSAR science.

The geophysical community recommends an InSAR program that enables critical science, built on significant multi-agency partnerships including NSF, USGS, NOAA, and DoD. This program would address the issue of mitigating the effects of natural disasters by creating a comprehensive global observation system and advancing modeling and technology in order to help forecast events such as earthquakes, volcanic eruptions, floods, and sea-level perturbations.

InSAR has been used to measure precisely changes that occur prior to, during, and after major disasters. Rapid advances in spaceborne observations, coupled with computationally intensive modeling, are revolutionizing our understanding of the natural forces that result in devastating impacts to our society. There is renewed enthusiasm within the scientific community that new spaceborne observations will lead to significantly improved predictive capability that provides decision makers (state agencies, Federal Emergency Management Administration (FEMA), U.S. Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), and the United Nations) with the information needed to meet societal needs in disaster preparedness and response and thereby reduce losses of life and property.

The science and technology resulting from research and development as part of an InSAR program would dramatically improve the nation's capacity to understand and protect our home planet against natural hazards such as earthquakes and volcanoes. The objectives are to:

- Characterize and understand motions of the Earth's surface and their variability on a global scale in order to accelerate development of predictive models that can anticipate the behavior of natural hazards such as earthquakes, volcanic eruptions, floods, and landslides.
- Demonstrate a hazard monitoring and warning system based on (InSAR measurements and the predictive models as a preliminary benchmark for an international cooperative system for global preparedness.
- Characterize the contributions of ground water, surface water, soil moisture, and snow pack to the global freshwater budget to determine how natural and anthropogenic processes redistribute water in both space and time.
- Determine the role of glaciers and ice sheets in sea-level rise and possible changes in Earth's climate. Characterize ocean surface behavior on a global, long-term scale and determine its effect on driving climate.
- Understand the three-dimensional structure of vegetation on the Earth's terrestrial surface and its influence on habitat, agricultural and timber resources, fire behavior, and economic value.
- Extend InSAR technologies to exploration, discovery, and the search for life beyond our home planet.

- Provide exciting educational opportunities for the emerging generation of scientists and engineers.

Many possible configurations for a spaceborne radar exist, but a sensor with the following capabilities would be able to address the major needs of the Earth science community:

- L-band wavelength
- Approximate weekly repeat cycle
- Millimeter-scale sensitivity
- Tightly controlled orbit to maximize usable InSAR pairs
- Both left and right looking for rapid access and more comprehensive coverage
- Along-track interferometry for surface water velocity measurements

An InSAR program would sustain and nurture science and technology for environmental observations needed for hazard assessment, mitigation, and response and for monitoring and predicting changes to solid-Earth components of the Earth system. It would provide exciting educational opportunities for an emerging generation of scientists and engineers. Through provision of a unique contribution to the existing suite of international Earth-observing capabilities, this program would strengthen the interagency network, foster opportunities for international partnerships, accelerate the progress of science, and provide global societal benefits through a comprehensive and coordinated Earth-observation system.

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Appendix 1

Agency Reports Calling for SAR and InSAR Missions

The 1995 report, *Spaceborne Synthetic Aperture Radar: Current Status and Future Directions*, to the Committee on Earth Sciences, Space Science Board, of the National Research Council notes that SAR/InSAR is an important tool that provides a unique contribution to studies of the Earth:

“SAR data provide unique information about the health of the planet and its biodiversity, as well as critical data for natural hazards and resource assessments. Interferometric measurement capabilities uniquely provided by SAR are required to generate global topographic maps, to monitor surface change, and to monitor glacier ice velocity and ocean features.”

The report also identifies SAR/InSAR as an important near term opportunity for disaster warnings as follows:

“The greatest set of unmet observational requirements is for systematic, widespread coverage. This can best be delivered by [...] enhancing our capabilities in synthetic aperture radar (SAR) and interferometric synthetic aperture radar (InSAR) systems. Applications of InSAR include robust observations of surface deformation, which complements time-continuous observations of deformation derived from GPS networks. Other major SAR hazards applications include monitoring sea ice, oil slicks, and inundation from flooding.”

This is considered particularly timely since:

“In the next few years, the governments of Canada and Japan will launch advanced synthetic aperture radar satellites, and there is a pressing need to work in advance on data access. Although we have demonstrated the capability through limited sporadic synthetic aperture radar (SAR) data, we currently have no operational radar satellite system that could truly help in a real-time manner, reduce hazards, help mitigate disasters, and realize goals of saving lives and reducing damage.”

The United States Group on Earth Observations (a subcommittee of the National Science and Technology Council Committee on Environment and Natural Resources) *Strategic Plan for the U.S. Integrated Earth Observation System* (2005) also addresses the need for SAR and InSAR data sets. Under the Global Earth Observation (GEO) agreement, such data sets would be available to researchers on a “full and open access”

basis, according to the WMO and ICSU terminology. The Global Earth Observation System of Systems (GEOSS) formulates both 2-year and 6-year targets for SAR/InSAR data, including the following 2-year targets:

—Facilitate global access to the 100-meter (C-band) and 30-meter (X-band) horizontal resolution digital terrain information produced during the Shuttle Radar Topography Mission (SRTM).

—Advocate integration of InSAR technology into disaster warning and prediction systems, in particular related to floods, earthquakes, landslides, and volcanic eruptions. The ERS (European Remote Sensing) and Envisat missions of the European Space Agency have pioneered these applications and shall be continued for global, long-term applications. As part of this effort, facilitate efficient exploitation of data from Japan’s upcoming Advanced Land Observation Satellite (ALOS). Its L-band SAR sensor is the first such sensor since 1998.

In addition, the following 6-year targets were identified:

—Facilitate widespread use of lidar and InSAR technologies for topography in areas of low relief. For floods and coastal hazards, the most crucial need is for high vertical resolution (less than 1 meter) topographic data, plus good shallow-water bathymetry.

—Advocate continuity and interoperability of all Global Positioning System (GPS) satellite constellations, e.g., U.S. GPS, European Galileo, Russian GLONASS (Global Orbiting Navigation Satellite System). This includes support of the global geodetic network services that define the orbits of the GPS satellites and thereby enable the use of GPS for precise geolocation. Applications of GPS essential to disaster response include precision topography, mapping support, and deformation monitoring, as well as geolocation for search and rescue operations.

—Advocate that the international satellite community, coordinated through the Committee on Earth Observation Satellites (CEOS), plan for assured continuity of critical sensing capabilities. For example, certain research systems should become operational systems and the projected lifetime of some systems should not result in service gaps of key satellite sensor data. Longer-term actions for monitoring of geohazards include realization of an integrated observation system of SAR interferometry and GPS.

—Advocate more rapid SAR processing for interferometry to enable strain mapping over large seismically active zones and to monitor landslide and subsidence in populated areas and along transportation corridors.

—Facilitate the development and sharing of critical airborne sensors and capabilities, such as hyperspectral sensors, high-resolution infrared sensors and lidar.

And finally, for the long-term, the report lists as 10-year targets:

—Advocate meeting various unmet needs for classes of satellite sensors. Of particular importance for the area of hazards and disasters is the global need for a significant increase in SAR satellites, both C-band and L-band. The disaster-management community needs an L-band system optimized for interferometry, and an expanded L-band capacity for better forest and fuel characterization. Monitoring the range of smoke and pollution plumes in the atmosphere around the globe requires expanded hyperspectral capability, which is currently limited to airborne sensors. A passive-microwave capability would help in determining soil moisture repeatedly over broad areas.

—Advocate development of systematic methods for rapid determination of shallow bathymetry, especially in turbid water. Such research is vital to characterizing near-shore bathymetry, whether for improved modeling of tsunami and storm surge or for documenting changes produced during such events.

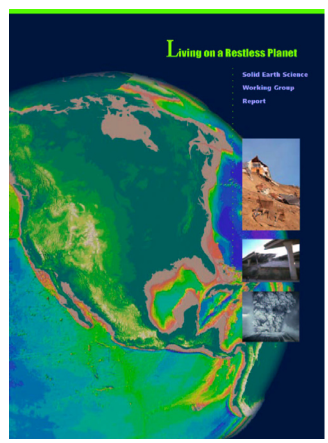
In adopting these targets, the following recommendations were formulated under GEO agreement, which address directly the goals of the InSAR workshop:

—GEOSS will promote enhancements of the automatic processing and evaluation of satellite imagery and production of digital topography, in support of rapid detection of fire or oil spills. GEOSS will also promote more rapid SAR processing for interferometry to enable strain mapping over large seismically active zones and to monitor landslide and subsidence in populated areas and along transportation corridors. (Rec #71)

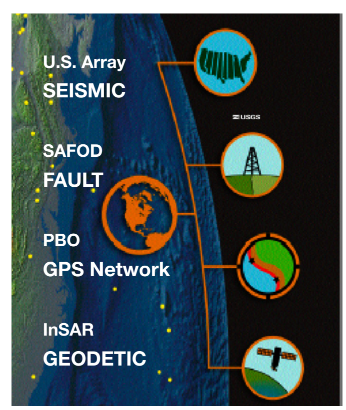
—GEOSS will support real-time data exchange and archiving among regional and local data centers. (Rec #73)

The GEOSS report notes that

"Continuity of SAR sensor data, including L-band and C-band, for interferometry and GPS capability is required to meet the needs of the Disaster societal benefits area. The Agriculture area needs continuity of a high-resolution satellite network (5–30 meters) for monitoring selected hotspots in agriculture, rangelands, forestry, fresh water and fisheries. Societal benefits in the Water area could be served by development of a plan to institutionalize surface flux measurements."



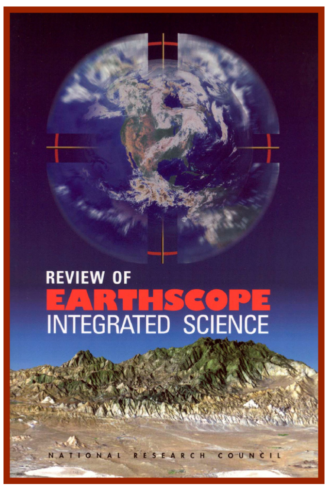
The NASA Solid Earth Science Working Group, in its 2002 report *Living on a Restless Planet,* places InSAR as its highest priority. Five of the six questions identified and discussed in the report can be addressed by InSAR (Table 1). The report states that "Weekly deformation maps are the highest priority" and calls for "InSAR everywhere all the time" by 2025. In its Review of NASA's Solid Earth Science Strategy (2004), the National Academies strongly endorse an L-band InSAR mission as NASA's top solid-Earth science priority.



InSAR is the fourth component of EarthScope. EarthScope is a major research initiative led by the National Science Foundation to investigate the structure and evolution of the North

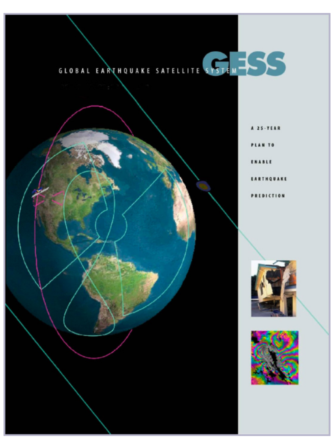
1. What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?
2. How do tectonics and climate interact to shape the Earth's surface and create natural hazards?
3. What are the interactions among ice masses, oceans, and solid Earth and their implications 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?

Table 1. Scientific challenges identified by SESWG (2002). InSAR would address the first five of these challenges.



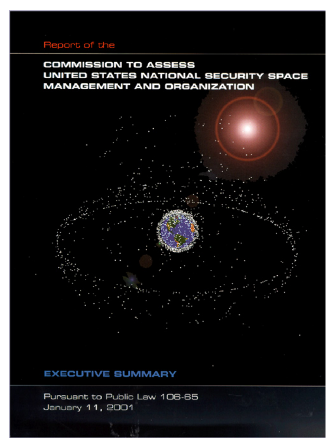
American continent and the physical processes controlling earthquakes and volcanic eruptions. The National Research Council's *Review of Earthscope Integrated Science* states that "InSAR (interferometric SAR) provides a means of measuring and monitoring the motion of the Earth's surface in great detail over wide areas, and should be regarded as an essential component of EarthScope."

The Global Earthquake Satellite System (GESS, 2003) study responds to the clearly articulated need within the solid-Earth science community for dense surface deformation data. It is a detailed implementation plan in alignment with the recommendations of the Solid Earth Science Working Group (SESWG), and charts the course for NASA to make major contributions to the interagency EarthScope program, while broadening those goals to a global scope.



The GESS study explored the requirements space for various components of an integrated system, but focused mission architecture studies on systems that deliver high-accuracy, high-resolution surface deformation using InSAR. Detailed science requirements were gathered from the wider community to guide the studies.

The major conclusion of the architecture studies is that a constellation of InSAR satellites is needed to address the requirements for monitoring a spectrum of steady and transient deformation processes. To ensure the ability to access any area on the surface of the Earth within 24 hours would require two LEO satellites in orbits above 1000 kilometers. A few MEO or GEO satellites would be equivalent to many spacecraft in LEO and would fully characterize the known transient processes such as postseismic relaxation, slow earthquakes, creep events, and accelerated slip, with full global coverage.



The DoD, in its 2001 *Report to the Commission to Assess United States National Security Space Management and Organization*, identified the benefits of InSAR for national security. High-resolution topography, underground activity detection, damage assessment, and trafficability are all items of interest that can be addressed by InSAR.

Appendix 2

Workshop Attendees

Discipline	*Name (Last, First)*	*Affiliation*
Advanced Signal and Image Processing	Duong, Tuan.	JPL
APANL-Volcanology	Mouginis-Mark, Pete	U HI Inst Geophysics & Planetology
Applied Physics	Espy, Samuel L.	Viz Multimedia
Archaeology	Comer, Douglas C.	Cultural Site Research and Management, Inc.
Archaeology	Giardino, Marco	NASA/SSC
Atmospheric Remote Sensing	Gutman, Seth I.	NOAA Forecast Systems Lab
Computer Engineering	Larrondo Petrie, Maria M.	FL Atlantic U
Computer Science	Aksoy, Demet	U C Davis, Comp Sci
Computer Science	Kulkarni, Arun D.	U TX Tyler, Comp Sci
Computer Science	Razak, Mohamed Zubair	American University
Computing/Visualization	Katz, Daniel S.	JPL
Crustal Deformation	Abdelsalam, Mohamed G.	U TX Dallas, Geosci
Crustal Deformation	Aly, Mohamed	Texas A&M
Crustal Deformation	Ambrose, Stephen	NASA HQ, Applied Sci Branch
Crustal Deformation	Amelung, Falk	U of Miami, Rosenstiel School
Crustal Deformation	Arvesen, John	High Altitude Mapping Missions, Inc.
Crustal Deformation	Bawden, Gerald	USGS
Crustal Deformation	Bilham, Roger	U CO CIRES
Crustal Deformation	Bodin, Paul	U Memphis, CERI
Crustal Deformation	Brooks, Benjamin A.	U HI, Geophys & Planetology
Crustal Deformation	Bruhn, Ronald	U UT, Geol & Geophys
Crustal Deformation	Buckley, Sean	U TX, Austin
Crustal Deformation	Cai, Yang	Carnegie Mellon U
Crustal Deformation	Calais, Eric	Purdue U
Crustal Deformation	Calzia, Jim	USGS
Crustal Deformation	Chadwick, John	ID St U
Crustal Deformation	Chen, Wang-Ping	U IL, Urbana-Champaign
Crustal Deformation	Combs, Jim	Geo Hills Associates
Crustal Deformation	Curlander, John	Vexcel
Crustal Deformation	DiLeonardo, Christopher	Foothill College, Earth Sci
Crustal Deformation	Dixon. Tim	U of Miami
Crustal Deformation	Dobson, Craig	NASA HQ
Crustal Deformation	Dokka, Roy K.	LA St U., Louisiana Spatial Reference Center
Crustal Deformation	Donnellan, Andrea	JPL
Crustal Deformation	Eckberg, Jon	U Houston
Crustal Deformation	El-Sobky, Hesham F.	Texas A&M U, Geol & Geophys
Crustal Deformation	Eneva, Mariana	Imageair
Crustal Deformation	Erten, Esra	Istanbul Tech U, Satellite Tech & Remote Sensing
Crustal Deformation	Fialko, Yuri	UCSD
Crustal Deformation	Fielding, Eric	JPL
Crustal Deformation	Forster, Rick	U UT
Crustal Deformation	Freed, Andy	Purdue U, Earth & Atmos Sci
Crustal Deformation	Freund, Friedemann T.	NASA GSFC
Crustal Deformation	Furuya, Masato	U CO, Phys & CIRES
Crustal Deformation	Ge, Linlin	U of New South Wales
Crustal Deformation	Glasscoe, Margaret T.	JPL
Crustal Deformation	Glowacka, Ewa	CICESE
Crustal Deformation	Gomez, Francisco	U MO, Geol Sci
Crustal Deformation	Gorkavyi, Nick	Greenwich Inst for Sci & Tech

Discipline	Name (Last, First)	Affiliation
Crustal Deformation	Guritz, Rick	ASF/Geophysical Institute
Crustal Deformation	Hammond, Bill	NV Bureau of Mines and Geology
Crustal Deformation	Helz, Rosalind	USGS
Crustal Deformation	Hensley, Scott	JPL
Crustal Deformation	Hooper, Andy	Stanford U, Geophys
Crustal Deformation	Hudnut, Ken	USGS
Crustal Deformation	Hurst, Kenneth	JPL
Crustal Deformation	Hurtado, Jr., Jose M.	U TX El Paso, Geol
Crustal Deformation	Ikkers, James	Atlantis Scientific Inc.
Crustal Deformation	Johnson, Daniel J.	U WA
Crustal Deformation	Jšrn, Hoffmann	German Aerospace Center (DLR), Remote Sensing Data Center (DFD)
Crustal Deformation	King, Christine	BRGM (French Geol Survey)
Crustal Deformation	Klein, Andrew	Texas A&M U, Geography
Crustal Deformation	Klein, Walter	NASA Dryden Flight Research Center
Crustal Deformation	Koli, Sidharam	Tata Teleservices Ltd.
Crustal Deformation	Kwoun, Oh-ig	USGS EROS Data Center
Crustal Deformation	LaBrecque, John	NASA
Crustal Deformation	Lohman Rowena	Caltech/Woods Hole
Crustal Deformation	Lu, Zhong	USGS EROS Data Center, SAIC
Crustal Deformation	Lundgren, Paul	JPL
Crustal Deformation	Madin, Ian	OR Dept of Geol & MIneral Industries
Crustal Deformation	Maxwell, Gregory A.	BTB
Crustal Deformation	McGuire, James	NASA/IPO
Crustal Deformation	McRaney, John	USC SCEC
Crustal Deformation	Mellors, Robert	San Diego St U, Geol
Crustal Deformation	Michel, Remi	CEA (Atomic Energy)
Crustal Deformation	Minster, Jean-Bernard	Scripps Institution of Oceanography
Crustal Deformation	Morgan, Ricky James	Morgan Optics Corp
Crustal Deformation	Motagh, Mahdi	GeoForschungsZentrum Potsdam (GFZ). Sec 2.1
Crustal Deformation	Mualchin, Lalliana	CA Dept of Transp
Crustal Deformation	Muller, Jordan	NASA GSFC — NRC
Crustal Deformation	Necsoiu, Marius	Southwest Research Inst
Crustal Deformation	Newman, Andrew	Los Alamos NL
Crustal Deformation	Panda, Bibhuti Bhusan	AMEC Earth & Environmental
Crustal Deformation	Pavez, Andres	Institut de Physique du Globe de Paris
Crustal Deformation	Peltzer, Gilles	UCLA (and JPL)
Crustal Deformation	Pieri, David	JPL
Crustal Deformation	Plag, Hans-Peter	NV Bureau of Mines and Geol
Crustal Deformation	Prescott, William	UNAVCO
Crustal Deformation	Price, Evelyn	U TX, Austin, Geophys
Crustal Deformation	Pritchard, Matt	Princeton U, Geosci
Crustal Deformation	Puyssegur, Beatrice	CEA (Atomic Energy)
Crustal Deformation	Raney, Jay	U TX Austin, Bureau of Economic Geol
Crustal Deformation	Rashed, Tarek	U OK, Geog
Crustal Deformation	Ravat, Dhananjay	Southern IL U, Carbondale, Geol
Crustal Deformation	Real, Charles	CA Geo Survey
Crustal Deformation	Rhodes, Brady P.	CSU Fullerton, Geol
Crustal Deformation	Rial, Jose A.	U NC, Chapel Hill
Crustal Deformation	Rosen, Paul	JPL
Crustal Deformation	Rosenthal, Sherri	Challenger Elementary School
Crustal Deformation	Rundle, John	U C Davis
Crustal Deformation	Rykhus, Russell	USGS EROS Data Center, SAIC

Discipline	Name (Last, First)	Affiliation
Crustal Deformation	Saikia, Chandan K.	URS Corp
Crustal Deformation	Sandwell, David	SIO/UCSD
Crustal Deformation	Sarychikhina, Olga	CICESE, Ensenada
Crustal Deformation	Sauber, Jeanne	NASA GSFC
Crustal Deformation	Schmidt, Schmidt	U OR, Geol
Crustal Deformation	Seelan, Santhosh K.	U N Dakota
Crustal Deformation	Serpa, Laura	U of New Orleans, Geol & Geophys
Crustal Deformation	Shum, C.K.	OH St U, Geodetic Sci
Crustal Deformation	Simons, Mark	Caltech Seiso Lab
Crustal Deformation	Sleeter, Benjamin	USGS
Crustal Deformation	Spiller, Wendy	Challenger Elementary School
Crustal Deformation	Stern, Robert J.	U TX Dallas, Geosci
Crustal Deformation	Taranik, James V.	U NV, Earth Sci & Eng
Crustal Deformation	Thatcher, Wayne	USGS
Crustal Deformation	Thurmond, Allison Kennedy	U TX Dallas, Geosci
Crustal Deformation	Trivedi, J. R.	Physical Research Lab
Crustal Deformation	Turcotte, Donald L.	U C Davis, Geol
Crustal Deformation	Ulas, Tuncay	Selcuk University
Crustal Deformation	Vasco, Don	Berkeley Laboratory
Crustal Deformation	Velicogna, Isabella	U CO, Phys & CIRES
Crustal Deformation	Vincent, Paul	LLNL
Crustal Deformation	Vincent, Mark	Raytheon/JPL
Crustal Deformation	Wang, Herb	U WI, Madison, Geol & Geophys
Crustal Deformation	Wang, Chao	Institute of Remote Sensing Applications of CAS
Crustal Deformation	Wdowinski, Shimon	U of Miami, Marine Geol & Geophys
Crustal Deformation	Webb, Frank	JPL
Crustal Deformation	Wessels, Rick	USGS — Alaska Volcano Observatory
Crustal Deformation	Wicks, Chuck	USGS
Crustal Deformation	Woldegiorgis, Leake	Ministry of Energy and Mines
Crustal Deformation	Yun, Sang-Ho	Stanford U
Crustal Deformation	Zebker, Howard	Stanford U, Geophys
Crustal Deformation	Zucca, Francesco	U of Pavia, Earth Sci
Cryosphere	Baek, Sangho	OH St U, Geodetic Sci
Cryosphere	Blanken, Peter	U CO, Geography
Cryosphere	Brenner, Anita C.	Science Systems & Applications, Inc, SSAI
Cryosphere	Brigham, Lawson W.	U.S. Arctic Research Commission
Cryosphere	Clemente-Colon, Pablo	NOAA/NESDIS
Cryosphere	Dozier, Jeff	UCSB, Env Sci
Cryosphere	Fricker, Helen Amanda	Scripps Institution of Oceanography
Cryosphere	Geiger, Cathleen	USA CRREL
Cryosphere	Hildebrand, Peter	NASA/GSFC
Cryosphere	Holt, Ben	JPL
Cryosphere	Hussein, Ziad A.	JPL
Cryosphere	Jezek, Kenneth	OH St U
Cryosphere	Joughin, Ian	U WA Polar Sci Ctr/Appl Phys Lab
Cryosphere	Kwok, Ron	JPL
Cryosphere	LaBelle-Hamer, Nettie	U AK Fairbanks/ASF
Cryosphere	Levy, Gad	NW Research Associates
Cryosphere	Miller, Norman	LBNL, Earth Sci
Cryosphere	Nghiem, Son V.	JPL
Cryosphere	Rignot, Eric	JPL
Cryosphere	Scambos, Ted	U CO CIRES, Natl Snow & Ice Data Ctr
Cryosphere	Shuchman, Robert A.	Altarum Institute

Discipline	*Name (Last, First)*	*Affiliation*
Cryosphere	Tulaczyk, Slawek	UCSC, Earth Sci
Cryosphere	Young, Sharolyn	National Ice Center
Cryosphere	Yu, Jun	U Vermont
DEM Production and Data Support	Atwood, Don	AK Satellite Facility
Disaster Management	Francis, Suresh	Kerala State Remote Sensing and Env Centre
Education	Kunnath, Maria Lorna A.	MLAK EduSoln
Education	Minh, Vo Quang	Can Tho U, College of Ag
Educational Outreach	Andrews, Jill	Caltech
Elect Eng	Klinger, Allen	UCLA
Emergency Management	Egan, Terrence M.I.	WA St Emergency Management Div
Engineering	Hadaegh, Fred Y.	JPL
Fluvial–Estuarine Sedimentology	Archer, Allen W.	KS St U, Geol
Forestry	Mickler, Robert A.	ManTech Environmental Technology Inc.
Geopositioning	Bethel, James	Purdue U, Engineering
High-Performance Computing	Norton, Charles	JPL
High School Outreach	McPherson, Ed	VA Tech: Learning Technologies
Hydroclimatology	Legates, David R.	U DE, Center for Climatic Research
Hydrology	Alsdorf, Doug	Ohio St U, Geol
Hydrology	Anderson, Michael L.	U C Davis, Eng
Hydrology	Archer, Frank	AL A&M U
Hydrology	Bailey, Kenneth D.	Bureau of Indian Affairs
Hydrology	Balser, Andrew W.	U AK, Fairbanks
Hydrology	Barber, Michael E.	State of WA Water Research Center
Hydrology	Becker, Matthew W.	NASA/GSFC, Hydrological Sci
Hydrology	Bosch, David	USDA-ARS, SEWRL
Hydrology	Brandt, Justin T.	USGS-WRD
Hydrology	Carnahan, Robert	U South FL, Civil & Environ Eng
Hydrology	Carras, Daniel	Astro & Physics Inst — Space Exploration Program
Hydrology	Chen, Kun-Shan	National Central U, TX
Hydrology	Cifelli, Robert	CO St U, Atmos Sci
Hydrology	Dinwiddie, Cynthia L.	CNWRA, SW Res Inst
Hydrology	Duffy, Christopher	Penn St U
Hydrology	Estep, Lee	NASA/SSC, Science Systems & Applications, Inc.
Hydrology	Godt, Jonathan	USGS
Hydrology	Green, Timothy R.	USDA, Ag Research Service
Hydrology	Hanson, Randy	USGS
Hydrology	Harris, Jasper L.	No Carolina Central U, Geog & Earth Sci
Hydrology	Heggy, Essam	Lunar &Planetary Inst
Hydrology	Henderson, Floyd M.	U at Albany, Geog & Planning
Hydrology	Holder, Curtis	U CO, Geog & Env Studies
Hydrology	Hong, Yang	UC Irvine, Civil & Envir Eng
Hydrology	Huberty, Brian	US Fish & Wildlife
Hydrology	Johnican, Michael D.	Intl Consortium of Env Toxicologists (ICET)
Hydrology	Kampe, Thomas	Ball Aerospace & Technologies Corp.
Hydrology	Laker, Mark	US Fish & Wildlife— Kenai National Wildlife Refuge
Hydrology	Lewis, Anthony J.	LA St U., Geog & Anthro
Hydrology	Li, Chunyan	Skidaway Inst of Oceanography
Hydrology	Lodhi, Mahtab A.	U of New Orleans, Geography
Hydrology	Long, David G.	Brigham Young U
Hydrology	Lu, Ning	CO School of Mines
Hydrology	Mandell, Wayne	US Army Environmental Center
Hydrology	Melesse, Assefa M.	FL Intl U
Hydrology	Nigam, Sumant	U MD

Discipline	Name (Last, First)	Affiliation
Hydrology	Nolan, Matt	U AK, Fairbanks
Hydrology	O'Neil, Calvin P.	USGS/Louisiana Mapping Liaison
Hydrology	Oppliger, Gary	U NV, Reno, Geol Sci & Eng
Hydrology	Parsiani, Hamed	U Puerto Rico, Mayaguez, Eng
Hydrology	Pierce, Lisa	CSUSB Water Resources Inst
Hydrology	Plant, William J.	U WA, Applied Phys Lab
Hydrology	Rahman, Abdullah F.	Ball St U, Geography
Hydrology	Rincon, Rafael	NASA/GSFC
Hydrology	Rogowski, Andrew S.	Penn St U
Hydrology	Salcedo, Ramiro	FII/CPDI
Hydrology	Savage, Nora	USEPA
Hydrology	Schmitz, Sandra	USGS
Hydrology	Scott, Kevin M.	USGS — Cascades Volcano Obs
Hydrology	Scrivani, John A.	VA Dept of Forestry
Hydrology	Sendabo, Degelo	Ethiopian Mapping Authority, Remote Sensing Dept
Hydrology	Shakir Hanna, Safwat H.	Prairie View A&M U
Hydrology	Shutko Anatolij	AL A&M U
Hydrology	Stefanov, William L.	NASA JSC, Earth Sci & Image Analysis Lab
Hydrology	Tansel, Berrin	FL International U, Civil & Env Eng
Hydrology	Tatlow, Maurice A.	AZ Dept of Water Resources
Hydrology	Traversoni, Leonardo	Universidad Autonoma Metropolitana
Hydrology	Tuwaletstiwa, Phillip	Land Informations System Office Hopi Indian Tribe
Hydrology	Uddin, Waheed	U MS, Engineering
Hydrology	Vande Castle, John	UNM, U.S. and Intl Long Term Ecological Research Network
Hydrology	Vazquez Bello, Jose L.	Universidad de Puerto Rico
Hydrology	Wang, Julian X.L.	NOAA/Air Resources Lab
Hydrology	Weininger, Etai	U MI, Ann Arbor
Hydrology	White, Dale A.	OH St U, Geog
Hydrology	Williams, David	USEPA
Hydrology	Xiao, Qingfu	UC Davis, Dept. Land, Air, and Water Resources
Hydrology	Xiao, Xiangming	U NH
Hydrology	Yang, Wenli	George Mason U, LAITS
Hydrology	Yeh, Jim	U AZ, Hydrology & Water Resources
Hydrology	Zheng, Chunmiao	U AL, Geol
Image Processing	Sundareshan, Malur K.	University of AZ, Elect & Comp Eng
Imaging Processing Software	HolcombDerrold, W.	Leica Geosystems/ERDAS
InSAR Applications in Disaster Management	Davies, Richard H.	Western Disaster Center
InSAR/SAR	Madsen, Soren N.	JPL
Instrument Manufacturer	Czajkowski, David	Space Micro Inc.
Ionosphere	Pi, Xiaoqing	JPL
IT	Wang, Jeff	Lifestronics, Inc.
Land Cover	Abdollahi, Kamran	Southern U & A&M College
Land Cover	Bergen, Kathleen	U MI, Ann Arbor, Nat Resources & Envir
Land Cover	Bourgeois, Edit Kaminsky	U New Orleans, Eng
Land Cover	Chapman, Bruce	JPL
Land Cover	Chisholm, Laurie	Center for the Study of Earth from Space
Land Cover	Chuang, Liu	Global Change Info & Research Center, Inst of Geog & Nat Resources, Chinese Academy of Sci
Land Cover	Corbin, Jan	NASA/KSC
Land Cover	Filippi, Anthony M.	TX A&M University, Geography
Land Cover	Finco, Mark	RedCastle Resources — USDA Forest Service
Land Cover	Gelder, Brian	IA St U

Discipline	Name (Last, First)	Affiliation
Land Cover	Graham, William D.	NASA Earth Sci Appl
Land Cover	Haack, Barry	George Mason U Geography
Land Cover	Heo, Joon	Forest One Inc.
Land Cover	Hiza, Margaret	USGS
Land Cover	Honea, Robert B.	ORNL (retired)
Land Cover	Hugli, Wilbur	U West FL
Land Cover	Iftekharuddin, Khan	U of Memphis, Engineering
Land Cover	Jenkins, Clinton	Duke U
Land Cover	Krim, Hamid	North Carolina St U
Land Cover	Lambert, Susan Carson	KLS & KLC Commonwealth Office of Tech, KY
Land Cover	Martinez, Luis	CERM, Remote Sensing Lab
Land Cover	Mascaro, Joseph	U WI, Milwaukee, Bio
Land Cover	McKerrow, Alexa	Southeast Gap Analysis Project
Land Cover	Musinsky, John	Conservation International
Land Cover	Nkongolo, Nsalambi	Lincoln U
Land Cover	Oluwoye, Jacob	AL A&M U
Land Cover	Peleg, Kalman	USDA
Land Cover	Pierce, Leland	U MI, EECS Dept
Land Cover	Pool, Duane B.	Ducks Unlimited, Inc.
Land Cover	Price, Kevin	U Kansas, Geography
Land Cover	Sayyed, Mohammed Rafi G.	Poona College, Geol
Land Cover	Sexton, Joseph	Duke U
Land Cover	Simard, Marc	JPL
Land Cover	Spruce, Joe	Science Systems & Applications, Inc, SSAI
Land Cover	Sun, Guoqing	U MD
Land Cover	Terrie, Gregory	NASA/SSC, Science Systems & Applications, Inc.
Land Cover	Toth, Charles	OH St U, Center for Mapping
Land Cover	Treuhaft, Robert N.	JPL
Land Cover	Wang, Susan	U MO, Columbia, Geog
Land Cover	Wang, Le	TX St U
Land Cover	Wardell, Lois	MI Tech
Land Cover	Xian, George	USGS EROS Data Center, SAIC
Land Cover	Zourarakis, Demetrio	KLS & KLC Commonwealth Office of Tech, KY
Landslides	Einstein, Herbert	MIT
Liquefaction	Bardet, Jean-Pierre	USC, Engineering
Mass Spec Based Autonomous Instr.	Adams, Frederick	NASA KSC
Mass Spectrometry	Follistein, Duke W.	NASA
Mechanical Engineering	Joshi, Ghanashyam	Southern U and A & M College, Engineering
Meteorology	Weinman, James	U WA, Atmos Sci
Mission Architecture	Smith, James	JPL
Mission Technology	Bar-Sever, Yoaz	JPL
Mission Technology	Cohen, David	Vexcel Corporation
Mission Technology	Rodriguez-Sanabria, Shannon	NASA GSFC
Mission Technology	Salisbury, Gary R.	Ball Aerospace & Technologies Corp
NASA Plans	Heath, Robby	Not available
Oceanography	Chandrayadula, Tarun	George Mason U
Oceanography	Chu, Peter C.	Naval Postgraduate School
Oceanography	Cox, Charles S.	Scripps Institution of Oceanography
Oceanography	Derby, Melissa	USDA-ARS, USHRL
Oceanography	Emery, Bill	U CO-CCAR CB 431
Oceanography	Foster, Ralph	U WA, Applied Phys Lab
Oceanography	Frasier, Stephen	U MA, Microwave Remote Sensing Lab
Oceanography	Gelpi, Craig	Northrop Grumman XonTech Special Studies

Discipline	Name (Last, First)	Affiliation
Oceanography	Graber, Hans C.	U of Miami, RSMAS
Oceanography	Huang, Norden E.	NASA GSFC
Oceanography	Kearney, Michael S.	U MD
Oceanography	Kite-Powell, Hauke	Woods Hole Oceanographic Inst
Oceanography	Lehner, Susanne	U of Miami RSMAS
Oceanography	Li, Xiaofeng	STG Inc., NOAA
Oceanography	McEnaney, Patrick	Monterey Bay Aquarium Research Institute
Oceanography	Meyer, Jim	Shannon Lab
Oceanography	Nagihara, Seiichi	TX Tech U,, Geosci
Oceanography	Ponnarasu, Mohanraj	BTech
Oceanography	Ross, Robert M.	Museum of the Earth, Paleontological Research Inst
Oceanography	Ryan, John	Monterey Bay Aquarium Research Institute
Oceanography	Segall, Marylin P.	U UT, Energy & Geosci Inst
Oceanography	Shen, Hayley H.	Clarkson U
Oceanography	Sletten, Mark A .	Naval Research Lab
Oceanography	Susanto, R. Dwi	Columbia U, LDEO
Oceanography	Yan, Yuhu	U MN
Oceanography	Zhang, Xin	SIO
Oceanography	Zheng, Quanan	U MD, Meteorology
Oceanography	Giuseppe	FL St U, Geophysical Fluid Dynamics
Orbit Constellations	Mortari, Daniele	TX A&M U
Physics Education	Peoples, Chris	Sunny Hills High School, Physics
Precise Positioning	Young, Larry	JPL
Precise Radio Metric Instr. for Navigation and Positioning	Srinivasan, Jeffrey	JPL
Radar	Eydgahi, Ali	U MD, Eastern Shore, Eng & Aviation Sci
Radar/Communication Systems	Scardelletti, Max	NASA Glenn Research Center
Remote Sensing	Berglund, Judith	Science Systems & Applications, Inc, SSAI
Remote Sensing	Vincent, Robert K.	Bowling Green St U, Geol
SAR and SAR Applications	Evans, Daniel D.	The Aerospace Corporation
Satellite Geopotential Data	Taylor, Patrick T.	NASA GSFC, Geodynamics Branch
Science/Art Exhibits	Gillerman, JoAnn	CA College of the Arts & Viper Vertex
Sensor Development and Improvement	Brown, Gary S.	VA Polytech Inst & State U, Eng
Soil Science	White, Jeffrey G.	NC St U, Soil Sci
Space Data/Signal Processing	Strobel, David J.	Space Micro Inc.
Spatial Statistics	Myers, Donald E.	U AZ
Systems and Platforms	Malliot, Harold	High Altitude Mapping Missions, Inc.
Technology	Moussessian, Alina	JPL
Threat Reduction	Jeffery, Christopher A.	Los Alamos NL
Vegetation structure	Siqueira, Paul R.	JPL
Volcanology	Froger, Jean-Luc	Institut de Recherche pour le Développement (IRD)

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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