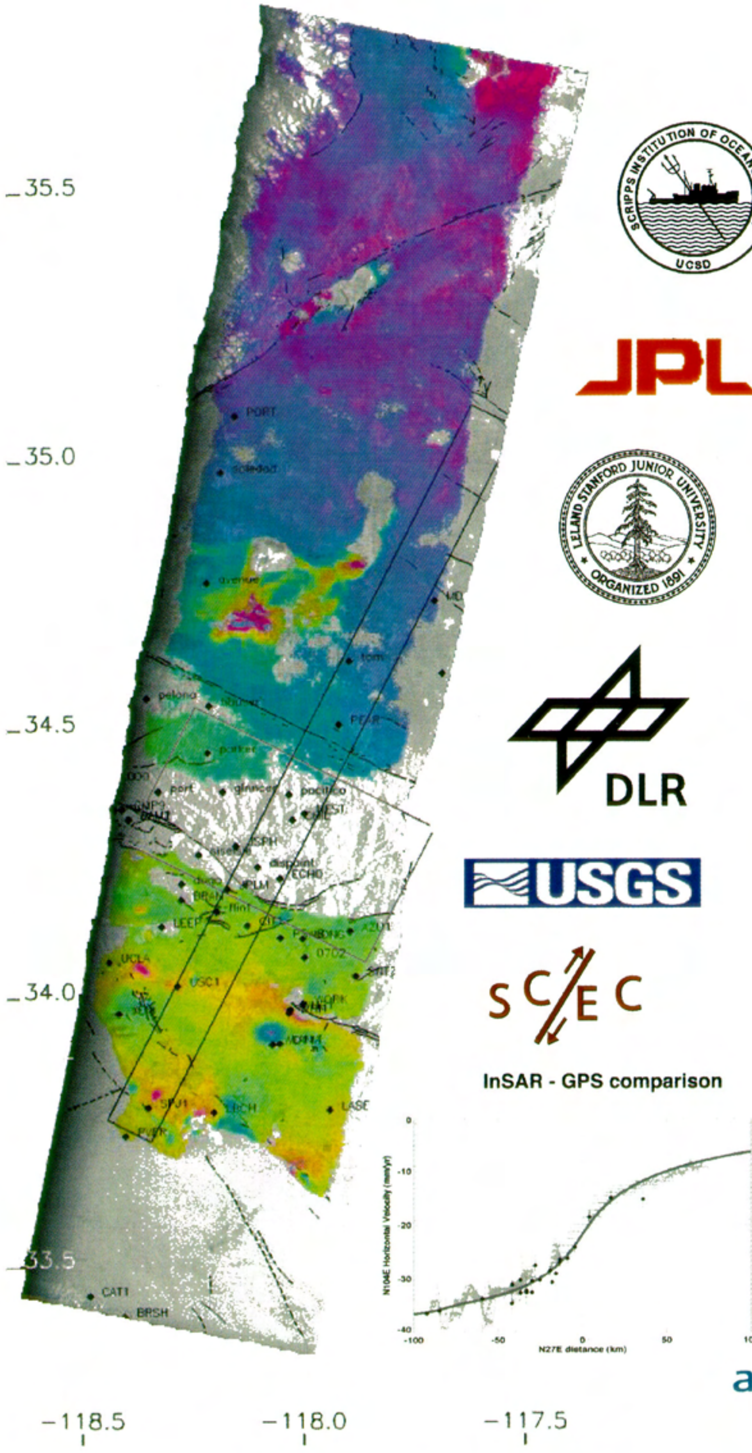
A Proposal in Response to NASA AO-01-OES-01
Earth System Science Pathfinder (ESSP) Missions

EARTH CHANGE AND HAZARD OBSERVATORY



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Earth System Science Pathfinder (ESSP) AO
Section B - Investigation Summary Form I

AO 01-OES-01 ESSP Announcement of Opportunity	Proposal No. ________ *NASA Use Only*

Principal Investigator			
Professor of Geophysics	**Jean-Bernard**		**Minster**
Title	*First Name*	*Middle Name*	*Last Name*

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Company/Institution
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Proposal Title
Earth Change and Hazard Observatory

Science/Application Research Supported
[ ] Earth System Variability and Trends
[**X**] Primary Forcings of the Earth System
[**X**] Earth System Responses and Feedback Processes
[**X**] Other (Specify) _____Natural Hazards_____
(As listed in NASA's Earth Science Research Strategy for 2000-2010 (Appendix A))

Scientific Theme, Application Research or Commercial Development topic: _____Scientific Theme_____

Abstract (Limit 150 words)

The Earth Change and Hazard Observatory (ECHO) is an L-band interferometric radar mission addressing two of NASA's Earth Science Enterprise research priorities: transformations of the Earth's surface, and variability of the Earth's ice cover and its impact on sea level. ECHO's primary scientific goals are to

- *Understand and model strain changes leading to and following major earthquakes*
- *Characterize three-dimensional magma movements to predict volcanic eruptions*
- *Assess the impact of ice sheet and glacier system dynamics on sea-level rise*

Unlike other sensors, ECHO will build time series of three-dimensional surface displacements of Earth's tectonically active areas and cryosphere with mm accuracy. The ECHO team will quantify processes such as strain accumulation along fault systems and magma migration, and will estimate the variability of ice discharge and its impact on sea level. Innovations in orbit control and ground system design result in efficient, timely data distribution and usage.

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Earth System Science Pathfinder (ESSP) AO Form
Section B - Investigation Summary Form II

AO 01-OES-01 ESSP Announcement of Opportunity	Proposal No. __________ *NASA Use Only*
Principal Investigator **Professor of Geophysics** **Jean-Bernard** **Minster** *Title* *First Name* *Middle Name* *Last Name*	
Proposal Title **Earth Change and Hazard Observatory**	
Mission Mode [**X**] Complete Mission	Cost (real year dollars) NASA ESE Cost $125.0M_ NASA Mission Cost $174.8M Total Mission Life Cycle Cost $288.2M
Anticipated Launch Vehicle: **DNEPR provided by the German Aerospace Center (DLR)**	Anticipated Launch Date: **October 2006**
Anticipated Instrument Carrier (if applicable): Astrium GmbH Flexbus	

Press Release Abstract (50 words)

The Earth Change and Hazard Observatory (ECHO), an unprecedented, dedicated interferometric radar mission, focuses on two of NASA's research priorities (1) the relation between earthquake and volcano hazards and minute surface deformations, and (2) the relation between sea level and climate change and changes in polar ice sheets and glaciers.

Co-Investigator(s)

Name	Institution	Responsibility	Funded	E-Mail
Paul Rosen	JPL	Space segment	Yes	par@parsar.jpl.nasa.gov
Howard Zebker	Stanford	Ground segment	Yes	zebker@stanford.edu
Tom Jordan	USC	SCEC liaison	Yes	tjordan@usc.edu
Ian Joughin	JPL	Ice sheet objectives	Yes	ian@radar-sci.jpl.nasa.gov
Eric Rignot	JPL	Ice sheet objectives	Yes	eric@adelie.jpl.nasa.gov
Gilles Peltzer	UCLA	Active tectonics	Yes	gilles@altyn.ess.ucla.edu
Paul Segall	Stanford	Crustal deformation	Yes	segall@pangea.stanford.edu
David Sandwell	SIO	Model corrections	Yes	sandwell@radar.ucsd.edu
Mark Simons	CalTech	Crustal modeling	Yes	simons@gps.caltech.edu
Wayne Thatcher	USGS	Volcanic objectives	Yes	thatcher@usgs.gov
Maria Zuber	MIT	SoCal natural lab	Yes	zuber@mit.edu

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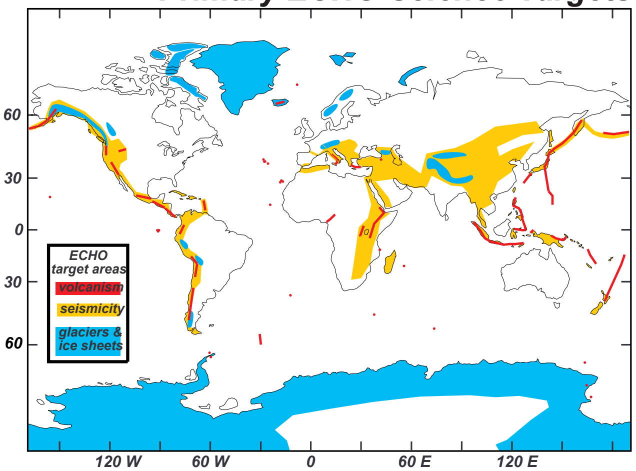
ECHO

Earth Change and Hazard Observatory

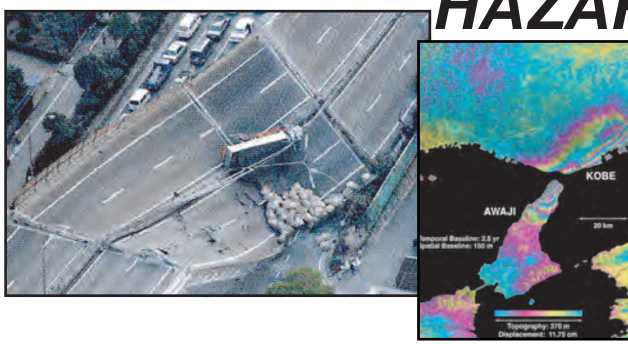
Mission Statement:
The Earth Change and Hazard Observatory is a dedicated L-band interferometric radar mission addressing two of the NASA Earth Science Enterprise strategic research priorities:
i) transformations of the Earth's surface and their predictability, and
ii) variability of the Earth's ice cover and its relation to sea level and climate change.
ECHO also contributes to the goals of the multi-agency EarthScope initiative.

Jean-Bernard Minster, SIO, PI
Howard A. Zebker, Stanford, Deputy PI
Paul A. Rosen, JPL, Deputy PI

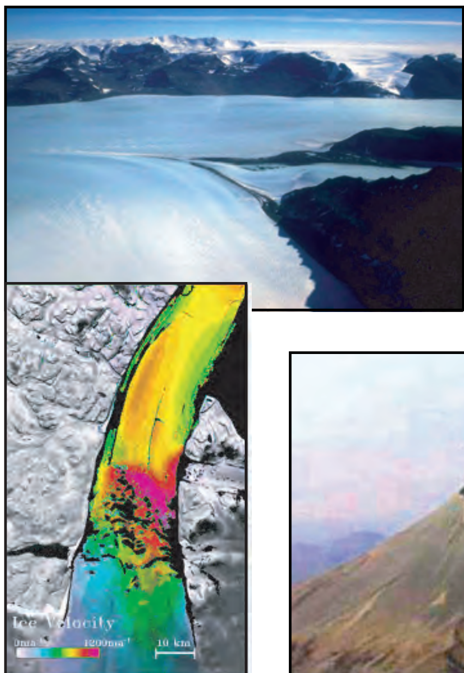
Primary ECHO Science Targets



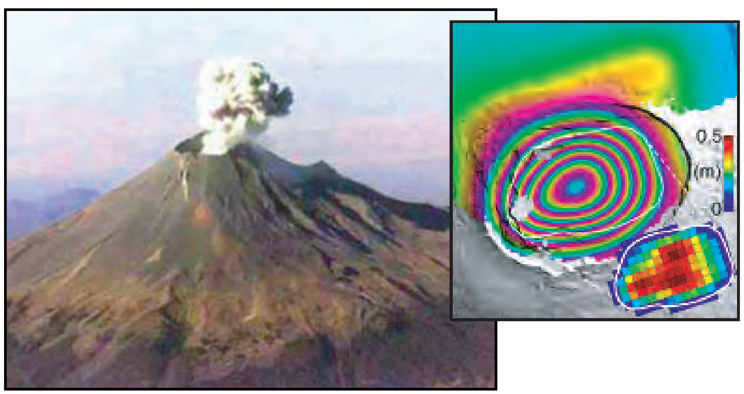
HAZARDS



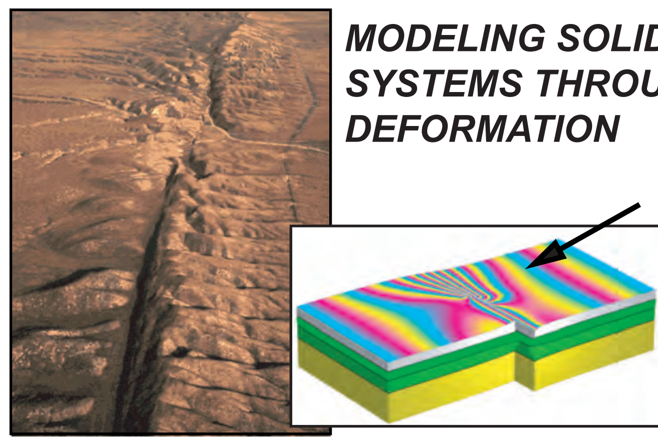
ICE

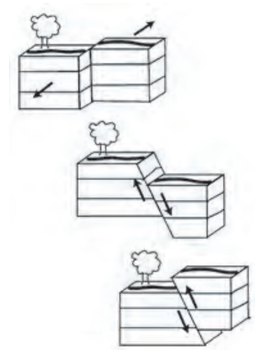


VOLCANOES



MODELING SOLID EARTH SYSTEMS THROUGH CRUSTAL DEFORMATION

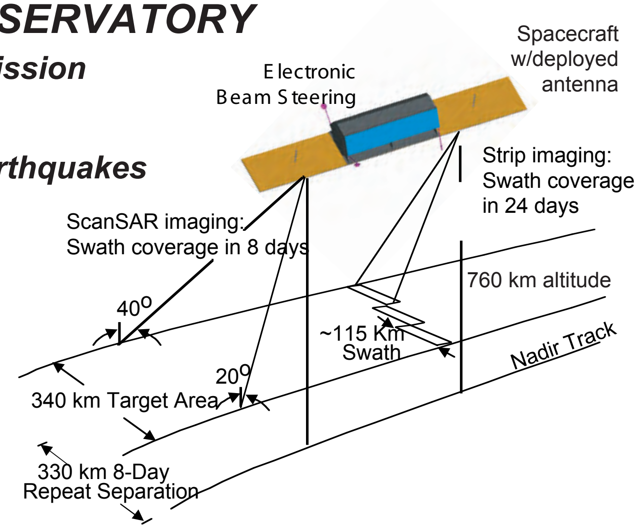




EARTHQUAKES

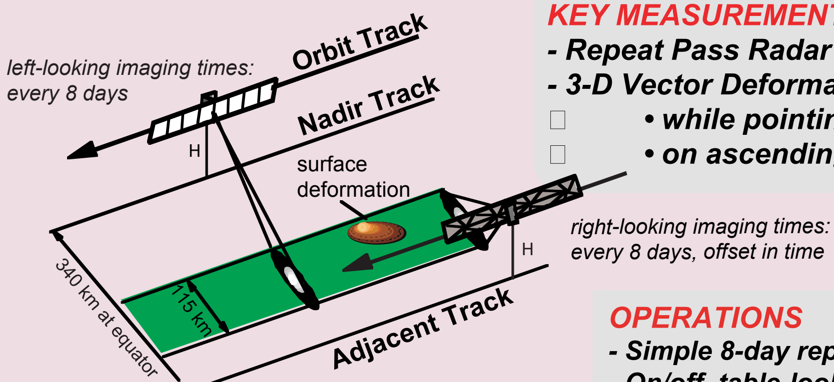
ECHO - EARTH CHANGE AND HAZARD OBSERVATORY

L-band Radar Repeat Pass Interferometry Mission



Primary Scientific Objectives:

- Understand strain changes in the Earth's crust leading to and following major earthquakes
- Characterize magma movements to predict volcanic eruptions
- Assess the impact of ice sheet and glacier system dynamics on sea-level rise



KEY MEASUREMENT TECHNOLOGY

- Repeat Pass Radar Interferometry
- 3-D Vector Deformation by observing:
  - while pointing to the left and right
  - on ascending and descending orbits

MISSION REQUIREMENTS

- 5 year baseline, 3 year minimum
- 7 minutes of data per orbit baseline,
  6 min/orbit minimum

SPACECRAFT REQUIREMENTS

- Pointing 0.05° 3-sigma yaw/pitch
  0.5° 3-sigma roll
- Maneuvers Left/right pointing at 0.1°/sec
- Downlink 300 Mbps X-band
- Storage 256 Gbits onboard

SPACECRAFT CHARACTERISTICS

- Bus Astrium TerraSAR X with deployment structure
- Mass 1533 kg wet, 1361 kg dry w/ contingency
- Power 673 W Avail., 574 W Bus+Radar (orbit avg.) w/c

NAVIGATION AND ORBIT

- Orbit Sun synchronous 6am/6pm
- Altitude 760 km
- Inclination 98.5°
- Control 250 m diameter orbital tube
- Knowledge < 10 cm using GPS ground analysis

LAUNCH VEHICLE

- DNEPR Oct 2006 (1700 kg to 400 km)
- Launch Margin 11%

OPERATIONS

- Simple 8-day repetitive mission cycle
- On/off, table-lookup commanding
- One high-latitude receiving station
- Distributed processing software

EDUCATION AND PUBLIC OUTREACH

- Leveraging of Southern California
  Earthquake Center EPO
- Coordination with established JPL
  Radar EPO

INSTRUMENT

- Single mode L-band (24 cm-wavelength)
- Dual carrier operations for ionospheric correction
- Strip mapping for 8 day target repeat
- ScanSAR mapping for 8 day global repeat
- Mass 569 kg w/ contingency
- Power 198 W (orbit avg.) w/ contingency
- Antenna 13.8 m x 2 m L-band active array
- Structure AEC-Able deployable frame
- Resolution 7 m x 25 m ground single look
- Accuracy 5 mm range displacement at 8 looks

COST ($RYM) AND SCHEDULE

Start Ph 2 — MCR — CDR — Phase 3/4 — Launch — Phase 5 — End

FY02	FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	Total	
0.20	17.97	46.05	51.34	42.96	12.49	3.99	-	-	-	175.00	NASA Cost
0.11	8.18	19.16	14.42	2.44	2.59	3.46	6.64	6.56	6.18	69.73	NSF Contribution
-	-	-	3.94	3.94	3.12	3.12	3.12	3.12	3.12	23.45	USGS Contribution
-	-	-	-	10.00	2.00	2.00	2.00	2.00	2.00	20.00	DLR Contribution
0.31	26.15	65.21	69.70	59.33	20.20	12.57	11.75	11.68	11.29	288.18	TMLCC

- Scientists from Scripps, Stanford, JPL, Caltech, USGS, MIT, USC, UCLA, Germany
- JPL Project Management, Development, Radar Electronics, MOS
- DLR Launch Vehicle, MOS
- Astrium Spacecraft - Ball Antenna - Vexcel Ground Segment
- SCEC Science and EPO Management

The ECHO Team

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3	C		Fact Sheet	Included	N/A
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58			Electronic Version of Proposal		N/A
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E. ENDORSEMENT SUMMARY

1. Principal Investigator and Deputies

   The PI and his deputies form a core consortium team for managing the mission, with the PI solely responsible for the mission, but assisted by the DPIs. The team members and authorizing officials of their institutions have endorsed the Step 2 proposal.

   a. Bernard Minster, Principal Investigator, Scripps Institution of Oceanography
   b. Charles Kennel, Director, Scripps Institution of Oceanography
   c. Paul Rosen, Deputy Principal Investigator, Jet Propulsion Laboratory (JPL)
   d. Charles Elachi, Director, JPL
   e. Howard Zebker, Deputy Principal Investigator, Stanford University
   f. Franklin M. Orr, Dean, School of Earth Sciences, Stanford University

2. Science Team Co-Investigators

   Science team members will receive funds from the ECHO project to perform critical algorithm development, calibration and validation of science data, and education and public outreach. Each co-Investigator and an authorizing official of their institution have endorsed the Step 2 proposal.

   a. David Sandwell, Scripps Institution of Oceanography
   b. Paul Segall, Stanford University
   c. Ian Joughin, JPL
   d. Eric Rignot, JPL
   e. Tom Jordan, Southern California Earthquake Center
   f. Gilles Peltzer, University of California at Los Angeles (UCLA)
   g. Mark Simons, California Institute of Technology
   h. Wayne Thatcher, US Geological Survey (USGS)
   i. Maria Zuber, Massachusetts Institute of Technology (MIT)

3. Industry Partners—Astrium GmbH, Ball Corporation and Vexcel Corporation

   Industry partners will receive funds from the ECHO project to build parts of the space segment and ground segment. A technical representative and an authorizing official of their institution have endorsed the Step 2 proposal.

   a. Bernhard Doll, Proposal Manager, Astrium GmbH
   b. M. Strodl, Vice President, Commercial, Astrium GmbH
   c. Thomas Kampe, Proposal Manager, Ball Aerospace & Technologies Corp.
   d. G.J. Chodil, Vice President, Ball Aerospace & Technologies Corp.
   e. David Cohen, Senior Engineer, Vexcel Corporation
   f. John C. Curlander, President and CEO, Vexcel Corporation

4. Agency Partners—US Geological Survey and National Science Foundation

   a. The ECHO Project will receive in-kind funding from the US Geological Survey through the contribution of the long-term archive and curation of ECHO data.
   b. The ECHO Proposal relies on substantial funding from the National Science Foundation. The Step 2 proposal is being submitted jointly to NASA and NSF. Upon favorable review by NSF, a mechanism for commitment will be established.

5. International Partner - German Aerospace Center

   a. The ECHO project relies on a contributed launch vehicle and mission operations from the German Aerospace Center (DLR). The definition of the commitment will be the subject of an MOU between NASA and DLR.

F. SCIENCE INVESTIGATION

The **Earth Change and Hazard Observatory** (ECHO) mission consists of a satellite Interferometric Synthetic Aperture Radar (InSAR), capable of measuring surface motions ranging from millimeters per year during strain accumulation between earthquakes to several meters per day on ice-streams. ECHO will address the following overarching science questions:

- How does strain accumulate along faults and plate boundaries, and how is it released during the earthquake cycle?
- What are the spatial and temporal deformation patterns of volcanoes worldwide, and how can these data help predict eruptions?
- What is the rate and variability of ice discharge, and what is its relation to sea level rise and climate change?

These questions address two of the five key research priorities of the NASA *Earth Science Enterprise* (ESE) *Research Strategy for 2000-2010:* Primary Forcings of the Earth System, and Earth System Responses and Feedback Processes. Specifically, ECHO is designed to characterize, understand, and model: *i) "How is the Earth's surface being transformed, and how can this information be used to predict future changes?"* and *ii) "How is global sea level affected by climate change*?" ECHO achieves these diverse goals through a single measurement—mm-level surface deformation at resolutions of tens of meters with worldwide accessibility.

ECHO's unique scientific potential stems from its ability to measure detailed deformation over wide areas. During the past two decades, space geodetic techniques, in particular GPS, have proven a powerful way to study deformation of the Earth's surface, leading to major advances in quantitative modeling capability. These measurements, however, require much field work and will always lack spatial continuity, which leads to aliasing and consequent ambiguity in interpretation. Hence, the first interferometric radar maps of the co-seismic displacement of the 1992 Landers earthquake [*Massonnet et al.*, 1993*; Zebker et al.,* 1994] were arguably the most exciting recent development in earthquake science.

Global, comprehensive, and finely detailed measurements of deformation make it possible to discover and analyze motions of the Earth's crust that simply pass unnoticed today. In particular, because ECHO will generate *time-series* of displacement maps, it will be a unique tool to detect slow (weeks to years) transient deformations that have only been inferred or observed occasionally in isolated seismic (e.g., *Dragert et al*., 2001), volcanic (e.g., *Wicks et al.*, 2001) or glacial areas (e.g., *Joughin et al*., 1996). This exciting new possibility will open a domain of spatial and temporal scales heretofore inaccessible to Earth scientists except by serendipity.

Because no mission dedicated to this purpose exists, spaceborne interferometry remains primarily a demonstration tool. International systems planned for launch, including ENVISAT, ALOS, and RADARSAT 2, are not optimized for interferometry and are not likely to provide data significantly better than the ERS and RADARSAT systems. Data availability, quality, and temporal and spatial coverage continue to be major concerns of scientists using these sensors.

The science community has endorsed the need for a mission like ECHO through the EarthScope inititiative. EarthScope is a major collaborative solid Earth science initiative sponsored by the National Science Foundation (NSF), NASA, and the US Geological Survey (USGS). EarthScope will lead to an unprecedented deployment of instruments and observatories that will greatly increase our knowledge and understanding of the structure, evolution, and dynamics of the North American continent. Collectively, ECHO and other EarthScope facilities will generate a synoptic time-series of images of the continent to provide an integrative framework for research on earthquakes, magmatic systems, regional tectonics, and associated hazards.

The science questions addressed by ECHO have a strong societal benefit. A significant fraction of the Earth's population lives in or near areas likely to experience earthquakes, volcanic eruptions, or the consequences of sea level change. Better understanding of these hazards through ECHO-related studies can help mitigate the consequences, potentially saving lives and reducing economic impact.

ECHO will achieve its objectives through a long-duration InSAR mission. A 5-year mission allows sufficient time to observe the slow rates of inter-seismic deformation along faults. A tightly controlled orbit guarantees that all measurement pairs will be interferometrically viable. An L-band radar (λ=24 cm) will overcome temporal decorrelation problems in regions of appreciable ground cover, which plague C-band systems, opening large areas of the Earth to geodetic study. In addition, ECHO will resolve and correct dispersive ionospheric delays by using two sub-bands separated by 70 MHz. Unlike existing radar systems, ECHO will image from either side, providing the multiple view angles necessary to obtain 3D vector displacement maps.

The ECHO science team consists of world leaders in radar interferometry and the analysis and modeling of deformation of the solid Earth and cryosphere. ECHO will use a novel distributed processing scheme whereby science investigators are provided with SAR data and the software tools necessary to generate the calibrated maps of surface displacement needed to meet the science objectives. The science team will calibrate and validate ECHO data, and will ensure that ECHO products and software are suitable for the science objectives.

F.1 Science Objectives and Justification

ECHO will bring a fundamentally new data type to the study of changes of the Earth's surface: time series of spatially continuous, vector maps of surface change associated with earthquakes, volcanoes, ice sheets, and glaciers. As with many new observational capabilities, ECHO will undoubtedly lead to major new discoveries, in addition to the contributions described below. The principal geographic focus areas include regions of active tectonics and regions of glaciation, or approximately 10% of the area of the Earth.

F.1.1 Seismic Hazards

NASA's ESE Research Strategy identifies surface deformation as the primary measurement needed to begin answering the question "*How is the Earth's surface being transformed and how can such information be used to predict future changes?*" ECHO will provide deformation measurements to address the following earthquake science objectives:

1. Detect and map inter-seismic and potentially pre-seismic transient strains, which remain elusive and raise a major challenge to our understanding of the earthquake cycle.
2. Derive models of faulting and crustal rheology from vector co- and post-seismic displacement maps, complementing conventional seismological and geodetic measurements.
3. Assimilate vector maps of surface deformations through various stages of the earthquake cycle in large-scale numerical simulations of interacting fault systems, currently a "data-poor" discipline.

Spatially continuous maps of vector surface displacement provide critical bounds on models of co-seismic fault rupture. By itself, InSAR provides maps of surface faulting complexity and constrains its extent at depth. In elastic models of the lithosphere, geodetic data can constrain the spatial distribution of slip on a fault plane (e.g., *Melbourne et al.,* 1997). When combined with seismic data, these models can estimate the temporal evolution of slip during an earthquake (e.g., *Chen et al.,* 2001). Such models permit us to estimate the distribution of co-seismic stress drop, to calculate ground acceleration, and to infer the characteristics of strain release in the shallow crust. Well-constrained co-seismic models of recent events also can be compared with inferences of earthquake magnitudes from geological field observations, providing a long-needed calibration of paleo-seismological inferences of historic earthquakes (e.g., *Rockwell et al.,* 2000).

Besides providing an understanding of co-seismic processes, accurate models of the co-seismic "kick" are required as input, along with post-seismic geodetic data, to constrain models of the post-seismic response of the crust [*Deng et al.,* 1998; *Pollitz et al.,* 2000]. Such post-seismic models (Fig. F-1) help constrain the rheological behavior of the lithosphere, thus providing clues to the long-term structural evolution of the tectonic plates and their boundaries.

Mapping slow Earth deformation poses the greatest scientific challenge for ECHO. This deformation includes the inter-7seismic strain accumulation leading up to earthquakes, as well as transient post-seismic strain relaxation following earthquakes. Such signals are subtle, with mm-sized displacements and long spatial wavelengths that are vulnerable to systematic measurement errors. These signals have only been detected with InSAR in limited regions

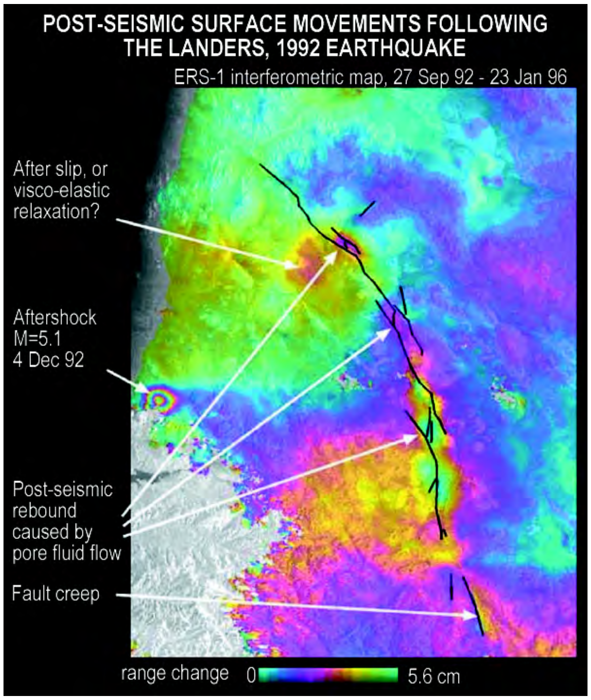

Figure F-1. This ERS-1 interferogram illustrates deformation signatures of several post-seismic processes after the 1992 Landers earthquake in California that were not observed in conventional geodetic data [*Peltzer et al.*, 1996]. Visible are the poro-elastic rebound in the fault stepovers, the effect of visco-elastic relaxation in the deeper crust, fault creep, and the effect of an aftershock. ECHO will make such observations routinely.

and under ideal conditions [*Peltzer et al.,* 2001]. Accumulation and release of strain in the Earth's crust is a first order indicator of future seismic hazard. Post-seismic fault creep and flow of the lower crust are crucial to the time-dependent stress transfer to neighboring faults. Stress diffusion has long been thought to cause earthquake clustering and the propagation of major seismic events along fault zones. For the first time, InSAR provides the means to map crustal strain with full spatial continuity. ECHO therefore has unprecedented potential to identify otherwise unknown areas of strain accumulation and fault interaction.

Current models of deformation are severely limited in detail, mostly due to imperfect knowledge of the boundary conditions. With GPS, at most a few hundred point measurements ever will be available in any region. ECHO will transform the field from "data poor" to "data rich," making possible study of earthquakes in extraordinary detail. We will effectively carry out a "stress analysis of the Earth," similar to that used by civil and mechanical engineers to study materials and structures. These ECHO-derived data will be the most important constraint on generalized earthquake models that simulate the dynamics of interacting fault systems.

The danger posed by blind thrusts in the Los Angeles (LA) basin provides an illustration of the potential contribution of InSAR-generated maps of surface deformation. The Southern California Integrated GPS Network (SCIGN), a 250-station, continuous-GPS network to monitor crustal deformation across the basin, provides time series of strain accumulation. Nevertheless, with a nominal station spacing of 10-15 km, there remain serious gaps. InSAR mapping shows that about half of the SCIGN sites in the LA basin are contaminated by spurious seasonal and long-term motion due to groundwater pumping [*Bawden et al.,* 2001]. These deformation features, ranging from a few km to tens of km, could be identified only through the continuous mapping capabilities of InSAR. Pinpointing their effects will permit SCIGN to better achieve the goals for which it was designed. Likewise, and over much wider regions, ECHO will provide a quantitative means of interpolating the displacement field between GPS sites [e.g., EarthScope Plate Boundary Observatory (PBO)]. Conversely, GPS provides valuable "tie" points in the calculation of interferograms.

Finally, ECHO may prove invaluable for disaster response following earthquakes. Northridge and Kobe results show that urban areas maintain interferometric correlation except where there has been extensive damage. Thus, interferometric decorrelation could help map the extent of destruction. Wide-scale damage maps would be most valuable for the largest events—say a great earthquake on the Cascadia subduction zone or the Wasatch front—or for earthquakes in inaccessible areas such as Caucasus, Tien Shan, or Tibet.

F.1.2 Volcanology

ECHO's volcanic hazard objectives flow from the same NASA ESE crustal deformation science priority just described under seismic hazards. Here science objectives specifically relate to improving our understanding of the volcanic cycle and to developing a predictive capability. ECHO's volcanology objectives are to collect deformation data in order to:

1. Derive models of magma migration from the spatial and temporal extent of deformation preceding and accompanying eruptions.
2. Quantify pressure changes at depth resulting from magma intrusion beneath many of the world's ~600 active volcanoes.
3. Analyze the spatial extent of new material deposited during an eruption, an important diagnostic of the eruption process.

Deformation data are the primary observables in understanding magma movement within volcanoes. Although uplift from the ascent of magma into the shallow crust has been observed prior to some eruptions, particularly on basaltic shield volcanoes, the spatio-temporal character of such transient deformation is poorly known. Little is known about deformation on most of the world's volcanoes because only a small fraction is monitored. ECHO's global access capability will permit study of many volcano types in different environments. InSAR has already been used at Mt. Etna to investigate the balance between lava production and volume change of the volcanic edifice during an eruption [*Massonnet et al.,* 1995; *Lanari et al*., 1998], and in the Galapagos Islands (Fig. F-2) to map dike intrusions [*Jonsson et al*., 2001] and magma chamber volume changes [*Amelung et al.*, 2000]. Detection and modeling of such transients could provide warning of impending eruptions, reducing loss of life and mitigating property damage.

Significant hazards are posed by active calderas that have been the source of large eruptions. For example, the Long Valley caldera has

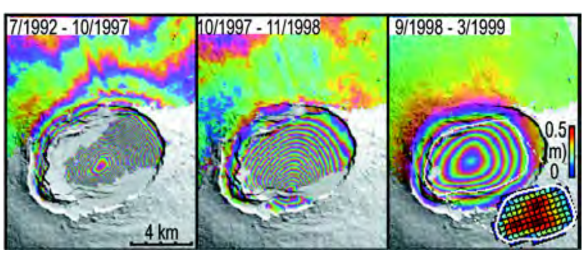

Figure F-2. Monitoring of volcanic regions can reveal unexpected phenomena, such as this series of interferograms from Sierra Negra on the Galapagos island of Isabela [*Amelung et al*., 2000]. For most of the 1990's, inflation due to magma chamber growth dominated, but in the 1997-98 period a "trap-door" faulting episode shifted the deformation towards the caldera rim. The high resolution of InSAR also led to a solution for a map of change in the magma distribution.

experienced several sequences of moderate earthquakes (M6) in the past two decades. The caldera itself has experienced ground uplift of 800 mm since 1979 [*Battaglia et al.*, 1999; *Langbein et al.,* 1993], probably as the result of the injection of 0.1 km^3 of magma beneath the caldera [*Langbein et al.,* 1993]. In view of such volcanic hazards, it is essential to complement ground-based geodetic data with InSAR deformation maps [*Thatcher and Massonnet,* 1997; *Simons et al.*, 2000].

ECHO also will provide unique observations of active surface processes on volcanic edifices. SIR-C yielded maps of active lava flow evolution on Kilauea volcano from the daily area of surface decorrelation over a 4-day period [*Zebker et al.,* 1996]. ECHO will monitor the growth of potentially unstable lava domes (e.g., Soufriere Hills, Montserrat, West Indies and Mt. Unzen, Japan). Collapse of such domes can lead to devastating pyroclastic flows. The remobilization of ash deposits to form lethal mud flows (lahars) could also be detected via decorrelation maps. Field observations of lava flows are difficult, often dangerous, and rarely permit an entire flow field to be studied simultaneously. The all-weather surface imaging capability afforded by ECHO will advance our understanding of these.

F.1.3 Ice Sheets and Glaciers

The impact of sea level change on coastal populations is of great societal importance. Glaciers are currently experiencing a global retreat, contributing to sea-level change. Potentially larger contributions from Greenland and Antarctica are less well known (*Report of Working Group I of the IPCC, 2001*). In response, NASA's ESE Research Strategy identifies two fundamental questions related to ice sheets and glaciers*: i) What changes are occurring in the mass of the Earth's ice cover? and ii) How is global sea level affected by climate change?*

The primary measurements identified by the *NASA ESE Strategy* to address these questions are ice-sheet velocity (InSAR) and precise topography (altimetry). ECHO data will help

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.

Ice sheets and glaciers can be driven out of balance either directly by climate through precipitation/melt change or by dynamic instability caused by a change in ice flow, which may or may not be climate related. The ICESat and GRACE missions will allow measurement of ice sheet thickening/thinning rates and mass change. ECHO will provide critical data for the complementary measurement of surface velocity, and hence ice discharge [*Rignot et al.,* 1997], needed to relate observations of ice volume change to ice dynamics (e.g., *Joughin et al.,* 1999). In particular, ECHO data will permit distinguishing the thinning caused by ice flow from that caused by accumulation and melt on both ice sheets and temperate glaciers.

Traditionally, ice sheets have been assumed to evolve slowly with dynamic response times of the order of centuries to millennia [*Paterson*, 1994]. Recent InSAR analyses challenge this model. Although only a small fraction of the world'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], and a post-surge stagnation front [*Mohr et al.*, 1998]. Decadal-scale acceleration and deceleration have been observed in West Antarctica (Figs. F-3 and F-4). InSAR also has been used to detect the migration of glacier grounding lines [*Rignot,* 1998], which is a sensitive indicator of thickness change. These observations of temporal variation have been too sparse to ascertain whether they constitute normal ice-sheet variability or indicate long-term change. Thus, ECHO will frequently (as often as every 8 days) monitor outlet glaciers in order to characterize and understand their short-term temporal variability. Comparison with 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 velocity data provided by ECHO will be used to validate existing models and to motivate the development of new ones. In conjunction with ice sheet models, ECHO 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.

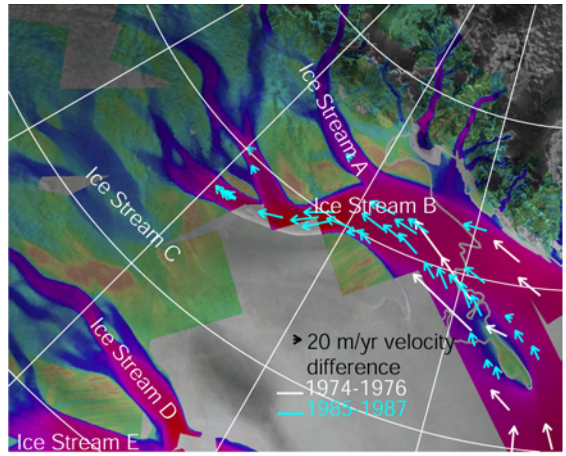

Figure F-3. Velocity change (vectors) on Ice Stream B between field measurements (1970's-1980's) and RADARSAT InSAR (1997; color coded). Deceleration rates of 5.5 m yr-2 were detected, suggesting Ice Stream B could stagnate in 80 years, as did neighboring Ice Stream C 150 years ago [*Joughin and Tulaczyk*, 2002].

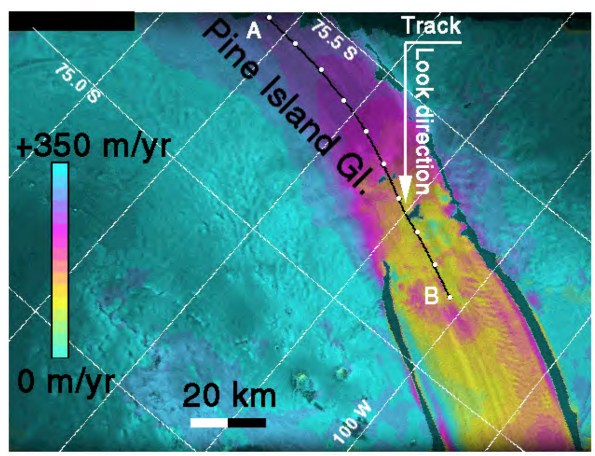

Figure F-4. This InSAR velocity difference indicates a 10% increase in velocity from 1996 to 2000 on Pine Island Glacier [*Rignot et al.,* 2001], which produces the largest ice discharge from West Antarctica. Additional data show an 18% increase from 1992 to 2000. This is the strongest evidence for ongoing thinning in this sector of West Antarctica.

F.1.4 Application Science

ECHO data will be useful for studying other geophysical phenomena of strong scientific value and societal benefit. One example (Fig. F-5) is the study and management of groundwater aquifer systems [*Hoffman et al.,* 2001*; Amelung et al.,* 1999]. Although withdrawal of water from subsurface aquifers represents only a small term in the global water cycle, the limited nature of this resource directly determines the habitability of many arid areas. ECHO observations will lead to better models and improved management of this important resource. Other examples include landslides, floods, oil extraction, and coastal erosion.

F.1.5 Underlying Physics of the Measurements

InSAR measures surface deformation through repeated observations of an area from one or more vantage points over time. The phase of a complex radar image incorporates the intrinsic phase scattering characteristics of the imaged surface and the propagation delay, which is proportional to the distance from the radar to the surface. The phase difference between two SAR images acquired at different times from nearly identical locations measures the changes in path lengths from the surface to the sensor. A map of this difference (an interferogram) includes both topography parallax and surface deformation that occurred in the time interval. The surface displacement field is isolated by removing the topographic component through other InSAR observations [*Gabriel et al.,* 1989] or independent elevation data [*Massonnet et al.,* 1994]. The relative positions of the surface scatterers within a resolution element may change over time (e.g., vegetation growth), adding temporal decorrelation noise. Other effects limiting the measurement accuracy include baseline-dependent geometric decorrelation, atmospheric and ionospheric refractive variability, and errors in the topography used in data reduction. Unlike existing systems, ECHO mission characteristics minimize these sources of error.

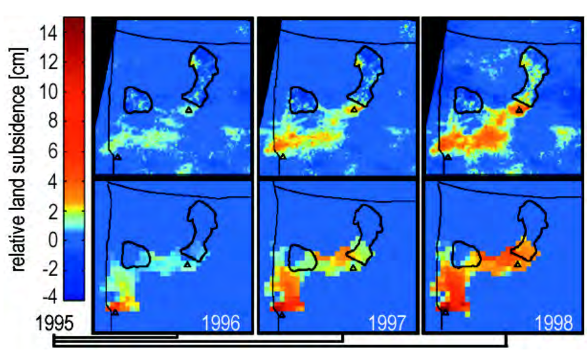

Figure F-5. Comparison of measured (InSAR) and modeled subsidence from groundwater removal in the Antelope Valley, California [*Hoffmann et al.*, 2001].

F.1.6 Mission Characteristics

ECHO will meet its science objectives with a low-cost SAR system aboard a single dedicated spacecraft (S/C). A 5-year mission is required to meet all these objectives. The L-band SAR uses two sub-bands with 70-MHz separation to permit ionospheric corrections similar to the L1/L2 GPS approach. While the instrument is based on existing technology, it represents a major leap forward in measurement capability. ECHO is optimized specifically to overcome the many limitations of existing systems (see Table F-1). Instrument and mission design elements for achieving the science objectives are

- L-band minimizes temporal decorrelation.
- No complications arise from competing science objectives or other instruments.
- Two sub-bands separated by 70 MHz allow correction of ionospheric effects.
- Onboard GPS for cm-level orbit and baseline knowledge improves calibration.
- Orbit maintenance within a 250-m tube guarantees that every scene is interferometrically viable.
- The S/C right/left roll capability allows the fixed-mount radar antenna to point to either side of the orbit plane, permitting vector displacement measurements and full coverage of polar regions.
- Frequent coverage for target areas allows averaging to reduce artifacts from atmospheric and other noise sources.
- Electronic beam steering minimizes S/C interactions for acquisition, and allows greater flexibility in science planning via wide-swath ScanSAR operations.

The mission is resilient with respect to degradation of these characteristics. Orbit control within a 250-m tube is a new capability; several LightSAR studies have indicated that such control is achievable. Even if orbit control were only comparable to ERS, the critical baseline (maximum baseline) scales with wavelength so that ECHO performance at L-band would be better by a factor of four than at C-band.

F.1.7 Relation to Past, Present, and Planned Missions

A dedicated InSAR mission measuring crustal deformation is needed to achieve significant increases in our ability to understand and perhaps forecast Earth surface change. Many InSAR applications have been demonstrated. Although impressive, existing InSAR systems are limited in scope and precision (Table F-1). ECHO will be a major advance over existing and planned systems.

ECHO will offer shorter repeat intervals to resolve fine space-time details of major events, and to provide practical response times to natural disasters. Short repeat times allow multiple acquisitions to eliminate (by averaging) noise caused by atmospheric propagation variations that limit current systems to cm or poorer accuracy in regions of even moderate humidity [*Massonnet et al.,* 1994*; Goldstein* 1995; *Zebker et al.,* 1997].

L-band avoids much of the temporal decorrelation that plagues C-band systems over vegetation [*Zebker et al.,* 1996] and temperate ice [*Rignot et al.,* 1996]. Using two sub-bands allows correction for ionospheric variations. Also, an experimental pass-to-pass ScanSAR synchronization mode will allow InSAR comparison of 340-km swaths (three times the nominal swath width) and could triple coverage on selected acquisitions, in area or in frequency.

RADARSAT has been used in a campaign mode to map Antarctica [*Jezek*, 1999], but the extent and accuracy are limited by the satellite's 24-day repeat cycle. ECHO will provide the first complete continuous monitoring of ice sheets and glaciers needed to study changes in ice mass and the related impact on sea level.

Restricted data availability limits the usefulness of the current generation of radar satellites. ECHO data will be freely provided to the scientific community via online access within 24 hours of downlink and tape delivery.

F.1.8 Relation to Existing Techniques

Tectonic plate motion and localized crustal deformation are measured by a variety of tools, including continuous GPS [*Bock et al.,* 1997]. In spite of their exceptional accuracy, these widely spaced measurements can spatially alias the geophysical signals of interest. In contrast, InSAR provides nearly spatially continuous maps of surface deformation, as illustrated by Figure F-1, showing post-seismic deformation following the 1992 Landers M7.6 earthquake. Only InSAR can generate this type of map.

InSAR and GPS are complementary in that GPS affords superior temporal resolution and long-term (decadal) stability, but InSAR provides strain maps at spatial densities several orders of

Table F-1: ECHO characteristics overcome many limitations of existing and planned SARs.

Sensor Characteristic	ALOS	ERS/ENVISAT	RADARSAT 1/2	ECHO
Prime Mission	Multipurpose	Multipurpose	Multipurpose	Dedicated InSAR
Repeat Period	44 days	35 days	24 days	8 days
Coverage	Few repeat pass areas	Limited/Global; limited repeat passes.	Few repeat pass areas.	Global; frequent collection over seismic/volcanic/ice
Orbit control	Moderate	Moderate	Poor/unknown	Excellent (all data good for interferometry)
Left/Right Imaging for Vector Measurement	No	No	Limited/Yes	Yes
Atmospheric	Poor	Poor	Poor	Good (can average multiple repeats)
Ionospheric	Poor	Good	Good	Very good (dual sub-band correction)
Temporal correlation	Good (L band)	Poor (C band)	Poor (C band)	Good (L band)
Data availability	Limited access	Moderate	Costly	Excellent
Wide-swath for greater coverage	ScanSAR but not for InSAR	ScanSAR but not for InSAR	ScanSAR but not for InSAR	InSAR-capable ScanSAR 340-km swath.

magnitude finer. Long-baseline strain- and tilt-meters, while exquisitely precise, are onerous to install and maintain, thus very few exist. ECHO will map sub-mm-level displacement, enabling worldwide deformation studies. ECHO will regularly collect data for the many areas that remain uninstrumented (e.g., Fig. F-2).

InSAR also allows mapping of faster processes, such as rapid ice flow [*Goldstein et al.,* 1993]. InSAR is the only way to map velocity over the featureless areas that comprise the majority of the ice sheets. Glacier motion is vastly under-sampled by *in situ* measurements (GPS) and optical imagery can only provide velocity estimates in crevassed areas (feature tracking).

F.1.9 Sensitivity Analysis

ECHO will vastly improve sampling of the deforming part of the Earth's surface. InSAR data from existing sensors hint at the power of these observations, but application has been limited to those areas where conditions are ideal. In addition to the description below, further sensitivity considerations are described in Sections F.1.1–F.1.3

For most fault systems, there is no ground infrastructure to monitor deformation. Even on heavily instrumented faults, measurements are too sparse for many applications. ECHO will allow estimation of strain accumulation on a worldwide distribution of locked faults. Even a minimum mission with accuracy reduced to 4 mm yr^{-1} would still provide an adequate sampling along fast-slipping faults and a globally distributed data set of slip distribution far more complete than existing ones.

ECHO acquisitions will provide concurrent observations of over 600 volcanoes, which is impractical with ground-based measurements. In many cases, ground-based instruments are not deployed until an eruption is imminent. Accuracies of 5-10 mm will allow detection of subtle motion leading up to eruptions. A reduction in sampling frequency to 2 months would impact our ability to model basaltic volcanoes that evolve rapidly, but should have less impact for silicious volcanoes formed by more viscous magmas. It would also result in longer delays in detecting potential eruptions.

ECHO will provide the first comprehensive mapping of ice sheet velocity with which to estimate ice discharge and determine controls on fast flow. Although RADARSAT has collected InSAR data for ice velocity, accuracies on fast moving glaciers are limited to ~5 m yr^{-1} with 1-5 km resolution [*Joughin et al*., 1999]. ECHO will improve accuracy to 1 m yr^{-1} at 100-m resolution. Limited InSAR data already have revealed a surprising degree of temporal variability in ice flow. ECHO will provide the frequent sampling needed to characterize the short-term variability of glaciers.

F.2 Measurement Objectives and Nature of Investigation

The ECHO mission consists of an L-band SAR interferometer optimized to collect the surface deformation data necessary to meet the science objectives described above.

F.2.1 Mission Overview

ECHO will fulfill the science objectives with a low-cost, SAR, launched on a contributed Russian Dnepr rocket. Because it is dedicated to, and configured for, repeat-track InSAR, ECHO will provide breakthrough performance for crustal deformation and ice motion science.

The S/C will fly a 5-year mission on a tightly constrained, 8-day exact-repeat Sun-synchronous polar orbit, at an 760-km altitude. The ground separation between orbit tracks is roughly 340 km at the equator. With three radar swaths averaging 115-km wide and steerable over a 340-km range, any point on the Earth can be imaged every 8 days. Complete coverage of any broad area requires 24 days (three 8-day repeats). An experimental ScanSAR mode yields a 340-km swath, allowing full coverage every 8 days. A more detailed description of the mission characteristics is included in Section F.1.6

F.2.2 Measurement Requirements

The ECHO measurement requirements are summarized in Foldout (F/O) Table F1-1. Many objectives require vector deformation measurements; hence observations from at least three different directions are needed. The most stringent resolution requirement is 35 m with 4 radar looks for characterizing fault geometries after earthquakes.

Characterizing inter-seismic strain accumulation is one of the highest priority goals; it is the one that drives accuracy requirements. The baseline-mission single-component accuracy requirement of 2 mm yr^{-1} over spatial scales of a few hundred km for inter-seismic objectives allows confident estimation of strain accumulation on locked faults with long-term slip-rates of 10-20 mm yr^{-1}. This also allows detection and limited measurement for the large fraction of faults that have substantially lower slip-rates. This requirement allows estimation of average strain rates of order 10^{-7} yr^{-1}. This stringent requirement will be achieved by averaging multiple observations (Fig. F-7). A 5-year mission is required to observe sufficient deformation in order to achieve the desired accuracy and to provide a sufficient sampling of earthquakes and other seismic events.

The baseline mission must cover the principal volcanic regions of the Earth (including arc volcanism, shield volcanoes, and calderas) at least monthly. Two components of displacement must be recorded with 5- to10-mm accuracy over distance scales of 25-50 km, as these are the scales of precursory inflation. This requirement is met with a single observation (Fig. F-6) so that multiple observations can be used to build time series of volcanic activity.

The ECHO ice sheet objectives require an accuracy of 1 m yr^{-1} over scales of 200 km and greater. This accuracy is needed to resolve small changes in velocity (e.g., 2.4 m yr^{-2} deceleration at the UpB camp, Antarctica), and for studies using inverse techniques to infer basal controls on fast flow. This requirement translates into a displacement accuracy of 11 mm over 8 days. Averaging of multiple observations (1-4) and/or longer intervals (> 8 day) can provide this accuracy. Coverage must ensure at least two full mappings (with multiple repeats) of ice sheet velocity in Greenland and Antarctica. Frequent acquisitions are required to monitor roughly 60 glaciers and ice streams for change.

F.2.3 Baseline Mission

The baseline 5-year mission meeting the above requirements has the characteristics listed in Section F.1.6. The L-band mission will enable inter-seismic studies globally. In the baseline mission, science data will be acquired at an average rate of 7 min/orbit. These data will be provided to users, along with the software necessary to process them to calibrated displacement maps.

F.2.4 Minimum Mission

Characterization of co-seismic and post-seismic portions of the crustal strain budget on several major plate boundaries is a minimum requirement. Global accessibility would still be required to sample a sufficient number of events. Measurement of inter-seismic deformation throughout a single plate boundary zone is also a minimum requirement.

Binary observation of the full set of ~600 active volcanoes is a minimum objective. A minimum subset of ice sheet objectives is a single ice sheet mapping and frequent sampling of ~40 glaciers.

F.2.5 Calibration/Validation Measurements

The ECHO *in situ* calibration and validation strategy will be based on the concept of *"natural laboratories"* which we define as geological targets of scientific interest, for which considerable ground truth is available (e.g., geodetic networks). Radar calibration (common range and phase delays) will require ground-based corner reflectors in the California's Mojave Desert and Alaska. Further details are given in Section F.4.10. Also, individual investigators may improve the accuracy of their baseline estimates using measurements that they acquire in the field.

F.2.6 Descopes Options

ECHO relies on a single simple instrument. Removal of the ScanSAR timing vernier would disable ScanSAR to ScanSAR operations, but save ~$1M if implemented before CDR. Removal of this experimental cabability would have no impact on the baseline mission. An additional $1M could be saved before PDR by removing the phase shifters for ScanSAR and electronic steering so that S/C roll would be needed to steer the beam. This does not compromise the baseline objectives, but loss of beam agility would add cost and complexity to the instrument tasking.

Replacing the Blackjack GPS receiver and associated Precision Orbit Determination (POD) activity with a commercial single-frequency GPS receiver is a descope that would save up to $5M if implemented at or before PDR. Orbits better than 1 m could be achieved with a cheaper commercial receiver. This accuracy is sufficient for navigation, but science analysis would rely more heavily on ground control for InSAR baseline estimation, making it more labor intensive and reducing the overall rate of science return.

Another descope that trades cost against science return, involves reducing the data volume by 15–25% so that it is possible to use only a single ground station, thus reducing the archive and distribution load to save roughly $3–5M. All of these reductions in hardware occur during Phase

3/4. In addition, the regional on-line archive concept could be scaled back, delaying delivery of data to the users by up to several months. This would save about $10M in hardware procurement, maintenance and operations. This could impact the science return in the timeframe of the mission, but would preserve the historical integrity of the data since all data will be stored at the EDC.

F.3 INSTRUMENTATION

The SAR instrument consists of a radar electronics package and a deployable active antenna. F/O Figure F1-1 shows the instrument block diagram. F/O Table F2-1 lists the instrument characteristics.

F.3.1 Instrument Overview and Functional Description

F.3.1.1 Radar Instrument Electronics. The radar electronics perform the transmit waveform generation to excite the antenna, and perform the receive echo downconversion and digitization. The radar instrument electronics will be built at the JPL, drawing on expertise in L-band radar design with heritage from the SeaSat and SIR programs. Developments in space-qualified electronics, and standardization of many of the hardware components allow for a capable and reliable low-cost radar. The instrument RF, digital, and mixed signal hardware, including the reference oscillator, digital chirp generator, up- and down-conversion mixers, filters, RF switches and amplifiers, analog-to-digital converter, high-rate data handling circuitry, and radar control and timing, will be housed in a shielded enclosure. The radar electronics will be *fully redundant*, allowing recovery from any single-point failure. The radar electronics mass will be ~69 kg (includes 30% contingency). The antenna control interface and power distribution electronics, to be built at Ball, will be housed separately as discussed below.

The radar will transmit and receive a single linear polarization (HH) in two frequency sub-bands (split-spectrum) separated to take advantage of the 80-MHz L-band frequency allocation. Subharmonic sampling will be used to combine the two sub-bands into a minimum-rate data stream using the least amount of hardware. Radar control will be accomplished using a simple table consisting of On/Off (GPS) times, and corresponding radar set-up and pointing parameters.

F.3.1.2 Radar Antenna. Ball will provide the phased-array antenna and deployment structure. Ball will procure the deployment structure, which is a deep-truss structure similar to the successful Seasat structure, from AEC-Able. AEC-Able is building a similar deployment structure for the RADARSAT 2 SAR antenna. The panel radiating element design is taken from SIR-C and therefore has minimal risk. The 13.8-m-by-2.0-m L-band antenna is made up of six 2.296-m-by-2.0-m panels. The two center panels are kinematically mounted to a fixed adapter truss that is mounted to the S/C. Deployable antenna “wings” on either side position the remaining four panels for radar operation. Transmit/Receive (T/R) modules distributed on each antenna panel maximize performance and reliability. This architecture minimizes the impact of an amplifier or DC/DC converter failure and eliminates the criticality of a bulky, expensive low-loss, high-power RF manifold. The antenna mass, including the deployment structure and T/R modules, is 477 kg (includes 30% contingency for the antenna and 20% for the deployment sturcture).

Ball will also supply the antenna Control and Power Distribution Unit (CPDU), which provides a well-defined electrical interface to the radar electronics and S/C. The CPDU receives its antenna commands and timing signals from the Radar Control and Timing Unit (RCTU) for distribution to the antenna panels. It receives and distributes antenna power from the S/C and collects and serializes engineering telemetry from the panels for delivery to the S/C telemetry processor. The CPDU mass, including CPDU-to-panel cabling, is estimated to be 23 kg (inludes 30% contingeny).

F.3.2 Instrument Design Rationale

The ECHO radar instrument is designed to meet the science and environmental requirements, while minimizing technical risk and cost. The design is based on a proven approach having only one operational data acquisition mode, which is one of 23 radar modes (not counting experimental modes) from the 1994 SIR-C missions. The L-band operating frequency is optimal for the science.

The ECHO radar antenna follows from a successful series of L-band and C-band antennas supplied by Ball for JPL radar projects, including SIR-C and SRTM. The design of the radar electronics for ECHO is based on the use of lightweight, compact components recently developed under NASA/JPL's Advanced Radar Technology Program (ARTP).

The JPL and Ball instrument design team has avoided duplication of functionality wherever possible. One example is the S/C On-Board Computer (OBC), which controls all the high-level operations, such as turn-on/turn-off of the radar. Instrument telemetry is routed as analog or discrete digital inputs to the S/C's telemetry processor, eliminating the need for telemetry sub-processors in the radar electronics. Critical calibration data are embedded in the radar high-rate science data in real-time during data acquisition.

Simplicity of design and implementation is also achieved with block redundancy (primary and redundant subsystems) for the radar, antenna-control, and power-distribution electronics. In the event of a failure, the redundant subsystem is switched in by powering it up and powering down the primary subsystem. This approach avoids the need for an elaborate primary/redundant switching network. Graceful degradation in the antenna RF electronics is inherent in the distributed system, which allows several T/R modules to fail without significant impact on the overall radar performance. With the exception of the data window position, no "hot" changes are permitted during a datatake, simplifying the radar operation.

Several features of the S/C bus that help simplify the design of the radar instrument are summarized in F/O Table F2-2.

F.3.3 Radar Requirements and Relation to the Science Objectives

Functional requirements for the ECHO S/C and instrument are summarized in F/O Table F1-1. The key science requirements driving the mission/instrument design are the measurement of surface change with accuracy of 2 mm yr^{-1}. These requirements impose functional requirements that drive the radar design: global access; high interferometric coherence; pixel-level geolocation; split-spectrum ionospheric corrections; and a 5-year mission lifetime.

The global access requirement drives the selection of a polar orbit. With these orbit parameters, the radar must allow data collection over all areas on the Earth's land surface. Instrument pointing will be achieved by a combination of precise S/C roll maneuvers to provide right-of-track or left-of-track pointing at a fixed angle from nadir, plus electronic beam steering to either scan rapidly across three beams (ScanSAR), or remain fixed at a single beam. The radar must achieve good performance (resolution, signal-to-noise, ambiguity level) over the range of incidence angles (swaths) encompassed by the three beams. To meet the ECHO science objectives, an 8-day repeat was chosen, resulting in a 340-km targetable ground-track separation at the equator. To best achieve global access in the shortest possible time, the radar swath width is maximized, constrained by antenna size and mass, data rate and signal-to-noise ratio (SNR). The nominal swath is 115 km. ECHO's three electronically steered beams ensure full global access.

The requirements for high coherence and measurement of long-term surface change drive the selection of L-band for ECHO. The requirements on deformation accuracy drive the selection of the radar resolution and thus the bandwidth. The need for ionospheric corrections leads to a split spectrum mode of operation for the radar.

The requirement for pixel-level geolocation drives the selection of one-second GPS time-ticks to control the on-off configuration of the radar. This control is handled by the S/C OBC, which has direct input from the S/C GPS receivers. The radar electronics handle the precise sub-second timing (e.g., the transmit inter-pulse period, the data window position, and the ScanSAR burst timing). Untracked errors in any of these parameters could affect the pixel location accuracy. The radar calibration telemetry includes a parameter to track the radar's reference Stable Local Oscillator (StaLO) frequency as a function of GPS time, allowing correction of radar timing drift errors in ground data processing.

The ECHO mission is designed to meet the requirement for high coherence through orbit and attitude control and careful attention to interferometric issues in the radar design. The three main sources of decorrelation are baseline, temporal, and thermal noise.

Baseline decorrelation results from imaging at different positions, with longer baselines yielding greater decorrelation. Baseline decorrelation also depends on the intrinsic spatial resolution. With the ECHO baseline controlled to within a 250-m tube, the 15-MHz range bandwidth meets the accuracy and spatial resolution requirements.

Temporal decorrelation is caused by wavelength-scale changes in the relative positions of sub-pixel scatterers. Longer wavelengths allow greater change before significant temporal decorrelation takes place. Comparative studies with C-band (5.6 cm wavelength) and L-band (24-cm wavelength) indicate that L-band maintains stronger correlation, particularly in vegetated areas [*Rosen et al.*, 1996]. The nominal 8-day repeat orbit also reduces temporal decorrelation for ice sheets and other areas that experience rapid surface change.

Thermal-noise decorrelation is directly related to the radar SNR, which depends on the backscatter (signal) from Earth's surface. The ECHO radar performance is designed to ensure millimetric accuracy over radar-dark regions.

The ECHO objective of measuring surface change over a 5-year mission places requirements on phase coherence. This is a significant departure from the 'standard' design constraints for SAR, where considerable emphasis is placed on radiometric stability to compare backscatter (i.e., σ^o) measurements. Radiometric fidelity is a lesser concern for ECHO when compared with phase fidelity. The 5-year mission also requires that redundancy must be inherent to the radar.

F.3.4 Maturity Matrix

The instrument technical maturity matrix is given in F/O Table F1-2. Elements of the ECHO radar electronics have direct heritage from SIR-C/SRTM Technology Readiness Level (TRL) 9. The NASA/JPL ARTP has focussed on reducing the mass and power consumption of these elements by a factor of ten from a SIR-C class instrument. The ARTP radar prototype is currently at TRL 7.

F.3.5 Operational Modes

The radar will nominally remain in the STANDBY state when not acquiring data. This maintains power to the StaLO in the Radio Frequency Electronics Subsystem (RFES) to assure good frequency and phase stability, and to the digital subsystem RCTU so it is always ready to receive commands. Sequences of datatake commands are generated on the ground and uploaded to the S/C OBC at daily intervals. Prior to a left-looking data take, the S/C will roll to achieve left-side pointing. Instructions to do this will be included in each uploaded datatake command. To initiate a data take, the S/C will set control signals to close relays in the radar RF Electronics and Antenna subsystems to enable operate power. A command will then be sent from the S/C OBC to the RCTU. The RCTU will parse out the appropriate control signals to the RFES and Antenna Electronics CPDU, and will begin the datatake at the next GPS pulse per second (pps) time-tick. Besides the Receiver gain setting and Caltone level setting, the radar command will include the following for each of the three antenna beams:

- Pulse Repetition Frequency (PRF)
- Elevation Steering Angle
- Data Window Duration (DWD) (# of samples)
- A series of entries for Data Window Position (DWP), with a corresponding DWP Dwell (DWPD) to indicate how long to use these positions before moving on to the next set.
- Command Pause-Before-Execution Setting, which allows for millisecond alignment of ScanSAR bursts for pass-to-pass ScanSAR interferometry.

The datatake will be executed using a fixed set of the above-listed set-up parameters, with the exception DWPs for three beams, which will sequence through up to 32 different values to accommodate the varying slant range during very long data-takes due to the Earth's oblateness. Each set of three DWPs will remain active for a duration specified in its corresponding DWPD command field. When the command's DPW/DWPD entries are all used up, the data collection will cease. The RCTU will set a status bit to reflect end-of-datatake to the S/C OBC. Power-down commands from the S/C CPU to the radar RF electronics and antenna, and a simultaneous command to the SSR to stop recording data, will end the datatake, and return the instrument to the STANDBY state.

Before the start of each data-take, the Antenna Electronics CPDU also receives a command which includes a matrix of bit values (instructions to power up each individual T/R module). The T/R module on/off settings will be maintained at the same state during any one datatake. Under normal operation, T/R modules will only be turned off (bit-value set to 0) prior to a datatake if a failure has been detected.

F.3.6 Concept Studies

Concept studies leading up to the current proposal include the 1-year TOPSAT mission design study, the 2.5-year LightSAR Phase A/B studies, the 3-year ARTP program, and the

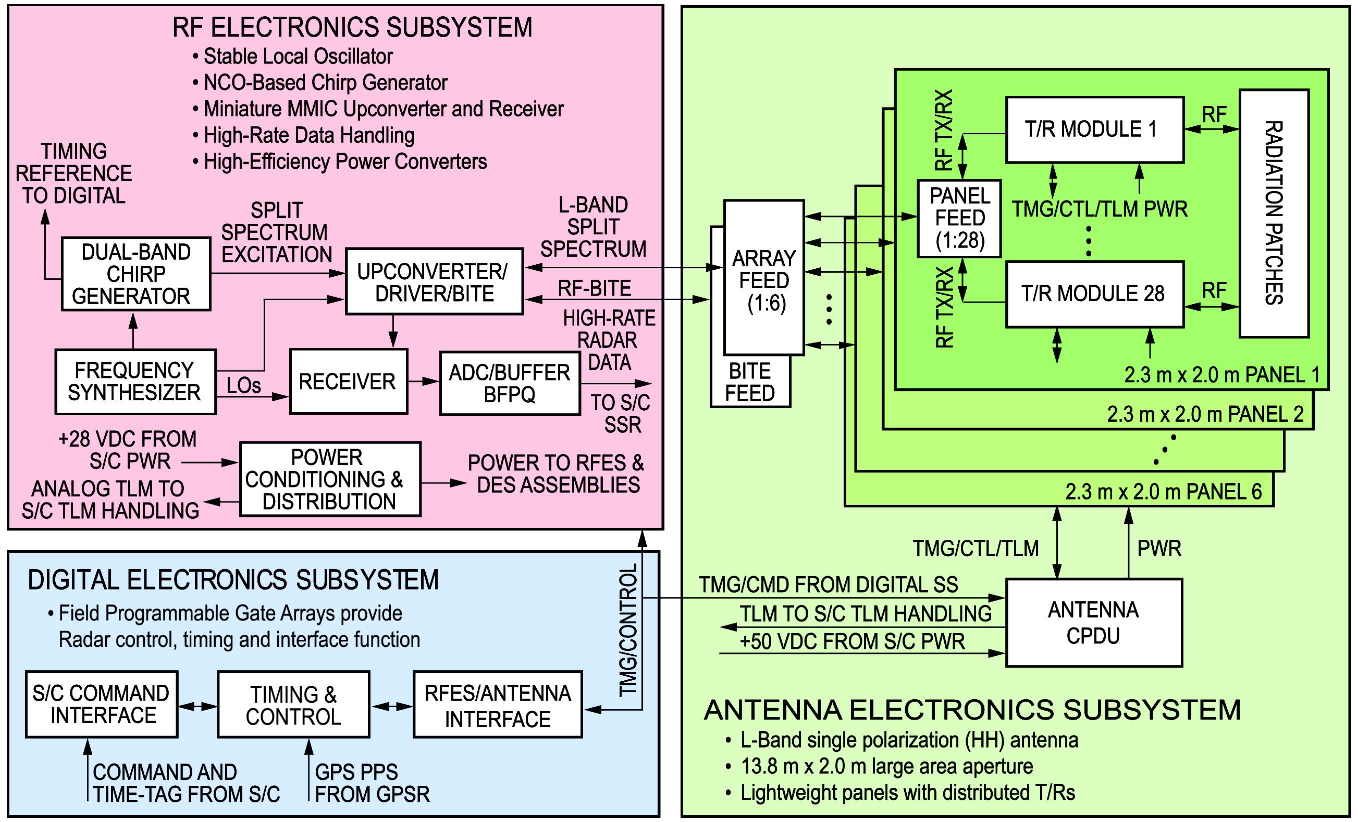

Figure F1-1. Block diagram of the ECHO Radar Instrument. The RFES, DES, and antenna CPDU are block redundant. The antenna panels degrade gracefully.

Table F1-3: System performance for ECHO beams.

Parameter	Near	Mid	Far	Requirement
Swath Width (km)	128	121	96	340 total
PRF (Hz)	1352.6	1263.1	1180.4	-
Boresight Ang (deg)	22.15	29.29	34.63	-
Min Look Ang (deg)	18.00	25.89	32.32	-
Max Look Ang (deg)	26.02	32.42	36.78	-
Range to midswath (km)	829	888	952	-
Start Coverage (km)	249	374	493	-
Stop Coverage (km)	377	495	589	-
Ground-Range Resolution (m)	20.5	15.8	13.6	35
Azimuth Resolution (m) (4-look)	27.6	29.6	31.7	35
Minimum σ^o_{NE} (dB)	-40.2	-38.2	-36.6	-24
Maximum σ^o_{NE} (dB)	-30.5	-31.8	-33.4	-24
Worst Azimuth Ambiguity (dB)	-23.7	-22.0	-20.0	-20
Worst Range Ambiguity (dB)	-38.0	-25.6	-25.6	-25
Ave. Radiated Power (W)	128.0	119.5	111.7	-
DC Power (W) †		199		††
fData Rate (Mbps)	130	144	126	<175

† Avg DC power value assuming 8.5 minutes of data collection per orbit, including 30% contingency
†† See Table G-5 for S/C capability

Table F1-1: Science Traceability Matrix (L-3).

Science Objectives	Scientific Measurement Requirements	Instrument Functional Requirements	Mission Functional Requirements
Understand strain changes leading to and following major earthquakes.	Globally distributed measurement of vector deformation rates to 2 mm yr^{-1} (single component accuracy), which implies deformation accuracy of 5-10 mm at 35-100 m resolution over a 5-year mission.	**Accuracy** • L-band Radar for high coherence. • Split-Spectrum for ionospheric correction. • Noise equivalent so better than -24 dB for radar-dark regions. **Accessibility** • 30 minutes of onboard storage for global accessibility within ground-station constraints. • Electronic beam steering in range **Calibration** • GPS for baseline knowledge and for orbit control. **Mission Duration** • High reliability for 5-year mission.	**Vector Measurement** • Ability to image left and right for vector measurements. **Accuracy & Interferometric Viability** • Orbit maintenance to repeat-tracks to within 250 m for short interferometric baselines (high coherence). • Precise orbit determination. • Instrument pointing to better than 0.05 deg. 1σ. • Frequent observations over a site to average out tropospheric and other noise sources. **Mission Duration** • Sufficient expendables for a 5-year mission duration. • High reliability S/C sufficient to enable 5-year mission duration.
Characterize three-dimensional magma movements to predict volcanic eruptions.	Globally distributed monthly measurements of deformation with 5-10 mm accuracy. Frequent measurements during eruptions.	As above with no additional drivers	As above plus **Accessibility** • 8-day repeat orbit for frequent monitoring of eruptions.
Assess the impact of ice sheet and glacier system dynamics on sea level rise and characterize temporal variability.	Ability to map vector ice motion for Greenland and Antarctica to 1 m yr^{-1} (single component accuracy). 5-year mission to study temporal variability.	As above with no additional drivers	As above plus **Accuracy & Interferometric Viability** • 8-day repeat to avoid temporal decorrelation & aliasing of fast motion. **Accessibility** • Polar orbit & left/right looking to image to both poles.

Table F1-2: Technical maturity matrix (L-2a). All elements of the ECHO radar electronics have direct heritage from SIR-C/SRTM (TRL 9).

Hardware Item	Item Description	Maturity	Maturity Rationale
StaLO/Frequency Synthesizer	Crystal oscillator & PLL frequency multipliers	TRL 7	SIR-C, ARTP
Chirp Generator	NCO-based DDS	TRL 7	SIR-C, ARTP
Upconverter/Driver	MMIC-based upconverter and SSPA	TRL 7	SIR-C, ARTP
Receiver	MMIC-based receiver	TRL 7	SIR-C, ARTP
ADC/Buffer/BFPQ/ Formatter	8-bit ADC/buffer with 8:4 BFPQ	TRL 7	SIR-C, ARTP
Radar Control & Timing	FPGA-based	TRL 7	SIR-C, ARTP
T/R Modules	MMIC-based transmit and receive amplifiers	TRL 7	SIR-C, SRTM
Antenna Panels	Microstrip phased array on honeycomb	TRL 9	SeaSat, SIR-A/B/C, SRTM
Antenna Control Electronics	Timing, serial command & telemetry bus	TRL 7	SIR-C, SRTM
Antenna Structure	Rigid, deep truss, composite tube with titanium end fitting, low CTE truss elements & thermal tape, bond joints, DOF fittings, snubber system	TRL 7	SeaSat, RadarSat-I/II
Deployment Mechanism	Pyrotechnic latch release, bearing design & lubrication, preload mechanisms, drive motor assembly, synchronization linkage, cable/spring powered elbow mechanism, outboard panel hinge latch	TRL 9	RadarSat

Table F2-1: ECHO instrument information.

Item	Value/Summary	Units
Sensor type	SAR	N/A
Number of instruments (including redundant units and spares)	1 instrument with built-in redundancy	N/A
Number of channels	1	N/A
Size, meters x meters x meters	13.8 x 2.0 x 0.05	m^3
Mass with contingency, kg and %	569 kg (28%)	kg, %
Power with contingency (nominal, peak, duty cycle, standby), watts and %	Nominal 198 W (30%) @ 8.5% Duty Cycle Peak 1793 W (30%) Standby 50 W (30%)	W, %
Data rate with contingency, kbps and %	175 Mbps (30%) (avg. 8.5 minutes/ orbit)	Mbps, %
Mechanical, electrical, and thermal layouts	(see Figs, technical section)	N/A
Optical layout including field of view (if appropriate)	(see Figs, technical section)	N/A
Ground and on-orbit calibration scheme	Geodetic ground control	N/A
Pointing requirements (knowledge, control, and stability), degrees	Knowledge 0.05 deg Control: 0.05 deg Stability: 0.05/10 s	degrees
Command and control requirements	1 radar command per data take	N/A
Flight software architecture and thousands of lines of software code used. Include new and reuse/retest/ redesigned code., KSLOC. (Use of existing or commercial off the shelf or hybrid software shall be identified)	Instrument on/off sequencing runs on S/C control computer. ~100 lines of code	
Definition of instrument operational modes over all science phases with power and data requirements, watts and kbps	Standby, 50 W, 20 kbs Datatake, 1793 W, 175 Mbps	

Table F2-2: Spacecraft bus features that help simplify the radar design.

Spacecraft bus feature	Impact on radar design
Accurate positioning	Allows radar commands to be uploaded well in advance of data-take.
Accurate, stable pointing/ yaw steering	Removes uncertainty in antenna pointing. Simplifies radar timing and control.
Powerful CPU	Removes need for radar CPU.
Solid-state recorder (SSR)	Simplifies buffering scheme/interface for science data stream.
Telemetry handling	Removes need for an additional dedicated radar telemetry processor unit.
GPS one-second time-ticks	Provides accurate timing reference for radar system on/off configuration.

Table F2-3: Radar electronics and antenna potential problems, associated risks, and mitigation plans.

Risk Area	Explanation	Likelihood	Consequence	Mitigation Plan
RFES/DES	Unit failure	L	L	Block redundancy for each subsystem
RFES/DES	Schedule slip	M	L/M	Request for pre-phase B risk reduction phase; schedule reserve
T/R modules	T/R module components difficult to find	M	L	Evaluate part availability early to facilitate mods to SIR-C designs
T/R modules, RFES Drivers	Multipaction enabled by HPA output power	L	H	Evaluate all high-power transmission lines and junctions, modify connectors as on SIR-C
Structure	Structure development schedule lags	L	M	Monitor this major subcontract closely to uncover problems ASAP
T/R module	T/R development schedule lags	L	M	Monitor this major subcontract closely to uncover problems ASAP
Panel	Panel flatness degrades due to large panel size	L	L	Construct panel as symmetrically as practical to minimize thermal distortions
Antenna Structure	Structure does not deploy	L	H	Pre-launch test of proven deployment system, redundant pyrotechnic cutters

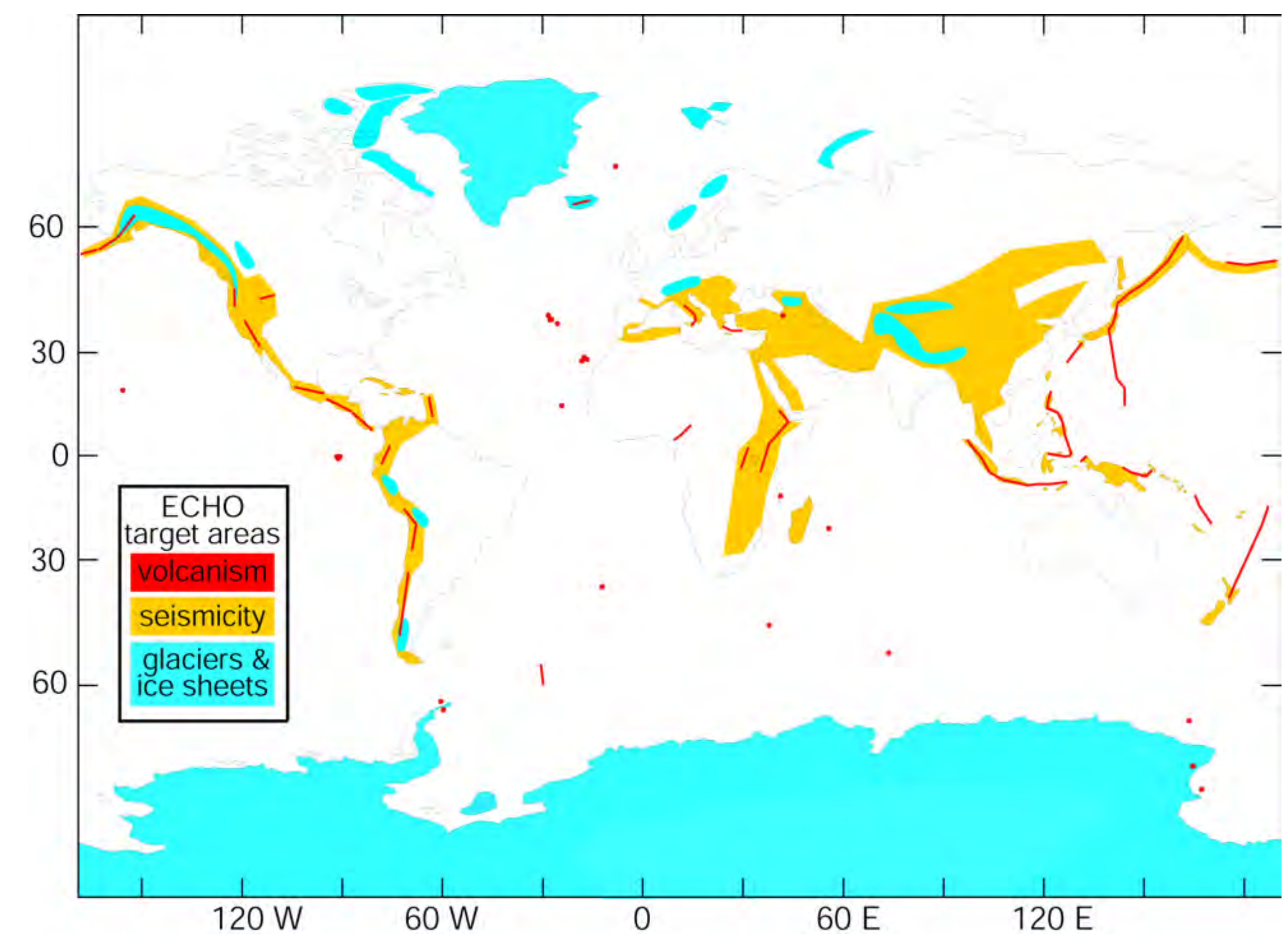

Figure F2-1. ECHO coverage areas for seismic, volcanic, and ice sheet objectives. Data for other natural hazards research can be collected worldwide.

prior study for the ECHO missions proposed to ESSP in 1996 and 1998.

F.3.7 Instrument Requirements and Performance

The performance is the same for the baseline and minimum mission.

F.3.7.1 Radar Performance. F/O Table F1-3 summarizes the overall radar performance. The bandwidth and pulse length for the split spectrum segments are fixed at 15 MHz /33.8 ms, and 7 MHz /33.8 ms, respectively. The remaining radar configuration parameters shown in the table were chosen to maximize performance within the swath constraints. The radar will have three swaths yielding a total combined swath width of 340 km, which is required for continuous coverage at the equator.

Amplitude weighting in elevation is necessary to meet the swath and ambiguity requirements. In order to minimize cost and retain simplicity, this is implemented in the antenna by using a uniformly driven aperture in amplitude for both transmit and receive, with the transmit amplitude taper achieved by using two types of HPA, and the receive taper achieved using post-LNA attenuators. This yields swaths between 104 and 141 km in width.

The maximum data rate assumed in determining the parameters for this design was 175 Mbps; the highest operational data rate used in the design was 144 Mbps, to give a 31 Mbps (21%) margin. The overlapping regions between adjacent beams are greater than 2 km, for mosaicking adjacent swaths in order to construct deformation maps over large areas.

One figure of merit for a SAR is the noise equivalent normalized backscatter (σ^o_{NE}), defined as the surface backscatter coefficient required to produce unit SNR in the radar image. SNR is then the ratio of the measured backscatter to the σ^o_{NE}, and surfaces with backscatter greater than σ^o_{NE} have a positive SNR. To meet the science requirements, the σ^o_{NE} should be lower than the minimum backscatter over the study area. Interferometric phase accuracy increases with SNR, all other noise sources being constant. Spatial averaging of the processed data can improve the InSAR phase accuracy, at the cost of degraded resolution.

The antenna dimensions and radiated power are closely linked to radar system performance, particularly SNR. An antenna 13.8-m in length and 2.0-m in height meets the requirements. The antenna is as long as possible, consistent with low fabrication costs for the antenna and deployment mechanism, while meeting science requirements. The worst case σ^o_{NE} occurs at the swath edges and is -30.5 dB.

The instantaneous dynamic range of the radar system is limited by the dynamic range of the (8-to-4 bit) Block Floating-Point Quantizer (BFPQ), which is 30 dB. An additional 8 dB (or more) of dynamic range is provided by a selection of receiver gain settings.

Other performance measures optimized in the design are the range and azimuth ambiguities. The range ambiguities meet or exceed the requirement of -25 dB for all three beams. The worst azimuth case ambiguities are -20 dB. Though acceptable, this level can be improved further by processing out the ambiguous signals at the cost of degraded azimuth resolution.

The radar PRFs for each beam position were selected by trading off the ambiguity levels while maintaining a duty cycle below 9.2% during radar operation. The design includes a choice of 16 commandable PRFs in the range of 1100–1700 Hz.

F.3.7.2 Command and Control Requirements and Performance. As mentioned previously, the S/C OBC controls the radar via a serial interface. The regular command sequence upload for ECHO will consist of a table of entries for each acquisition. The parameters required to control the radar are:

- Start Time, synchronized with the on-board GPS time to the nearest second.
- PRF, selectable from a set of 16, in the range 1100–1700 Hz. Three PRF settings, one for each beam, are required for a datatake.
- Elevation Steering Angle, selectable from a set of 10, to accommodate left and right-looking ScanSAR. Three Steering Angle settings, one for each antenna beam, are required for a ScanSAR datatake. For a fixed beam (non-ScanSAR) datatake, the three angle entries in the command are simply set equal so that the radar effectively has a single mode.
- Receiver DWP start, specified in terms of number of 256-pulse blocks of the ADC sample clock (~5 μs increments) from the signal starting the transmit event (PRF pulse). A minimum of three DWP settings, one for each antenna beam, is required for a datatake. Additional sets of DWPs may be included for

long datatakes, where the DWP must drift to accommodate altitude changes with latitude.

- DWPD Time, specified in number of ScanSAR bursts. For long datatakes requiring DWP drift, this parameter sets the duration for which each DWP is valid. Each set of three DWPs will have an accompanying DWPD Time.
- Receiver DWD, specified as a number of 128-sample block. Three DWD settings, one per beam, are required for a datatake.
- Receiver Gain, specified in 2 dB steps over a range of at least 8 dB, to accommodate the range of backscatter.
- Caltone Level, specified in 6 dB steps over a range sufficient to accommodate the receiver gain range.
- Command Pause-Before-Execution Setting, specified in ms over a range of 0 to 999 ms, to allow for millisecond alignment of ScanSAR bursts for pass-to-pass ScanSAR interferometry
- Stop Time, synchronized with the on board GPS time to the nearest second. (The actual end of data collection will precede this stop time by a fraction of a second. The datatake ends on a ScanSAR burst boundary when the DWP control table entries expire. The Stop Time then triggers the S/C OBC to return the radar instrument to the Standby state.)

In addition, the antenna CPDU also receives the following command:

- *Antenna Transmit/Receive Module Control*, commandable to activate specific T/R modules, giving the capability to turn-on/turn-off individual T/R modules.

F.3.8 Technology/Development Risks

F.3.8.1 Risk Assessment. ECHO radar design goals are reliability, system performance meeting or exceeding mission functional requirements, low cost, and low schedule risk. JPL and Ball have considered potential problem areas. F/O Table F2-3 shows risk assessments and mitigation strategies. The developmental and operational risk of the radar electronics has been greatly reduced by the small number of subassemblies, the simplicity of design, and the development team's experience with similar designs. Because of this, and in order to reduce cost, the ECHO radar development plan is to breadboard only selected items deemed necessary, to proceed directly to prototype for most assemblies, and to build the flight units following successful prototype evaluation. Many of the electronics prototype assemblies will become part of the Ground Support Equipment (GSE) used for testing the flight assemblies, thus minimizing the GSE cost. While spare parts will be purchased, and major subassemblies will be swappable, there will be no separate engineering model. Parts will be subjected to burn-in as required to reduce risk and improve reliability.

For the antenna, the majority of the risk assessments are low and, more importantly, the majority of the potential problem areas have a low likelihood of occurrence. Management's focus in the ECHO antenna development effort will be to minimize the likelihood of problems, through careful monitoring. JPL and Ball will maintain the risk matrix in F/O Table F2-3 throughout the course of the program as a management tool, reporting monthly to the team.

F.3.8.2 Risk Mitigation. The radar electronics design includes block redundancy (primary and redundant subsystems) to reduce the risk of subsystem failure. To reduce development risk, radar development includes an 8-month risk reduction phase, beginning fourth quarter 2002. The objective of this phase will be to set up a small, focused team to produce a detailed radar system design, described by the following documents:

- Radar Instrument Functional Requirements/ Functional Design
- Radar Instrument Interface Specification
- Radar Instrument Design Specification
- Software Requirements Document
- Software Design Document
- Radar Instrument Integration and Test Plan

The design of the science data acquisition command word set and the functional requirements/ functional design of the radar flight software will also be completed in this period.

The antenna and radar electronics teams will work closely during the risk reduction phase on the detailed instrument design. Work will also begin on the detailed design and procurement of the T/R modules and the antenna deployment structure, both of which are long lead items, and represent interface uncertainties.

The digital electronics are essentially off-the-shelf technology using digital logic families and components with a heritage of reliable performance in space. The majority of the digital logic will be implemented in Field-Programmable Gate Arrays (FPGAs), which are available as highly reliable rad-hard parts and are being flown in missions such as Cassini. These boards and spares will be assembled and tested in a manner similar to the RF electronics.

F.3.9 Instrument Development/ Construction Schedule

The schedule for radar instrument design, fabrication, integration and test is shown in the master schedule in Figure H-3 in the Management volume. The radar instrument schedule assumes a 12-month Phase 2 risk-reduction phase, a 9-month detailed design period (PDR to CDR), and 17-months for sensor fabrication, integration, and test. This allows 8 months for integration with the S/C and 1 month for launch vehicle integration.

Detailed design of the flight software will be completed by the middle of Phase 2. A test version of the radar flight software will be developed using a S/C I/F simulator provided by Astrium (6 months before CDR). This test version will be used during the sensor integration and test period. Final delivery of the radar flight software will be a year before launch.

F.4 Anticipated Science Return

The ECHO mission will distribute SAR data and software needed to produce surface deformation maps for the science objectives described above. Scientists using ECHO data will be able to routinely produce 3D displacement maps associated with earthquakes, post- and inter-seismic deformation, volcanic activity, and glacier flow. Also, as part of the validation activities, the science team will produce and distribute several deformation maps as part of the *natural laboratories* validation.

F.4.1 Expected Results

ECHO-derived products promise significant advances in the areas of seismic, ice sheet, volcanic, and subsidence research. For earthquake studies, ECHO seeks to provide the first continuous series of velocity and strain-rate (spatial gradient of velocity) maps of the Earth's major tectonic zones. These data will be enormously beneficial for earthquake science and hazards studies. First, these maps will likely reveal previously unknown zones of strain accumulation. When combined with other geologic and seismic data, ECHO-derived strain-rate maps should yield substantial improvements in seismic hazard assessments. Other ECHO products will provide invaluable information on slip distribution, fault geometry at depth, and crustal rheology, resulting in significant advancements in modeling earthquake physics. Finally, ECHO-derived decorrelation maps will allow investigators to evaluate the distribution of damage following earthquakes and other natural disasters.

For volcano studies, ECHO will provide continuous deformation maps for active volcanoes, yielding unprecedented information about the transport of magma in the Earth's crust. ECHO-derived deformation maps will be inverted to determine the geometry and volume of the magma sources at depth. Because ECHO provides global coverage it will be possible to image any of the Earth's active volcanoes. Detecting changes in surface deformation patterns will help identify volcanoes likely to erupt in the near future. This will flag areas requiring additional seismic and geologic investigations for the issuance of eruption forecasts. After eruptions, ECHO will provide accurate maps of the spatial extent of newly erupted material, information important in understanding the eruptive process and in identifying the potential for future hazards (e.g., those due to lahars).

ECHO will produce velocity maps of the major outlet glaciers and ice streams in Greenland and Antarctica to aid estimation of ice sheet mass balance and associated sea level change. These data will provide much tighter constraints on the contribution of ice-sheet discharge to present-day sea-level change. ECHO will provide a time series of ice velocity data to detect and help characterize short-term fluctuations in ice velocity. The data will also be used to detect shifts in grounding line position, which are sensitive indicators of change in the ice-sheet/ice-shelf system. Finally, the data will provide a valuable new data set for determining the controls on fast flow and improving ice sheet models.

F.4.2 Relation to EarthScope

ECHO will increase NASA's role in a major solid earth science initiative, EarthScope. A collaborative NASA/NSF/USGS venture, EarthScope is a distributed, multi-purpose set of instruments and observatories that will greatly increase understanding of the structure, evolution, and dynamics of the North American continent. Interferometry is a component of this program, and ECHO will serve as the prime instrument for supplying spatially continuous crustal deformation data. EarthScope's three other components are: USArray, a continental scale seismic array to provide a coherent 3-D image of the lithosphere and deeper Earth, SAFOD (San Andreas Fault Observatory at Depth), a borehole observatory across the San Andreas Fault to directly measure physical conditions under which earthquakes occur, PBO, a fixed array of strainmeters and GPS receivers to measure plate boundary deformation at a range of temporal scales.

F.4.3 Relationship of Products to Science Objectives

The ECHO science objectives seek answers to several important Earth science questions based on analysis of high-resolution deformation measurements provided by ECHO. The mission will produce SAR data and software for generating vector deformation maps. These deformation maps are the products required to answer the questions that motivate the ECHO science objectives. A detailed mapping of the science requirements into the instrument and mission design characteristics needed to generate these products is given in the Science Traceability Matrix (F/O Table F1-1). The Science Team will demonstrate the validity of these data for meeting the science objectives. The detailed analysis of these data needed to answer the science questions will be performed during the AO specified Science Data Analysis Projects (SDAP) and under of the EarthScope initiative.

F.4.4 Science Data to Be Returned

The raw measurements acquired by ECHO are digitized, offset-video samples of radar echo returns. The project will reformat these to produce the product to be distributed, along with the precision orbit estimates, to science users. This processing includes browse SAR (~100 m resolution) images. The project will also develop and provide software to the science community for processing and calibrating these data to geolocated vector displacement maps. These displacement maps are the common products for seismic, volcanic, ice-sheet, and subsidence studies. They are used to derive discipline-specific measurements (e.g., maps of seismic strain and glacier velocity) needed to meet the science objectives.

F.4.4.1 Data Products. The basic ECHO products are SAR signal data, Doppler analysis, precision orbit state vectors, and other meta-data necessary to produce calibrated measurements of deformation using the ECHO supplied software. Many difficulties in processing SAR data stem from the inconsistent data formats. ECHO will maintain a uniform and consistent format to simplify processing.

F.4.4.2 Demonstration Science Data Products. The science team has the responsibility for ensuring that ECHO data are fully calibrated and validated. Because of the global scope of ECHO science, and because of the combinatorial explosion of possible higher level data products (e.g. multiple interferograms, stacked to mitigate tropospheric noise, and processed into deformation time series), it is not practical to implement a centralized processing of ECHO data to high-level. Instead, the science team will prepare and distribute properly verified software together with the SAR data. The validation of the data and of the processing software (including the effectiveness of the specific algorithms) will be performed based on the concept of *"natural laboratories"*. The science leads for each of these laboratories are identified in Table F-2. We will select three such areas, characterized by (1) the richness of the scientific issues they pose (2) the human interest aspects and (3) the availability of readily accessible ground truth, in the form of other geophysical data that can be integrated with ECHO data. For each natural laboratory, demonstration science questions to be answered by the Science Team using ECHO data are:

Southern California plate boundary zone:

What is the geographical and temporal distribution of deformation?

Is compressional tectonics in southern California accommodated primarily by horizontal motions ("escape from LA") or by vertical motions?

What are the respective tectonic and non-tectonic (e.g. ground water) deformation signals?

Hawaiian volcanic edifice:

What are the timing and areal patterns of deformation associated with the eruptive cycle?

West Antarctica

What are the time dependent dynamics of the ice sheet, ice streams, and ice shelf?

What is the variability in ice discharge from West Antarctica?

We note that a common scientific thread is the use of repeated measurements to build a picture of vector deformation continuous in space and densely sampled in time. When assimilated into three-dimensional time-dependent physical models of the subsurface, such maps will help support significant scientific advances over past or current SAR missions. Our Cal-Val strategy is to use these geological targets to develop and validate the tools and approaches for producing higher-level data products and verify them under controlled circumstances. These higher-level data products will be made available through the distributed ECHO archive.

F.4.4.3 Data Coverage and Mission Phases. ECHO coverage will focus on the areas shown in F/O Figure F2-1 for meeting seismic, volcanic, and ice-sheet objectives. Additional data will be collected at targeted sites worldwide for subsidence studies. Following commissioning and on-orbit checkout, ECHO will collect data during a single 5-year deformation mapping phase, during which time ~250 TB of SAR data will be collected.

ECHO will image all areas of seismic interest at least four times/year from at least three different directions to allow vector measurement. This coverage yields at least 20 images from each direction over the 5-year mission for the seismic and volcanic areas shown in F/O Figure F2-1. The large number of images collected over each site is required to reduce tropospheric and other artifacts through averaging. Coverage at regular intervals ensures there will always be an up-to-date reference image for measuring co- and post-seismic deformation associated with earthquakes. Volcanoes will be imaged monthly from at least two different directions.

When seismic or volcanic activity is detected, ECHO coverage will be stepped up to provide the frequent temporal sampling necessary for monitoring such activity.

The mission will include two complete mappings of the Greenland and Antarctic Ice Sheets, separated by 3 years. Each mapping will include multiple repeats (5 to 8) to reduce noise by averaging. Roughly 60 ice streams and outlet glaciers will be monitored more frequently (as often as 8 days) to detect velocity change and grounding line migration. ECHO will also image the worldwide distribution of glaciers outside of Greenland and Antarctica several times.

The coverage will follow a stable and repetitive schedule to simplify mission planning. Earthquakes, volcanic eruptions, and other natural disasters occur spontaneously and globally and must be imaged at the first available opportunity. In response to such events, unscheduled acquisitions will interrupt routine mapping. Enough leeway will be maintained in the acquisition plan to quickly and easily reschedule any preempted acquisitions.

F.4.5 Data Processing

The ECHO project will supply users with a suite of InSAR processing software to allow them to process the data to SAR images, interferograms and geocoded and calibrated displacement maps. Current PCs and Macs can process a 100-km scene in roughly 15 minutes. This time should drop dramatically by the time of launch. The ECHO software package will allow users to process and calibrate the data without specialized SAR processing knowledge.

SAR data will be received and formatted at the receiving stations as they are acquired. Vexcel has installed similar systems for processing at various facilities around the world. The SAR signal data are the basic archived data sets. These data will be processed to higher level products by users using the ECHO software package.

In addition to algorithm development, the Science Team will provide software training and support to the science community. This model of software development and support has been successfully employed in GPS processing and SAR processing packages at JPL, Scripps, Stanford, and other institutions. A more detailed description of the user processing package is given in Section F.4.7.

F.4.6 Data Quality

Interferometric measurement errors are determined by such factors as system performance, scattering properties, vegetation, tropospheric water content, and imaging geometry. In extreme conditions (e.g., open water), measurements are not possible. For any interferometric system, there is a variety of imaging conditions, leading to a wide range of measurement accuracy. The ECHO radar is designed to meet the measurement requirements under circumstances that apply to the majority of the Earth's land surface. The following subsections describe the sources of measurement error and how they impact data quality.

F.4.6.1 Decorrelation Noise. Decorrelation between InSAR images causes phase error that is directly proportional to displacement error.

Interferometric decorrelation is caused mainly by thermal noise (i.e., system noise), baseline length, and temporal effects.

The ECHO instrument has been designed so that over a nominal range of target backscatter, baseline and thermal-noise decorrelation is kept below 4 mm at 35-m resolution with a 250-m baseline, which is below the anticipated level of tropospheric error (see Fig. F-6). Spatial averaging (e.g., more radar looks) can further reduce decorrelation noise at the expense of resolution.

Temporal decorrelation causes additional noise. The L-band radar and 8-day repeat period were selected to minimize, to the greatest extent feasible, temporal decorrelation. Further reduction in temporal decorrelation noise will be achieved by averaging data from several observations (see Fig. F-6).

F.4.6.2 Influence of Baseline Knowledge on Measurement Accuracy. Precision InSAR processing requires knowledge of the S/C orbit to within a few centimeters. ECHO will use the onboard Blackjack GPS receiver to provide precise orbital products. These products will be available for on-line distribution within 3 days of acquisition.

The radial component of the TOPEX/POSEIDON (T/P) orbits is precise to within 3 cm when determined by GPS alone [*Bertiger et al*., 1994]. Although the other components are less well determined (about 10 cm RMS) for T/P, several factors should improve performance for ECHO. The GPS receiver technology carried by ECHO is more mature than for T/P and avoids systematic errors in P-code data in the presence of Anti-Spoofing. Bertiger et al. [1994] confirmed this improvement. This heritage indicates that the GPS data should easily determine the relative vector orbital separation ("baseline") between ECHO passes with 10 cm or better accuracy.

Baseline errors affect displacement estimates in two ways. First, baseline errors combine with topography to produce small biases, which are typically negligible [*Zebker et al.*, 1994]. Second and more significantly, errors in the baseline yield systematic phase patterns ("tilts") in the interferograms.

With ECHO baseline estimates, tilt magnitudes range from several millimeters to a few centimeters. While this accuracy is sufficient for many studies, some form of baseline refinement will be necessary to meet the measurement requirements listed in F/O Table F1-1. At least 4 to 6 control points typically are required. These points need not be "radar visible" and in most cases do not require *in situ* measurements of displacement. For example, the baseline can be estimated using points outside the deformation field of a volcano where displacement is assumed to be zero. Stationary points near the coast or estimated velocities provide adequate control for ice sheets [*Joughin et al.,* 1998b]. ECHO coverage will be selected to maximize such opportunities.

F.4.6.3 Tropospheric Errors. Studies have shown that turbulent mixing of water vapor in the troposphere produces artifacts in interferometric maps [Massonnet *et al*., 1994; Goldstein, 1995; Zebker *et al.*, 1996]. Tropospheric delay will be the dominant form of error for many ECHO measurements.

To evaluate this error, we have used GPS derived tropospheric delay estimates from a number of sites around the globe to quantify the effects of error out to length scales of 200 km. Using these data, we constructed an error model that includes the tropospheric noise, thermal and baseline decorrelation noise, and baseline estimation error. Figure F-6 shows results that reflect typical operating conditions. The colored regions indicate a range of accuracies that meet the science objectives. The upper curve shows the single observation accuracy for geophysical length scales up to 200 km. The control points used in the model are spaced at distances comparable to the geophysical scale and bound the area of interest. Consequently, the errors decrease with scale, since the baseline solution removes errors at wavelengths much above the control-point spacing.

Figure F-6 indicates that the single observation accuracy meets the requirement of 1 cm for length scales below 50-km (for volcanic studies). In cases requiring better accuracy, multiple observations will be used to reduce tropospheric error. This will yield an improvement of $N^{-1/2}$, where N is the number of independent observations. Although results illustrated in Figure F-6 only extend to 200-km length scales, extrapolation of the results indicates that the ice and interseismic requirements can be met. For interseismic studies, an average of 4 to 20 interferograms are needed, while ice requirements are met with 1 to 4 interferograms.

F.4.6.4 Ionospheric Errors. The ionosphere also introduces propagation error. Unlike tropospheric delays, which are non-dispersive, iono-

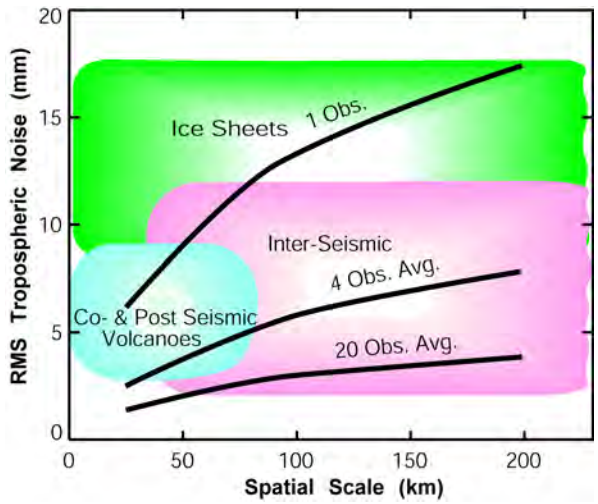

Figure F-6. Modeled error for ECHO single-component displacement estimates, including effects of tropospheric path delay, decorrelation, and baseline error. Ionospheric effects are not included, as they will be largely removed using the dual sub-band correction. Water vapor is the limiting source of error. Different curves show the effects of averaging interferograms. The horizontal axis represents the maximum scale of interest; error dependence on scale reflects the power-law nature of the troposphere. Boxes show the ranges of ECHO measurement requirements.

spheric delays are proportional to the square of the radar wavelength, and thus, are a factor of 16 worse at L-band than C-band. Past experience with L-band (SEASAT, JERS-1) shows that the ionosphere is not a dominant source of high-spatial-frequency error for interferometric studies. The uncertainty in the average excess path length, however, will likely lead to undesired "tilts" in the final deformation maps.

ECHO will use two methods for removing ionospheric affects. First, the dispersive nature of the ionosphere will be exploited to perform a two-frequency correction (two sub-bands separated by 70 MHz). Second, averaging of multiple interferograms will remove any resisdual ionospheric errors.

F.4.6.5 Relative Accuracy of Vector Components. ECHO is the first radar mission designed to make three-component vector displacement measurements. Existing systems (e.g., ERS-1/2), yield scalar maps along the radar line-of-sight. Application-specific assumptions do allow limited 3-D vector measurements with ERS-1/2 data from crossing orbits, particularly for ice sheets [*Joughin et al.*, 1996], but apply in only limited circumstances. Conversely, ECHO will provide true vector data by combining information from ascending left- and right-looking, and descending left- and right-looking passes. Figure F-7 shows how line-of-sight range displacement errors map into the relative precision in the East, North, and vertical directions.

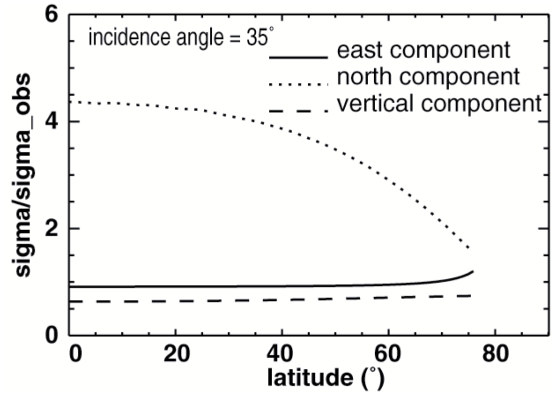

Figure F-7. Relative sensitivity of ECHO measurements in the directions east, north and vertical as a function of latitude, assuming four independent observations at mid-swath on the four line-of-sight directions of the satellite (ascending left- and right-looking, and descending left- and right-looking). For example, if the phase noise corresponds to 1 mm of range change in the four directions of observation, the associated error at low latitudes is ~3 mm in the north component and ~0.7 mm in the east and vertical components. Averaging several observations of slow deformation processes will reduce the error.

F.4.6.6 L-band Data Over Ice Sheets. ECHO's L-band wavelength is four times longer than existing C-band systems such as ERS-1/2 and RADARSAT, so that is better suited to measuring the fast motion of ice streams.

Deep penetration of L-band signals into the firn potentially could yield significant geometric decorrelation due to volume scattering interactions. L-band airborne interferometric data collected in 1995 over the Greenland Summit and other Greenland sites by the NASA/JPL TOPSAR indicate that increased L-band decorrelation over dry snow facies is not a significant concern for ECHO [*Rignot et al.*, 2001].

F.4.7 Algorithm Development and Validation

The Science Team will provide algorithms for generation of higher-level products. Vexcel will develop GUI interfaces for these programs and distribute the processing code to the science community at no cost to users. The Science Team will validate the ECHO data and the ability to generate the necessary higher-level products using the Vexcel package.

F.4.7.1 Processing Software Development. The Project-supplied algorithms and software will:

- Form images, interferograms, range displacement maps, calibrated vector displacement maps, topographic maps, and correlation maps using ancillary data;
- Geocode products using precise orbits and topographic information;
- Estimate baselines from precise orbit solutions and using image-derived methods;
- Calibrate products from corner reflector analysis and provide tools for estimating temporal phase stability; and
- Verify products with a statistical package comparing ground truth GPS to interferometrically derived displacements.

JPL and Vexcel are world-leaders in developing production-grade processors for science applications and research; Stanford, Scripps, and Caltech have developed InSAR code for reasearch. Repeat Orbit Interferometry (ROI)_PAC, developed at JPL and Caltech and used in over 30 institutions worldwide, is a research code suite designed to perform ECHO-like ROI on ERS, JERS, and RADARSAT data. All the processing functionality listed above is currently included in the ROI_PAC distribution. Calibration and verification packages for SAR data also exist at JPL but have not been distributed.

Existing software will be upgraded for the ECHO mission characteristics, including:

- Pre-processing of ECHO telemetry, signal data, and ephemeris information to standardize radar image processing.
- Upgrade of the image-formation processor to incorporate an ionospheric correction. This will include split-spectrum range processing and azimuth auto-focus processing.
- Upgrade of strip-mode processors to accommodate ECHO-radar-specific configuration changes, including gain, beam-pointing, and data window position changes.
- Upgrade of JPL SRTM-based Repeat Orbit ScanSAR Interferometric (ROSI) preprocessor and processor for ECHO data.
- Upgrade calibration tools to use specific ECHO ancillary products and ground-truth data sets to generate
- Upgrade verification tools for ECHO specific data and meta-data.

F.4.7.2 Software Validation. The science user processing software will be validated and quality-checked prior to launch using simulated data as well as existing ERS and JERS data. Post-launch software validation will be included implicitly in the effort to validate the measurements against ground truth collected within natural laboratories (Section F.4.10).

F.4.8 Analysis Approach

Other than calibration and validation, data analysis will be the responsibility of scientific investigators. The first step common to all disciplines is the generation of range displacement maps (interferograms) in as many as four viewing directions obtainable with ECHO. Data and software will be provided to investigators, allowing them to produce calibrated radar line-of-sight displacement maps and vector displacement maps. This approach is consistent with the current InSAR processing methodology, in which SAR signal data is the preferred product requested by users. This approach also allows users to incorporate any site-specific data (e.g., GPS data) they may have into the processing.

F.4.9 Data Archiving and Distribution

ECHO will provide free and open distribution of ECHO data in a manner consistent with NASA and U.S. Government data policy. The ECHO ground system will distribute data to the science community in two ways: Internet access, and requests to the long-term archive.

Data will be received at 2 ground stations. From there, the data will be moved to a network of several online servers with Internet-2 connections to provide users with online access within 24 hours from reception. Data will be kept online on this server network for at least 1 year from reception when demand is expected to be high. All ECHO data also will be available online throughout the mission at the San Diego Supercomputing Center (SDSC/NPACI). In addition, the data will be permanently archived at the USGS EROS data center (EDC) (meeting AO App. 6 requirements) from where users can request tape delivery of the data. DPI Zebkev will be responsible for the delivery of the ECHO SAR data products.

F.4.9.1 Data Formats. All low-level SAR products will be archived in CEOS format. Images and maps will use EOS-HDF format for compatibility with EOSDIS.

F.4.10 Data Validation and Calibration

The Science Team will use dense GPS networks (e.g., SCIGN and EarthScope) for validation. The Science Team will determine the various calibration parameters (e.g., instrument delays). In addition, consistent with the current state of the art, displacement maps will be individually calibrated (e.g., InSAR baseline solution) by users using the ECHO processing software.

The Science Team will fully calibrate, validate, and evaluate the ECHO data products. Calibration and quality assessment of mission products by Science Team members includes: (1) calibration of the radar instrument, (2) validation of the processing software, (3) evaluation of the GPS orbit determinations, (4) validation of interferometric measurements, and (5) periodic checks to assess the performance and stability of the instrument.

F.4.10.1 Calibration of the Radar. Precise geolocation of the data requires that slant-range pixel spacing and slant range to the first sample be known to approximately the 0.2-pixel level. Several factors that determine the geolocation accuracy, including knowledge of the position of the radar antenna phase center, the time delay to the first range sample, and the time interval between samples. There are also additional delays internal to the radar.

Most of these delays will be measured as part of the pre-launch sensor calibration and testing activities, and on-orbit drift will be monitored with the Built-In Test Equipment (BITE). In orbit, the radar will be calibrated using precisely located corner reflectors to determine unknown delays and the antenna phase centers. These corner reflectors are located on the Rosamond Dry Lake in the Mojave Desert. This test site has been used for many years as a calibration site for NASA's TOPSAR and for the SIR-C/X-SAR. These reflectors will be supplemented with existing reflectors in Delta Junction, Alaska. The result of the pre- and post-launch calibration activities will be a file containing calibration data for distribution with the processing software

F.4.10.2 Orbit and Baseline Evaluation. ECHO orbit knowledge will be evaluated by following the procedure used for the T/P orbit quality assessment. Specifically, the quality of the ECHO orbit quality will be determined by comparing overlapping sections of adjacent, 30-hour orbit arcs centered at noon UTC [*Bertiger et al.*, 1995].

Baseline accuracy will be assessed over an area of known topography where the baseline can be determined using ground control.

F.4.10.3 Measurement Validation. The ultimate products that will be derived from the ECHO data are maps of surface displacement vectors. The quality of these products will be assessed through comparisons with *in situ* displacement estimates. These validation data will be acquired using conventional geodetic techniques, such as the GPS at sites representing various environmental and surface conditions. The prime objective of these validation experiments is to assess the precision of the ECHO displacement maps and assess impacts of system noise, and atmospheric and ionospheric artifacts.

At lower latitudes, measurement validation will rely on existing, continuously operating GPS arrays in the Western U.S. and Japan. In addition to the current South California Integrated Network (SCIGN), the EarthScope PBO will deploy several hundred more permanent GPS monuments along the West Coast of North America. These arrays will provide vector displacement comparisons over a wide range of station spacings. This will facilitate the assessment of both short- and long- wavelength errors. The Japanese GPS network currently contains over 1000 stations.

Kilauea volcano, Hawaii, is probably the world's best-monitored volcano, including a 15-station permanent GPS array. Kilauea experiences tremendous gradients in atmospheric moisture, and will be an excellent place for validating algorithms for removing atmospheric delay artifacts.

Validation and evaluation of glacier and ice-sheet data will rely on existing GPS measurements of ice velocity. These measurements are primarily those acquired during the Siple Coast Project in West Antarctica [*Whillans and Van der Veen*, 1987]; and those measured every ~30 km at the 2000-m contour line of Greenland by NASA's Polar Research Program.

As part of the validation activities, the Science Team will produce several higher level products over areas of high scientific priority. These products will be used to confirm the ability to produce displacement maps for the relevant disciplines over broad geographic areas. A summary of these products is given in Section F.4.4.2.

F.4.10.4 Radar Performance and Stability Evaluation. Radar performance will be evaluated with a tool that allows semi-automated analysis of data collected over corner reflector sites. This tool will perform tests to evaluate the statistics and signal quality of the data. Throughout the mission, phase stability will be assessed by checking long strips of data collected over regions with little or fixed surface deformation (e.g., Antarctic Plateau).

F.4.10.5 Schedule for Calibration and Validation Activities. Post-launch calibration activities will begin once the radar begins collecting data. These activities will be completed over a 3-month commissioning period. Once the instrument is calibrated, data will be released to the science community along with the calibration data and report.

The validation and evaluation experiments will occur during the first year. A full year is needed to obtain enough data to fully quantify errors due to tropospheric and ionospheric delays. The Science Team will generate an interim validation report after the first 3 months. A complete validation report will be issued at the end of the first year.

Radar performance evaluation will occur weekly during the commissioning period. For the rest of the first year, quality checks will be performed monthly. Performance will be evaluated every 3 months for the rest of the mission. Radar housekeeping telemetry and receive-only noise data samples will be screened as acquired to monitor instrument health

F.5 SCIENCE TEAM

The ECHO Science Team consists of a multi-institutional, multi-national, consortium of both academic and Government scientists. Collectively, team members bring the proper balance of expertise in InSAR, and Earth science analysis and modeling to the mission. Responsibility for meeting ESSP program objectives of providing calibrated and validated data lies with the PI, supported by the team. The team role also includes development and support of the InSAR processing software and support of education and public outreach efforts. In addition to the individual roles described below, team members' responsibilities are organized by focus areas in Table F-2. Curriculum vitae are provided in Appendix L.1.

In addition to the team members listed here, DLR will assign and fund additional German science team members, whose research will focus on the complementarity of ECHO and TerraSAR-X.

BERNARD MINSTER, Professor of Geophysics, SIO, PI: Fully responsible for all aspects of the mission and for the science team management. Establishes and operates a *Science Data Acquisition Planning Facility* on the UCSD campus and works with the Science Team to establish acquisition priorities with input from the broader scientific community. Participates in Southern California Cal/Val experiments. Acts as a liaison to EarthScope and to the commercial and application SAR communities.

PAUL ROSEN, Radar Scientist, JPL, Deputy PI: Ensures that S/C and instrumentation are configured to meet science objectives. Coordinates the development and dissemination of algorithms for interferometric SAR processing. Conducts radiometric and geometric calibration of the radar instrument using ground corner reflectors.

HOWARD ZEBKER, Professor of Electrical Engineering and Geophysics, Stanford, Deputy PI: Responsible for overall ground system architecture and validation algorithms definition and development. Responsible for assuring the quality of the SAR data distributed during the mission. Conducts Cal/Val experiments.

Table F-2: Science team focus groups. (Leads shown in italics)

Data Product definition & Availability	Seismic Objectives	Volcano Objectives	Ice Sheet Objectives	Orbit Control & Knowledge	InSAR algorithms & calibration	Education & Outreach
Zebker	*Jordan*	*Segall*	*Joughin*	*Sandwell*	*Rosen*	*Minster*
Sandwell	Peltzer	Thatcher	Rignot	Zuber	Zebker	Sandwell
Rosen	Simons	Simons	Minster	Segall	Simons	Jordan
Joughin	Minster	Zebker	Sandwell	Jordan	Joughin	Rignot
Peltzer	Segall	Zuber	Zuber	Rosen	Rignot	Thatcher

TOM JORDAN, Professor of Geophysics, USC, and Director of SCEC, Co-I: Ensures a heavily leveraged and ECHO-tailored education and outreach program with SCEC. Defines and promotes the role of ECHO data in integrative science activities. Communicates ECHO achievements to the National Academies, and ensures coordination with EarthScope .

IAN JOUGHIN, Glaciologist, JPL, Co-I: Specifies mission science requirements for glacier and ice sheets. Conducts Cal/Val experiments under the West Antarctic natural laboratory.

GILLES PELTZER, Professor of Geophysics, UCLA, Co-I: Conducts Cal/Val experiments under the Southern California natural laboratory. Specifies science requirements for earthquake studies. Investigates the effects of atmospheric delay on the recovery of large-scale deformation patterns.

ERIC RIGNOT, Glaciologist, JPL, Co-I: Conducts Cal/Val experiments as part of the West Antarctic natural laboratory, focusing on Pine Island and Thwaites Glaciers.

PAUL SEGALL, Professor of Geophysics, Stanford, Co-I: Coordinates the validation of ECHO-derived estimates of crustal deformation within natural laboratories in California and Hawaii.

DAVID SANDWELL, SIO, Co-I: Assembles ancillary data needed for first-order corrections to interferograms, with a focus on tropospheric effects. Validates the use of these corrections. Conducts calibration of InSAR and ancillary data using the dense GPS array in Southern California.

MARK SIMONS, Assistant Professor of Geophysics, Caltech, Co-I: Conducts Cal/Val experiments using modeling and continuous GPS. Coordinates data acquisition of volcanic events during the mission.

WAYNE Thatcher, Senior Research Scientist, USGS, Menlo Park, Co-I: Acts as liaison to the USGS and EDC. Develops an ECHO database for several volcanic sites distributed worldwide, analyzed at least once per month.

MARIA ZUBER, Professor of Geophysics, MIT, Co-I: Develops techniques to merge the small-scale deformation patterns derived from ECHO InSAR with the more accurate point-wise displacement measurements from the Southern California natural laboratory.

F.5.1 Team Activities

In addition to the above, team activities are targeted towards the following deliverables for the instrument calibration effort:

- ECHO instrument and navigation system requirements derived from measurement requirements.
- Design of the calibration plan, including GPS measurement and deployment of corner reflectors or other ground-based instruments
- Development, testing, validation, and delivery of the user InSAR processing software package.
- Derivation of calibration parameters including: time offset to first sample, inter-sample spacing, and along-track latency between the actual time of a pulse relative to the annotation time.

The PI will convene 3–4 science team meetings per year, depending on the mission phase. Prior to launch, meetings will focus on setting mission requirements and processing code development. After launch, team meetings will focus on Cal/Val activities. The PI will also convene and chair at least one science workshop per year to secure input from the scientific community concerning the mission and coverage priorities. Guests from the commercial and applica-tions communities will be invited to attend these workshops. The PI will appoint key discipline scientists from outside the core team to chair working groups on the ECHO science themes.

F.6 PLANS TO RESOLVE OPEN SCIENCE ISSUES

There are currently no open science issues to be resolved.