UC Irvine

UC Irvine Previously Published Works

Title

Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI)

Permalink

<https://escholarship.org/uc/item/4mt992cc>

ISBN

9781424414888

Authors

Donnellan, A
Rosen, P
Graf, J
et al.

Publication Date

2008-08-19

DOI

10.1109/AERO.2008.4526249

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI)

Andrea Donnellan, Paul Rosen, Jim Graf, Adam Loverro, Anthony Freeman, Robert Treuhaft, Robert Oberto, Marc Simard,
Eric Rignot, Ronald Kwok, Xiaoping Pi
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
818-354-4737
Andrea.Donnellan@jpl.nasa.gov

J. Bryan Blair, Waleed Abdalati, Jon Ranson
NASA Goddard Spaceflight Center
Greenbelt, MD, 20771

Howard Zebker
350 Serra Mall
Stanford University
Stanford, CA 94305

Bradford Hager
Department of Earth, Atmospheric, and Planetary Science
Massachusetts Institute of Technology
Cambridge, MA 02139

Hank Shugart
Department of Environmental Sciences
University of Virginia
Charlottesville, VA 22904

Mark Fahnestock
CSRC/EOS 236A Morse Hall
University of New Hampshire
Durham, NH 03824

Ralph Dubayah
Department of Geography
University of Maryland
College Park, MD 20742

Abstract—The National Research Council Earth Science Decadal Survey, Earth Science Applications from Space, recommends that DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice), an integrated L-band InSAR and multibeam Lidar mission, launch in the 2010–2013 timeframe. The mission will measure surface deformation for solid Earth and cryosphere objectives and vegetation structure for understanding the carbon cycle. InSAR has been used to study surface deformation of the solid Earth and cryosphere and more recently vegetation structure for estimates of biomass and ecosystem function. Lidar directly measures topography and vegetation structure and is used to estimate biomass and detect changes in surface elevation. The goal of DESDynI is to take advantage of the spatial continuity of InSAR and precision and directness of Lidar. There are several issues related to the design of the DESDynI mission, including combining the two instruments into a single platform, optimizing the coverage and orbit for the two techniques, and carrying out

the science modeling to define and maximize the scientific output of the mission.^{1,2}

TABLE OF CONTENTS

1. INTRODUCTION	2
1. SCIENCE	2
2. INSTRUMENTS	5
4. MISSION DESIGN.....	7
5. CONCLUSIONS	8
6. ACKNOWLEDGEMENTS.....	8
REFERENCES.....	8
BIOGRAPHIES.....	9

¹ 1-4244-1488-1/08/\$25.00 ©2008 IEEE.

² IEEEAC paper #1223, Version 5, Updated December 17, 2007

1. INTRODUCTION

In 2004, at the request of NASA, NOAA, and the USGS, the National Research Council appointed the Committee on Earth Science and Applications from Space to develop consensus recommendations for Earth and environmental science and applications from space. In 2007, the final report was published and included a recommendation for a Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI) mission [1]. DESDynI is an L-band InSAR and laser altimeter for studying surface and ice sheet deformation for understanding natural hazards and climate, and vegetation structure for ecosystem health.

DESDynI addresses many of the scientific objectives assigned high priority by the decadal survey. It will measure the height and structure of forests, changes in carbon storage in vegetation, ice sheet deformation and dynamics, and changes in Earth's surface and the movement of magma. These measurements will improve our understanding of the affects of changing climate and land use on species habitats and atmospheric CO₂. DESDynI measurements will also facilitate the monitoring of species habitats, understanding the response of ice sheets to climate change and the impact on sea level, and forecasting the likelihood of earthquakes, volcanic eruptions, and landslides.

1. SCIENCE

NASA hosted a workshop in July 2007 to assess the DESDynI mission, articulate the expected scientific return from DESDynI, and recommend next steps for the mission [2]. The mission will be used to improve forecasts of the likelihood of earthquakes, volcanic eruptions, and landslides, help scientists understand the effects of changing climate and land use on terrestrial carbon storage, fluxes of carbon dioxide to the atmosphere, and species habitats, and study the response of ice sheets to climate change and their impact on sea level. The primary mission objectives for DESDynI are to:

- (1) Determine the likelihood of earthquakes, volcanic eruptions, and landslides.
- (2) Predict the response of ice sheets to climate change and impact on sea level.
- (3) Characterize the effects of changing climate and land use on species habitats and carbon budget.

And as an application:

Figure 1. Surface deformation map of the 1999 Hector Mine earthquake, derived from ERS radar data. Each color fringe represents 10 cm of ground displacement from the earthquake.

- (4) Monitor the migration of fluids association with hydrocarbon production and groundwater resources.

The science objectives of DESDynI for solid Earth, cryosphere, and ecosystems result in a number of requirements for measurement of solid Earth and ice sheet surface deformation, forest structure, and ice thickness and kinematics. Level 1 requirements for the mission have been drafted, and from these requirements the instrument and spacecraft requirements must be developed. A summary of the science objectives and level 1 requirements follows.

Solid Earth

DESDynI will be used to help define how we prepare for, mitigate against, and respond to major geohazards. US annualized losses from earthquakes are \$4.4B/yr [3], yet current hazard maps have an outlook of 30–50 years over hundreds of square kilometers [4] making prioritization of retrofitting difficult. Volcanic eruptions destroy cities and towns, eject ash clouds that disrupt air travel, and disrupt regional agriculture. Recurrent flood hazards threaten civilian safety and commerce worldwide. Mississippi River flooding in 1993 caused \$15–20 billion damage and displaced 70,000 people. The 2004 tsunami in southeast Asia killed over 140,000 people. Sea level change, land subsidence, and landslides are becoming more problematic with development in high-risk areas. The New Orleans levee system is subsiding at an average rate of 8 mm/yr [5], which must be understood and factored into reconstruction plans.

Figure 2. Mangrove forest height and inferred biomass density from SRTM calibrated with Lidar (ICESat/GLAS and airborne) and field data. Mangroves contribute 11% of global total carbon export to the ocean. Mangrove forests are in danger of being lost entirely due to economic development and sea level rise. 35% of mangrove forests have disappeared and 60% could be lost by 2030 [6].

Precise measurement of surface deformation (Figure 1) coupled with models can improve assessment of risk from natural hazards, which ultimately can minimize loss of life and destruction of property. Forecasting of earthquakes, volcanoes, and landslides is greatly improved by an understanding of how the surface deforms and moves, which can be used to infer subsurface processes. Earthquake risk assessment requires knowledge of the mechanisms that control both transient and steady state aseismic fault slip.

Observation of pre-slip can aid in mitigating losses from landslides. Measurement of uplift and subsidence yields insights into the size, location, and movement of magma within volcanic chambers. Detailed crustal deformation measurements have been crucial to better understanding these natural hazards, yet only a small fraction of the world's active volcanoes and faults are instrumented. DESDynI provides the opportunity to image the deformation field associated with these events and infer the causative deformation sources at depth globally and systematically.

The first requirement of solid Earth for the DESDynI mission is to characterize the nature of deformation at plate boundaries and the implications for earthquake hazards by measuring surface deformation and surface disruption [7]. Measurement of surface deformation is used to discriminate between faults and assign potential hazard. It requires 3-dimensional (vector) global coverage of actively deforming areas with 100 m resolution imagery accurate to 5% of the rate of the deforming zone or to 1 mm/yr. 200 km width

imagery across the deforming boundary is required as is unaliased temporal sampling with week-timescale measurements, particularly immediately following an event. Measurement of surface disruption with 20 m resolution over a 400 m zone across the fault is required to infer the mechanical properties of the earthquake fault zone.

The second requirement for solid Earth for DESDynI is to characterize how magmatic systems evolve in order to understand under what conditions volcanoes erupt. Again, this requires measurement of surface deformation, this time to infer the volume of magma in the chamber and potential hazards. This requires coverage of the Earth's active volcanoes, which requires an initial exploratory survey of all of the volcanoes to discover which are deforming. Again, 3-dimensional (vector) deformation with 100 m imagery is required. Measurement of surface disruption at 20 m resolution throughout the area of eruption is required to infer the volume of magma released.

Ecosystems

The rate of increasing atmospheric CO₂ over the past century is unprecedented, at least over the last 20,000 years [8]. Vegetation ecosystems, especially forests, store carbon, thus changes in these systems impact the global carbon budget and the amount of CO₂ in the atmosphere. Major sources of uncertainty in global carbon budgets derive from large errors in the current estimate of carbon storage in vegetation and changes in land cover [9] Disturbances, either from natural phenomena such as fire or wind or from

Figure 3. Mosaic of ice velocities determined from 10 years of ERS 1/2 data in Antarctic overlaid on a radar map.

human activities such as forest harvest and subsequent recovery, complicate the quantification of carbon storage and release. The resulting spatial and temporal heterogeneity of terrestrial biomass coupled with a lack of biomass surveys for most of the world make it difficult to estimate terrestrial carbon stocks and dynamics.

DESDynI will provide globally consistent and spatially resolved estimates of vegetation structure from which aboveground biomass (e.g. Figure 2) and ecosystem function can be derived [6, 10, 11]. These structure and biomass estimates will be used to characterize and quantify changes in terrestrial carbon sources and sinks resulting from disturbance and recovery. They will also be used to characterize forest structure for biodiversity assessments.

DESDynI is particularly suited for quantifying vegetation in three dimensions yielding vegetation height, vertical profiles, and disturbance recovery patterns that are required to characterize species habitat and assess ecosystem health. Accurate measurements of vertical structure will be used to improve models of photosynthetic function and ecosystem productivity. These parameters are used to couple feedback effects between the terrestrial part of climate change in general circulation models (GCMs). USDA Forest Service fire spread models require structural inputs such as canopy height, canopy cover, vertical biomass profiles, and canopy base height. The destructive fires of 2007 in southern California highlight the need for improved fire spread models for forest fire preparedness and mitigation.

Developing globally consistent and spatially resolved estimates of above ground biomass and carbon stocks

requires observation of the global vegetated cover with 100 m spatial resolution accurate to 10 Mg/hectare or to within 20% at least once per year during the growing season [9]. Understanding changes and trends in terrestrial ecosystems and their functioning as carbon sources and sinks requires observation of global vegetated cover with 100 m spatial resolution. Measurements must be accurate to 2–4 Mg/ha/year or to within 20% of the change and must be made monthly to seasonally over the life of the mission, which must have a minimum duration of 5 years. Characterizing habitat structure for biodiversity assessments requires a horizontal resolution of better than 25 m and a vertical resolution of 2–3 m of the canopy profile. Achieving these measurement goals requires the combination of the multibeam full-waveform Lidar with radar polarimetry.

Cryosphere

Ice sheets and glaciers are experiencing dramatic changes that have the potential to raise sea level substantially in the coming decades (Figure 3). Despite the scientific and societal importance, and their sensitivity to climate change, they remain one of the most under-sampled components of the Earth System. Recently flow rates of outlet glaciers around many parts of Greenland and Antarctica have increased significantly, more than doubling in some cases. These accelerations and increased melt rates have been causing the glaciers and ice sheet margins to thin by as much as meters to tens of meters per year, as their ice is lost to the surrounding seas. These phenomena raise the question of ice sheet stability and the potential of these ice sheets to contribute to relatively rapid rises in sea level. As a result, the authors of the Decadal Survey [1] identified as one of their highest-priority questions: “Will there be a catastrophic collapse of the major ice sheets, including Greenland and West Antarctica, and if so, how rapidly will that occur? What will be the pattern of sea level rise as a result?”

DESDynI would help address these questions by providing comprehensive observations of ice sheet surface dynamics, which are directly related to ice sheet stability. The interferometric radar would precisely measure surface velocities of the rapidly changing outlet glaciers, enabling improvements in ice sheet modeling capabilities to facilitate improved projections of ice sheet contributions to sea level rise in response to the changing climate

Sea ice is another component of the Earth system that is changing rapidly and in ways that can affect climate worldwide. Ice cover in both the Arctic and Antarctic play a critical role in the global climate system by modulating the exchange of moisture and energy between the ocean and the atmosphere, and influencing oceanic and atmospheric circulation. In the Arctic, the ice cover has been diminishing

Figure 4. Illustration of how Interferometric Synthetic Aperture measures surface deformation with a zero-length baseline (left panel). The phase of the radar wave changes between two passes if a point on the ground moves. Measurements from a finite baseline (right panel) can be used to measure forest structure because the interferometric phase return from various altitudes within trees (the top and bottom of the tree are shown for illustration) is different for different locations of the satellite forming the baseline.

substantially, while in the Antarctic there have not been substantial changes. Understanding the interactions among the ice, ocean, and atmosphere, and their future behavior requires comprehensive observations of sea ice extent, concentration, and thickness. These are best derived from multiple satellite observations from existing and future missions such as DESDynI, AMSR-E, SSM/I, Cryosat, ICESat, and ICESat-II.

InSAR on DESDynI will augment those observations by providing detailed information on the mechanisms of deformation and transport of polar sea ice cover. This information can improve structural models of sea ice behavior to help understand the interactions among the ice, ocean, and atmosphere, and how they may behave in the future. If the Lidar is designed with sufficient precision, it can be used to provide ice thickness information that is critical to understanding its present and future behavior. Understanding our cryosphere requires measurement of surface deformation as well as thickness of sea ice. The objective is to quantify the interactions among ice masses, oceans, and the solid Earth and their implications for sealevel change [7]. This requires global coverage of ice masses and the measurement of surface displacement to quantify ice fluxes in order to infer global mass balance. Surface displacements must be measured on rapidly moving ice masses with horizontal velocities accurate to the greater of 2 m/yr or 10% of the total velocity. Vertical subsidence must be measured to 5 mm. Weekly observations are required to quantify temporal changes at 100 m resolution.

The second requirement is to quantify sea ice mass balance and how it is changing over the Arctic and Southern Oceans at inter-annual timescales over a minimum of 5 years. From

this follows the need to 1) quantify changes in sea ice thickness by measuring sea ice freeboard to a vertical accuracy of 15 cm with a spatial resolution of 25 m, and 2) quantify how sea ice motion and circulation are changing at kilometer scales with 100 m resolution. The latter requires daily time scales to provide uninterrupted time series to cover advance and retreat of seasonal/perennial ice cover over a minimum of 5 years.

2. INSTRUMENTS

DESDynI's instruments are an L-band radar and a multi-beam Lidar. The radar instrument will be used to measure surface deformation of the solid Earth and cryosphere and will be used in other modes to study ecosystems. The Lidar will be used primarily to support the ecosystem science objectives of DESDynI, but may be used for studying ice sheet mass balance, and possibly the solid Earth.

Table 1. Radar operating modes for DESDynI

Mode	Application
Strip Map (single- or dual-pol)	Volcanic, earthquake, ice sheet deformation
ScanSAR (single- or dual-pol)	Tectonic deformation
Full-polarimetry (strip map)	Ecosystems and carbon stocks
Zero baseline	Surface Deformation
Finite baseline	Vegetation Structure and biomass

Figure 5. Using single polarization finite baseline interferometry the average phase, somewhere in the tree, can be determined (A). A polarization such as VVVV might illuminate the ground more than the volume, as suggested by the darker ground surface in A, drawing the phase center down to the X shown in Figure 5A. A polarization such as HVHV might illuminate the volume more than the ground drawing the phase center closer to the top of the canopy as in B. Multiple polarizations, in effect add contrast and can be used to estimate structure from the systematic changes in InSAR phase and coherence as a function of polarization.

Radar

The DESDynI radar instrument is an L-band (1.2-GHz) synthetic aperture radar (SAR) system with multiple polarizations that can be operated in several modes (Table 1). The radar instrument will be operated as repeat pass Interferometric Synthetic Aperture Radar (InSAR) to measure surface deformation, and ice sheet dynamics (Figure 4, left panel). An InSAR satellite passing over a location before and after an event, such as an earthquake, tectonic deformation, volcanic inflation, or ice sheet motion, at exactly the same point in inertial space (zero baseline) can measure how the ground shifts between passes, producing a radar interferogram. The phase of the radar wave changes between two passes if a point on the ground moves. An InSAR image of the point-by-point phase difference of the wave on the surface is used to create a map of the movement of the surface over time. The radar instrument can take observations through cloud cover, without sunlight, and can measure sub-centimeter changes. The radar phase differences between the ends of a nonzero baseline are proportional to the difference between the arrival times of the waves at each end of the baseline. For each component of a vegetated surface (leaves, branches, trunks, ground) this radar phase difference, called the interferometric phase, is therefore proportional to the height of that component (Figure 4 right panel). Combined with a related quantity called the interferometric coherence, the interferometric phase can be used to measure ecosystem structure using finite baseline interferometry (Ref. C). One way to approach this is to carry out campaigns during the mission that offset the orbit to provide the finite baselines required for estimating forest structure.

It has been shown that a single, finite-baseline InSAR phase-coherence pair are insufficient to estimate the complex structure of forests [12]. The single-baseline “underdeterminedness” has been addressed by various researchers using external calibration in the form of field [e.g. 13] and/or Lidar [6] measurements. It has also been addressed by using multiple baselines [e.g. 14], multiple frequencies [15], and/or multiple polarizations [e.g. 16]. In various operating modes, DESDynI can realize all of these modes of structure estimation except the multifrequency mode, which might be accessible via collaboration with other missions. For example, InSAR measurements at different polarizations will be used to estimate vegetation structure and biomass. Figure 5 shows schematically that InSAR at different polarizations changes the phaser (and the coherence) of the InSAR measurement [17]. Multipolarization interferometry is a method of adding contrast between the ground and the tree volume and can be used to estimate vertical forest structure by the systematic differences in interferometric response to each polarization [16], as suggested in Figure 5. Each phase is weighted by how strong the return is. Some polarizations are sensitive to the ground, for example, ground bounce HH-HH and the direct return VV (Figure 5A), while other polarizations are sensitive to volume such as the cross polarizations HV-HV (Figure 5B).

The radar instrument operates in the L-band and will have two sub-bands separated by 70 MHz for ionospheric correction. The split spectrum techniques are used to correct phase delays introduced by ionospheric propagation. The mission is also designed with a sun-synchronous dawn-dusk orbit to minimize ionospheric effects. The ionosphere is most quiet at dawn. Some DESDynI radar data will be affected by ionospheric distortions, including Faraday rotation, phase delays, and scintillation. Ongoing research into correction for Faraday rotation appears promising [18]. Indications are that it will be possible to correct data collected in fully polarimetric mode. Research into scintillation effects is currently focused on determining the expected frequency of occurrence and severity of such events at the 6 am and 6 pm observation times of DESDynI.

Lidar

The DESDynI Lidar instrument is a multiple-beam Lidar operating in the infrared (about 1,064 nm) with a spatial resolution of 25 meters producing a spatial resolution of forest canopy height of 1 m. Lidar (Light Detection and Ranging) uses light in the visible spectrum transmitted in a narrow beam. It allows detailed observations of vegetation structure in tree canopies and accurate measurement of ice sheets, glaciers, and topography [19].

Lidar systems transmit pulses of laser light downward and receive various reflections from the surfaces of leaves and other forest elements, including the ground (Figure 6). The round-trip travel times are directly related to the heights of

Figure 6. The return signal waveform from Lidar contains information on the height and structure of forest canopy.

the reflecting vegetation elements. The profile of vegetated surfaces resulting from a time sequence of reflections can be used in an empirical regression to field data to derive biomass. Moments of the profile, such as mean height, are most often used to establish correlative relations with field biomass. The multibeam laser altimeter accurately measures the distance between the canopy top and bottom elevation in forests. It also measures the vertical distribution of intercepted surfaces and the size and distribution of vegetation components within the vertical distribution.

4. MISSION DESIGN

DESDynI takes advantage of the precision and directness of the Lidar with the global spatial coverage of the radar. The radar and Lidar measurements for ecosystem studies need to be made in close proximity in time enabling cross calibration and validation. Forest growth, budding, and dropping of leave occur on fairly short timescales, thus each of the measurements must be made within a few weeks of the other [1]. InSAR and Lidar measurements have similar mission requirements. For example, a sun-synchronous dawn-dusk orbit is required for the radar measurements to minimize effects of the ionosphere and for the Lidar to reduce effects of reflected solar radiation, especially in the tropics. The ionosphere is most quiet and the minimum cloud cover is at dawn. However, combining science and measurement objectives in addition to two instruments onto a single spacecraft results in competing design trades. We believe that a solution exists which yields a mission that meets Earth science objectives including those of Solid Earth, Cryosphere, and Ecosystems. The following outlines some of the competing differences between the InSAR and Lidar science measurements.

For a vegetation Lidar mission a higher inclination polar orbit is preferred, but for an ice Lidar mission a lower

inclination such as 94° is preferred. The 98° inclination planned for DESDynI maintains the sun-synchronous orbit and is acceptable for both the Lidar and InSAR measurements for this mission. The preferred orbit altitude for a Lidar instrument is a 400–600 km due to the need for increasing power and telescope aperture size with increasing altitude. The InSAR requires a higher orbit, preferably in the range of 700–800 km for swath coverage and to reduce atmospheric drag. A 600 km orbit is acceptable for both the InSAR and Lidar instruments; hence the orbit should be designed near this altitude.

A long (~ 90 -day repeat) is desired for Lidar to provide full geographic coverage. The Lidar is a nadir-pointing instrument with a 25 m diameter beam spot size that produces distributed spot-beam ground tracks. InSAR, on the other hand, requires rapid repeats in order to observe deformation processes typically on weekly timescales. Discrimination between postseismic processes requires a 14-day repeat for a duration of at least two years in order to avoid aliasing and for a signal to emerge out of the errors [20]. Grounding line dynamics studies require that the repeat measurements be made out of cycle with the tides (7 and 14 days). In addition, rapidly changing targets, such as leaves moving in the wind, or rapidly moving ice measurements require short time scale repeat observation to minimize decorrelation. Week-timescale measurements, or an 8-day repeat orbit, result in a ground track spacing for the Lidar measurements of 350 km at the equator, which is not desirable for calibrating the radar measurements. A possible compromise is a 12-day repeat orbit in combination with off-nadir pointing for the Lidar instrument. This may achieve the needed Lidar coverage without undue compromise to the InSAR measurements. Unlike the Lidar instrument, the radar instrument looks to the side at a $25\text{--}30^\circ$ angle, which means that the two measurements will not be made exactly coincident in time. However, as long as the radar instrument is collecting data, the measurements will be made within a few days or weeks of each other.

Competing trades between the need for near zero (less than 250 m offset) repeat pass radar interferometry for deformation studies and finite (0.6–1.5 km) baseline radar interferometry for vegetation structure estimates are workable by splitting the mission into campaigns. The ground track for DESDynI can be perturbed to provide the finite offsets needed for estimating vegetation structure, without drifting the orbit. At the beginning and end of the mission during northern summer a finite baseline campaign can be accomplished by cycling the spacecraft three-seconds ahead of normal orbit position and then back on eight-day centers for three months. Moving the spacecraft 3-seconds in its orbit will result in a 1.5 km offset to the ground track at the equator and acceptable but smaller offsets at higher latitudes. The 250 m tube will be maintained during this finite baseline campaign allowing the near-zero baseline science to be continued but now for two separate but consistent ground tracks, one the nominal

mission track and the other offset by 1.5 km. The impact to the mission will be increased temporal decorrelation due to a 16-day repeat vs. the desired 8-day repeat for the deformation science and an increase in Delta-V of 15–40 m/s. The main mission campaign will consist of the near-zero baseline fixed orbit with Lidar and ScanSAR on an 8-day repeat cycle and quad-pole radar measurements during the growing season. The mission can be designed in a similar manner, but for a 12-day orbit, to improve Lidar coverage.

Another mission scenario endorsed by the National Research Council Decadal Survey is to fly the InSAR and Lidar on separate platforms, which would allow both instruments to fly in orbits optimized for their key science objectives. This would ensure maximum data acquisition to meet discipline science requirements and opportunities for cross calibration activities.

Radar science measurements require collection, storage and downlink of large volumes of data. Relative to the radar the Lidar downlink requirements are minimal, and hence all of the collected Lidar data can be down linked. The mission is planned to observe the land and ice masses only, which cover 30% of the Earth's surface. Solid Earth, vegetation and cryosphere science requires observation of Earth's deforming zones, forested areas and ice sheets representing about 40% of the land surface. Therefore, it is not necessary to keep the radar instrument turned on continuously and this results a manageable data downlink strategy. There will still be a large amount of data, however (about 600 GB/day), thus a clear data processing and distribution strategy will need to be developed early in order to maximize the use of the data.

5. CONCLUSIONS

DESDynI will be the first mission to collectively study the solid Earth, the ice masses, and ecosystems systematically and globally. It uses L-band interferometric synthetic aperture radar and multibeam Lidar to achieve its objectives, which are to characterize the effects of changing climate and land use on species habitats and atmospheric CO₂, predict the response of ice sheets to climate change and impact on sea level and forecast the likelihood of earthquakes, volcanic eruptions, and landslide. DESDynI will achieve these goals by measuring the height and structure of forests, changes in carbon storage and vegetation, ice sheet deformation and dynamics, and changes in the Earth's surface and the movement of magma. Mission compromises are possible that enable co-manifesting the InSAR and Lidar instruments and address the three science disciplines.

6. ACKNOWLEDGEMENTS

We'd like to thank the numerous other scientists and engineers contributing to DESDynI within the NASA centers and at the universities. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA and at NASA Goddard Space Flight Center.

REFERENCES

- [1] Anthes, R.A., B. Moore III, et al., *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, National Research Council Committee on Earth Science and Applications from Space, National Academies Press, 11820, 2007.
- [2] DESDynI Writing Committee, Zebker, H., H. Shugar, M. Fahnestock, eds., *Report of the July 16–19, 2007 Orlando, Florida Workshop to Assess the National Research Council Decadal Survey Recommendation for the DESDynI Radar/Lidar Space Mission*, NASA, 2007.
- [3] FEMA (Federal Emergency Management Agency), *HAZUS99 Estimated Annualized Earthquake Loss for the United States*, Available from FEMA Publications Warehouse, Jessup, Md. 366, February 2001.
- [4] Petersen, M.D., W.A. Bryant, C.H. Cramer, T. Cao, M. Reichle, A.D. Frankel, J.J. Lienkaemper, P.A. McCrory, and D.P. Schwartz, *Probabilistic Seismic Hazard Assessment of for the State of California*, US. Geol. Survey Open File Report, 96-706, 1996, revised 2003.
- [5] Dixon, T.H., F. Amelung, A. Ferretti, F. Novali, F. Rocca, R. Dokka, G. Sella, S.W. Kim, S. Wdowinski, D. Whitman, *Subsidence and flooding in New Orleans*, *Nature*, 441, 587–588, 2006.
- [6] Simard, M., K. Zhang, V.H. Rivera-Monroy, M. Ross, P. Ruiz, E. Casteneda-Moya, E. Twilley, E. Rodriguez, *Mapping height and biomass of mangrove forests in the Everglades National Park with SRTM elevation data*, *Photogrammetric Engineering and Remote Sensing*, 72, 299–311, 2006.
- [7] Solomon, S., et al, *Living on a Restless Planet*, Solid Earth Science Working Group Report, NASA, JPL 400-1040, 2002.

- [8] IPCC Climate Change 2001: The Scientific Basis, Chapter 3, The Carbon Cycle and Atmospheric Carbon Dioxide, 185, 2001.
- [9] Houghton R.A., Aboveground forest biomass and the global carbon balance. *Global Change Biology*, 11, 945-958, 2005.
- [10] Drake J.B., Dubayah R.O., Clark D.B., Knox R.G., Blair J.B., Hofton M.A., Chazdone R.L., Weishampel J.F., Prince S.D., Estimation of tropical forest structural characteristics using large-footprint Lidar, *Remote Sensing of the Environment*, 79,: 305–319, 2002.
- [11] Treuhaft R.N., Asner G.P., Law B.E., Structure-based forest biomass from fusion of radar and hyperspectral observations, *Geophysical Research Letters*, 30, 1472–1475, 2003.
- [12] Treuhaft RN, Madsen SN, Moghaddam M, Van Zyl JJ., Vegetation characteristics and surface topography from interferometric radar. *Radio Science*, 31, 1449–1485, 1996.
- [13] Kelldorfer, J. Walker, W., Perce, L., Dobson, C. Fites, JA, Hunsaker, C., Vona, J., Clutter, M., Vegetation height estimation from Shuttle Radar Topography Mission and National Elevation Datasets, *Remote Sensing of the Environment*, 93, 339-358, 2004.
- [14] Reigber A, Moreira A., First demonstration of airborne SAR tomography using multibaseline L-band data, *IEEE Transactions on Geoscience and Remote Sensing* 38:2142-2152, 2000.
- [15] Neeff T., Dutra L.V., dos Santos J.R., da Costa Freitas C., Araujo L.S., Tropical forest measurement by interferometric height modeling and P-band radar backscatter, *Forest Science*, 51, 585-594, 2005.
- [16] Papathanassiou K.P., Cloude S.R., Single-baseline polarimetric SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, 39, 2352–2363, 2001.
- [17] Cloude SR, Papathanassiou KP, Polarimetric SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing* 36: 1551-1565, 1998.
- [18] Freeman, A., "Calibration of Linearly Polarized Polarimetric SAR Data Subject to Faraday Rotation," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 42, no. 8, pp. 1617–1624, 2004.
- [19] Lefsky MA, Cohen WB, Parker GG, Harding DJ., Lidar remote sensing for ecosystem studies, *Bioscience* 52, 19–30, 2002.
- [20] Donnellan, A., G. Lyzenga, J. Parker, Optimal InSAR

Revisit Times for Estimating Postseismic Mechanisms, Fall AGU Meeting, San Francisco, 2006.

BIOGRAPHIES

Andrea Donnellan is the DESDynI Science Lead and QuakeSim principal investigator at NASA's Jet Propulsion Laboratory and is a research professor at the University of Southern California. Donnellan uses GPS and InSAR satellite technology coupled with high performance computer models to study earthquakes, plate tectonics, and the corresponding movements of the earth's crust. She has been a geophysicist at JPL since 1993. She received a B.S. from the Ohio State University in 1986, with a geology major and mathematics minor. She received her M.S. and Ph.D. in geophysics from Caltech's Seismological Laboratory in 1988 and 1991 respectively. Donnellan received an M.S. in Computer Science from the University of Southern California in 2003. She held a National Research Council Postdoctoral Fellowship at NASA Goddard Space Flight Center. Donnellan was a Visiting Associate at the Seismological Laboratory at Caltech from 1995 to 1996. In 1996 Donnellan received the Presidential Early Career Award for Scientists and Engineers, in 2003 the Women in Aerospace Award for Outstanding Achievement, and in 2006 she was the MUSES of the California Science Center Foundation Woman of the Year.

Paul Rosen is currently the manager of the Radar Science and Engineering Section at NASA's Jet Propulsion Laboratory. His focus centers on scientific and engineering research and development for methods and applications of Synthetic Aperture Radar (SAR) and interferometric SAR. He has developed and promoted scientific applications of differential interferometry, including crustal deformation mapping and hazard assessment, and has led several proposals for surface deformation satellite missions. Dr. Rosen was the Shuttle Radar Topography Mission (SRTM) Project Element Manager for Algorithm Development and Verification, and led a SRTM metrology tiger team in 2001. He received NASA's Exceptional Service Medal (2001) and NASA's Exceptional Achievement Medal (2002) for his work on SRTM. Prior to JPL, Dr. Rosen worked at Kanazawa University, Kanazawa, Japan studying wave propagation in plasmas, and the dynamics and observations of Saturn's rings. Dr. Rosen is a visiting faculty member and lecturer at Caltech, and has served on the UCLA Extension Program faculty. He has authored or co-authored over 30 journal articles and two book chapters. Dr. Rosen received a Ph.D in Electrical Engineering from Stanford University.

He received both his M.S. and B.S in Electrical Engineering from University of Pennsylvania.

Jim Graf received a BSE from Princeton University in 1972 and an MS from Colorado State University in 1976. He has been employed in various space-related developments for 33 years, ranging from the development of ion thruster technology to the management of the Quick Scatterometer Mission and the Mars Reconnaissance Orbiter Mission. He is the recipient of NASA's Outstanding Leadership Medal and an Aviation Week's 1999 Laurel for Space. He is presently the Deputy Director for Earth Science and Technology Directorate at the Jet Propulsion Laboratory.

Adam Loverro is an Associate System engineer at the Jet Propulsion Laboratory. Since coming to JPL two and a half years ago he has provided system engineering support in the formulation, and study of numerous early space mission concepts. Before coming to JPL he was a space vehicle engineer for the Iridium satellite constellation. He has a BS in Aerospace Engineering from the University of Notre Dame and is currently working towards a MS in Aerospace Engineering from Purdue University.

Anthony Freeman (M'83, SM '94, F '00) received the B.Sc. (Hons.) degree in mathematics in 1979 and the Ph. D. degree in astrophysics in 1982, both from the University of Manchester Institute of Science and Technology, Manchester, England. Dr. Freeman is currently the Earth Science Research and Advanced Concepts Program Manager at the Jet Propulsion Laboratory (JPL). JPL has a broad portfolio of Earth Science missions as well as planetary science missions and this office is responsible for all of JPL's future work in this area. Prior to this position, he was section manager of the Mission and Systems Architecture Section at JPL, responsible for all advanced mission studies at JPL and prior to that instrument manager for the LightSAR Radar Program at JPL. His research interests include correction of Faraday rotation, modeling of polarimetric radar scattering signatures, and the design of P-Band spaceborne SARs. He has been awarded the NASA Exceptional Service Medal for calibration of SIR-C mission data, numerous NASA new technology awards, and holds two patents.

Robert Treuhaft is a principal research scientist at the Jet Propulsion Laboratory, California Institute of Technology. From 1982-1987, he developed and published a model of tropospheric turbulence in wide use by the astronomical community. In 1991, he performed the first measurement of relativistic deflection by a planet (Jupiter) using Very Long Baseline Interferometry. Radio atmospheric models were applied to an optical interferometer on Mt. Wilson from 1993-1995. From 1996 to the present, Treuhaft has developed and demonstrated models of the response of interferometric SAR in terms of estimated vegetation structural parameters. Using those models on forests in Oregon, he led a team that produced forest vegetation density profiles from InSAR and subsequently the first InSAR-structure-based estimates of forest biomass. From 1998-2003 Treuhaft also worked on the estimation of surface altimetry from GPS scattered signals and published a demonstration of 2-cm altimetry from a lake (Crater Lake). He currently holds a grant with Brazilian collaborators to measure tropical-forest structure in Costa Rica and Brazil with multibaseline interferometric SAR. He received a BS in physics from Yale University (1976) and a PhD in physics specializing in high-energy nuclear constituents from the University of California at Berkeley (1982).

Bob Oberto is a Senior Spacecraft Systems Engineer at NASA's Jet Propulsion Laboratory. He has served in a number of roles including the Principal Investigator of the NASA Exploration Design Team, a multi-NASA center design activity. Bob has been the Project Manager of the JPL Design Teams where he managed all concurrent design team activities at JPL. He also led JPL's Advanced Concept Design Team (Team-X) for several years where he developed over 375 space exploration concepts. Bob was the Project Manager of the Interferometer Program Experiment II that flew on board the Space Shuttle. He has been involved in all aspects of robotic interplanetary exploration, from mission concept development to interplanetary flight operations. Bob was a U.S. Navy Commander and Aviator who served in the Gulf War. He was screened for aviation squadron command and performed carrier flight operations in the West Pacific, Central America, Indian Ocean and North Arabian Sea. He was the technical lead for aviation mishap investigations. In the Navy he accumulated 3020 flight hours and made 203 carrier landings. Bob has a B.S. in Aerospace Engineering from the University of Southern California and an MS in Aerospace Engineering from the University of Colorado at Boulder.

Marc Simard is a Senior Engineer and Scientist with the Radar Science and Engineering Section at the Jet Propulsion Laboratory since 1998. He obtained a Ph.D. in radar remote sensing and M.Sc. in physics in 1998 and 1994 respectively from Université Laval, and a B.Sc. in Physics in 1992

from Queen's University (Canada). Dr. Simard is the Principal Investigator of two NASA-funded projects on mapping vegetation 3D structure using Shuttle Radar Topography Mission data and ICESat. He is also Co-investigator for NASA's International Polar Year: An Interferometric Ka-band Synthetic Aperture Radar: A New Technique for Glacier and Ice-sheet Topography Mapping. In addition, Dr. Simard also works on the development of algorithms and software for UAVSAR including the Point Target Simulator and UAVSAR processor (i.e. JurrassikProc). Dr. Simard participated in several field campaigns for radar calibration. He is a member of NASA's ICESat Science Team, NASA's Biodiversity and Ecological Forecasting team and also a member of NASA's Land Cover Land Use Change Team.

Eric Rignot is principal scientist for the Radar Science and Engineering Section at NASA's Jet Propulsion Laboratory's (JPL), Pasadena, Calif. His research interests are geoscience applications of radar interferometry and polarimetry. He is a principal investigator on several NASA-funded

projects to study the mass balance of the Greenland and Antarctic ice sheets using radar interferometry combined with other methods; the interactions of ice shelves with the ocean; and the dynamic retreat of Patagonian glaciers. He received the JPL Lew Allen Director's Award for Excellence in 1998. Dr. Rignot is a member of the American Geophysical Union, and the International Glaciological Society. Dr. Rignot holds a Ph.D in electrical engineering from the University of Southern California in Los Angeles, Master's degrees in aerospace engineering and electrical engineering from the University of Southern California, a Master's degree in astronomy from the University of Paris VI Pierre et Marie Curie in France, and a Bachelor's degree in engineering from Ecole Centrale des Arts et Manufactures in Paris, France.

Ronald Kwok is a Senior Research Scientist at NASA's Jet Propulsion Laboratory, Pasadena, CA. His research interest includes the mass and energy balance of the Arctic and Southern Ocean sea ice cover and the role of the sea ice in global climate.

Dr. Kwok received NASA's Exceptional Achievement Award for his work on the circulation of Arctic Ocean sea ice. He has authored or co-

authored over 90 journal articles and 9 book chapters. He received his Ph.D. degree from Duke University, Durham, N.C. and was a postdoctoral fellow at the University of British Columbia, Vancouver, B.C.. Dr. Kwok is a Fellow of the IEEE, a member of the American Geophysical Union and the American Meteorological Society.

Xiaoqing Pi is a senior staff member at the Jet Propulsion Laboratory, California Institute of Technology. He has involved in a number of research and system development projects sponsored by NASA, NSF, DoD, and FAA in areas of global assimilative ionospheric modeling, measuring

ionospheric scintillation and irregularities, modeling of ionospheric current system, satellite orbit prediction, and ionospheric remote sensing using global navigation satellite systems and synthetic aperture radar. He received B.S. and M.S. degrees in Radio Wave Propagation and Antenna and Space Physics, respectively, from Wuhan University and Ph.D in Astronomy from Boston University. He has received a number of awards from NASA for his achievements in research and development for ionospheric modeling and remote sensing.

J. Bryan Blair received a B.Sc. degree in pure mathematics from Towson State University, Baltimore, MD, in 1987, and a M.S. degree in computer engineering from Loyola College, Baltimore, in 1989. Since 1989, he has been with the Laser Remote Sensing Laboratory at NASA Goddard Space Flight Center,

Greenbelt, MD, where he has worked on numerous airborne and spaceborne Lidars. He was the Flight Software lead for the Mars Orbital Laser Altimeter (MOLA). He was the instrument designer and lead engineer for the SLICER airborne Lidar. He was the Instrument Scientist and Data System lead for the Shuttle Laser Altimeter (SLA) that was successfully flown on the Space Shuttle in 1996 and 1997. He is the Principal Investigator for the Laser Vegetation Imaging Sensor (LVIS), and his goal is to develop advanced laser altimeter techniques to enable wide-swath Lidar mapping from space. Bryan is also the Concept Lead for the Multi-beam Lidar instrument for measuring vegetation height and structure, and land and ice topography for the BioMM/DESDynI concepts. He continues to work on algorithms and techniques for analyzing laser altimeter return waveforms for vegetation measurements, topographic change detection, and the production of highly accurate digital elevation models of land and ice surfaces. He has been the Lidar lead for numerous field campaigns in Costa Rica, Greenland, Iceland, Australia, the Azores, and many locations around the U.S.

Waleed Abdalati conducts research on high-latitude glaciers and ice sheets using satellite and airborne instruments. He has led or participated in 8 field expeditions to remote regions of the Greenland ice sheet and the ice caps in the Canadian Arctic. From 2000 to the present, he has been Manager of

NASA's Cryospheric Sciences Program, overseeing NASA-funded research efforts on glaciers, ice sheets, sea ice, and polar climate. For the last four years he has served as Program Scientist for NASA's Ice Cloud and land Elevation Satellite (ICESat), which has as its primary objective understanding changes in the Earth's ice cover. Dr. Abdalati received his Ph.D. from the University of Colorado in 1996 and worked as a research scientist at NASA's Goddard Space Flight Center from 1996 through 2000. In 1999 he received the Presidential Early Career Award for Scientists and Engineers.

K. Jon Ranson received B.S. and M.S. degrees in Earth Resources from Colorado State University and Ph.D. from Purdue University. He has used remote sensing technology for studies of the Earth's surface since the 1970s starting with Skylab and Landsat 1 and 2 MSS data for geologic and forest cover mapping. Later his research was

focused on bi-directional reflectance behavior of vegetation canopies and microwave backscatter characteristics of crops and trees. In 1986, Dr. Ranson joined the Biospheric Sciences Branch at NASA's Goddard Space Flight Center. While at Goddard, Dr. Ranson continued with using optical remote sensing for forest ecosystem studies and has become involved with using radar and Lidar for forest biomass analysis. In addition to his research activities, he is currently the Project Scientist for NASA's EOS Terra spacecraft and Acting Branch Head for the Biospheric Sciences Branch. He has also served as Acting Program Manager for Land Cover and Land Use Change and the former Remote Sensing Science Programs at NASA HQ. Dr. Ranson is a member of IEEE Geoscience and Remote Sensing Society and the American Geophysical Union.

Howard Zebker received a BS degree from Caltech in 1976, the MS from UCLA in 1979, and the Ph.D. from Stanford in 1984. He holds a joint appointment in the Geophysics and Electrical Engineering departments at Stanford, and studies Earth processes from the viewpoint of spaceborne

instruments. His group is involved in basic research ranging from crustal deformation related to earthquakes and volcanoes to global environmental problems as evidenced in the flow and distribution of ice in the polar regions. The group is also developing new observational technologies

such as radar interferometry. He is involved in the definition and scientific applications of new spaceborne imaging systems, especially those containing imaging radar systems.

Bradford H. Hager is the Cecil and Ida Green Professor of Earth Sciences in the Earth, Atmospheric, and Planetary Sciences Department at the Massachusetts Institute of Technology (MIT). He applies precision geodesy and other geophysical observations along with numerical modeling to the study of mantle convection, crustal

deformation, and earthquakes. From 1980 until he joined MIT, he was a professor of geophysics at the California Institute of Technology. Dr. Hager has chaired or been a member of several NRC committees concerned with solid-Earth science. These include the U.S. Geodynamics Committee, the Geodesy Committee, the Committee for Review of the Science Implementation Plan of the NASA Office of Earth Science, and the Committee to Review NASA's Solid-Earth Science Strategy. Dr. Hager is a fellow of AGU. He was the 2002 recipient of the Geological Society of America's Woollard Award in recognition of distinctive contributions to geology through the application of the principles and techniques of geophysics; he also received AGU's James B. Macelwane Award for his contributions to understanding of the physics of geologic processes.

H.H. "Hank" Shugart received B.S. and M.S. degrees in Zoology from the University of Arkansas and a Ph.D. in 1971, also in Zoology, from the University of Georgia. He is a systems ecologist whose primary interests are in the dynamics of forest ecosystems. He has been the W.W. Corcoran Professor of Environmental

Sciences at the University of Virginia since 1984 and before that worked at the University of Tennessee and at Oak Ridge National Laboratory. An important focus of his work is simulating changes in forest structure and composition over time, in response to both internal and external sources of perturbation, at spatial scales ranging in size from small forest gaps to entire landscapes and at temporal scales of years to millennia. He is the author or coauthor of 347 publications including 15 books, 77 book chapters and 142 papers in peer-reviewed journals. He was designated as the inaugural selection as "Distinguished Scientist" at the University of Virginia in 2006 and is a foreign member of the Russian Academy of Sciences.

Mark Fahnestock is from the University of New Hampshire. He received a BS degree in Geology from the University of Rochester in 1984 and a doctorate in Geology from the California Institute of Technology in 1991. Since then he has worked as a glaciologist investigating ice

flow mechanics and surface conditions on the large ice sheets. His research covers many aspects of land-based ice. He has worked in Greenland and Antarctica on a variety of projects and participated in several Antarctic and Greenland field excursions. His recent interests focus on the controls underlying rapid ice flow and on atmospheric interactions that determine surface conditions on the large ice sheets. The primary tools for this work are satellite-derived and surface observations and interactions with ice sheet modelers.

Ralph Dubayah is a Professor in the Geography Department at the University of Maryland College Park, and a Fellow at the University of Maryland Institute for Advanced Computer Studies. His main research areas are landcover characterization and the land surface energy and water

balances. He leads a NASA EOS Interdisciplinary Science Investigation (IDS) on the use of remote sensing for macroscale hydrological modeling. Most recently he is the principal investigator for the Vegetation Canopy Lidar (VCL), the first NASA Earth System Pathfinder (ESSP) mission, which will measure the three-dimensional structure of the Earth's topography and forests. He serves in various U.S. national organizations, including the Remote Sensing Committee of the American Geophysical Union (chair).