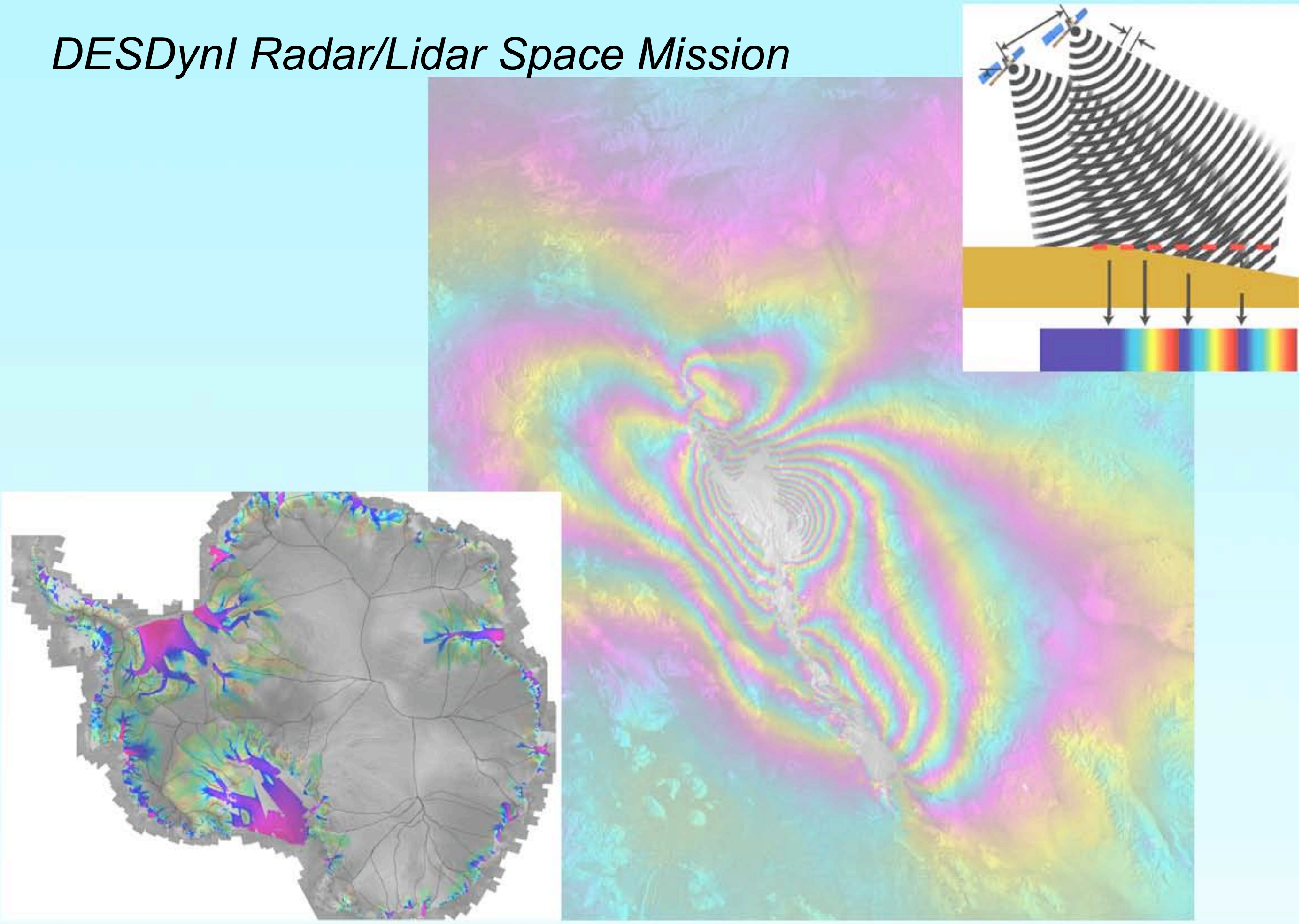
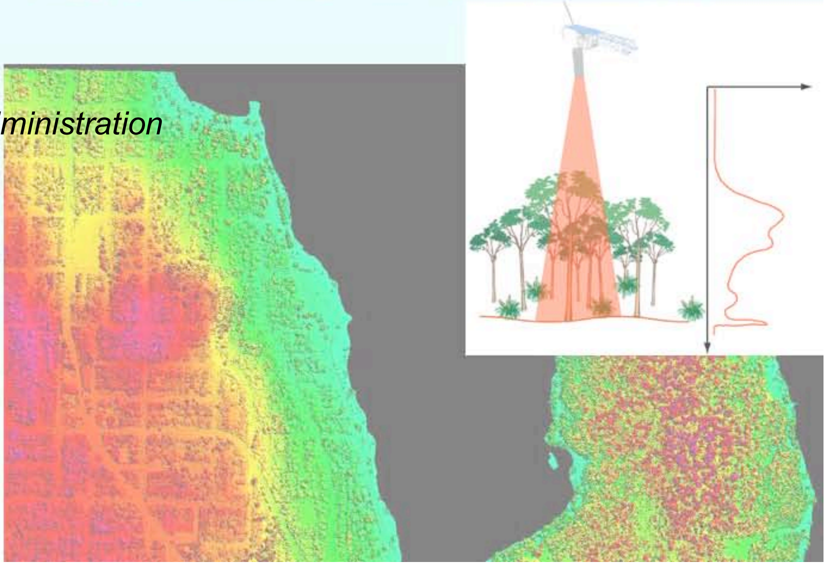
Report of the July 16-19, 2007 Orlando, Florida Workshop to Assess the

National Research Council Decadal Survey Recommendation for the

DESDynI Radar/Lidar Space Mission





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Prepared by
DESDynI Writing Committee

Acknowledgements

This report summarizes the main discussions of a workshop held to assess the 2007 recommendation by the National Research Council Decadal Survey that NASA implement a space mission, DESDynI, consisting of a radar and lidar instruments for the purpose of measuring Earth surface deformation, ecosystem structure, and dynamics of ice. 140 scientists attended and discussed the science objectives, measurement approaches, and across-discipline synergies enabled by the mission.

Many, if not most, of the attendees contributed to this report through discussions, presentations, posters, and writing at the meeting. Particular thanks are due to the writing team: Kathleen Bergen, Sean Buckley, Craig Dobson, Andrea Donnellan, Ralph Dubayah, Yuri Fialko, Eric Fielding, Rick Forster, Tony Freeman, Brad Hager, Forrest Hall, Richard Houghton, Ken Jezek, Mike Lefsky, Bill Pichel, Hans-Peter Plag, Eric Rignot, Paul Rosen, Sassan Saatchi, and Randolph Wynne.

We would also like to acknowledge the NASA folks responsible for sponsoring the workshop and for their help organizing both the meeting and the report: thanks to John LaBrecque, Diane Wickland, and Seelye Martin.

We hope that this report faithfully conveys the positive feeling shared by the participants that the DESDynI mission represents a significant and necessary step forward in understanding our Earth.

Cheers,

Howard Zebker, Editor
Hank Shugart, Ecosystem Structure Editor
Mark Fahnestock, Cryosphere Editor

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Workshop to Assess the
National Research Council Decadal Survey Recommendation for the
DESDynI Radar/Lidar Space Mission

Executive Summary

140 scientists from many disciplines attended a NASA-hosted workshop in Orlando, Florida on July 16 to 19, 2007 to assess a National Research Council Decadal Survey recommendation that NASA implement the DESDynI Mission concept. DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) is a proposed space mission addressing critical research in the solid Earth, ecological, and cryospheric sciences, using spaceborne interferometric radar (InSAR) and multiple-beam lidar instruments. The mission would 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 to study the response of ice sheets to climate change on the impact on sea level. The foremost recommendation from the workshop participants is that NASA implements the DESDynI mission as quickly as possible. The workshop participants affirmed that DESDynI confronts the most important scientific issues in the above disciplines, supported the rapid implementation of the mission, and expressed great enthusiasm for the societal benefits of the information that the mission provides.

The meeting was called by Mike Freilich, Director of NASA's Earth Science Division, with specific charges to:

1. Examine the DESDynI mission as recommended by the National Research Council in light of the scientific goals articulated in its panel chapters
2. Articulate the expected scientific return of DESDynI
3. Identify the potential synergistic approaches with respect to ICESat-II and other space-based missions
4. Recommend next steps for mission refinement, additional research, and consideration of other space-based observations that are required to meet the expressed DESDynI scientific goals.

The DESDynI mission is designed to investigate some of the most important scientific issues confronted by scientists in the fields of solid Earth science, terrestrial ecology, and cryospheric science. DESDynI uses satellite-borne interferometric synthetic aperture radar (InSAR) to measure cm-level crustal deformation and ice motion, and also for resolving vertical vegetation structure, at 10's of m spatial resolution worldwide. It uses a precision lidar instrument for detailed measurements of vegetation structure. The proposed mission objectives meet the needs of the various science disciplines present at the workshop. Global observations of surface deformation from DESDynI will improve location estimates and time-dependent probabilities of earthquakes, volcanic eruptions, and landslides. It will also provide measurements of variations in ice flow patterns and velocities providing constraints on the dynamic response of ice sheets to climate, thus improving forecasts of global sea level rise. The radar and lidar instruments on DESDynI will improve understanding of the response of terrestrial biomass, which stores a large pool of carbon, to changing climate and land management.

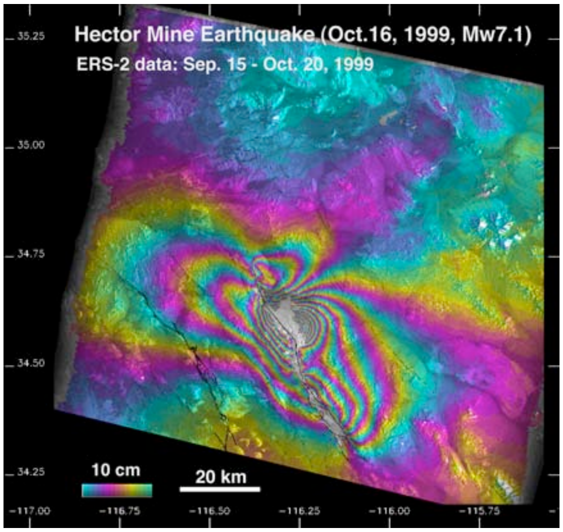

Figure 1. A primary DESDynI product is a surface deformation map, such as this view of the 1999 Hector Mine earthquake, derived from ERS radar data. Each color "fringe" represents 10 cm of ground displacement from the earthquake.

The mission needs to yield global lidar coverage over the life of the mission, and radar coverage at short (about 8 day) repeat intervals for resolution of fast geophysical processes and for minimizing atmospheric delay variations in InSAR products. The radar should operate within the L-band portion of the spectrum, with large enough bandwidth to allow accurate ionospheric corrections. Spatial radar resolution should be about 20 m, the lidar spot size should be about 25 m, and vertical accuracies of the InSAR and lidar should be 1-2 mm and 2-10 cm, respectively.

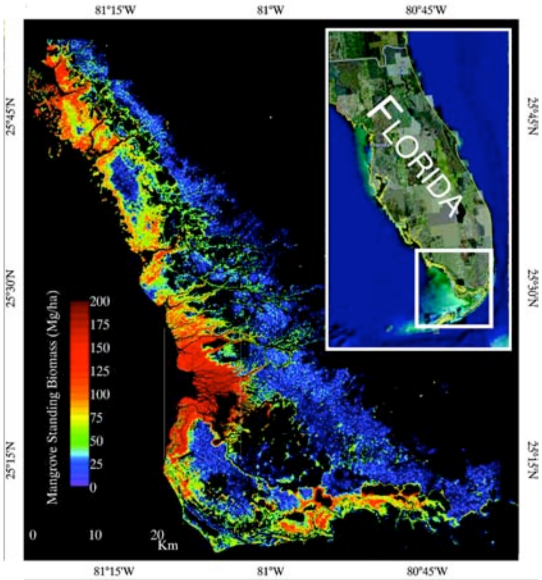

Figure 2. DESDynI will provide data to understand the distribution of carbon stocks worldwide, similar to this biomass map of southern Florida derived from SRTM radar data and calibrated using airborne lidar.

DESDynI provides a heretofore unavailable capability to illuminate critical science objectives of these three Earth sciences, objectives of significant scientific importance and central to issues of the sustainability of life on Earth. The proposed mission objectives meet the needs of the various science disciplines present at the workshop. The participants endorsed the approach and mission implementation options outlined by the NRC and expressed eagerness to get started on developing this mission, resolving to:

1. Conduct the studies recommended to tackle outstanding technical issues, refine mission attributes, and advance algorithm development
2. Support NASA in taking the steps to advance DESDynI to formulation
3. Establish working partnerships to reconcile implementation conflicts
4. Conduct this work in a way that does not impact readiness to proceed

There was a wide range of science objectives held by scientists in the multiple disciplines represented in the workshop, with associated potentials for conflicts in instrument design, orbital configuration, and operational procedures. The attendees worked across scientific communities to refine and to examine alternatives in requirements to meet needs of all three major sets of science questions in the DESDynI mission framework. The range of objectives presents consequent potential for conflicts in instrument design, orbital configuration, and operational procedures. A central goal of the workshop was to explicate and examine these possible conflicts and identify appropriate mission and science trade-offs that result from these conflicts.

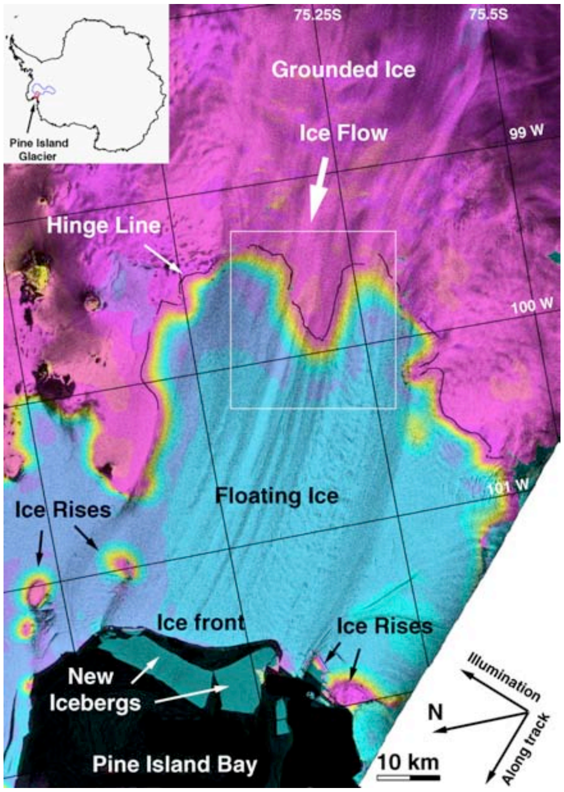

Figure 3. The third major focus of DESDynI is the role of glaciers and ice sheets for controlling and diagnosing Earth's climate. The interferogram above shows the grounding line of the Pine Island Glacier on Antarctica- its recession or advance follows climate change.

The participants identified several areas of concern that will require future study, though the general consensus among participants is that compromises are possible to accommodate the principal science objectives. The challenges follow largely from placing both the InSAR and lidar instruments on a single platform and the disciplinary observing requirements for each discipline's science objectives versus the instrumental capabilities. Nonetheless, rigorous study of the trade-offs involved for various implementation options is required.

Interdisciplinary technical discussions indicated that compromise solutions are likely to exist for the following issues:

1. Orbital repeat interval: 8 days is preferred by solid Earth and ice, and 8 days or shorter repeat times are best for the vegetation height from InSAR due to temporal decorrelation. Longer repeats yielding finer track spacing are preferred for the lidar to achieve adequately dense coverage of the Earth's vegetated surface. Use of a slightly longer repeat with relaxed constraints on off-nadir lidar pointing might mitigate aspects of this issue, with orbits of approximately 12 day repeat interval.
2. Orbital altitude: An 800 km altitude minimizes atmospheric orbit degradation and instability for InSAR, while a 400 km altitude is optimal to limit lidar power requirements and telescope size. It appears that using a compromise altitude of 600 km is possible and would satisfy all disciplines.
3. InSAR repeat-track baseline: A zero length interferometer baseline is preferred by the solid Earth and ice communities to measure surface deformation, as opposed to multiple nonzero baselines preferred by the ecologists to resolve the canopy structure. All groups' needs are probably met using baselines of approximately 200 m, plus several sets of baseline offsets ranging from 500-1000 m.

The workshop attendees also identified topics that will require further study to optimize satellite designs. Both the formulation of these compromises and, in some cases, collection of background data necessary to understand the novel aspects of the mission capabilities, need to proceed as soon as possible, and the attendees recommend that NASA conduct any studies necessary to confirm these compromise solutions.

Identified areas requiring more detailed scientific study to examine possible conflicts and mission deficiencies, where focused investigations should be initiated as soon as possible, include:

1. What is the time interval before temporal decorrelation of InSAR becomes a factor, for all proposed investigations? What is an acceptable time lag between lidar and radar measurements of vegetation?
2. To what extent can L-band HH and HV data, with the lidar profiles, provide the measurements required for forest aboveground biomass, disturbance and recovery assessment? Is full polarimetry needed for vegetation science? Is interferometric polarimetry required?
3. What are the set of possible algorithms and projected accuracies for combining lidar, SAR, and/or InSAR data for estimating vegetation vertical structure and biomass? What is the accuracy of vegetation height and other structural parameters estimated from InSAR and how is it affected by small numbers of baselines and temporal decorrelation? Are existing allometric equations adequate for the desired accuracies?
4. Can the lidar instrument proposed for DESDynI achieve the necessary accuracy and repeatability to have value for measuring ice sheet and glacier surface elevation change and for measuring sea ice freeboard? Does a sun synchronous orbit covering ±83° latitude significantly limit useful cryospheric science?

It will also be useful to consider DESDynI in the context of other missions and capabilities that will be available contemporaneously. Certainly GPS systems will provide valuable ancillary data for all three disciplines, and the development of a terrestrial reference frame for GPS reduction is critical. Other SAR satellites from the international constellation operating at different frequencies will help to provide a diversity in the measurements for all of the backscatter modeling and analysis work. Optical systems such as the MODIS spectrometer or its successors should provide useful additional constraints on vegetation models.

Recommendations:

The primary recommendation of workshop participants is that NASA proceed as quickly as possible to implement the DESDynI mission. DESDynI addresses scientific issues among the most important within the solid Earth, ecosystem, and cryospheric science disciplines. These science goals are critical to the understanding of the Earth system as it relates to natural disasters and climate change. The proposed technology is well-suited to answer these fundamental science questions.

With the above in mind, the workshop concludes with the following specific recommendations, which can be addressed during mission formulation:

1. Conduct studies to assess the options proposed to resolve/minimize the apparent incompatibilities among requirements for baselines, orbit, and altitude. Potential orbit modification during the mission to optimize instrument performance is one such study.
2. Examine deploying the radar and lidar instruments on separate platforms, each in its optimal orbit. Examine the possibility of integrating the DESDynI lidar with the ICESat-II satellite.
3. Develop a better understanding of how non-nadir lidar pointing can be used to fill gaps and increase the spatial density of coverage for vegetation structure while maintaining the necessary accuracy.
4. Advance the development of algorithms for lidar-radar fusion and lidar-InSAR fusion to estimate canopy structure, dynamics and biomass. Analysis of the combination of lidar and radar data is reasonably understood at present, while the potential of lidar-InSAR techniques is high but not yet fully developed. Both approaches require further development.
5. Develop and demonstrate the ability to derive vegetation height and estimate biomass from InSAR measurements across a range of the Earth's biomes. Acquire new data to test and explore lidar-InSAR capabilities for vegetation structure and to be used in developing data fusion algorithms
6. Formalize the specific scientific requirements necessary to move the mission to implementation.

In summary, the workshop provided both answers and recommendations for further study to respond to the specific charges to the workshop. The participants examined the recommended DESDynI mission and ratified the scientific goals articulated in the Decadal Survey. They spelled out specifically the expected scientific return of DESDynI according to the nominal mission description, and agreed that with suitable implementation and operational compromises all major science goals can be met. Discussions regarding potential synergistic approaches with respect to ICESat-II and other space-based missions operating at the same time opened up other implementation possibilities and opportunities. Placing the vegetation lidar on a separate platform, possibly with the ICESat-II lidar, or operating DESDynI in tandem with international missions, remain intriguing possibilities but may not be necessary for meeting the science objectives. Yet they may represent cost-effective alternatives. Finally, the attendees recommended a number of focused studies for mission refinement, additional research, and consideration of other space-based observations that are required to meet the expressed DESDynI scientific goals.

1. Rationale / Context for Workshop: Decadal Survey Recommendations

NASA hosted a workshop from July 17-19, 2007 in Orlando, Florida for the purpose of assessing the National Research Council (NRC) Decadal Study recommendation that NASA implement the DESDynI Mission concept. The DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) platform consists of spaceborne interferometric radar (InSAR) and multiple-beam lidar instruments to measure surface deformation for understanding natural hazards and climate and vegetation structure for understanding ecosystem health.

The meeting was called by Dr. Michael Freilich, Director of NASA's Earth Science Division, with specific charges to:

1. Examine the DESDynI mission as recommended by the National Research Council in light of the scientific goals articulated in its panel chapters.
2. Articulate the expected scientific return of DESDynI.
3. Identify the potential synergistic approaches with respect to ICESat-II and other space-based missions.
4. Recommend next steps for mission refinement, additional research, and consideration of other space-based observations that are required to meet the expressed DESDynI scientific goals.

The meeting consisted of plenary presentations describing NASA programmatic goals and the major recommendations of the Decadal Survey, several break-out sessions addressing the four parts of the above charge, tutorial and other scientific summary presentations, and a poster session.

The major scientific objectives for DESDynI defined by the Decadal Survey are:

1. Determine the likelihood of earthquakes, volcanic eruptions, and landslides: US annualized losses from earthquakes are \$4.4B/yr yet current hazard maps have an outlook of 30–50 years over hundreds of square kilometers.
2. Characterize the effects of changing climate and land use on species habitats and carbon budget: The rate of increase of atmospheric CO_2 over the past century is unprecedented, at least during the past 150,000 years. The structure of ecosystems is a key feature that enables quantification of carbon storage. Changes in this carbon storage are associated with the release of greenhouse gases and create feedback in the climate/terrestrial carbon systems.
3. Predict the response of ice sheets to climate change and impact on sea level: Ice sheets and glaciers are exhibiting dramatic changes that are of significant concern for science and international policy. These indicators of climate remain one of the most under-sampled domains in the system.
4. Monitor the migration of fluids associated with hydrocarbon production and groundwater resources: Management of our hydrological resources is applicable to every state in the union.

Specific goals for the three principal areas of investigation over a nominal 5 year mission are:

1. Solid Earth

- Help define how we prepare for, mitigate against, and respond to major geohazards.
- Determine when and where earthquakes will occur.
- Identify regions of impending volcanic activity.
- Determine any observable precursory deformations for earthquakes and volcanoes.
- Quantify the relationships between earthquake faulting and magmatism, and between crustal stress changes and earthquakes.
- Observe the rates of depletion or recharge of groundwater and hydrocarbon reservoirs.

2. Ecosystem Structure

- Understand how changes in climate, land use, and other human activities affect the carbon cycle, including carbon storage in aboveground biomass and changes in carbon sources and sinks that determine atmospheric concentrations of greenhouse gases such as CO_2 and CH_4.
- Measure the 3-dimensional structure of vegetation, including canopy height, vertical profile of canopy elements, and/or the volume scattering of canopy elements, in order to quantify carbon storage in aboveground biomass worldwide at fine resolution, including changes and trends.
- Quantify the effects of disturbance, including deforestation, species invasions, and wildfires, and recovery on terrestrial carbon sources and sinks and their feedbacks to climate.
- Understand the effects of climate change, land use changes, and other disturbance and recovery processes on ecosystem services, habitats and biodiversity.
- Characterize horizontal and vertical habitat structure for conservation and biodiversity assessments.

3. Cryosphere

- Study glaciers and ice sheets and their relationship to global sea level rise, local hydrology and anticipated changes in climate.
- Assess Arctic and Antarctic sea ice cover and its relation to global climate change and biological processes.
- Measure water stored as seasonal snow and its variability.
- Understand interactions between the polar atmosphere and sea ice, snow extent, and surface melting.

The NRC recommended that NASA proceed with the DESDynI mission, comprising both interferometric radar and multiple-beam lidar sensors, as the best available technology for addressing this set of science goals. The mission could be implemented on one or two platforms. The lidar needs to yield both statistically-valid sampling of the Earth’s vegetated surface over the life of the mission, and radar coverage needs to be at short (about 8 day) repeat intervals for resolution of rapid geophysical processes and for minimizing atmospheric delay variations in InSAR products. The radar should operate within the L-band portion of the spectrum, with large enough bandwidth to allow accurate ionospheric corrections. Horizontal spatial radar resolution should be about 20 m, the lidar spot size should be about 25 m, and vertical accuracies of the InSAR and lidar should be 1-2 mm and 2-10 cm, respectively.

The outcome of the workshop, summarized in this document, is the assessment that DESDynI meets the above science objectives, and that further studies are needed to resolve issues identified in the course of the workshop. The workshop attendees agreed by consensus that i) DESDynI has an appropriate set of instrumentation for these research objectives, ii) that suitable compromises between differing system requirements for each set of science goals likely exist, and iii) that several detailed implementation studies beyond the scope of a three-day workshop are needed and will likely result in a cost-effective mission that properly addresses the science goals.

2. Assessment of the scientific and societal benefits of the recommended DESDynI mission

The first workshop charge, and first set of breakout sessions, called for an assessment of the scientific and societal benefits accruing from the DESDynI mission as described in Chapters 2-4 of the Decadal Survey report. These were elucidated in the NRC report and were examined in detail and distilled by workshop participants. The benefits vary by discipline, and are described in this section. Additional scientific and societal applications enabled by the mission and its technology that lie beyond those identified by the NRC Decadal Survey are described in Appendix A.

Solid Earth science. The NRC Decadal Survey identified three main strategic roles and several science questions for each in the area of solid-earth science. The first role is basic research focused on observations aimed at forecasting and mitigating the effects of natural hazards. Specifically:

1. What observations can be used to improve the reliability of hazard forecasts?
2. What are the opportunities for early detection, ongoing observation and management of extreme events?
3. What are the viable policy options for managing events that threaten human life and property?
4. Can human systems be managed to reduce their vulnerability before such events occur?
5. How can the information, including uncertainties, be communicated to decision-makers who can use this information for the benefit of society?

The second critical role for solid Earth science concerns discovering and managing resources. Questions here are:

1. How can we improve our ability to locate new resources that can be produced economically?
2. How can we improve our ability to produce known resources more safely and effectively?
3. How can we limit potential environmental damage resulting from their exploitation?
4. How can we monitor long-term changes in soil characteristics and Earth surface topography to understand soil degradation and erosion?
5. How can we predict the extent and size of landslides?

The third role promoted the enabling of basic science:

1. What new observations, coupled with improved modeling capability, are most likely to advance our fundamental understanding of nature?
2. How can this fundamental understanding be used for decreasing hazards from natural disasters and to protect and improve our economy?

Natural hazards pose an enormous threat to people and infrastructure in many parts of the United States and the world. The NRC Decadal Survey took this as the primary motivation for the crustal deformation measurement capability of the DESDynI mission, and much of this section is paraphrased from that report (NRC Decadal Study, B. Hager, Ed., 2007).

Natural hazards currently produce huge annualized losses. Earthquakes cost $4.4 billion per year for the US alone. Ongoing and ever-present 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; recent earthquake-spawned tsunamis in southeast Asia killed over 140,000 people. Climate-induced sea-level change, land subsidence, and landslides as well are becoming more problematic with development in high risk areas. Risk assessment and consequent successful policy development can minimize loss of life, destruction of property, and suffering, but these require precise measurements and powerful geophysical models in concert with population and infrastructure mapping.

Figure 4. Volcanic eruptions are but one of the natural hazards that cost billions of dollars and tens of thousands of lives annually. Volcanoes such as Mt. Redoubt in Alaska (above) not only threaten people and property on the ground but are a major aircraft hazard- ingestion of volcanic ash can immediately destroy jet engines.

Earthquake forecasting, risk assessment, and mitigation require knowledge of the mechanisms that control both transient and steady-state aseismic fault slip. Improvements in measurement techniques lead directly to advances in understanding earthquake physics and help identify areas for further study. The recent discovery of transient aseismic fault slip in the Cascadia and Japanese subduction zones has been a big surprise to Earth scientists. These events are closely associated with microseismic tremor. Detailed crustal deformation measurements have been crucial to these discoveries, yet we still need to refine our understanding of the spatial distribution of the 3D deformation field of these events and image the causative deformation sources at depth globally and systematically.

We now know that stress transfer processes can trigger seismic activity. Current research is aimed at elucidating the nature of earthquake-earthquake interactions, rigorously quantifying the statistical likelihood of linkages, and exposing time-dependent processes such as post-seismic relaxation or state and rate fault friction that influence triggered activity. However, at this time longer-range interactions are still not mechanically understood. Because interaction of these should produce deformation signatures, synoptic spaceborne crustal deformation imaging offers the best means of detecting and elucidating the causes and effects that may link regional earthquake events.

In fact identification of precursory deformation phenomena remains the Holy Grail for solid Earth natural hazards research. Current earthquake hazard maps are coarsely resolved in both time and geography. Such maps depict probability of exceeding a certain amount of shaking over the next 30 to 100 years, depending on the map. The spatial resolution is typically on the order of tens to hundreds of kilometers. These maps are based on information about past earthquakes observed in the geological or historical record. DESDynI measurements of crustal deformation will yield insights into earthquake behavior, including answers to questions such as whether high strain rates indicate the initiation of failure on a fault or quiet release of stress, and how stress is transferred to other faults. These scientific studies will lead to improvement of earthquake hazard maps both spatially and temporally.

Similarly, deformation observations of volcanoes are perhaps the best means to characterize growing hazards to neighboring populations (Ewert and Harpel, 2004). Volcanoes also present hazards to aviation passengers worldwide through the ingestion of volcanic ash by jet engines (Salinas and Watt, 2004). One key to successful mitigation of these hazards is the detection of volcanic unrest through uplift and subsidence, which may precede eruptions and which may be marked by noticeable changes in craters. Only a small percentage of the world's 600 active volcanoes are instrumented sufficiently to facilitate eruption predictions, thus direct observational constraints on the style and dynamics of magma ascent are still lacking. Such constraints are crucial for forecasting the replenishment and pressurization of shallow magma chambers that may potentially feed volcanic eruptions. Because episodes of volcanic unrest episodes for any given volcano may be quite infrequent, and with so few volcanoes adequately monitored, a global and synoptic observation system capable of detecting the ongoing magmatic unrest will result in dramatic improvements of our understanding of volcanic activity and the associated societal hazards.

Current outstanding problems in volcano monitoring and hazard prediction include the determination of the size and shape of magmatic reservoirs from geodetic, seismic, gravity, and other geophysical observations, identification of the type of magmatic unrest associated with eruptions, characterization of detectable deformation prior to volcanic eruptions, and prediction of the volume and size of impending eruptive events. High quality geodetic observations of active neovolcanic areas are needed to provide important constraints on timescales and mechanisms of these processes.

The second societally-relevant contribution from a crustal deformation space mission is to help with management and appropriate exploitation of natural resources. As world population increases, we are experiencing an increasing demand for non-renewable resources. In particular the need for hydrocarbon resources will continue to increase for at least the next few decades. This will result in increased activity to discover hydrocarbon-bearing reservoirs as well as increasing production from existing reservoirs.

Management of hydrocarbon resources involves many factors, including measurement of surface deformation. Extraction of oil or gas from reservoirs leads to subsidence as voids and low-pressure volumes fill with subsiding overburden, and the reverse occurs as water is injected into the reservoir. Observing the subsidence pattern illustrates the physical footprint of the active areas and can help assess storage properties and help guide extraction strategy. It is also important in areas where ongoing subsidence from years of production results in significant subsidence in inhabited areas. In the U.S., for example, such settling is problematic in Houston and in Long Beach, CA, for example.

The existence of life on Earth depends critically on the availability of fresh water. Human dependence on this resource is amply demonstrated during droughts around the world. Ground water, surface water, soil moisture, and snow pack all factor into the global fresh water budget, and we need to measure and understand how natural and anthropogenic processes redistribute water in both space and time.

The characterization of how the land surface above aquifers responds to ground-water pumping provides important insights on the subsurface controls of the aquifer system, the location of ground-water barriers and conduits, the extent of the aquifer, and when combined with ground-water level and pumping records, provides critical hydrodynamic properties of the aquifer systems that are necessary for measuring changes in the ground-water supply, modeling the aquifer system, and constraining the terrestrial water budget. Deformation measurements with national coverage and routine acquisition would significantly advance our ability to characterize both regional and continental scale aquifer systems and would provide the first uniform quantification of our national aquifer system. Measurements of land subsidence ascribed to hydrology could join an increasing number of space-based techniques such as time variable gravity (GRACE-II) and surface microwave reflectivity and emissivity (SMAP) as important new remote sensing techniques for water resource management.

The NRC Decadal Survey panel presented a surface deformation InSAR mission that would collect data worldwide to address these important needs. Space geodetic observations provide detailed information about the surface deformation due to natural and anthropogenic causes. These observations are essential for understanding deformation of the tectonic plates and the fluid behavior of the mantle below.

Over the last decade, InSAR has proven to be a valuable tool for detecting, monitoring, and forecasting changes in the Earth's surface due to seismic, volcanic, tectonic, hydrologic phenomena. For example, observations of deformation from subsurface flow of magma and of the accumulation of tectonic strain within the crust are needed to better understand and predict volcanic and seismic phenomena. InSAR is capable of providing help in assessing damage after the events and evaluating the risk of future events by understanding and monitoring the processes involved. Because individual events are often separated by long periods of time and because they are globally distributed, we need a globally synoptic system to effectively increase our capability to understand and effectively predict these events. Overall, InSAR observations produce important and otherwise unavailable data enabling comprehensive, global measurements to better understand and predict changes in the Earth system.

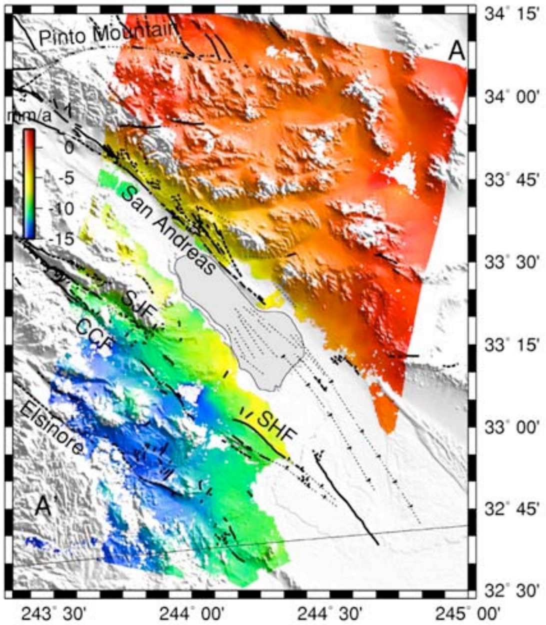

Figure 5. Line of sight velocity of the Earth's surface, in millimeters per year, from a stack of ~40 radar interferograms collected over the southern San Andreas Fault (SAF) between 1992 and 2000. Colors denote the ground velocity along the satellite line of sight. Black lines denote Quaternary faults (SJF - San Jacinto fault, CCF - Coyote Creek fault, SHF - Superstition Hills fault). The line-of-sight (LOS) velocity field clearly reveals the relative motion between the Pacific and North American plates (Fialko, 2006). These faults are currently believed to pose the largest seismic risk in California.

The DESDynI mission will provide global measurements of surface deformation with millimeter-level accuracy in three dimensions. These observations will allow the broad science community to address the fundamental science questions described above. InSAR has already become a primary tool for measuring coseismic deformation and postseismic transients,provided there is adequate coverage. Accurate and robust measurements of subtle secular and precursory deformation are the new frontiers in the crustal deformation studies, and are also pivotal for the solid Earth natural hazards research. DESDynI would be the first such mission dedicated to these measurements and science objectives. Detecting and quantifying small strain signals require massively redundant interferograms to beat down the noise and alleviate the effects of decorrelation. This implies frequent and persistent observations over the target areas. Figure X illustrates a deformation image formed by stacking 40 interferograms over a southern section of the San Andreas fault in California.

Ecosystem structure. Among the most pressing issues in global ecosystem science are understanding: i) the global carbon cycle and its influences on the atmospheric greenhouse gases, notably CO_2 and CH_4, that drive climate change, ii) sustainability of ecosystem health and services, and iii) habitat and related biodiversity responses to climate and land-use changes. Systematic, global data are essential for addressing these topics. Scientists and decision makers need the global capacity that remotely sensed data provides to quantify present conditions and trends in carbon, water and nutrient cycles, to manage natural resources, to project future trajectories of change, to respond to disturbances such as wildfire and invasive species, and to provide the best information for strategic decisions (Bergen, et al., 2006).

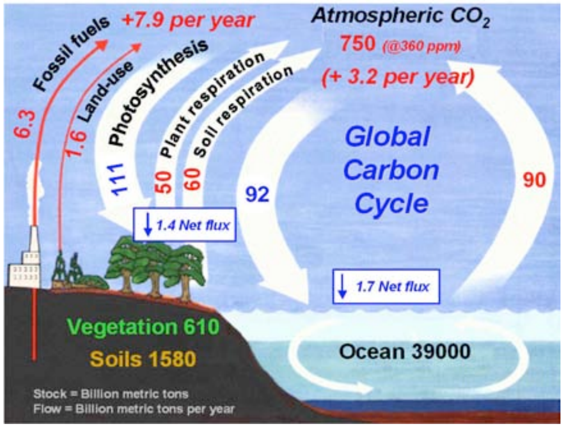

Figure 6. Carbon is stored in many places on Earth, and quantifying the fluxes between stocks is a major science objective of DESDynI. The total storage of greenhouse gases within the atmosphere is a critical element of the climate system.

The Decadal Survey identified key questions that can be addressed through the DESDynI mission. These are grouped in three science themes for understanding and managing ecosystems:

Theme 1 - Disruption of the carbon, water and nitrogen cycles.

1. How does climate change affect the carbon cycle?
2. How does changing terrestrial water balance affect carbon storage by terrestrial ecosystems?
3. What are the management opportunities for minimizing disruption in the carbon, nitrogen, and water cycles?

Theme 2 - Changing land and marine resource use.

4. What are the consequences of uses of land and coastal systems, such as urbanization and resource extraction, for ecosystem structure and function?
5. How does land and marine resource use affect the carbon cycle, nutrient fluxes, and biodiversity?
6. What are the implications of ecosystem changes for sustained food production, water supplies, and other ecosystem services?
7. What are the options for diminishing potential harmful consequences on ecosystem services and enhancing benefits to society?

Theme 3 - Changes in disturbance cycles.

8. How does climate change affect disturbances such as fire and insect damage?
9. What are the effects of disturbance on productivity, water resources, and other ecosystem functions and services?
10. How do climate change, pollution and disturbance interact with the vulnerability of ecosystems to invasive species?
11. How do changes in human uses of ecosystems affect their vulnerability to disturbance and extreme events?

To address these key questions, DESDynI will provide worldwide data on vegetation vertical and horizontal structural attributes. Specifically, DESDynI will:

1. Develop globally consistent and spatially resolved estimates of aboveground biomass and carbon stocks.
2. Make globally consistent and spatially resolved measurements of vegetation vertical structure to understand changes and trends in terrestrial ecosystems and their functioning as carbon sources and sinks.
3. Characterize and quantify the three-dimensional structural response to disturbance.
4. Quantify changes in terrestrial carbon sources and sinks resulting from disturbance and recovery.
5. Characterize habitat structure for biodiversity assessments.

<u>Carbon.</u> As recommended by the Decadal Survey, the DESDynI mission will provide previously unavailable information about the world's terrestrial ecosystems to meet the goals of estimating carbon stocks and their change with time, vegetation structure and composition, characterization of habitats, and the biogeochemical cycles that couple these to the ecosystem. This information will help answer key scientific questions for understanding and managing ecosystems and the global carbon cycle, and, thus, be of considerable benefit to society. For studies of carbon stocks and cycles, the DESDynI mission will enable much-improved estimates of terrestrial sources and sinks of carbon by providing the data required for two kinds of information: (1) the magnitudes and distributions of aboveground carbon stocks in the world's forests, and (2) the distributions of forest disturbance and recovery that affect terrestrial carbon sinks and sources.

A major source of uncertainty in global carbon budgets derives from large errors in the current estimates of carbon storage in vegetation (i.e., carbon stocks). Disturbances, either from natural phenomena, such as fire or wind, or from 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 complicates the estimation of terrestrial carbon stocks and dynamics. For most of the world, systematic biomass surveys are nonexistent or unavailable. Many developed countries collect land cover and forest inventory data through painstaking field measurements, but the sampling and methods vary substantially, and global analyses of these data are difficult and subject to potential bias and substantial uncertainty. Patterns of recovery following disturbance are important but difficult to ascertain and quantify.

Better measurements of the distributions of aboveground woody carbon stocks could improve estimates of carbon emissions due to tropical deforestation where current emissions estimates differ by more than 100%. More than half of this difference arises from uncertainties in the amounts of forest biomass affected by clearing, harvest, and other human activities. DESDynI measurements of forest height and vertical structure will provide estimates of forest carbon stocks that are lacking in most tropical regions.

The DESDynI mission will provide a unique capability to estimate terrestrial carbon sinks. While the existing optical satellites are fairly good at observing the large changes in carbon stocks that accompany deforestation, they are poorly suited for observing the more subtle changes associated with forest recovery. This is significant because most of the planet's forests are recovering. They are less than 200-400 years old. Because only a small fraction are disturbed each year, and existing optical satellite observations are biased toward carbon emissions and against carbon sinks. Repeated sampling of forest height and vertical structure over the 5-year duration of DESDynI could estimate the rate of accumulation of carbon in growing forests. Potentially even more important than the dramatically improved global carbon estimates, spatially detailed data obtained from DESDynI will show where the greatest changes in carbon sinks and sources are occurring.

Globally, the magnitudes and distributions of terrestrial carbon storage along with changes in sources and sinks for atmospheric CO_2 remain the most significant uncertainties in Earth's carbon budget. These uncertainties severely limit accurate terrestrial carbon accounting; our ability to evaluate terrestrial carbon management schemes; and the veracity of atmospheric CO_2 projections in response to further fossil fuel combustion and other human activities. The importance of DESDynI, or DESDynI-like satellites, for documenting or verifying national sources and sinks of carbon for compliance with international reporting, the Kyoto Protocol and its successors, or other carbon management and policy objectives cannot be overstated.

<u>Ecosystem Properties</u>. The DESDynI mission is expected to yield new insights about global habitats and associated changes in biodiversity and ecosystem health that can be used to inform decision making in conservation and the preservation of biodiversity. It will provide information in the form of model products for use in resource management and climate change impacts assessment, including estimates of forest productivity and timber production, fire fuel loads, and improved projections of a variety of ecosystem functions (e.g., biogeochemical cycling and nutrient controls on carbon sequestration, water relations for drought and stress management, and ecosystem vulnerability and health resilience).

Vegetation height, vertical profiles, and disturbance recovery patterns also are required to characterize habitat and assess ecosystem health. The three-dimensional structure of vegetation reveals the habitats for many species and is a significant control on biodiversity. Canopy height and the vertical distribution of leaves and branches influence where and how other species utilize the ecosystem for food, shelter, and territory. Habitat use and habitat specialization are two fundamental features that influence species richness and abundance across ecosystems. Accurate and consistent 3D measurements of forest structure at the landscape scale are needed for assessing impacts to animal habitats and biodiversity following disturbance. Recent studies have demonstrated the critical importance of spatial and vertical structure for habitat characterization and biodiversity studies. For example, forest structure metrics from lidar are strongly related to bird biodiversity (Goetz et al., 2007) and habitat selection (Bergen et al., 2007).

DESDynI's measurements of ecosystem structural properties also are required for use in ecosystem and biogeochemical cycling models to better constrain and/or quantify functional processes that are key indicators of ecosystem health. The cycling of water and nutrients such as nitrogen is required knowledge to assess ecosystem and vegetation health and carbon cycling. Processes related to the physiological use of light, nutrients, and water are highly dependent on ecosystem structure, vegetation composition, and consequently on dynamic changes in structure. For example, the availability of light to drive canopy photosynthesis is directly related to the vertical distribution of canopy elements. Thus, accurate measurements of vertical structure should improve models of photosynthetic function and ecosystem productivity used, for example, to couple feedback effects between the terrestrial part of climate change in General Circulation Models (GCM's) . On a more local management-level, the most common fire-spread model currently used by the USDA Forest Service requires structural inputs such as canopy height, canopy cover, vertical biomass profiles, and canopy base height that have been derived from airborne lidar observations.

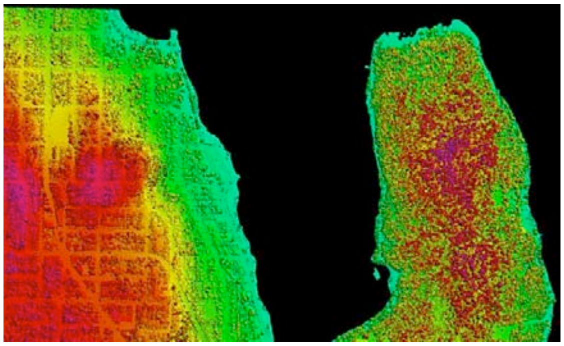

Figure 7. Biomass map of Puget Sound area derived from lidar vegetation profiles. DESDynI will provide such maps worldwide, enabling the first accurate global inventory of aboveground biomass and its horizontal variation. Over the mission lifetime the change in biomass in response to habitat disturbance and regeneration will also be measured.

Cryospheric science. Earth's ice sheets, ice caps, glaciers and sea ice cover are rapidly changing. The recent and unexpected thinnings and acceleration of ice at locations around the Greenland and West Antarctic ice sheets of as much as 10s of meters per year, along with diminishing sea ice extent over the Arctic Ocean basin and its marginal seas are now well documented observations. These are frequently cited in both the scientific literature and the popular press as powerful evidence of climate change. At issue now is predicting whether thinning, acceleration, and retreat will continue into the future and if so, determining how society must respond to the consequent increasing sea level as well as fundamental changes to the physical environment, wildlife and even transportation around the Arctic Ocean.

The Decadal Survey explicitly recognized the importance of Earth's changing cryosphere and the implications of those changes on society by noting in the Executive Summary the following important science 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?"

To answer these questions, the Decadal Survey posed the following objectives:

1. Understand glaciers and ice sheets sufficiently to estimate their contribution to regional and local hydrology and global sea level rise and to predict their response to anticipated changes in climate.
2. Understand sea ice sufficiently to predict its response to, and influence on, global climate change and biological processes.
3. Measure how much water is stored as seasonal snow and its variability.
4. Understand the interactions between the changing polar atmosphere and the changes in sea ice, snow extent, and surface melting.

The DESDynI interferometric synthetic aperture radar and the ICESat-II laser altimeter can measure essential physical variables necessary for reaching these objectives. Specifically, laser altimeters such as the current ICESat-I mission contribute to measuring elevation over time that can be interpreted in terms of present volumetric changes in the fresh water reservoir of the polar ice sheets or the flux of fresh water entrapped in the moving sea ice cover of Arctic waters. SAR and InSAR instruments measure ice surface structure, extent, and most importantly surface velocity that all can be used to solve the fundamental equations which describe the motion of the ice. Indeed, the dynamical information derivable from InSAR velocity fields establishes the observational basis for developing predictive models of how the ice sheets will respond to future climate changes. As illustrated in figures x and x, InSAR has been successfully used to develop large scale maps of ice sheet and sea ice motion. As such, the Decadal Survey panel on water resources and global hydrological cycle ranked DESDynI as the highest priority mission for addressing sea ice thickness, and glacier surface elevation and velocity. Development and deployment of DESDynI will significantly improve the quality and spatial coverage of these measurements and, most importantly, will carry these observations into the future from a consistent global vantage.

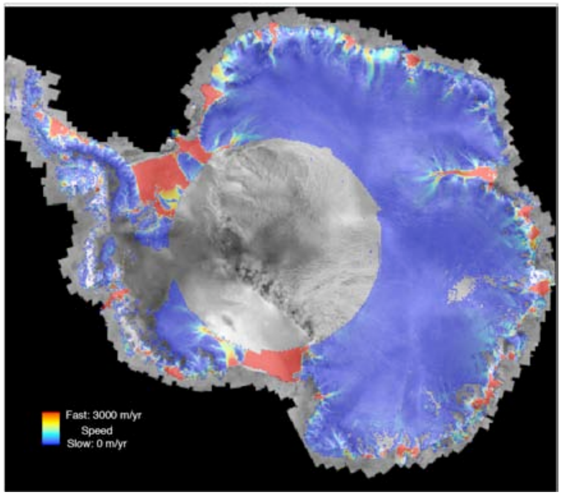

Figure 8. Velocities of Antarctic glaciers and ice streams obtained from InSAR sensors. Surface velocity is an important component affecting net outflow rates from the great ice sheets, and its variability a strong indicator of instabilities in the ice that can lead to catastrophic collapse and subsequent rapid sea level rise.

DESDynI instrumentation will play a critical role for the study of finer scale phenomena as well. The multi-beam lidar, plus InSAR-derived elevation changes, would provide new constraints on rapidly changing mountain glaciers and outlet glaciers; the smaller lidar footprint and multiple beams is very helpful for these rough glaciers. Assessing glacier retreat and flow worldwide requires the global accessibility and precise distance measurements provided by the DESDynI satellite.

For the Arctic and Southern Oceans, the instruments on DESDynI provide high-resolution data to address key questions on the role of sea ice in global climate. The L-band ScanSAR provides repeat coverage of the sea ice covers for derivation of sea ice motion, and the lidar provides estimates of sea ice freeboard. These measurements provide data for the following questions relating sea ice thickness and cover to changes in the Earth's climate:

1. How is sea ice extent and thickness changing in the Arctic and Antarctic?
2. How does sea ice motion and circulation vary and change at kilometer and daily length/time scales?
3. What is the current sea ice mass balance and how is it changing at inter-annual time scales?

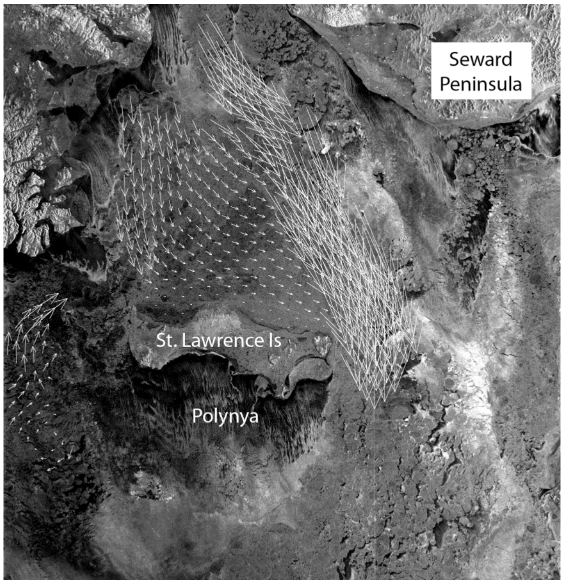

Figure 9. Sea ice motion measured from repeat SAR imagery (courtesy R. Kwok). Motion of the Antarctic Ice Sheet measured during over 48 days during the fall of 2000 using the Radarsat-1 C-band radar.

3. DESDynI measurements, synergistic missions, and other observations needed to fulfill science objectives

The second set of workshop breakout sessions considered the measurements and technical approaches envisioned by the Decadal Survey panel as well as related requirements introduced by breakout session participants to add details to the mission's configuration and/or operations. This discussion includes not only the data specifically acquired by the DESDynI instrumentation, but also inputs from other platforms and ground campaigns.

Solid Earth science. The approach to obtaining crustal deformation measurements is straight-forward. The best technology for obtaining these data worldwide and with adequate coverage is spaceborne InSAR (see InSAR Report, 2003, for a recent review of InSAR methods and applications). In this method a satellite radar system is flown in an orbit that repeats its ground track periodically, and the difference in distance (radar range) from the satellite to each point on the ground is recorded (Figure X). Under certain observation conditions, such as very close (<1000 m) orbit track repeats in space and roughly weekly to monthly revisits in time, the distance changes can be recorded at mm precision. Images of these displacements can then be related to geophysical processes on and under the ground by, for example, elastic or visco-elastic models of the crust. Finer spacing in both space and time increase the accuracy of the measurements.

The technical measurement requirements for an InSAR mission capable of meeting DESDynI goals for solid Earth science are:

1. L-band wavelength to minimize decorrelation effects
2. Approximate weekly repeat cycles for observing rapid processes and to ensure sufficient numbers of scenes to lower atmospheric delay variations
3. mm-scale displacement sensitivity in three dimensions
4. 10-20 m multi-look resolution to identify areas and mechanisms of deformation
5. Tightly-controlled orbit to maximize usable InSAR pairs
6. Both left and right looking for rapid access and more comprehensive coverage

These data should be collected over all major tectonic plate boundaries, at intraplate locations with historical earthquake activity, over the world's 600 potentially active volcanoes, and other areas where detailed deformation observations are useful. DESDynI's coverage from a 600 km sun synchronous orbit will include all volcanoes across all continents including the interior of Antarctica. DESDynI data will be supplemented by a variety of other data sources and types such as GPS, including collaborations with other science teams, assets and negotiations sponsored by non-NASA U.S. agencies, and several international sensor partners.

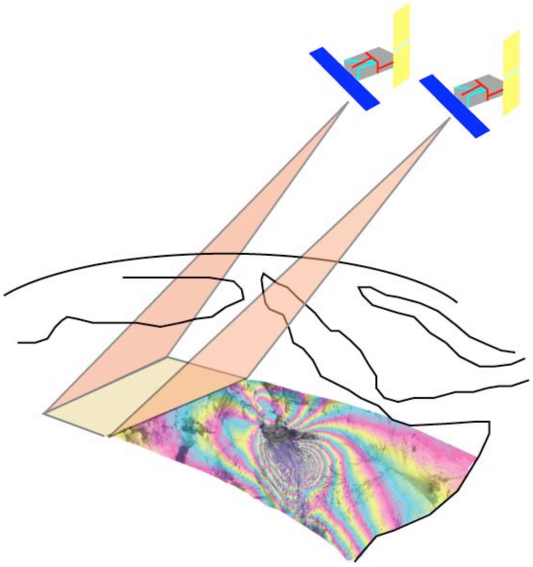

Figure 10. InSAR data are acquired using two successive passes of a synthetic aperture radar satellite over an area of interest. The first satellite records the reflected radar signal. Similar measurements on the second overflight permit measurements of the difference of line of sight distance to the surface with mm precision.

At the moment, the US research community relies on InSAR data collected by several international radar satellite missions, including those flown by the European (ERS-2, Envisat), Canadian (Radarsat-1) and Japanese (ALOS) space agencies. None of these missions were designed with interferometry as the primary application, such that data acquisition and availability still remain the most limiting factors for Solid Earth and geohazards research. Frequent and persistent acquisitions of InSAR data are crucial for adequate coverage and accurate measurement of small strain signals associated with interseismic and postseismic deformation, as well as for a rapid and efficient response in case of major natural disasters like earthquakes or volcanic eruptions. DESDynI will provide unique observational capabilities beyond the return from the international suite of sensors (L-band, short repeat times, tight orbit control, left/right looking geometry, 3-D vector displacement recovery) that will satisfy the science requirements, as outlined in the Decadal Survey. Such observations will provide critical information on the location, extent, and potential damage, including necessary uncertainties, to decision-makers to manage events that threaten human life and property.

The DESDynI mission as proposed will be highly synergistic with several future international InSAR observation systems. Table 1 lists international InSAR programs that are likely to be active in the timeframe of the DESDynI mission.

Table 1. Operational Radar Satellites Contemporaneous with DESDynI

Satellite system	Agency	Wavelength
ENVISAT and SENTINEL-1	**ESA**	**C-band**
RADARSAT	**CSA**	**C-band**
ALOS	**JAXA**	**L-band**

In particular, a combination of InSAR observations at different frequencies (L-band and C-band) and imaging geometries will result in a more complete characterization of the surface displacement field. A coordinated operation of DESDynI with prospective international L-band missions (for example, the successor to the Japanese ALOS mission) opens up an exciting opportunity for a constellation of InSAR satellites that will further reduce the revisit time, and dramatically improve the rapid response capabilities in case of major natural disasters. This is described more in the international collaboration section of this report.

Ecosystem structure. The following technical requirements for measurements of ecosystem structure meet the Decadal Survey's goals for ecosystem structure:

1. Measurements over Earth's terrestrial ecosystems comprising a statistically rigorous sampling of height and profiles and/or contiguous global coverage
2. Vegetation height and profiles: Maximum vertical height measurement accuracy to ~1 m, vertical resolution of canopy profile of 2 to 3 m, and at ~25 m spatial resolution or better in a sampling mode
3. Aboveground biomass and changes including disturbance, at a spatial resolution of 100 m to 1 km for contiguous forest biomass, and within-pixel accuracy of +/- 10 tons or 20% (whichever is greater) at 1 ha spatial resolution for sampled forest biomass
4. Changes at a scale of 1 km and precision of 2-4 tons/ha/year.
5. Re-visit time monthly to seasonal
6. The measurement technique must produce useful results within the above uncertainties over areas with significant topographic relief

Lidar systems transmit pulses of laser light downward and receive various reflections from the surfaces of leaves and other forest elements, including the ground. The round-trip travel times are directly related to the heights of 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 collection of these profiles over the life of the DESDynI mission covers about 5% of the Earth's vegetated surface during its intended five-year lifespan. In order for these samples to be used in a statistically valid way for interpolation with the SAR data, it is important that they be well-dispersed across the Earth's land surface, with a desire to have approximately 40 to 50 lidar samples within every square kilometer cell after 3 years. With data over a 5-year mission, the estimate of atmospheric carbon flux from interannual variations in above ground biomass from disturbance would be measured to accuracies significantly better than current ground-based estimates. With an extended 7-year mission lifetime, ecosystem dynamics could potentially be monitored from disturbance through early stages of succession to assess the effects of vegetation recovery on global carbon sinks.

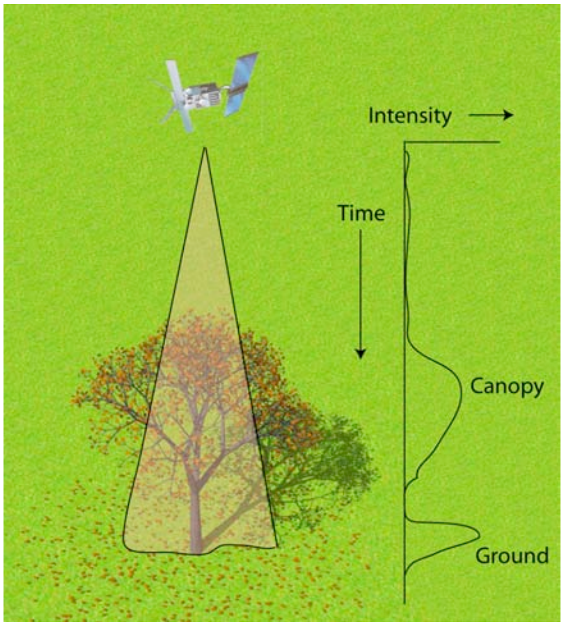

Figure 11. Lidar profiles are collected over vegetation by recording the intensity of laser pulses reflected from various parts of the canopy. Differencing the canopy and ground reflections yields tree height, and can distinguish structural changes vertically and horizontally.

Lidar coverage is usually restricted to near-nadir incidence angles and thus requires interpolation between observed points to obtain landscape scale estimates of vegetation structure and biomass. To interpolate the lidar profiles, DESDynI will use the imaging radar to sweep the landscape, its radio waves penetrating into the forest canopy and scattering from the large woody components that constitute the bulk of aboveground biomass and carbon pool. The radar provides two particular types of measurements that can complement and extend the lidar measurements to a full spatial coverage of global vegetation:

1. Single or multiple polarization backscatter measurements. The sensitivity of backscatter measurements at different wave polarizations to the size and orientation of woody components and their density enables estimation of live aboveground woody biomass (carbon stock) and structural attributes such as volume and basal area from L-band radar data. The sensitivity of L-band radar degrades over dense, leafy forests of medium to high biomass and limits its use to forests with low to modest biomass density.
2. InSAR measurements. These allow the radar sensor to measure the vertical structure of vegetation from which biomass can be estimated over a variety of forests globally. An InSAR observation with nonzero baseline provides phase and coherence that can be combined with polarimetric measurements to further resolve the vertical and horizontal distribution of vegetation structure.

The maturity of the algorithms for inferring biomass and vegetation structure using radar data acquired in these modes are quite different. And thus the questions that must be addressed and the studies that need to be conducted to advance the algorithm maturity vary depending on the mode to be used for meeting the wall-to-wall mapping accuracies. At this stage, we do not know precisely which of these modes will best satisfy all ecosystem structure requirements.

The methods for estimating forest biomass directly from radar backscatter and polarimetric measurements have been established in the past two decades (Dobson et al. 1992; LeToan et al. 2004, Saatchi and Moghaddam, 2000; Saatchi et al., 2007).

The promising technique of InSAR for estimating vegetation vertical structure follows from similar measurements of position used in the solid Earth and cryospheric science fields. Application of this method for ecosystem structure studies remains experimental and has not yet been demonstrated under a sufficient range of ecosystems or environmental conditions nor have its sensitivities been well-quantified. DESDynI offers the opportunity to explore this new and potentially powerful technique for measuring vegetation structure as well as to benchmark it in comparison with the well-established approaches using lidar and SAR polarimetry.

A single InSAR interferogram can measure only one height, such as the canopy height. One image pair, then, is insufficient to uniquely specify vertical characteristics of even the simplest 3-D forests (Treuhaft et al. 1996). There are two ways in which InSAR observations have been used to estimate more complicated vegetation structure: i) combining the phase and/or coherence from a single observation with some combination of field data and/or lidar (Hagberg et al.,1995; Askne et al. 1997, Kellndorfer et al. 2004) and/or lidar (Simard et al. 2006); or ii) use multiple InSAR observation pairs with models to estimate vertical vegetation characteristics without external calibration.

Applications of the second method have added InSAR observations of different frequencies (Neeff et al. 2005 using P and X band phase to estimate tree height), InSAR observations of different polarizations (Papathanssiou and Cloude 2001, to estimate tree height), and InSAR observations of different baseline lengths (Treuhaft and Siqueira 2000, to estimate tree heights; Reigber and Moreira 2000, Treuhaft et al. 2002 to estimate vegetation profiles). The majority of the applications of both methods are concentrated at C-band where both airborne and spaceborne data are available. Availability of lidar sensors as a calibrating source and some degree of polarization and baseline diversity, make DESDynI uniquely capable of an optimal hybrid approach, spanning the possibilities of both of the published options above to estimate vertical structure.

Together, lidar and radar measurements will yield vegetation structure globally, provide the magnitude of forest biomass in boreal, temperate, tropical regions, and with frequent observations, regardless of atmospheric condition and cloud cover, improve estimates of forest recovery on annual basis, monitor and identify forest disturbance such as fire, logging, and deforestation and characterize changes of vegetation structure during post disturbance recovery.

While DESDynI can achieve its goals for ecosystem structure without any additional space-based observations, there may be considerable benefits to planning DESDynI as an element within a radar sensor constellation involving planned programs of other nations. Of particular interest would be synergism with a P-band SAR (one is currently being considered in Europe), given that P-band is more sensitive to medium to high biomass forests than is L-band. Enhancements in the frequency of global coverage by combining observations from multiple sensors would improve the ability to characterize change through time. The opportunity to explore other InSAR approaches is also of interest, such as configurations in which DESDynI offers one of several L-band sensors or observes in concert with the German TanDEM X-band mission. These synergies can be achieved through cooperation with international partners starting in the DESDynI planning phase. Potential value-added synergistic InSAR programs are described in a later section of this report.

Geographic context is often useful for interpretation of ecoregions, physiognomy, and vegetation type to most accurately apply retrieval algorithms and for scientific analysis. Landsat TM/ETM+/LDCM or MODIS/VIIRS, depending on scale of interest, provide this information. Classifications derived from operational VNIR sensors are expected to continue to be widely available and will be used to provide useful, complementary contextual observations for DESDynI.

Cryospheric science. The technical measurement requirements for a radar mission capable of meeting DESDynI goals for the cryosphere are very similar to the requirements for solid Earth science, differing slightly in the reasons for those requirements that have to do with the character of the target. We distinguish here between requirements for studying the ice sheets and those for studying sea ice. The technical measurement requirements for ice sheet research are:

1. L-band wavelength to minimize decorrelation effects over snow, firn, and bare ice
2. Approximate weekly repeat cycles for maintaining interferometric fringe visibility on rapidly deforming ice such as coastal areas of Antarctica

3. Few mm-scale displacement sensitivity in three dimensions
4. 2-5 m single look resolution for measuring rapid displacements
5. Tightly-controlled repeat orbit to maximize usable InSAR pairs and minimize decorrelation effects on snow and firn
6. Both left and right looking for rapid access, three-dimensional motion mapping, and more comprehensive polar coverage

For a comprehensive view of the Earth's cryosphere, these data should be collected not just over the entire ice sheets in Greenland and Antarctica, including if possible the south pole, but also over all smaller-glaciated areas in the rest of the world (Alaska, Patagonia, Himalaya, Arctic Islands, Scandinavia, Alps, etc.), and over areas underlain by permafrost (Siberia, Northern Canada and Alaska, etc.). DESDynI data will be supplemented by a variety of other data sources and types, including collaborations with other science teams, assets and negotiations sponsored by non-NASA U.S. agencies, and several international sensor partners.

No existing mission is designed with interferometry as the primary application, or with the polar regions as the primary science goal, such that data acquisition, quality and availability still remain the limiting factors for cryosphere research. A short repeat cycle is crucial for maintaining fringe visibility required to observe vertical motion of ice associated with the interactions of glacier grounding lines with ocean tides, inflation/deflation of the ice surface caused by subglacial events, rapid ice deformation associated with iceberg calving events, ice-shelf rifting, and glacier surging. Frequent and persistent acquisitions are required to observe the seasonal variability in velocity of glaciers in response to climate forcing, abrupt glaciological events such as glacier surging, iceberg calving, ice-shelf collapse, and to improve the precision of measurements through data stacking, including on very slow moving areas such as ice divides and domes of interior Greenland and Antarctica. For example, most of Antarctica's glaciers discharge directly into marginal ice shelves or less frequently into sea ice-covered oceans; simply completely measuring the 'grounding line' location that defines Antarctica's inland ice as well as any subsequent changes to it would be a clear mission 'success'. Data stacking will also be an important strategy to mitigate the influence of ionospheric perturbations on L-band radar signals. DESDynI will provide unique observational capabilities well beyond the return from the international suite of sensors (L-band, short repeat times, tight repeat orbit control, left/right looking geometry, 3-D vector displacement recovery) that will satisfy the science requirements, as outlined in the Decadal Survey. Such observations will provide surface deformation and flux information, including uncertainties, to determine the present-day contribution of ice sheets and glaciers to sea level rise and help improve numerical predictions of the spatial and temporal patterns of their contribution to sea level rise, with obvious and important benefits for decision makers.

The DESDynI mission as proposed will be highly synergistic with several other ongoing and future missions, including international SARs such as Envisat ASAR/Sentinel-1, ALOS PALSAR, and Radarsat-1/2/3. In particular, a combination of InSAR observations at different frequencies and imaging geometries will result in a more complete characterization of the deformation field. More broadly speaking, however, the data on ice motion and dynamics to be collected with DESDynI will be synergistic with observations of temporal changes in the Earth's gravity field as measured by GRACE and GRACE follow-on missions, observations of ice surface topography and elevation changes as measured by ICESat-I and ICESAT-II missions, observations of ice thickness collected by airborne systems on outlet glaciers along the periphery of ice sheets and over ice caps, and targeted field campaigns that acquire in situ data not obtainable from remote sensing satellites. This combination of satellite and airborne resources is essential to address the overarching science objectives of cryosphere research of determining glacier and ice sheet mass balance and developing a capability to predict the evolution of glaciers and ice sheets in a changing climate.

Technical requirements for sea ice research are:

1. Wide-swath ScanSAR 2-day repeat mapping of the sea ice covers in both the Arctic and Antarctic

2. 100 m multi-look resolution for measuring sea ice deformation
3. Multi-year continuous time series to cover advance and retreat of seasonal and perennial ice cover over the 5-year nominal duration of the mission

The wide-swath SAR imagery should be routinely acquired over the Arctic and Southern Oceans. Sea ice motion and deformation are derived from repeat coverage. The response of the ice cover to large-scale gradients in atmospheric and oceanic forcing is concentrated along narrow zones of failure (up to tens of kilometers in width) resulting in openings, closings or shears. In winter, openings dominate the local brine production and heat exchange between the underlying ocean and the atmosphere. Convergence of the pack ice forces the ice to raft or pile up into pressure ridges and to be forced down into keels, increasing the ice-ocean and ice atmosphere drag. Only using sea ice kinematics derived from high resolution Synthetic Aperture Radar (SAR) imagery have we been able to approach the spatial length scale required to observe these processes. Since 1996, the US research community has relied on the wide-swath coverage of the RADARSAT and Envisat imaging radars as a tool for acquiring the high resolution (~100 m) observations of the Arctic ice cover; the continuation of these observation with the DESDynI SAR is crucial for understanding the basin-scale behavior of sea ice kinematics on a seasonal and inter-annual time scale, and the mass balance of the Arctic and Southern Ocean sea ice covers.

4. Instrument, Spacecraft, and Orbit Issues

The proposed DESDynI mission instrumentation package contains an L-band synthetic aperture radar capable of interferometric analysis plus a multiple-beam lidar instrument. Implementation of these instruments at useful sampling geometries implies a set of constraints on the operation of the spacecraft and its instrument package. Accommodating the wide range of science objectives for the DESDynI mission inevitably leads to conflicts in observation time, use of spacecraft resources, and orbital considerations. Two breakout sessions at the workshop were devoted to these difficult issues, and the general consensus was that workable engineering compromises appear to exist for most of these problems. In this section we describe the various technological needs for addressing the science goals and identify possible implementation scenarios. Specific engineering studies to resolve issues, but which are beyond what could be accomplished in two days' discussion at the workshop, were identified and are discussed in the following section of this report. Again, the reports are organized by science area.

Orbital issues are particularly critical for this radar/lidar mission, where 1) radar instruments must be pointed off-nadir while lidar performance decreases significantly as incidence angle increases and 2) the short repeat cycle required for radar measurements of deformation restricts the geographic coverage of the lidar for ecosystem structure. A separate subsection giving orbital preferences by science area is added after the discipline reports.

Solid Earth science. Solid Earth deformation measurements will depend primarily on interferometric analysis of data acquired by the DESDynI L-band SAR instrument. InSAR requires that two or more images be acquired in compatible modes with nearly identical geometry to measure the deformation between the acquisition dates. The geometric requirement is met by having the satellite or satellites repeat the same track over the Earth on subsequent cycles of orbits.

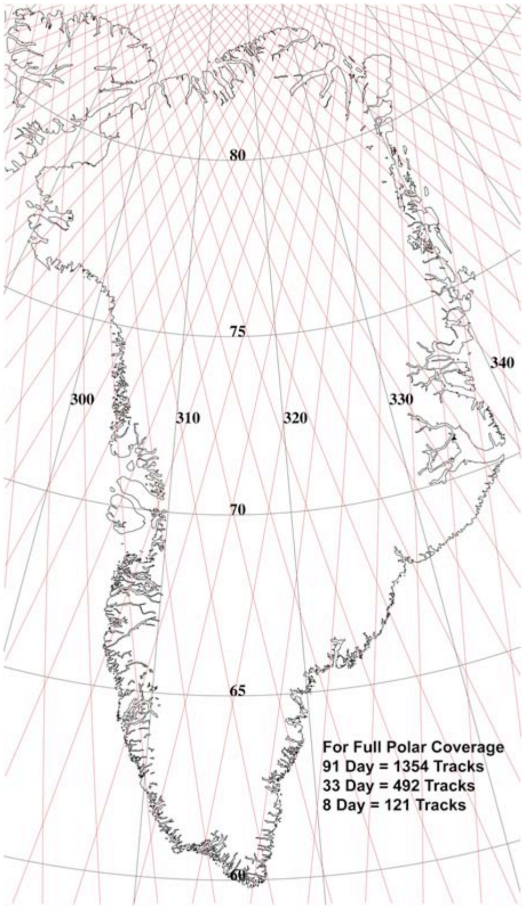

Figure 12. Orbit nadir tracks show the relationship between repeat interval and spacing of ground tracks. The image above shows coverage over Greenland for an 8-day repeat cycle. Lengthening the repeat interval results in more finely spaced tracks and denser spatial coverage for lidar measurements. The radar measures a wide swath and coverage is not a driving factor, rather, radar tracks are preferred to repeat quickly to see rapid geophysical changes.

For complete global coverage, the SAR instrument must be able to image a cross-track area larger than the spacing between the tracks at the equator. If the tracks are 350 km apart at the equator, then the SAR instrument could use either a wide swath in a ScanSAR mode to cover the entire 350 km width each orbit, or use three regular strip-map mode swaths that are about 120 km wide each but offset from each other to cover the full width in three orbits. Some solid Earth deformation would be best imaged by a wide swath ScanSAR mode and others would be better addressed with the higher spatial resolution of the strip-map mode, so a SAR instrument capable of both modes would be best. To allow interferometry between ScanSAR images, the SAR instrument must include a system to ensure synchronization of the radar bursts between orbits.

Measurements of deformation require precise knowledge of the spacecraft orbit for use in the InSAR processing. This can be achieved by including one or more GPS instruments on the satellite. The distance between the satellite positions for a given repeated track is called the baseline. The longer the baseline, the more noise is added to the InSAR measurements of surface deformation. To meet the solid Earth deformation requirements, the baseline between orbits used for InSAR should be less than roughly 1 km, and preferably less than 250 m. Keeping the satellite within an orbit tube that is 250 m in diameter would ensure that all pairs of SAR images can be used for InSAR measurements. Because drag from the variable outer edge of the atmosphere increases at lower satellite altitudes, it is much easier to keep the satellite in a small orbit tube at elevations of 600 km or higher above the Earth's surface. Lower altitudes would require a large increase in the amount of fuel required onboard to consistently adjust the orbit.

The length in sidereal days of the repeat cycle for the satellite orbit is important for solid Earth deformation, because it is a fundamental limit on the temporal sampling of any deformation signals. Rapid imaging of the area of a disaster is necessary for effective response to disasters such as earthquakes or volcanic eruptions, within a day or two if survivors are to be located. Short repeat cycles and constellations greatly reduce the delay in acquiring new images (Fielding et al., 2005; Wyss et al., 2006). In addition, a short repeat cycle also reduces the noise in InSAR measurements caused by temporal decorrelation. The choice of the orbit-repeat cycle is primarily linked to the choice of the spacing between the orbits at the equator, orbital inclination, and the satellite altitude. A short repeat cycle will best sample rapid deformation events, but will also cause a larger separation between the orbits. The optimum repeat cycle for solid Earth deformation with complete global coverage is 8 days, with a track separation about 350 km at the equator.

Solid Earth deformation involves three-dimensional displacement of the surface, and a single InSAR measurement only measures the component in the line of sight. To determine all three components, the InSAR data must be acquired on both ascending and descending orbits and with both right-looking and left-looking geometries, relative to the spacecraft motion.

Ecosystem structure. As discussed above, DESDynI will acquire ecosystem structure data using a profiling multiple-beam lidar and a swath-mapping radar instrument. The lidar measures profiles in a narrow swath beneath the spacecraft. Analysis of the lidar return as a function of time gives the canopy heights, important for biomass models, and also yields the vertical distribution of canopy elements. These measurements can be made at incidence angles up to perhaps 10 degrees due to errors that increase with the resulting 'effective slope' induced by the combination of the off-nadir angle and the actual ground topography.

For some applications vegetation structure estimates are needed over the full surface in order to account for horizontal variations in canopy structure and characterize diversity beyond the spatially-limited lidar measurements. Fortunately, in DESDynI wall-to-wall mapping capability is provided by an L-band SAR, which can operate in amplitude-only, polarimetric, or interferometric modes. Demonstration of algorithms for inferring biomass and vegetation structure using data acquired in these various modes differ significantly, especially for the single-band InSAR as would be collected by DESDynI.

The use of single and multiple polarization L-band radar to map biomass is well established and richly documented in the scientific literature (Dobson et al. 1992, Imhoff 1995, Le Toan et al. 2004). However, these results establish clearly the limits of L-band power backscatter to map biomass above about 60 to 100 Mg ha^{-1} (Dobson et al., 1992). Biomass within many important global biomes, particularly in the tropics, exceeds these values. Tropical biomass ranges up to 500 Mg ha^{-1} (Keller et al. 2001, Chave et al. 2003, Houghton 2005). Biomass in temperate coniferous systems can exceed 1000 Mg ha^{-1} (Lefsky et al. 1999)

Another method for inferring biomass at still higher densities is the use of InSAR to measure either canopy heights or, if multiple baselines are available, the vertical structure of the canopy. InSAR has been used to estimate vertical forest structure at C-band (Treuhaft et al. 1996, Lin and Sarabandi 1999, Sarabandi and Lin 2000, Treuhaft and Siqueira 2000, Slatton et al. 2001, Treuhaft et al. 2002, Kellndorfer et al. 2004), L-band (Cloude and Papathanassiou 1998, Reigber and Moreira 2000, Papathanassiou and Cloude 2001), and X-band (Neeff et al. 2005, Balzter et al. 2007). The use of InSAR to map vegetation vertical structure and consequent biomass in a repeat-track DESDynI acquisition mode, with small numbers of baselines, requires further study before modifications of the DESDynI baselines can be considered. The fusion of InSAR data with the lidar sampler to potentially improve InSAR vegetation structure observations is at a lower stage of maturity yet, with sparse literature on the subject (Slatton et al. 2001, Simard et al. 2006, Hyde et al. 2007). Yet it is likely that the lidar samples can improve the InSAR measurements if some lidar pixels overlap InSAR, acquired “sufficiently near-by” both in space and in time. Because the SAR must view the landscape at larger off-nadir angles than the lidar, the measurements are not acquired simultaneously. However, it may be sufficient to acquire both sets of data within the same phenological stage of the forests.

Because the SAR must point off nadir, the SAR and lidar do not measure the same geographic location at the same time. In order to interpolate the lidar data using the SAR data, it is necessary for the two observations at a given location to be made reasonably close in time. A period of about 3 weeks and/or acquisition within the same vegetation phenological stage is likely to be adequate, but this requirement needs to be better quantified in future studies.

In order to adequately sample the Earth’s ecosystems with the lidar, measurements must be made to maximize geographic coverage. End-of-mission spacing of ground tracks of ~1 [1-3] km at the equator is required. In order to adequately capture horizontal spatial variability in forest structure, about 40 to 50 lidar samples within each square kilometer of the Earth’s vegetated surface will be needed. A longer repeat orbit, such as 45 days, that drifts slightly and allows coverage to fill in across orbital cycles is desired.

Cryospheric science. As for the Solid Earth deformation studies, ice flow and flexure measurements will depend primarily on interferometric analysis of data acquired by the DESDynI L-band SAR instrument. Many of the requirements for orbit configuration and SAR instrument capabilities for ice studies have their origins in the same constraints required for observations of solid Earth deformations and hazards. Observations of sea ice displacement would rely primarily on wider-swath ScanSAR operation, and in general do not have the same accuracy requirements as land-based ice. The lidar instrument as proposed in the Decadal Survey DESDynI mission concept appears to have limited utility for measurements of broad-scale topographic change in the cryosphere. The lidar sensor’s series of profiles needs further elaboration but if it were to include capabilities that allowed high-accuracy pointing knowledge and measurement repeatability similar to the lidar capabilities of the ICESat-II mission concept in the Survey report, then substantial cryospheric benefits and synergies with ICESat could certainly result. The mission’s coverage limits for the lidar (thought to be ±83 latitude) are a concern when compared to ICESat but note that this latitude limit would include all of Greenland, most of the Arctic Ocean, essentially all of the Southern Ocean’s sea ice, all but about 20% of Antarctica’s interior ice, and most critically, could put a much higher number of lidar measurements (individual shots and crossovers) on specific smaller ice masses, glaciers and ice caps, which are currently causing the majority of eustatic sea level rise (Meier, Science, 2007). The real key to using the proposed lidar is that the elevation measurements from the repeated 8-day swath of small footprint profiles, although limited spatially, would reveal most meteorology-driven surface changes (accumulation, melting, evaporation, sublimation, firn densification) on the major ice sheets better than ICESat-I/II.

These factors are a major complication to deciphering the overall elevation change signal in terms of sea level. This is a clear synergy with ICESat-I/II as it is unlikely to obtain high temporal frequency data. This detailed coverage, combined with the lidar's notional swath of smaller lidar footprints suggests that further analysis of this sensor's actual capabilities for robust ice measurements is urgently needed.

InSAR-based ice motion measurements will depend primarily on the higher-resolution swaths of a strip-map mode, and would use the left and right looking capability of the SAR to obtain interferograms of a subject glacier from multiple viewing geometries, allowing 3D vector displacement to be obtained. Required knowledge of the orbit for InSAR processing is similar to the Solid Earth case discussed above. Baseline requirements for InSAR are also similar to the Solid Earth case, with the additional complication of enhanced baseline-related decorrelation due to volume scattering over the snow and firn. In the ice case, longer baselines increase noise relative to the desired motion signal both because of this decorrelation and because of poorly known surface topography at the scale of the InSAR data. Adequate understanding of the effects of volume decorrelation at L-band can be derived from previous data and studies with ALOS PALSAR of glaciers and ice sheets. The choice of orbital repeat interval has an impact on the ability to form interferograms because of temporal decorrelation – this effect is most pronounced at low elevations which can be subject to substantial surface melt, and on glaciers in high accumulation areas, such as southeast Alaska and Patagonia, where snow events occur and subsequent compaction is rapid; repeat period also has an impact on the ability to track fast moving glaciers, where displacements over a single repeat period produce fringe densities high enough to be aliased in imagery with the few decimeter multi-look resolution. If instrument resolution is high enough in single-look data, specular feature tracking can be used to overcome this last limitation.

Orbital Issues for the DESDynI Mission. Each discipline has preferred orbits and imaging geometries to achieve its mission objectives. While these differ, one goal of the workshop participants was to understand what, if any, class of orbits could best accommodate most of the mission objectives. First, we list the specific desires for each community:

> **Solid Earth Science.** The primary mode of the DESDynI radar instrument for solid Earth science is the formation of a repeat-pass interferometer to measure 3D vector surface displacements. This measurement requires repeated observations at nearly the same spacecraft position and orientation over varying time intervals.
>
> The use of exact repeat orbits will enable this interferometer measurement for the duration of the DESDynI mission. A repeat orbit is a special condition, achieved by careful selection of altitude and orbit inclination, wherein a spacecraft retraces its path through space at a regular interval commensurate with the mean orbital period. This interval is the defining characteristic of repeat orbits.
>
> Selection of the repeat cycle interval has a profound effect on what science is enabled. For long-term deformation, longer intervals (monthly to seasonal) between observations may be permissible, as deformation in these regions is slow and regular and decorrelation is low for most areas at L-band frequency. For short-term transient deformation, longer intervals may impair the ability to exactly reconstruct the physical behavior due to aliasing and displacement error. Previous analysis (see InSAR Report, 2005, for example) has shown that an observation interval of between 8-14 days might be acceptable, with shorter (8 days) intervals preferred. Beyond 14 days it is not possible to discriminate between various postseismic deformation processes and a 14 day interval requires two years to discriminate between processes (Donnellan and Lyzenga, 2006).
>
> Sun synchronous orbits oriented parallel to the sun terminator are also preferable for solid Earth science. At the sun terminator, the error introduced by the ionosphere is minimized and consistent, thus reducing the error in the measurement of the surface deformation signal. The sun-synchronous characteristic of an orbit, that is an inclination of near 98.5° for a retrograde orbit, or 81.5° for a prograde orbit, with limited variations of

altitude, is key to maintaining orientation to the sun terminator.

Finally, the repeat-pass interferometric measurement is very sensitive to the length of the physical baseline between observations. Minimizing this baseline throughout the mission reduces unwanted biases from surface topography and degradation of the measurements by reduced interferometric correlation. Lower altitude sun-synchronous orbits introduce higher magnitude perturbations due to atmospheric drag, especially during solar events, and thus complicate the maintenance of the tight baseline in a repeat orbit. Orbits at least 600 km in altitude are likely necessary to minimize orbit perturbations.

Ecosystem structure. For ecosystem structure, the primary quantitative measurement from DESDynI is from a multiple-beam lidar to measure canopy height and the vertical profiles of the vegetation structure. These high precision measurements will be combined with DESDynI's SAR and/or InSAR measurements to produce structural characteristics and biomass estimates globally.

The lidar samples must be well-dispersed geographically and constitute a representative sample of the Earth's vegetated surface. While the exact spatial density of lidar ground samples required for DESDynI is not precisely known, previous studies suggest that this spatial density would likely have to produce 40-50 lidar samples per square kilometer. To achieve this orbit ground tracks should be spaced between 1 km – 3 km (lidar samples are contiguous in the along-track direction). Selection of a long or non-repeating orbit is one way to achieve this sample density. The 8-day repeat requirement for the InSAR results in an orbit track separation of 345 km at the equator, whereas a repeating orbit with cycle lengths of ~45 days achieves orbit-track spacing of 60 km. Pointing the lidar instrument off-nadir is another implementation which could be used to improve lidar sampling density. However, accuracy of height measurements may suffer significantly, especially for larger incidence angles resulting from wider orbit-track spacing.

The lidar and SAR observations for a given point on the Earth should be acquired within a reasonably short period of time (preferably 21 days or less) – and at least within the same phenological stage of the forest.

Lidar beam-track crossing points are also important for improving the calibration of lidar measurements. As repeat cycle length increases, the number of spatially distinct crossover-points increases.

Finally, lidar measurements are very sensitive to orbital altitude. The lidar signal strength weakens as a function of the square of the orbit altitude; thus, doubling the altitude can require, for example, a quadrupling of laser power or telescope collecting area.

The L-band SAR must acquire global wall-to-wall coverage of the Earth's vegetated surface on monthly to seasonal basis in order to provide the data for interpolation of the lidar measurements and to quantify changes in vegetation structure over the course of the mission.

Cryospheric science. Coverage across the Earth's polar regions is of primary concern to the cryospheric science communities because of 1) the albedo-feedback mechanism that appears to be causing dramatic declines in Arctic sea ice area and thus accelerated warming of the underlying Arctic Ocean and its marginal ice masses (like Greenland); and 2) the vast potential store of water-equivalent sea level rise in Antarctica's (and Greenland's) vast ice sheet cover. Near polar (i.e. close to 90° inclination) inclination orbits are able to provide extensive coverage in these regions. However, full coverage with a nadir looking lidar would require an exactly polar, or 90° inclination orbit and all crossovers would then fall at either pole. The side looking InSAR illuminates the surface roughly between 350 km and 700 km from the satellite nadir point (although this is dependent on spacecraft altitude), which is roughly 3°-6° in latitude on the Earth's surface. Sun-synchronous orbits have an inclination of around 97° and 98°, thus with this orbit complete coverage of the poles is not possible without the left/right look design for the spacecraft mentioned earlier.

As for solid Earth science, repeat-pass interferometry is the primary measurement for observing 3D vector motion of glacial systems. However, glaciers move over a wide range of velocities. To avoid fringe aliasing and temporal decorrelation effects, cryospheric science research requires relatively short intervals between observations, between 2-3 days at C-band but perhaps 8-10 days at L-band. This repeat interval likely enables interferometric observations of all but the fastest glaciers. On the fastest moving glaciers (e.g. Jakobshavn Isbrae in Greenland at 10+ km/yr), repeat pass requirements are hourly at C-band and sub-daily at L-band, which is probably not achievable with a single satellite on a polar orbit.

We note that frequent (every 3-8 days) polar observations with SAR imaging are enabled by high inclination orbits. This feature enables more frequent access to information about ice-front position, calving events, glacier surges, and sea ice motion.

Workable compromises appear to be possible for the orbit and operational issues described above. Several of these were agreed to at the workshop, subject to a more thorough review and verification by engineering studies recommended to follow the meeting. The three major compromises discussed and described at the workshop were:

1. **Orbital repeat interval:** 8 days is preferred for Solid Earth and Ice, 8 days or shorter repeat times are best for the vegetation height InSAR due to temporal decorrelation. Longer repeats for global coverage are preferred for both by the radar and the lidar measurements for ecosystem structure. Use of a slightly longer repeat with off-nadir lidar pointing might mitigate this issue, using orbits of approximately 12-16 day repeat time. Alternatively, during the vegetation observing epochs, very short repeat periods could be used (3-4 days) and with the ascending node shifted after every interferometric pair to allow more coverage. During the nominal mission lifetime, a 12-16 day repeat would be desired to achieve better nadir coverage for the lidar component of the mission. Shifting between different repeat orbits will require fuel and command/control activities and must be carefully conducted to avoid jeopardizing overall mission goals.
2. **Orbital altitude:** 800 km minimizes atmospheric orbit degradation and instability for InSAR, while a 400 km altitude is optimal for lidar operation. It appears that a compromise altitude of 600 km is possible and would satisfy all science requirements. Regardless of the altitude chosen, any consequent shifts in the latitude coverage of the Earth below should be well defined, so that the various communities can see how ‘global’ coverage will change.
3. **Interferometric operating baseline:** zero length is preferred by the Solid Earth and Ice science communities, as opposed to multiple nonzero baselines preferred for ecosystem science. Generally, for vegetation height and vertical profile interferometry, baselines ranging between 500 m to 2 km are desired. Depending on how well topography is known, this will affect deformation estimates desired by the other communities. A non-zero baseline however has the ability to be used to derive an L-band DEM, a useful product in its own right for the other principal users of DESDynI. Hence, it is envisioned that a non-zero baseline could be used at the beginning of the mission lifetime, near the end, and perhaps for one or two observing epochs extending to approximately 3 months, during the mission.

Unresolved issues that were deemed too complicated to answer in a three-day meeting are described in the following section.

5. Questions remaining to be addressed by detailed science and engineering studies

While it is clear to the workshop participants that operational and engineering comprises can be reached to permit resolution of the major scientific goals set for the DESDynI mission, finding the optimum solutions to these conflicting needs in many cases will require detailed mission studies. In this section we define the needed work identified at the workshop. Certainly other engineering and science studies will be identified as the mission concept matures.

In this section we discuss these necessary continuing steps, again organized by science area.

Solid Earth science. Solid Earth science and applications will benefit mainly from complete and repeated observations of Earth's surface displacements at the sub-cm level over the mission lifetime. Questions to be addressed in order to enable solid Earth science and applications are therefore related to (1) the determination of highly accurate surface displacements, (2) the interpretation of surface displacements in terms of causing processes, and (3) the integration of surface displacement observations in applications of societal relevance.

Relevant solid Earth processes exhibit temporal scales from seconds (e.g., co-seismic displacements) to secular within the time window of the mission duration (e.g., isostatic adjustments), and spatial scales from local (e.g., local subsidence, volcanoes) to near-global (e.g., great earthquakes, glacial isostatic adjustment). Extracting surface displacements from InSAR observations therefore poses a major challenge in order to avoid temporal and/or spatial aliasing or biases.

Key problems to be addressed are related to:

1. Algorithm development for the integration of ground-based, such as GPS, and space-based observations
2. Improved separation of geophysical signals from tropospheric effects and orbital errors through optimal use of a priori information in the analysis of InSAR observations
3. Improvements of the global geodetic reference frame and the linking of InSAR observations to this reference frame
4. Better understanding of the spatial and temporal scales of some of the geohazards, in particular volcanic eruptions and landslides, in order to support the use of the observations in early warning and emergency response applications
5. Better understanding of limitations for Earth science applications from mission parameters such as repeat time and altitude
6. Better understanding of potential synergies of solid Earth, hydrology, atmosphere and ionosphere applications

The main ingredients for the determination of surface displacements from InSAR include at a minimum a high-resolution global DEM and information on tropospheric water vapor content. Additional data of ionospheric TEC, for example, from GPS/GNSS is likely to improve the correction of ionospheric path-delay based on InSAR observations alone. Ground-based GPS/GNSS measurements of Earth phenomena can provide a much higher temporal resolution than InSAR, highlighting the importance to develop algorithms for integrating ground-based and space-based observations. This will be particularly important if the repeat time is increased above the anticipated 8 days.

If an a priori deformation model is available, moderate or short-wavelength surface displacements can be separated from atmospheric effects and orbital errors using InSAR time series techniques such as persistent scatterers (Ferretti, et al., 2001) and small baseline subset InSAR (Berardino, et al., 2002). However, how to separate long-wavelength deformation signals from atmospheric effects and orbital errors still remains unsolved. Moreover, strategies of how to make best use of a combination of a priori information on surface deformation, DEM, tropospheric water vapor, and ionospheric TEC are still in a research stage and need to be studied in more detail and validated. Particular emphasis should be on consistent treatment of errors in the a priori information.

As emphasized by the Decadal Survey, a stable global geodetic reference frame is indispensable for all satellite missions. Moreover, for most Earth science applications, the surface displacements need to be given relative to such a stable, global geodetic reference frame. For example, for scenarios of future changes in local sea level coastal subsidence or uplift need to be given in a reference frame well tied to the Center of Mass of the Earth system. Glacial isostatic adjustment and elastic loading, due to both past and present changes in ice load, respectively, is important for the conversion of ice surface displacements into ice volume and mass changes. The deformation of the solid Earth surface due to ice loads has large spatial scales and need to be referred to the same reference frame as that of the ice surface displacements. Large earthquakes have displacement fields exceeding by far the size of several adjacent images. Likewise, postseismic deformation, which is a key quantity for earthquake process studies, can have spatial scales of the order of 1000 km. For all these phenomena it is crucial to relate the displacements from different interferograms to the same unique reference frame in order to capture the large-scale displacement pattern.

Historically, the reference frame has been derived from a variety of “standard” locations but these have been largely supplanted by GPS methods. While the methods of extracting the reference frame from GPS data are well understood at present, there is no comprehensive operational plan underway to set this important standard. Needed improvements include tidal corrections, better understanding of nonlinear variations over time, and corrections for factors such as seismic or isostatic deformation. As proposed by Herring et al. (2007), an improved frame would have to be based on a dynamic reference Earth model (DREM), which would account for all major processes leading to surface displacements (tides, surface loading, tectonic process, large earthquakes) and make use of geodetic observations through data assimilation. The development of such a model is a major task for geodesy and Earth science over the next several years and is a mandatory prerequisite for the utilization of InSAR for studies of processes with spatial scales considerably larger than the size of individual images.

For some applications, in particular early warning and disaster damage assessments, high temporal resolution and low latency are key requirements. Potentially hazardous volcanoes and unstable slopes can be monitored with a repeat period of eight days in order to indicate the development of hazardous events, but in critical phases early warning requirements may very likely need shorter repeat periods. In many cases, the relevant time scales in the critical phase before volcanic eruptions and landslides (i.e., the time interval when non-linear deformation indicates an impending event) are not well understood. Further studies are required to better understand the processes prior to eruptions and, in particular, landslides and the characteristic time scales. This would allow us to assess the applicability of InSAR with a repeat period of eight days or longer for early warning and the need for additional observations during critical periods. In these cases, supporting measurements with airborne lidar and InSAR can be used to achieve improved temporal resolution, and airborne lidar in particular can provide for improved lidar spatial coverage. In cases of earthquakes, landslides, and volcanic eruptions, emergency response requires rapid information on the extent of damage. Surface displacements and decreased interferometric correlation are indicative of damage. In order to reduce the latency, airborne lidar and InSAR can support the mapping. In all these cases, the appropriate algorithms for the combination of the spaceborne and airborne observations need to be developed.

For the generation of 3D velocity vectors, different look angles would be very advantageous. This could be achieved through appropriate constellations realized in cooperation with international partners (see next section). Moreover, such constellations could also help to improve temporal resolution. However, parameters of optimal constellations need to be determined through appropriate studies.

A potentially significant contribution of InSAR to hydrology might result from combining reflectivity and surface deformation from InSAR (and also reflection GPS) with GRACE regional mass changes and the ongoing and planned surface soil moisture measurements using passive radiation such as SMAP. Significant synergy is possible between GRACE regional gravity changes, which mainly are related to hydrology, and surface subsidence and uplift due to aquifer changes in charge. This could provide significant improvements in water resource estimates. Moreover, landslide vulnerability assessments would benefit from this information. It is therefore recommended that these synergies are explored in studies based on existing observations.

Ecosystem structure. A number of details regarding how ecosystem structure science requirements constrain mission implementation and operations options need yet to be resolved. Workshop break-out sessions identified the following questions:

1. Is full polarimetry needed for ecosystem structure? Would HH, HV be adequate?
2. What is an acceptable time lag between lidar and radar measurements of vegetation?

Specific research tasks and other activities were recommended:

1. Advance the development of algorithms for lidar-SAR fusion to estimate structure and biomass. Simple algorithms currently exist, but further development is warranted.
2. Acquire new data to test/explore lidar-SAR capabilities for vegetation structure and to be used in developing data fusion algorithms, such as combinations of airborne lidar, LVIS,or ICESat with ALOS PALSAR, UAVSAR, or other data acquired by international sensors
3. Develop a better understanding of how to compensate for non-nadir lidar pointing to fill gaps in coverage for vegetation

A strong program of distributed ground measurements is also critical for ecosystem structure algorithm development and validation. Sufficient samples of vegetation structures in each of the global vegetation biomes and perhaps IGBP (International Geosphere Biosphere Programme) vegetation physiognomic classes and disturbance types will need to be identified. Because ground sampling can be intensive, efforts should be made to capitalize on any existing programs to develop a consistent set of ground data and at the same time to reduce redundancy of measurements. Ground plots need to be co-located and co-registered with lidar samples. It is strongly recommended that a calibration and validation program of airborne lidar campaigns be established, also using standardized measurement protocols to the extent possible.

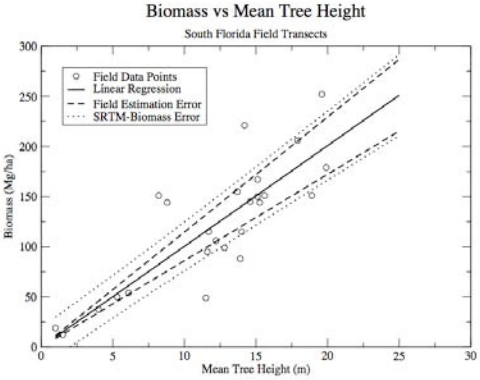

Figure 13. Biomass and other ecosystem structure parameters are derived from allometric equations verified by field experiments. The appropriate set of regressions must be completed once DESDynI is fully defined and all wavelengths, polarizations, and InSAR modes set.

Additionally, workshop participants recognized the potential for L-band InSAR to yield measurements of ecosystem structure that may be commensurate in quality with those from lidar and/or lidar-SAR data fusion. They recommended that research be conducted to establish a more solid scientific foundation for this alternative approach and/or lidar-InSAR synergism. The following questions need to be addressed:

1. How accurately can L-band InSAR serve as a data fusion product with lidar to achieve vegetation horizontal and vertical structure requirements? How will the accuracy depend on the number and length of baselines, as well as their repeat times and polarization characteristics?

2. How can the lidar vegetation measurement be improved by fusion with InSAR observations? How near in space and in time will the lidar and InSAR samples need to be acquired?
3. How compatible will the combined lidar-InSAR inferences of vegetation structure be with the carbon, and ecosystem models that currently use other measurements of structure?
4. What is the time interval before temporal decorrelation of InSAR becomes a factor for measurements of ecosystem structure?
5. How is the accuracy of vegetation height and other structural parameters estimated from InSAR affected by small numbers of baselines and temporal decorrelation?

In order to develop the ability to derive vegetation height and estimate biomass from InSAR measurements across a range of the Earth's biomes, the following studies and activities will be required:

1. Studies to understand better how radar interferometry can be used to provide needed vegetation structural parameters, and evaluate it in comparison with lidar-polarimetric SAR analyses
2. Studies to quantify the effects of sampling design and measurement accuracy, frequency, and resolution on the ability to reduce uncertainties in global above-ground biomass and changes in carbon stocks for lidar-only, lidar-SAR, InSAR-only, and combined observations
3. Develop new algorithms for lidar-InSAR fusion (none currently exist) to estimate structure and biomass
4. Studies to understand how the 3-D InSAR vegetation structure data will be used in models

Thus, immediate studies using existing satellite data such as ALOS for L-band inteferometric data, together with lidar data from ICESat, and possibly Calipso, data as well as aircraft radar data from AIRSAR or UAVSAR and lidar data from LVIS, all acquired over well-characterized sites should be conducted.

Cryospheric science. The DESDynI mission's short repeat interval determination of accurate spatial patterns of a number of cryospheric phenomena, such as variable ice flow, localized surface subsidence on glaciers or permafrost, ice sheet grounding line location, advance, and retreat, meteorologically-crucial phenomena such as accumulation/ablation and densification, and patterns of sea ice deformation and export, will enable new approaches to understanding the changing ice cover on Earth that are not permitted with past, existing or approved missions. The challenges that remain in order to reach cryospheric research goals for the DESDynI mission can be categorized as:

1. Studies related to instrument and measurement quality: impacts of baseline-related decorrelation at L-band over firn, trade-offs in repeat interval period versus temporal decorrelation, and development of techniques for using multiple interferograms to refine measurements in low signal to noise regions and for using multiple interferograms of rapid events not acquired simultaneously; trade-offs in repeat interval period versus the detectability of subsidence and grounding line migration on the fastest and most relevant (to mass balance) glaciers and ice streams
2. Use of these refined time series of displacement to improve our understanding of processes, including field measurement and model studies of the ocean-atmosphere-ice interactions that are leading to change, focused by the new views of these systems that the DESDynI InSAR will provide, tools for data assimilation in numerical models of ice sheet flow to improve model parameterization, detailed modeling of physical controls on fast flow and more accurate determinations of boundary conditions
3. Evaluation of the proposed lidar sensor's pointing knowledge, swath geometry ability to repeat measurements, continuous sampling footprint/resolution, atmospheric impacts, and estimated shot/laser lifetime in the proposed 600 km altitude, ±83 latitude coverage, and sun synchronous orbit are essential. Some knowledge of cloud conditions likely to be faced can be derived from ICESat-1 data and coverage of the dynamic ice sheet margins and changing smaller ice masses can be readily determined.
4. Integration of the detailed global picture of cryospheric interactions with the Earth's

climate system to provide improved estimates of future climate change directions

There is a long history of C-band InSAR measurements of ice velocities on the ice sheets of Antarctic (Goldstein et al., 1993; Rignot, 1998; Joughin et al., 1999), and Greenland (Joughin et al., 1995; Rignot et al., 1995; Kwok and Fahenstock, 1996), as well as mountain glaciers (Rignot et al., 1996; Vachon et al., 1996; Fatland and Lingle, 1998). There have been limited studies of L-band on ice sheets and glaciers because until recently the only available data sources since SeaSat were SIR-C and JERS-1. The short duration of the Space Shuttle-based SIR-C missions provided studies of mountain glaciers in the Patagonian Icefields (Rignot et al., 1996; Rott et al., 1998; Forster et al., 1999) that indicated higher L-band coherence than at C-band. SIR-C orbital restrictions prevented ice sheet observations. The poor orbit information and restricted distribution of for JERS-1 limited its ice velocity applications to only a few studies (Kimura et al., 2004; Cheng and Xu, 2006) which reported high coherence and produced velocity maps for slow moving Antarctic inland ice at two specific locations.

The recent availability of L-band SAR from PALSAR on JAXA's ALOS satellite provides the opportunity to further test L-band's capabilities and limitations for ice measurements over diverse ice sheet and mountain glacier conditions. For example, the increased penetration depth over C-band can reduce temporal decorrelation by scattering from deeper layers less susceptible to melt or accumulation. However, it is unclear if the greater penetration may also contribute to volume scattering decorrelation and reduced signal-to-noise in small grain-sized dry snow conditions. PALSAR data of the ice sheets from its standard 46-day repeat orbit could be used to address these and other questions. Other questions include determining experimentally the noise equivalent sigma-zero of the darkest areas of snow in Greenland and Antarctica at L-band so that important parts of the ice sheets are not below the noise floor of the radar imaging system. The split spectrum technique proposed for the DESDynI SAR to reduce ionospheric noise could also be tested with PALSAR data of Antarctica and Greenland. A more realistic simulation of the DESDynI mission could be done with PALSAR if it is temporarily placed in an eight-day repeat orbit, possibly near the end of its mission life.

6. International mission synergies

A special session highlighting representatives of several international space agencies, including presentations by the some of these agencies and subsequent discussions during the workshop, suggested that significant opportunities exist for the development of collaborative efforts that would constitute a virtual international SAR constellation that would leverage U.S. investments in the DESDynI mission. Partnerships with international partners could provide significant advantages to the development and scientific return of the DESDynI Mission. Likewise the development of the DESDynI mission could also spur the development of international collaboration on global InSAR satellite systems. Areas for international collaboration include the development and refinement of InSAR processing algorithms, the development of an InSAR data system, and extensions of DESDynI capabilities such as shorter repeat times between observations, wavelength or polarization diverse measurements, and more comprehensive coverage.

Refinement of InSAR processing algorithms: In order to address its scientific objectives, DESDynI will operate at L-Band. However, much like in optical imaging, a truer and more powerful insight into the nature of the Earth system is enabled by multi-spectral InSAR observations. Lower frequencies penetrate deeper into vegetation, ice, and dry soils, providing a stronger and longer lasting correlation over longer time periods. Airborne experiments suggest that lower frequencies offer greater robustness to saturation in the retrieval of biomass. Unfortunately these lower frequencies also tend to offer lower spatial resolution and have a higher susceptibility to ionospheric dynamics. Still, if a European VHF radar is launched within the DESDynI time frame it would be very useful, especially for vegetation biomass measurements. At the other end of the spectrum, several international agencies have launched and are planning SARs that operate at C-Band and X-band. These data, although not ideally suited to the scientific goals of the DESDynI mission, do provide data sets for the development of processing algorithms and preliminary insights into the physics of the Earth System.

Development of an InSAR data system: InSAR data sets address many needs of scientific research, commercial enterprise, and the military. Therefore the scientific community has been motivated, if hard pressed, to develop the databases necessary to conduct high temporal resolution, long duration studies of global tectonic, cryogenic, and ecological change. Recently, NASA in partnership with NSF and USGS have been working to build partnerships with Japan, Canada, and Germany to provide InSAR data to the scientific communities as an outgrowth of the Western North America InSAR (WInSAR) consortium in which the agencies pooled resources to provide data to a collaborative consortium of academic researchers. A similar effort is underway with ESA for access to Envisat ASAR data. The challenge has been that the US has no InSAR in orbit, therefore reciprocity in data sharing has posed problems. Nonetheless a data system is in development through agreements with Canada and Japan for access to the ALOS and Radasat satellites. The objective is a data system that is global in nature modeled after the very successful Global Geodetic Observing System data system. There is a strong belief that ready access to InSAR data will bring an equally strong advance in observational and analysis capability as it did in geodetic science. The availability of DESDynI and its open data system will provide a significant data source that will give impetus to the development of an International SAR Information System. DESDynI is unlikely to be launched within the next 4 years, however the promise of DESDynI could be used to vastly expand access to data from presently orbiting SAR satellites. These data, though not as capable as those projected from DESDynI, will help to extend our knowledge of the Earth system and the refinement of InSAR processing algorithms.

Extension of the DESDynI mission capabilities: Japan, Argentina and Germany have indicated a desire to continue the development of L-Band InSAR missions. Japan has flown two such missions -- JERS-1 and ALOS -- and plans are developing for an ALOS-2. Argentina is developing its SAOCOM satellite as a component of COSMO-Skymed and Germany has indicated a strong desire to participate in an L-Band mission partnership. The space agencies of all three countries have indicated a strong desire to discuss partnerships. These partnerships might include several advantages over the strict DESDynI plans: Radiometric compatibility between sensors, that is operation at the region of the spectrum, would provide significant opportunities such as the ability to fly in formation for the recovery of precision topography, the recovery of variable baselines for the imaging of vegetation, the recovery of surface deformation, the extension of InSAR observations that would extend beyond a single mission's lifetime, and finally high temporal resolution, critically important to disaster management. It is unlikely that DESDynI will be designed for a lifetime longer than 5 years, yet the objectives of disaster management and climate change observations will demand longer operational periods. Therefore intermission compatibility will be essential to the development of a long lived system.

In summary, DESDynI will provide a strong contribution to the development of an international SAR constellation that would address the needs of the scientific community. DESDynI could be leveraged to encourage our international partners to participate in an international data system that allows the free exchange of SAR data, a radiometric compatibility for formation flight and near synoptic global observation, multi-frequency global SAR coverage, and finally an observational capability that would extend beyond the lifetime of any single mission. International collaboration in the development of important Earth observation systems is the objective of the Group on Earth Observation. DESDynI will make NASA a strong partner in the development of an international collaboration on SAR observation that will provide returns well beyond the capability of any single mission.

7. Summary of major conclusions and recommendations

The workshop participants all agreed that there is great enthusiasm for the DESDynI mission concept. The consensus view was that the DESDynI mission as described by the NRC Decadal Survey accurately summarizes and conveys the feeling of multiple science communities that the science objectives are critical to evaluating aspects of the sustainability of human life on Earth and that the proposed mission implementation, including options noted in the Decadal Survey and identified at this workshop, meets the various science objectives presented at the workshop.

The attendees also showed a significant willingness across communities to identify flexibilities in requirements and find compromises or alternatives that satisfy the needs of all three disciplines. Again, the consensus view was that workable compromises appear to exist in the allocation of spacecraft resources and orbital configuration to meet the science goals.

All expressed eagerness to get started on developing this mission, resolving to

-conduct the studies recommended to resolve issues, refine mission attributes, and advance algorithm development

-support NASA in taking the steps to advance DESDynI to formulation

-establish working partnerships to resolve implementation conflicts

-conduct this work in a way that does not impact readiness to proceed

Nonetheless, there are areas of concern that will require continued study. These are:

-*Orbital repeat interval*: 8 days is preferred by Solid Earth and Ice and would enable InSAR uses for vegetation structure. Longer repeats are preferred for ecosystem structure to acquire adequate lidar geographic coverage. Use of a slightly longer repeat with off-nadir lidar pointing might mitigate this issue, with orbits of 12-16 day repeat time.

-*Orbital altitude*: 800 km minimizes atmospheric orbit degradation for InSAR, while a 400 km altitude is optimal for lidar operation. It appears that a compromise altitude of 600 km is possible and would satisfy all scientific objectives.

-*Interferometric operating baseline*: zero length as preferred for the Solid Earth and Ice science, as opposed to multiple nonzero baselines for ecosystem structure. This is probably resolvable with planned baselines of approximately 500-1000 m for some fraction of the mission to be determined.

Several areas require more scientific study. Specific questions that need more information include:

1. What is the time interval before temporal decorrelation of InSAR becomes a factor, for all proposed investigations?

2. Is full polarimetry needed for ecosystem structure, or would HH and HV together be adequate? Can full polarimetry be used by other science disciplines?

3. What is the necessary accuracy of lidar altimetry for ice sheet topography and elevation change studies; does additional detail from smaller continuous footprints in a swath configuration offer advantages for smaller glaciers and ice caps in the sun synchronous coverage?

4. What is an acceptable time lag between lidar and radar measurements of vegetation given that one instrument will be at or close to nadir and the other will be off-nadir?

With the above in mind, the workshop makes the following specific recommendations:

1. *Mission configuration scenarios*. Conduct studies to assess the options proposed to resolve/minimize the apparent incompatibilities among requirements for baselines, orbit, altitude and coverage including developing a better understanding of how to compensate for non-nadir lidar pointing to fill gaps in coverage.

2. *Spacecraft configuration:* Examine deploying the InSAR and lidar on separate platforms – each in its optimal orbit. Also look at possibility of integrating DESDynI lidar with ICESat-II.

3. *Ecosystem structure coverage*: Develop a better understanding of how non-nadir lidar pointing can be used to fill gaps and increase the spatial density of coverage for vegetation structure while maintaining the necessary accuracy.

4. *Algorithm development*. Advance the development of algorithms for lidar-radar fusion and lidar-InSAR fusion to estimate canopy structure, dynamics and biomass. Analysis of the combination of lidar and radar data is reasonably understood at present, while the potential of lidar-InSAR techniques is high but not yet fully developed. Both approaches require further development.

5. *Advanced analysis*. Develop and demonstrate the ability to derive vegetation height and estimate biomass from InSAR measurements across a range of the Earth's biomes. Acquire new data to test and explore lidar-InSAR capabilities for vegetation structure and to be used in developing data fusion algorithms.

6. *Setting mission requirements*. Formalize the specific scientific requirements necessary to move the mission to implementation

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Appendix A. Additional science opportunities

InSAR is an excellent way to quantify surface subsidence associated with extraction of ground water or natural gas and petroleum. Extraction in excess of natural recharge leads to loss of reservoir pressure, and depending on reservoir characteristics and rate of extraction, can lead to permanent loss of reservoir capacity. The spatially detailed InSAR images lead to greatly improved understanding of reservoir structure and extent, while time series of subsidence from multiple SAR passes allows improved management of reservoir capacity.

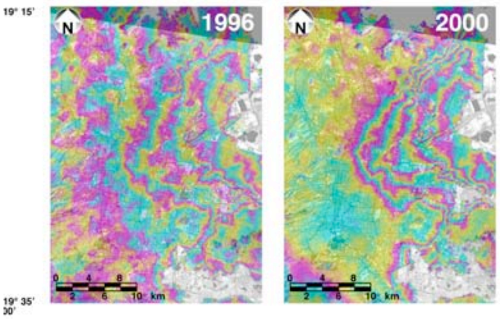

Figure A1. Interferograms of Mexico City spanning 3 and 6 months respectively in 1996 and 2000. The 6 month interferogram shows up to 15 cm of subsidence, equivalent to a maximum subsidence rate of 30 cm/yr near the city center. From Cabral et al., 2007.

In addition to the primary DESDynI science applications discussed in the body of this report, an L-Band polarimetric InSAR in a repeat orbit can provide many other kinds of environmental information, not obtainable by any other type of remote sensing, including currently available SAR systems (InSAR Workshop Summary Report, 2004). This versatility provides many opportunities for unique scientific investigations as well as valuable societal benefits.

In the field of oceanography, DESDynI SAR ocean measurements will contribute to answering the following questions:

1. How does the ocean surface behave on a global, long-term scale and how does it drive the climate?
2. How can we better predict hazards at sea?
3. What is the nature of physical processes in coastal, frontal, and marginal ice zones and how do they affect biological processes?

An L-Band SAR instrument can provide valuable information for improvement of ocean forecasting, management of ocean ecosystems and hazard response. Particular measurements that can be made by DESDynI include:

1. High-resolution (sub kilometer) wind measurements in coastal regions, marginal ice zones and in straits, channels, and lakes. DESDynI measurements offer a unique opportunity for comparison with the km-scale, high temporal revisit measurements made by the L-Band scatterometer on the SMAP mission.
2. Storm morphology (e.g., for hurricanes and polar mesoscale cyclones) for improved weather forecasting. Since L-band SAR pulses have little or no attenuation by rain, improved storm surface wind measurements may be possible. DESDynI and SMAP measurements in combination again offer a unique capability.

Other parameters can be derived from currently available SARs, but would benefit significantly from frequent, systematic observations by DESDynI, especially in the territorial waters of the US. These include:

1. Wave spectra and significant wave height measurements for marine safety.
2. Oil spill location, extent, and movement for protection of sensitive wetlands.
3. Post-hurricane oil-platform and coastal-change detection for marine transportation safely.
4. Location of current systems, convergence zones, upwelling, river and runoff plumes, internal waves, and eddies for pollution/marine-debris monitoring and ocean ecosystems studies. (Jackson and Apel, 2004)

In the field of hydrology, an L-band polarimetric InSAR can provide high-resolution data to address key questions relating to the hydrologic cycle:

1. How do groundwater, surface water, soil moisture, and snowpack contribute to the global freshwater budget and how do natural and anthropogenic processes redistribute water in both space and time?
2. How does the land surface vary with time and how does it influence the dynamic water supply?
3. How can remote sensing technology improve water resource management and hydrological hazard mitigation associated with flooding and land subsidence?

DESDynI's unique contributions to address these questions include:

1. High-resolution, localized measurements of soil moisture for bare soil and low vegetation cover at the hectare scale, which is easily related to land cover maps. These will complement the global, km-scale, high temporal repeat measurements provided by the SMAP mission.
2. Valuable and timely information on the location and extent of coastal and river flooding, through dense cloud cover and heavy rain, and beneath tree canopies.
3. Characterization of aquifers and groundwater storage – L-Band InSAR data can define areas of deformation caused by fluid injection and withdrawal.
4. Assessment of levee stability, a problem demonstrated in New Orleans as a result of Katrina. In addition to the New Orleans area, other areas, such as the Sacramento River Delta have levees that are degrading dangerously.
5. The seasonal build-up of snowpack spatial extent for use in runoff estimates.

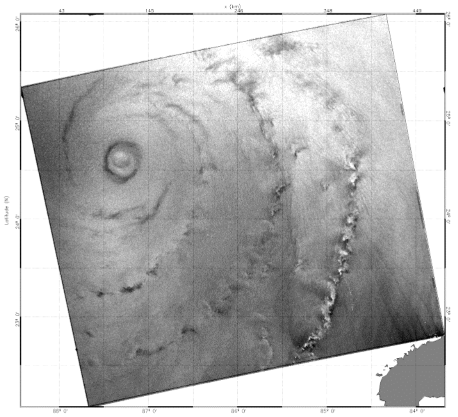
Hurricane Rita 09-22-2005 03:44:55 GMT

Figure A2. Envisat SAR backscatter image of Hurricane Rita 09/22/2005 at 03:44 UT located just north of Cuba in the Gulf of Mexico. Detailed eye structure, rain-band/convection-cell location, and waves are imaged.

The DESDynI L-Band SAR provides untapped potential to map fine structure in the ionosphere in polar regions that are sparsely instrumented with ground-based GPS measurements via two approaches:

1. Polarimetric SAR to estimate the Faraday rotation imposed on the radar signal as it propagates through the atmosphere.
2. A split-spectrum approach to examine the phase differential between two frequencies.

Both can be used to generate high-resolution (sub-km scale), 2-D maps of Total Electron Content (TEC) in the area of the ionosphere seen by the radar line-of-sight as DESDynI passes over. Initial results from the Japanese PALSAR system indicate that these measurements will have the same precision (about 1 TECU) as GPS-based measurements. Using these techniques DESDynI will measure the fine structure of ionospheric irregularities and traveling ionospheric disturbances on global scales, the latter generated by gravity waves. During relatively quiet periods of ionospheric activity, DESDynI will allow detailed study of the variations in the Earth's magnetic field in the polar region.

Appendix B. List of Participants

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