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

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

1. INTRODUCTION

Earth’s land surface is constantly changing and interacting with its interior and atmosphere. In response to the interior, plate tectonics deform the surface, causing earthquakes, volcanoes, mountain building, and erosion, which includes landslides. These events can be violent and damaging. Forests, growing on the land surface, store carbon, which can be released into our atmosphere through logging and burning. Our ice sheets, sea ice, and glaciers are key indicators of our climate and have been undergoing dramatic changes. These land surface processes can be characterized and monitored from space using Synthetic Aperture Radar (SAR) and Light Detection and Ranging (lidar). In 2007, a mission to measure changes in land, ice, and vegetation structure, called DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice), was recommended by the National Research Council Committee on Earth Science and Applications from Space [1]. DESDynI consists of an L-band SAR designed to operate as an interferometric SAR (InSAR) and a multi-beam lidar for understanding natural hazards, carbon balance, forest use, and climate change.

1. SCIENCE

DESDynI will be the first mission to systematically and globally study the solid Earth, the ice masses, and ecosystems all of which are sparsely sampled at present. The primary mission objectives for DESDynI are to:

1. Determine the likelihood of earthquakes, volcanic eruptions, and landslides
2. Characterize habitat structure for biodiversity assessments
3. Predict the response of ice masses to climate change and impact on sea level
4. Understand the behavior of subsurface reservoirs

Precise measurement of surface deformation derived from DESDynI’s InSAR coupled with models can improve assessment of risk from natural hazards, which ultimately can minimize loss of life and destruction of property. US annualized losses from earthquakes are $4.4B/yr, yet current hazard maps have an outlook of 30–50 years over hundreds of square kilometers. Volcanic eruptions destroy cities and towns, eject ash clouds that disrupt air travel, and disrupt regional agriculture. Sea level change, land subsidence, and landslides are becoming more problematic with development in high-risk areas. Forecasting of earthquakes,
The rate of increasing CO$_2$ in the atmosphere over the past century is unprecedented for at least over the last 150,000 years. Terrestrial ecosystems, largely in the form of forests, take up and store carbon, thus changes in these systems impact the global carbon budget and the amount of the greenhouse gases CO$_2$ and CH$_4$ in the atmosphere. A major source of uncertainty in global carbon budgets derives from large errors in the current estimate of carbon storage in forest vegetation. DESDynI will be used to measure vegetation structure to understand changes and trends in terrestrial ecosystems and their functioning as carbon sources and sinks, and characterize and quantify changes resulting from disturbance and recovery. Vegetation height, vertical profiles, and disturbance recovery patterns are also required to characterize habitat and assess ecosystem health. These parameters can be used to couple feedback effects between terrestrial ecosystems and the atmosphere in general circulation models (GCMS). USDA Forest Service fire spread models require structural inputs such as canopy height, canopy cover, vertical biomass profiles, and canopy base height. The recent destructive fires of 2007 in southern California highlight the need for improved fire spread models for forest fire preparedness and mitigation.

Ice sheets and glaciers are experiencing dramatic changes that have the potential to raise sea level substantially in the coming decades. Flow rates of outlet glaciers around many parts of Greenland and Antarctica have increased significantly, more than doubling in some cases. These accelerations and increased melt rates have been causing the glaciers and ice sheet margins to thin by as much as tens of meters per year as their ice is lost to the surrounding seas. These phenomena raise the question of ice sheet stability and the potential of these ice sheets to contribute to relatively rapid rises in sea level. As a result, the authors of the Decadal Survey identified as their highest-priority questions, “Will there be a catastrophic collapse of the major ice sheets, including Greenland and West Antarctica, and if so, how rapidly will that occur? What will be the time patterns of sea level rise as a result?” DESDynI will provide comprehensive observations of ice sheet and glacier surface dynamics, which are directly related to their stability as a response to the changing climate. Sea ice is another component of the Earth system that is changing extremely rapidly and in ways that can affect climate worldwide. Comprehensive observations of sea ice extent, transport, concentration, and thickness, derived from multiple satellite observations, including DESDynI will improve our understanding of the interactions between the ice, ocean, and atmosphere, and their future behavior.

The science objectives of DESDynI for solid Earth, cryosphere, and ecosystems result in a number of requirements for measurement of solid Earth and ice sheet surface deformation, forest height and structure, and ice thickness and kinematics.

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

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

The solid Earth science objectives for the DESDynI mission are to

1. Characterize the nature of deformation at plate boundaries and the implications for earthquake hazards
2. Characterize how magmatic systems evolve to understand under what conditions volcanoes erupt
3. Characterize landslides and detect pre-slip
4. Characterize aquifer, hydrocarbon, and CO$_2$ reservoirs withdrawal and recharge

This is accomplished by measuring surface deformation and surface disruption [2]. Measurement of surface deformation is used to discriminate between faults and assign potential hazard and to infer the volume of magma in the chamber and potential hazards. It requires 3-dimensional (vector) global coverage of actively deforming areas with 100 m resolution imagery accurate to 5% of the rate of the deforming zone or to 1 mm/yr. 200 km width imagery across the deforming boundary is required as is unaliased temporal sampling with week-timescale measurements, particularly immediately following an event. Measurement of surface disruption with 20 m resolution over a 400 m zone across the fault is required to infer the mechanical properties of the earthquake fault zone. Measurement of surface disruption at 20 m resolution throughout the area of eruption is required to infer the volume of magma released.

DESDynI will provide globally consistent and spatially resolved estimates of vegetation height and structure from which aboveground biomass and ecosystem function can be derived [3, 4, 5]. These structure and biomass estimates will
be used to characterize and quantify changes in terrestrial carbon sources and sinks resulting from disturbance and recovery. They will also be used to characterize forest structure for biodiversity assessments. Ecosystems science objectives for DESDynI are to

1. Characterize global distribution of aboveground vegetation biomass
2. Quantify Changes in terrestrial sources and sinks of carbon resulting from disturbance and recovery (net terrestrial carbon flux)
3. Characterize habitat structure for biodiversity assessments

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

Developing globally consistent and spatially resolved estimates of above ground biomass and carbon stocks requires observation of the global vegetated cover with 100 m spatial resolution accurate to 10 Mg/hectare or to within 20% at least once per year during the growing season [6]. Understanding changes and trends in terrestrial ecosystems and their functioning as carbon sources and sinks requires observation of global vegetated cover with 100 m spatial resolution. Measurements must be accurate to 2–4 Mg/ha/year or to within 20% of the change and must be made monthly to seasonally over the life of the mission, which must have a minimum duration of 5 years. Characterizing habitat structure for biodiversity assessments requires a horizontal resolution of better than 25 m and a vertical resolution of 2–3 m of the canopy profile. Achieving these measurement goals requires the combination of the multibeam full-waveform Lidar with radar polarimetry.

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

Sea ice is another component of the Earth system that is changing rapidly and in ways that can affect climate worldwide. Ice cover in both the Arctic and Antarctic play a critical role in the global climate system by modulating the exchange of moisture and energy between the ocean and the atmosphere, and influencing oceanic and atmospheric circulation. In the Arctic, the ice cover has been diminishing substantially, while in the Antarctic there have not been substantial changes. Understanding the interactions among the ice, ocean, and atmosphere, and their future behavior requires comprehensive observations of sea ice extent, concentration, and thickness. These are best derived from multiple satellite observations from existing and future missions such as DESDynI, AMSR-E, SSM/I, Cryosat, ICESat, and ICESat-II.

InSAR on DESDynI will augment those observations by providing detailed information on the mechanisms of deformation and transport of polar sea ice cover. This information can improve structural models of sea ice behavior to help understand the interactions among the ice, ocean, and atmosphere, and how they may behave in the future. If the Lidar is designed with sufficient precision, it can be used to provide ice thickness information that is critical to understanding its present and future behavior. Understanding our cryosphere requires measurement of surface deformation as well as thickness of sea ice. The science objectives are to

1. Quantify the interactions among ice masses, oceans, and the solid Earth and their implications for sea level change [2]
2. Quantify the interactions of glaciers with the atmosphere
3. Quantify sea ice mass balance and how it is changing

This requires global coverage of ice masses and the measurement of surface displacement to quantify ice fluxes in order to infer global mass balance. Surface displacements must be measured on rapidly moving ice masses with horizontal velocities accurate to the greater of 2 m/yr or 10% of the total velocity. Vertical subsidence must be measured to 5 mm. Weekly observations are required to quantify temporal changes at 100 m resolution.

The second requirement is to quantify sea ice mass balance and how it is changing over the Arctic and Southern Oceans at inter-annual timescales over a minimum of 5 years. From this follows the need to 1) quantify changes in sea ice thickness by measuring sea ice freeboard to a vertical accuracy of 15 cm with a spatial resolution of 25 m, and 2) quantify how sea ice motion and circulation are changing at kilometer scales with 100 m resolution. The latter requires daily time scales to provide uninterrupted time series to cover advance and retreat of seasonal/perennial ice cover over a minimum of 5 years.
3. INSTRUMENTS

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

The DESDynI radar instrument is an L-band (1.2-GHz) synthetic aperture radar (SAR) system with multiple polarizations that can be operated in several modes. The radar instrument will be operated as repeat pass InSAR to measure sub-centimeter changes in surface deformation and ice sheet dynamics. The radar instrument can also be used to measure ecosystem structure using non-zero baseline interferometry, while radar backscatter at different polarizations will be used to estimate vegetation structure, biomass, and woody components of forests.

The DESDynI lidar instrument is a multiple-beam lidar operating in the infrared (about 1,064 nm) with a proposed spatial resolution of ~25 meters and forest canopy height accuracy of 1 m. The multi-beam laser altimeter accurately measures the distance between the canopy top and bottom elevation in forests. It also measures the vertical distribution of intercepted surfaces and distribution of vegetation components within the vertical distribution. The smaller lidar footprint resolution reduces forest height errors caused by topography and the multiple beams are designed to maximize the sampling density required to improve accuracy of global biomass estimates.

Forest growth, budding, and dropping of leaves occur on fairly short timescales. Flying DESDynI instruments near-simultaneously will provide a capability for fusing the InSAR and Lidar data to provide a robust, validated measure of ecosystem structure. The lidar can also be used to measure the vertical change of disrupted surfaces from earthquakes, volcanoes, and landslides. The mission takes advantage of the precision and directness of the lidar with the global spatial coverage of the radar.

4. CONCLUSIONS

DESDynI will be the first mission to collectively study the solid Earth, the ice masses, and ecosystems systematically and globally. It will characterize processes, frequent measurements to understand temporal changes, and a five-year duration to estimate long-term trends and determine subtle rates. It uses L-band interferometric synthetic aperture radar and multibeam Lidar to achieve its objectives, which are to characterize the effects of changing climate and land use on species habitats and atmospheric CO$_2$, predict the response of ice sheets to climate change and impact on sea level and forecast the likelihood of earthquakes, volcanic eruptions, and landslide. DESDynI will achieve these goals by measuring the height and structure of forests, changes in carbon storage and vegetation, ice sheet deformation and dynamics, and changes in the Earth’s surface and the movement of magma. Existing related systems provide only opportunistic science. Of all of the recommended decadal survey missions DESDynI meets the needs of the largest portion of the science community with numerous applications including earthquakes, volcanoes, landslides, ice sheets, sea ice, glaciers, and ecosystems.

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REFERENCES


