DESDynI – Deformation, Ecosystem Structure and Dynamics of Ice

MAKING THE MOST OF DESDYNI – AN OVERVIEW OF THE PROPOSED MISSION

Paul A. Rosen, Howard Eisen, Yuhsyen Shen, Scott Hensley, Scott Shaffer, Louise Veilleux, Jet Propulsion Laboratory
Jon Ranson, André Dress, Bryan Blair, Scott Luthcke, Goddard Space Flight Center
Ralph Dubayah, University of Maryland
Bradford H. Hager, Massachusetts Institute of Technology
Ian Joughin, APL, University of Washington

IGARSS 2011, Vancouver, Canada
July 27, 2011

© 2011 California Institute of Technology. Government sponsorship acknowledged
DESDynI Science

Recommended by the NRC Decadal Survey for near-term launch to address important scientific questions of high societal impact:
- What drives the changes in ice masses and how does it relate to the climate?
- How are Earth’s carbon cycle and ecosystems changing, and what are the consequences?
- How do we manage the changing landscape caused by the massive release of energy of earthquakes and volcanoes?

Planned by NASA as one of the following 4 Decadal Survey TIER 1 Missions
- SMAP
- ICESat-II
- DESDynI
- CLARREO

Ice sheets and sea level
- Will there be catastrophic collapse of the major ice sheets, including Greenland and West Antarctic and, if so, how rapidly will this occur?
- What will be the time patterns of sea level rise as a result?

Changes in ecosystem structure and biomass
- How does climate change affect the carbon cycle?
- How does land use affect the carbon cycle and biodiversity?
- What are the effects of disturbance on productivity, carbon, and other ecosystem functions and services?
- What are the management opportunities for minimizing disruption in the carbon cycle?

Extreme events, including earthquakes and volcanic eruptions
- Are major fault systems nearing release of stress via strong earthquakes?
- Can we predict the future eruptions of volcanoes?
The DESDynI Working Group is managed by the DESDynI Steering Committee representing the three principal disciplines identified by the Decadal Survey – Solid Earth, Ecosystem Structure, Cryospheric Science – and ESDIS, ESMPO.

- The Steering Committee oversees and coordinates the activities of three groups.
- Mission Design Study Group – Includes but not limited to center design and project scientists.
- Interagency/International Coordination Group – Develops potential partnerships that could benefit DESDynI.
- DESDynI Science Study Group – Three Co-chairs provide scientific guidance and coordination.
DESDynI Science Study Group Membership

• Ian Joughin, Applied Physics Lab, U Washington (Dynamics of Ice)
  – Anthony Arendt, Geophysical Institute, U Alaska
  – Mark Fahnestock, U New Hampshire
  – Ronald Kwok, JPL
  – Eric Rignot, UC Irvine
  – Christopher Shuman, U Maryland-Baltimore County
  – Ben Smith, Applied Physics Lab, U Washington

• Ralph Dubayah, U Maryland (Ecosystem Structure)
  – Kathleen Bergen, U Michigan
  – Richard Houghton, Woods Hole Research Center
  – Josef Kellindorfer, Woods Hole Research Center
  – Jon Ranson, GSFC
  – Sassan Saatchi, JPL
  – Hank Shugart, U Virginia

• Bradford H. Hager, MIT (Deformation/Solid Earth)
  – Tim Dixon, U Miami
  – Andrea Donnellan, JPL
  – David Harding, GSFC
  – Rowena Lohman, Cornell University
  – Jeanne Sauber, GSFC
  – Howard Zebker, Stanford University
Proposed DESDynI Science to Implementation

Ecosystem Structure
- Biomass, Vegetation Structure, Effects of changing climate on habitats and CO₂, disturbance

Cryosphere
- Ice velocity, thickness
- Response of ice sheets to climate change & sea level rise

Solid Earth
- Surface Deformation
- Geo-Hazards
- Water Resource Management

L-band Polarimetric SAR
- 91-day repeat
- ~370 km orbit
- 25 m spot
- 5 beams

Multibeam Profiling LIDAR
- 13 day repeat
- ~600 km orbit
- 250-500 m orbit control
- 220 km swath
- Full resolution over swath
- 5, 20+5, 40, 80 MHz modes
  - SP, DP, QQP, QP modes

Two spacecraft not at same scale
Proposed DESDynI Lidar Mission

- Lidar Multi-Beam Sampling Provides:
  - Global, direct measurements of vegetation structure
  - Surface topography of land, water, and ice.
Proposed DESDynI SAR Concept

- 3 primary modes:
  - Solid earth deformation, ice sheets and glaciers: Single pol (H or V)
  - Ecosystem Structure: Quad pol
  - Sea-ice: Low BW single pol

- Data acquired Left or Right of spacecraft track, ascending and descending

- Wide swath in all modes allows for 13 day repeat with overlap at equator (2-5 passes over a site depending upon latitude)
- Coverage is limited by downlink bandwidth and selection of mode
Dynamics of Ice: Primary Goal and Science Objectives

Characterize response of polar ice sheets to climate change

Ice dynamics: predictive models of sea level rise
- flow processes and rheology
- grounding line change
- flux gates
- boundary conditions

Sea ice dynamics: coupling to ocean and atmosphere
- motion and export
- thickness and volume
- inputs to GCM/ocean models
Despite spare spatial and sporadic temporal sampling, existing SAR data reveal large variations in glacier flow. **DESDynI would provide fine temporal sampling of all rapidly evolving outlet glaciers and ice streams.**
Near simultaneous observations of thickness (lidar) and ice deformation (SAR) would resolve the contribution of dynamics and thermodynamics to the distribution of ice thickness - needed inputs for global model initialization and validation.
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Requirements</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenland/Antarctic Ice Sheet velocities (Winter)</td>
<td>Slow ice: 1 m/yr, 100 m res</td>
<td>Radar, In winter, 3-D</td>
</tr>
<tr>
<td></td>
<td>Fast ice: 5 m/yr, 500 m res</td>
<td></td>
</tr>
<tr>
<td>Grounded margins Ice Sheet velocities</td>
<td>5 m/yr, 500 m res</td>
<td>Radar, All year, 3-D</td>
</tr>
<tr>
<td>Greenland/Antarctic Ice Sheet elevations</td>
<td>1 m, 1000 m res</td>
<td>Lidar, All year, height</td>
</tr>
<tr>
<td>Greenland/Antarctic Ice Sheet elevation change</td>
<td>1 m/yr, 2500 m res</td>
<td>Lidar, All year, dh/dt</td>
</tr>
<tr>
<td>Mountain Glaciers velocities and elevation</td>
<td>As observation resources permit</td>
<td>Radar/Lidar, Opportunistic</td>
</tr>
<tr>
<td>Arctic and Antarctic Sea Ice thickness</td>
<td>0.6 m, 25 km res</td>
<td>Lidar</td>
</tr>
<tr>
<td>Arctic and <em>Antarctic</em> Sea Ice velocities</td>
<td>100 m/day, 5 km res</td>
<td>Radar, All year, 2-D</td>
</tr>
</tbody>
</table>
Lidar 2-yr mission surface elevation & change requirements

Signal recovered to 7.4 cm (1σ), or ~3% of the signal variance.

<table>
<thead>
<tr>
<th>Mission Configuration and data used</th>
<th>Spatial Resolution (km X km)</th>
<th>2 Year Trends (cm/yr)</th>
<th>1 Year Trends (cm/yr)</th>
<th>6 month change (cm)</th>
<th>No. of Obs.</th>
<th>Post-fit Obs. Residual (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 50% random pass loss from clouds unless otherwise noted.</td>
<td>2.5</td>
<td>71.2</td>
<td></td>
<td></td>
<td>27</td>
<td>1.18</td>
</tr>
<tr>
<td>2. 30 m along-track sampling unless otherwise noted.</td>
<td>5</td>
<td>21.4</td>
<td>54.9</td>
<td></td>
<td>83</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4.3</td>
<td>11.7</td>
<td>16.8</td>
<td>482</td>
<td>1.66</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3.9</td>
<td>8.9</td>
<td>12.4</td>
<td>2447</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Data acquired from a 2-yr mission.

Can further optimize sampling with pointing control.
• Interferometrically derived displacement, with errors:

\[ d_{LOS} = \frac{\lambda}{4\pi} \left( \Delta \phi_{\text{flat}} + \frac{B_z}{\rho_0 \sin \theta_0} z \right) + n_{SNR} + n_{\text{tropo}} + n_{\text{iono}} + n_{\text{surf}} \]

including topography and baseline errors, propagation and surface effects

• Errors are broken out in the requirements flow
  
  – SNR/MNR
  – Phase error
  – Geometric Correlation
  – Temporal Correlation
  – Volumetric Correlation
  – Geolocation Error
  – Digital Elevation Error
  – Ionosphere
  – Troposphere
  – Surface changes
  – Baseline knowledge
  – Rotational Correlation

DESDynI is proposed to reduce these errors to meet challenging measurement requirements

- Small baselines to minimize topographic error and geometric decorrelation effects
- L-band wavelength to minimize temporal decorrelation effects
- Many samples over time to minimize propagation media effects
Meeting Ice Sheet/Glacier Velocity Requirements

- For slow ice, use interferometry
- For fast ice, use speckle tracking

- Under fairly conservative assumptions given, and previous formulas, requirements can be met:
  - Fast ice (Req: 5 m/yr or greater)
    - ✓ 1.3 m/yr
  - Slow ice (Req: 1 m/yr or greater)
    - ✓ 0.9 m/yr

✓ Vector measurements through ascending/descending, right/left in winter

- To be confirmed:
  - That correlations are supported in over 80% of ice regions (fastest moving and dark areas)

### Assumptions

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar Mode</td>
<td>Single-Pol 20+5MHz</td>
</tr>
<tr>
<td>Interferogram</td>
<td>13 days</td>
</tr>
<tr>
<td>Observations</td>
<td>Asc &amp; Des; Winter</td>
</tr>
<tr>
<td>Wavelength</td>
<td>24 cm</td>
</tr>
<tr>
<td>Correlation+</td>
<td>0.6 (fast) 0.4 (slow)</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>5 mm</td>
</tr>
<tr>
<td>Product Resolution</td>
<td>100 m x 100 m - slow</td>
</tr>
<tr>
<td></td>
<td>500 m x 500 m - fast</td>
</tr>
<tr>
<td>Pointing</td>
<td>Left &amp; right</td>
</tr>
<tr>
<td>Number of obs</td>
<td>4 per direction</td>
</tr>
<tr>
<td>Matching resolution</td>
<td>100</td>
</tr>
</tbody>
</table>

* Includes SNR, Temp, Geom, Vol Correlations
Understand the physics of earthquakes and volcanoes, apply to mitigation of natural hazards, monitor/manage water and hydrocarbon extraction and use

- Tectonic/fault processes
- Magmatic processes
- Manage water use/storage and hydrocarbon extraction, CO₂ sequestration, landslides

Time series interferograms show onset of activity and how it progresses toward eruption
Frequent Temporal Sampling to Understand Earthquake Mechanisms

Variations in interseismic, coseismic, and postseismic displacements are visible on a wide range of time scales. Disentangling coseismic from postseismic displacements, and observing postseismic deformation requires frequent temporal sampling.

GPS East (red) and North (blue) position time series at continuously operating site CARH centered on the time of the September, 2004 Mw 6.0 Parkfield earthquake. A linear trend has been subtracted from each component.
DES DynI would greatly spatial and temporal coverage of deformation globally.

- EarthScope covers the Western US with ~1000 GPS stations at km to 10’s of km spacing.
- Most detailed study of a plate boundary to date.
- Map at left shows PBO Western US permanent stations.

- But DES DynI would cover the globe with ~$10^{11}$ pixels at 10’s of m spacing.
  - Temporal evolution with nearly contiguous coverage at fine resolution.
- Would improve our models of earthquakes/volcanoes/hazards many-fold.

A typical event interferogram rich with information about the subsurface.
## Deformation Baseline Requirements at MCR

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Requirements</th>
<th>Coverage</th>
</tr>
</thead>
</table>
| Deformation of Events (co-seismic, post-seismic, | Near weekly: $\leq 2 \sqrt{L} \text{ mm}$  
Yearly: $\leq 0.5 \sqrt{L} \text{ mm}$,  
0.5 km $< L < 50$ km,  
$L = \text{length scale in km}$.  
Resolution: 10-20 m | Radar, Every Cycle, 2-D                                                                                  |
| volcanoes, landslide, aquifers, etc)             |                                                                                                                                                                                                              |                                                                          |
| Deformation Rates (interseismic velocities)      | $\leq 0.2 \sqrt{L} \text{ mm/yr}$,  
0.5 km $< L < 50$ km,  
$L = \text{length scale in km}$.  
Resolution $\leq 1000$ m | Radar, Every cycle, 2-D,  
*All high strain rate areas shown*                                                                                     |                                                                          |
| Global Co-seismic Deformation                     | $< 5 \sqrt{L} \text{ mm}$,  
0.5 km $< L < 50$ km,  
$L = \text{length scale in km}$.  
Resolutions $\leq 100$ m  
Applies for earthquakes of magnitude $> 7$ at depths $< 50$ km. | Radar, 2 per year, 2-D                                                                                                   |
# Interseismic Requirements over Scale

## Assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar Mode</td>
<td>Single-Pol 20+5MHz</td>
</tr>
<tr>
<td>Interferogram (plus stacking)</td>
<td>600 days</td>
</tr>
<tr>
<td>Observations</td>
<td>Asc &amp; Des</td>
</tr>
<tr>
<td>Wavelength</td>
<td>24 cm</td>
</tr>
<tr>
<td>Correlation(^+)</td>
<td>(\gamma_0 e^{-t/T}, T = 200) days ((\gamma &lt; 0.1) per interferogram)</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>20 mm</td>
</tr>
<tr>
<td>Product Resolution</td>
<td>1000 m x 1000 m</td>
</tr>
<tr>
<td>Pointing</td>
<td>Left or Right</td>
</tr>
<tr>
<td>Stacking Period</td>
<td>3 years</td>
</tr>
</tbody>
</table>

\(^{+}\) \(\gamma_0\) includes SNR, Geom, Vol Correlations

## Rate Error vs Length Scale

- 2-D vector measurements through ascending/descending, right or left
- Margin introduced through additional data not considered
  - Polarimetric data
  - Overlap due to orbit convergence

\(0\) mm: \(4\) mm: \(8\) mm: \(12\) mm: \(16\) mm: \(20\) mm
Meeting DESDynI Deformation Requirements

- For targeted phenomena (L1.1), use single or short period interferograms in short stacks
- For interseismic deformation (L1.2), use long period interferograms over mission duration in long stacks.

Under stated assumptions given, and previous formulas, requirements can be met:
- L1.1a (Req: 14 mm at 50 km scale)
  - 14 mm
- L1.1b (Req: 3.5 mm at 50 km scale in 1 year)
  - 2.7 mm
- L1.2 (Req: 1.4 mm/yr at 50 km scale)
  - 1.4 mm/yr

To be confirmed in Phase A:
- That accuracies are supported in over 80% of deformation regions (correlations and atmosphere model improvements)

**Assumptions**

<table>
<thead>
<tr>
<th>Radar Mode</th>
<th>Single-Pol 20+5MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interferogram</td>
<td>L1.1: 13 days</td>
</tr>
<tr>
<td></td>
<td>L1.2: 600 days</td>
</tr>
<tr>
<td>Observations</td>
<td>Asc &amp; Des</td>
</tr>
<tr>
<td>Wavelength</td>
<td>24 cm</td>
</tr>
<tr>
<td>Correlation*</td>
<td>$\gamma_0 e^{-\frac{T}{T}}$, T = 200 days</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>20 mm</td>
</tr>
<tr>
<td>Product Resolution</td>
<td>L1.1: 20 m x 20 m</td>
</tr>
<tr>
<td></td>
<td>L1.2: 1000 m x 1000 m</td>
</tr>
<tr>
<td>Pointing</td>
<td>Left or Right</td>
</tr>
<tr>
<td>Stacking Period</td>
<td>L1.1: 1 year</td>
</tr>
<tr>
<td></td>
<td>L1.2: 3 years</td>
</tr>
</tbody>
</table>

* $\gamma_0$ includes SNR, Geom, Vol Correlations
Ecosystem Structure: Primary Goal and Science Objectives

Characterize the effects of changing climate and land use on terrestrial carbon cycle, atmospheric CO₂, and species habitats

- Characterize global distribution of aboveground vegetation biomass and carbon
- Quantify changes in terrestrial biomass and carbon resulting from disturbance and recovery
- Characterize habitat structure for biodiversity assessments
Global Carbon Modeling

- Carbon model data and modeling scales must be near the scale of disturbance and environmental gradients (about 1 – 10 ha)
  - Coarse forest structure inputs in carbon models produce vastly inaccurate fluxes compared to proposed DESDynI measurement scales

**Error in Carbon Flux**
(as resolution decreases from tree scale to 10 km)

- DESDynI structure data would revolutionize carbon modeling by providing inputs at fine spatial scales
- Accurate, global forest structure inputs do not exist, even at 10 km resolution, resulting in large model errors

<table>
<thead>
<tr>
<th>Measurement Grid Cell Resolution</th>
<th>Flux Error [MgC/ha/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hectare</td>
<td>1.6, 8</td>
</tr>
<tr>
<td>0.5 km x 0.5 km</td>
<td>10.12</td>
</tr>
<tr>
<td>1 km x 1 km</td>
<td>12.58</td>
</tr>
<tr>
<td>5 km x 5 km</td>
<td>20.13</td>
</tr>
<tr>
<td>10 km x 10 km</td>
<td>26.55</td>
</tr>
</tbody>
</table>

Assumed Growth Rates
- Low Rate [1 Mg/ha/yr]
- High rate [5 Mg/ha/yr]
Characterization of Habitat Structure and Biodiversity

Radar & Lidar can map and measure landscape structure

Lidar and Radar can map and measure vertical structure & biomass

Vegetation 3D Structure: Radar and Lidar Fusion

Lidar Transect Canopy Profiles

Lidar Height and Within-Canopy Vertical Structure

Radar Bands & Derived Biomass

High: 30 kg/m²
Biomass
Low: 0 kg/m²

Upland conifer
Lowland conifer
Northern hardwoods
Aspen/lowland deciduous
Grassland
Agriculture
Wetlands
Open water
Urban/barren
## Ecosystem Structure Baseline Requirements at MCR

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Requirements</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aboveground Woody Biomass (High Density)</td>
<td>&lt; the greater of 10 MgC/ha or 20%, capped at 25 MgC/ha&lt;br&gt;Resolution: 1 km resolution</td>
<td>Lidar, 1 map</td>
</tr>
<tr>
<td>Aboveground Woody Biomass (Low Density)</td>
<td>&lt; 10 MgC/ha, when biomass is &lt; 40 MgC/ha&lt;br&gt;Resolution: 100 m</td>
<td>Radar, Seasonally</td>
</tr>
<tr>
<td>Aboveground Woody Biomass Disturbance</td>
<td>50% change in biomass</td>
<td>Radar, Quad-pol, Yearly</td>
</tr>
<tr>
<td>Canopy Height Profiles</td>
<td>Resolution: 25 m&lt;br&gt;Along-track Posting: 30 m&lt;br&gt;Vertical resolution: 1 m</td>
<td>Lidar 98.5% canopy cover</td>
</tr>
</tbody>
</table>
Experiments over boreal, temperate, and tropical forests have shown that radar backscatter is related to the amount of live aboveground biomass of vegetation.

L-band linearly cross-polarized (HV) backscatter has a strong sensitivity to biomass up to 100 Mg/ha.

Backscatter sensitivity to biomass depends on radar incidence angle, environmental condition, and surface slope.

Speckle noise, spatial variability of vegetation structure, and radar resolution cell are factors influencing biomass estimation accuracy from radar measurements.

\[ \sigma_{pq}(b) = A_{pq} \left(1 - e^{-B_{pq}b}\right) + C_{pq} b^{\alpha} e^{-B_{pq}b} \]

- \( p, q \): H or V polarization
- \( b \): Aboveground Live Biomass (Mg/ha)
- \( A_{pq}, B_{pq}, C_{pq} \) are calibration coefficients

Recommended algorithm for biomass estimation from radar measurements used only for radar design and performance analysis.
Error in $\sigma_o$ Measurements

• The error/variability in the backscatter measurements, $\Delta\sigma_{pq}$ ($pq=hh,hv, vv$), are a function of speckle, thermal noise, temporal variability of the backscatter, calibration errors (which in turn depend on pointing DEM errors) and area projection correction terms as given by the following equation.

$$
\Delta\sigma_{pq} = \left[ \left( \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N_{os}}} + \frac{1}{\sqrt{N}} \frac{1}{\sqrt{N_{ot}}} \frac{1}{SNR} \right) \sigma_{pq} + \frac{1}{\sqrt{N_{ot}}} \Delta\sigma_{pq,t} + \frac{1}{\sqrt{N_{ot}}} \Delta\sigma_c + \frac{1}{\sqrt{N_{os}} \sqrt{N_{o}}} \Delta\sigma_a \right]
$$

• Since SAR uses a coherent imaging source, the image data is subject to speckle noise as well as thermal noise.
• Backscatter is also sensitive to weather, wind, vegetation health, ground cover, soil moisture and other factors.
  - Empirical data for several biomes and times ranging from 14 days to several years (restricted to the same season) show variability in the 0.5 – 0.75 dB range at L-band.
• In large slope area removing the area projection correction associated with the broadside imaging geometry can be a major source or error.

Key to reducing measurement error: good calibration, good topo knowledge, number of pixels to average, and number of observations.
Meeting radar biomass requirements

Requirement: Accuracy < 10 MgC/ha, when biomass is < 40 MgC/ha, at 100 m resolution

<table>
<thead>
<tr>
<th>Mode (Pol, BW)</th>
<th>Speckle Identical Obs.</th>
<th>Speckle Diverse Obs.</th>
<th>Total Obs.</th>
<th>Biomass Accuracy (%)</th>
<th>Biomass Accuracy (MgC/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH/HV/VV, 20 MHz</td>
<td>24</td>
<td>12</td>
<td>36</td>
<td>25</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>HH/HV/VV, 40 MHz</td>
<td>6</td>
<td>12</td>
<td>18</td>
<td>27</td>
<td>&lt; 11</td>
</tr>
<tr>
<td>HH/HV, 20 MHz</td>
<td>60</td>
<td>12</td>
<td>72</td>
<td>27</td>
<td>&lt; 11</td>
</tr>
<tr>
<td>HH/HV, 40 MHz</td>
<td>24</td>
<td>12</td>
<td>36</td>
<td>28</td>
<td>&lt; 11</td>
</tr>
<tr>
<td>HV, 40 MHz</td>
<td>60</td>
<td>12</td>
<td>72</td>
<td>28</td>
<td>&lt; 11</td>
</tr>
<tr>
<td>HV, 20 MHz</td>
<td>132</td>
<td>12</td>
<td>144</td>
<td>28</td>
<td>&lt; 11</td>
</tr>
<tr>
<td>HH, 20 MHz</td>
<td>132</td>
<td>12</td>
<td>144</td>
<td>30</td>
<td>&lt; 12</td>
</tr>
</tbody>
</table>

- Quasi-pol 20 mode with three observations per year in each season meets low biomass requirement
- Many modes come close to meeting the requirement
**ECOSYSTEM REQUIREMENTS FLOW**

**ECOSYSTEM STRUCTURE**

- **Global Biomass**
  - +/- 10 MgC/ha or 20% (but < 25MgC/ha)
  - 1000 m resolution

- **Global Transects of Vertical Canopy**
  - 25 m resolution
  - 30 m along-transect posting
  - 1000 m across-transect posting
  - 1 m vertical resolution
  - 98.5% canopy cover

- **Global Biomass**
  - +/- 10 MgC/ha or 20% (but < 25MgC/ha)
  - 100 m for areas < 40 MgC/ha annual

- **Global Disturbance**
  - > 50% change, 100 m resolution annual

**Measurement Method**

- **Achieve biomass accuracy by measuring height metrics to 1 m in resolution cell -> 25-m spot profile**

- **Measurement Method**

- **This is a direct pass-through of lidar transect and coverage requirements**

- **Measurement Method**

- **Biomass sensitivity -> L-band quad-pol radar reflectivity**

- **225 looks asc/des to beat down speckle/thermal noise -> 10 m res**

- **Thermal noise relative to speckle noise -> NES0**

- **Global coverage -> obs. Strategy**

- **Multiple seasons over 3 years to minimize temporal variability**

**Measurement Method**

- **This is a direct pass-through of lidar transect and coverage requirements**

**L-band SAR**

- **Quad-pol**
  - 10 m resolution
  - -25 dB NES0

- **13-day repeat orbit**
  - ~240 km observable swath
  - 609 km altitude orbit
  - 250 m repeat orbit control
  - 1/20 deg pointing control

- **Left/right Observations**
  - Ascending/Descending Obs

- **Seasonal Vegetation**
  - Winter ice sheets
  - Every opportunity sea-ice
  - Every-repeat deformation

- **Minimum 2 years**

- **Minimum 3 years**
All L1 Requirements collectively map to the mission concept

Dynamics of Ice
- Ice sheet dynamics
- Glacier dynamics
- Sea ice dynamics

Ecosystem Structure
- Global Biomass/Carbon
- Changes in Global Biomass/Carbon and Disturbance
- Habitat and Biodiversity

Solid Earth Deformation
- Tectonic processes
- Magmatic processes
- Sequestration, land-slides, aquifer change

All System Requirements Traceable to Science

1 micron 15 mJ lidar
25 m spot / 30 m sampling
1 m receive aperture
5 beams / 5 m placement
1415 m cross-track spacing
371 km altitude orbit
Uniform cross-track land/ice coverage over mission
Minimum 2 years

L-band SAR
Quad-pol
10 m resolution
-25 dB NESA0
13-day repeat orbit
~240 km observable swath
609 km altitude orbit
250 m repeat orbit control
1/20 deg pointing control
Left/right Observations
Ascending/Descending Obs
Seasonal Vegetation
Winter ice sheets
Every opportunity sea-ice
Every-repeat deformation
Minimum 3 years
## Proposed Key & Driving Radar Instrument Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Projected Performance</th>
<th>Key/Driven Radar Parameters</th>
</tr>
</thead>
</table>
| The Radar shall operate at L-Band (1215 to 1300 MHz) | L-Band Instrument, bandwidth consistent with NTIA constraints | • Antenna Size  
• System Bandwidth (constraint) |
| The Radar shall have a field of regard no smaller than the repeat-cycle ground track spacing at the equator including terrain effects | For 13-day repeat, ground track separation at the equator=208 km; 4 km reserved for terrain effects, 6 km for overlap; Predicted swath >218 km for primary science modes | • Antenna Config  
• Reflector Diam & F/D  
• Feed Length  
• # of Elements |
| The Radar shall be capable of operating in Single, Dual, and (Quasi) Quad-Polarization modes | Radar supports single, dual, and quasi-quad linear polarization modes over full swath; full BW quad-pol over reduced swath | • On-Board Data Throughput  
• Co and Cross-Pol Rx Channels |
| The Radar shall operate with a Noise Equivalent Sigma Zero value of at most -25 dB from 30-46° incidence angle | $\text{NE}_\sigma_0$ -33 to -25 dB over 30-46° for 20 MHz BW modes | • Antenna Size  
• Peak Tx Power  
• Pulsewidth  
• DC Pwr/Thermal |
| The total Radar Multiplicative Noise Ratio shall be less than -15 dB | Expect -15.2 dB total MNR  
-20 dB max Ambiguity Level  
-20 dB ISLR  
-20 dB QNR (4-bit BFPQ) | • Antenna Sidelobes  
• Timing Jitter  
• Data Quantization |
| The post-calibration Radar relative accuracy across the swath shall be:  
- <0.1 dB Amplitude  
- <1.5° Phase | Expect 0.091 dB, 0.44° total relative  
0.01 dB, 0.34° Reflector/Feed misalignment  
0.09 dB, 0.27° components outside Cal Loop  
0.01 dB, 0.06° Cal Loop residual (exclusive of RFI effects) | • Built-In Calibration Performance  
• Antenna Pattern Knowledge/Stability |
Radar Design to Meet Critical Requirements

• Repeat Period requirement for Deformation science drives the Radar Swath
  - 13-day Repeat Period => 218 km Swath Width

• Sensitivity requirement for Biomass (cross-pol) drives Antenna Size and Radar Power

• Accuracy requirements for Deformation and Biomass drive Electronics & Mechanical Stability and Calibration

• A new Sweep SAR technique was adopted as a means to achieve much wider swath than conventional SAR strip-mapping, without the performance sacrifices associated with the traditional Scan SAR technique

Conv. Strip Mapping:
< ~70 km Swath

Conv. Scan SAR:
non-uniform along-track sampling

Resulting (~40 day repeat) does NOT meet Deformation and Ice Science Requirements

Resulting degradation in effective azimuth looks does NOT meet Ecosystem Science Requirements

05.03 - 31
SweepSAR Implemented with Array-Fed Reflector

- Implementing the SweepSAR technique using an Array-Fed Reflector Antenna has these benefits:
  - On Transmit, all Feed Array elements are illuminated (maximum Transmit Power), creating the wide elevation beam
  - On Receive, the Feed Array element echo signals are processed individually, taking advantage of the full Reflector area (maximum Antenna Gain)
Radar Design Process

- SweepSAR with Array-Fed Reflector is a new type of Radar, requiring development of new tools for performance simulation and analysis.
- During the course of the pre-A study phase, analyses have been performed for:
  - Repeat Periods 8 to 16 days; Altitudes 540 to 761km
  - Reflector Diameters 6 to 15 m; F/D 0.75 to 1.0; Feed Offset 0 to -2 m
  - Feed Lengths 2.5 to 5 m; Number of elements 8 to 32; Element Spacings 13 to 24 cm
  - Transmit Peak Power 800 W to 4.2 kW; Bandwidths 5 to 80 MHz; Pulsewidths 5 to 100µs

Antenna Modeling:
- Patterns calculated using HFSS, Grasp
- Includes Feed Blockage, Feed/Reflector interaction, Boom Scattering

RF Performance Modeling:
- Tx Power, Rx Noise Figure, Efficiency, error estimates
- Includes Rx Protection, Built-In Cal, RFI mitigation, integrated Energy Storage

Inst Performance Modeling:
- Computes sensitivity, swath, ambiguities, datarate,... based on instrument parameters, antenna patterns, mode,...

Mission Simulations:
- Datatke scheduling, target coverage, telecomm & energy resource usage, science priority,...

Mission Performance:
- Science reqmt compliance based on model inversion

Digital Perf Modeling:
- On-Board Processing Algorithms, errors
- Includes Quantization, Timing, Rx Beamforming, Filtering, Calibration

Mechanical Perf Modeling:
- Configuration studies
- Structural analysis
- Thermal analysis
- Alignment, Distortion, Dynamics errors

Are resources affordable?

Is Science met?

Radar Engineering, Datataking Geometry and Science Compliance parameters to be combined into Integrated Performance Model to streamline analysis in Phase-A

05.03 - 33
Radar System Parameters

• Instrument Parameters for selected point design
  – Repeat Period 13 days; Altitude 609 km
  – Reflector Diameter 12 m; F/D 0.75
  – Feed Length 3.25m; Number of Elements 16 x 2; Element Spacing 15cm el 13cm az
  – Fully Polarimetric; 8 Receive Beams per Polarization
  – Transmit Peak Power 1240W

• Mode-Dependent Command Parameter Settings and Resource Usage

<table>
<thead>
<tr>
<th>Primary Modes</th>
<th>Polarization</th>
<th>Swath Start (km)</th>
<th>Swath End (km)</th>
<th>PRF (Hz)</th>
<th>Bandwidth (MHz)</th>
<th>Pulse Width (μs)</th>
<th>Threshold NEσ(0) (dB)</th>
<th>-25 dB Swath (km)</th>
<th>DC Power (W)</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamics of ice - Glacier</td>
<td>VV</td>
<td>323.9</td>
<td>543.2</td>
<td>1955</td>
<td>20+5</td>
<td>20+5</td>
<td>-25</td>
<td>219.3</td>
<td>618</td>
<td>423.6</td>
</tr>
<tr>
<td>Dynamics of ice - Sea Ice</td>
<td>VV</td>
<td>319.8</td>
<td>551.9</td>
<td>1955</td>
<td>5</td>
<td>20</td>
<td>-25</td>
<td>232.2</td>
<td>588</td>
<td>90.0</td>
</tr>
<tr>
<td>Ecosystem Structure - Low Biomass</td>
<td>HH, HV, VH, VV</td>
<td>323.9</td>
<td>546.1</td>
<td>1955</td>
<td>20</td>
<td>20</td>
<td>-25</td>
<td>222.2</td>
<td>984</td>
<td>1376.4</td>
</tr>
<tr>
<td>Ecosystem Structure - Forest Change</td>
<td>HH, HV</td>
<td>323.9</td>
<td>546.1</td>
<td>1955</td>
<td>20</td>
<td>20</td>
<td>-25</td>
<td>222.2</td>
<td>707</td>
<td>688.2</td>
</tr>
<tr>
<td>Deformation</td>
<td>HH</td>
<td>323.9</td>
<td>542.2</td>
<td>1955</td>
<td>20+5</td>
<td>20+5</td>
<td>-25</td>
<td>218.3</td>
<td>618</td>
<td>423.6</td>
</tr>
</tbody>
</table>

1 Swath set to max available for analysis purposes
2 PRF = Pulse Repetition Frequency

• S/C Attitude Control System is required to perform Zero-Doppler Steering (yaw and pitch steering to remove the variation in Doppler centroid along the orbit due to earth’s rotation)
Some Radar System Performance Estimates

- Performance over the swath for the Primary Modes: Ecosystem Structure and Deformation

**Ecosystem: Quasi-Quad-Pol (HH, HV, VH, VV)**
20 MHz Bandwidth

- **Frequency**: 1257.5 MHz
- **Mech Boresight Angle**: 34.2°
- **Altitude**: 609 km
- **Tx Power**: 1240 W
- **PRF**: 1955 Hz
- **PBW**: 1100 Hz
- **BW**: 20 MHz
- **Tx pulse length**: 40 μsec
- **Data rate**: 137.3942 Mbps
- **Swath**: 222.1612 Km
- **NESZ threshold**: -25 dB
- **Inc Angle (near)**: 30.5895°
- **Inc Angle (far)**: 45.6846°
- **Swath Start**: 323.911 km
- **Swath End**: 546.1023 km
- **Diameter**: 12 m
- **N Beams**: 8
- **Elev spacing**: 15 cm
- **Azim spacing**: 13 cm
- **Elevation Tilt**: 0
- **Azimuth Tilt**: 0
- **HV Quasi-Quad Pol

**Deformation: Single-Pol (HH) 20 MHz Bandwidth**

- **Frequency**: 1257.5 MHz
- **Mech Boresight Angle**: 34.2°
- **Altitude**: 609 km
- **Tx Power**: 1240 W
- **PRF**: 1955 Hz
- **PBW**: 1100 Hz
- **BW**: 20 MHz
- **Tx pulse length**: 20 μsec
- **Data rate**: 421.3959 Mbps
- **Swath**: 218.2844 km
- **NESZ threshold**: -25 dB
- **Inc Angle (near)**: 30.5895°
- **Inc Angle (far)**: 45.4615°
- **Swath Start**: 323.911 km
- **Swath End**: 542.1964 km
- **Diameter**: 12 m
- **N Beams**: 8
- **Elev spacing**: 15 cm
- **Azim spacing**: 13 cm
- **Elevation Tilt**: 0
- **Azimuth Tilt**: 0
- **HH Single Pol

- The Quasi-Quad-Pol mode (simultaneous H & V Tx, multiplexed in frequency) is used rather than “True” conventional Quad-Pol (time-interleaved H & V Tx) to mitigate ambiguities and gaps
Radar Instrument Configuration

- Radar Instrument Computer
- RF Electronics Back-End
- Beamforming Processor / Control & Timing Distribution
- Transmit/Receive Module
- Digitizer / Calibration Processor
- Power
- Reflect/Boom Deployment Controller
- Feed RF Aperture
- Radar Instrument Feed/Electronics Structure
- S/C Bus
- to Reflector
Technology Advancement Status

• V5 and On-Board Processing Implementation:
  – Xilinx Inc, NEPAG (NASA EEE Parts Assurance Group), and XRTC (Xilinx Radiation Test Consortium) are performing radiation and reliability qualification testing of Xilinx flight V5 FPGA (XQR5VFX130); flight part production is expected in June 2011
  – Prototype designs of the on-board processing algorithms and FPGA hardware using the Xilinx commercial V5 FPGA (XC5VFX130T-1FF1738C) are in progress; prototype design of the First-Stage Processor and Second-Stage Processor hardware, along with the timing circuits for implementation of on-board processing algorithms are underway

• GaN and TRM:
  – GaN amplifiers have been designed and tested to demonstrate >60% power added efficiency, enabling increased transmit power and reduced DC power (and thermal dissipation); several parts from 3 vendors are undergoing preliminary screening and radiation testing
  – Prototype designs for the TR module Transmit, Receive, Receive Protection, and Energy Storage subcircuits have been tested; fabrication and assembly of the full TR prototype is underway

• SweepSAR DES Algorithms and Airborne Demo:
  – The SweepSAR Demonstration is an airborne radar system using an array-fed reflector (Ka-Band) with digital beamforming to emulate the DESDynl SweepSAR measurement technique using scaled geometry and timing
  – The SweepSAR Airborne Demo is the first-ever demonstration of the SweepSAR technique, reducing DESDynl implementation risks by enabling evaluation of SweepSAR data collection in a real-world environment, to uncover issues and enable performance studies that cannot be done by simulation alone
Outlook for DESDynI

• DESDynI concept presented here passed its Mission Concept Review in January 2011
• President’s FY12 Budget Proposal (February 2011) reset the go-forward plan for DESDynI
  – Lidar mission to be contributed, not funded by NASA
  – Radar mission to be implemented more affordably
• NASA continues to invest in DESDynI
  – Forming a Science Definition Team
  – Continuing trade studies at JPL
• NASA is currently exploring options for reducing cost
  – Reducing number and scope of science requirements levied on DESDynI
    + DESDynI in combination with other satellites to approach DESDynI requirements
  – Find international partners interested in the science and technology
  – Find domestic partners that would increase utility of DESDynI data
Summary

• DESDynI as presented here would provide exciting scientific returns in three distinct science disciplines by exploiting the complementary power of wide-area mapping radar and vertically-profiling lidar

• DESDynI would provide direct benefits to society as its measurements are used to help forecast sea level rise and the likelihood of earthquakes or volcanic eruptions and to improve forest inventories and carbon monitoring

• DESDynI measurements would be unique and available to the world for scientific use
  – L-band full-resolution, full-swath, 13 day repeat capability would revolutionize our ability to characterize natural hazards, quantify ice dynamics, and monitor Earth’s changing terrestrial carbon stocks
  – 5-beam 1-micron 25-m footprint profiling lidar in space was optimized to produce unprecedented estimates of terrestrial carbon storage and ice topography
  – Accuracy/resolution/coverage would be orders of magnitude improvement over existing scientifically available data

• DESDynI is still in pre-formulation!

• However, in light of recent budgetary direction, new ideas for implementing DESDynI more affordably must be explored vigorously