Report from the ICESat-II Workshop

June 27–29, 2007
Linthicum, Maryland

Sponsored by the
National Aeronautics and Space Administration

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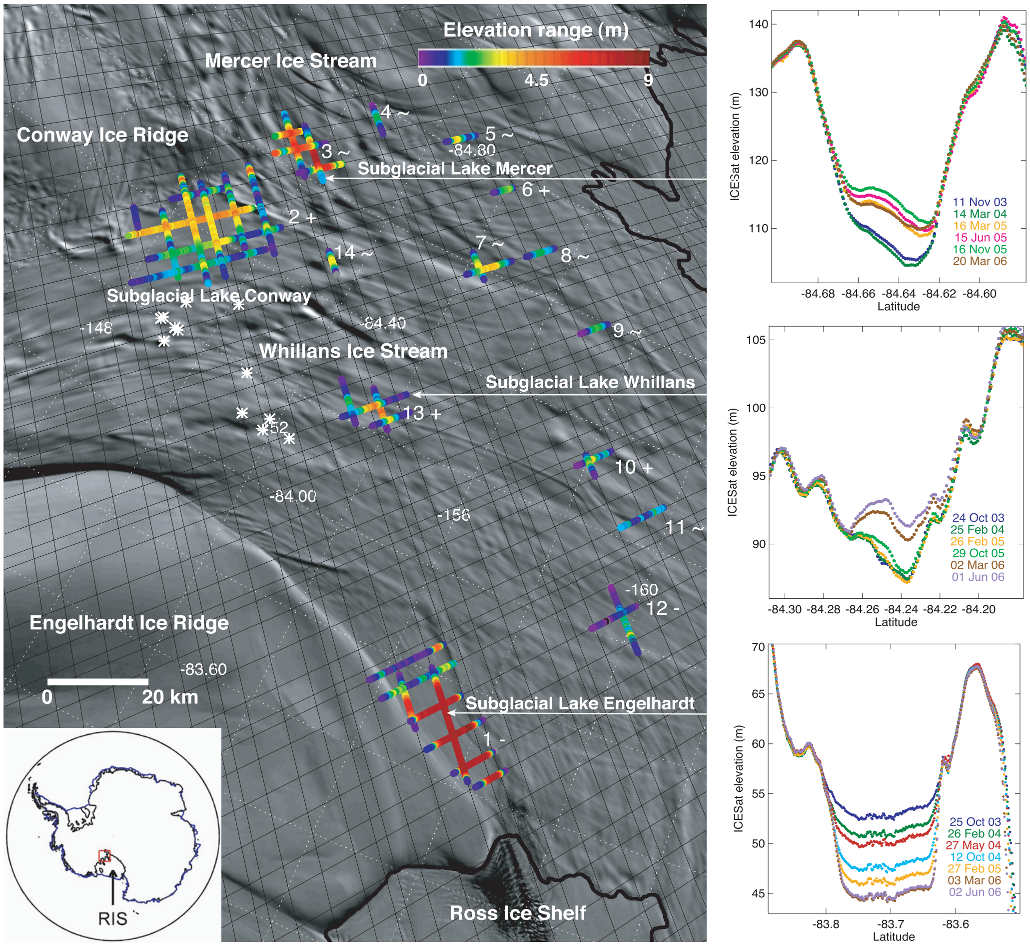


Figure 2. Left panel: Locations of elevation change events identified through repeat-track analysis of ICESat data. Straight black lines show the reference ground tracks, and colored track segments show range in elevation amplitude for each elevation change event. Events cluster into 14 elevation change regions that are either rising (+), falling (-), or oscillating (~). Ice flow is from top left toward lower right. The background image is MODIS Mosaic of Antarctica (MOA) and the inset map shows its location in Antarctica. The bold black line indicates the break-in-slope associated with the grounding zone of the Ross Ice Shelf (RIS). Right panels: ICESat elevation profiles across examples of each type of region (+, -, ~) (Fricker et al. 2007).

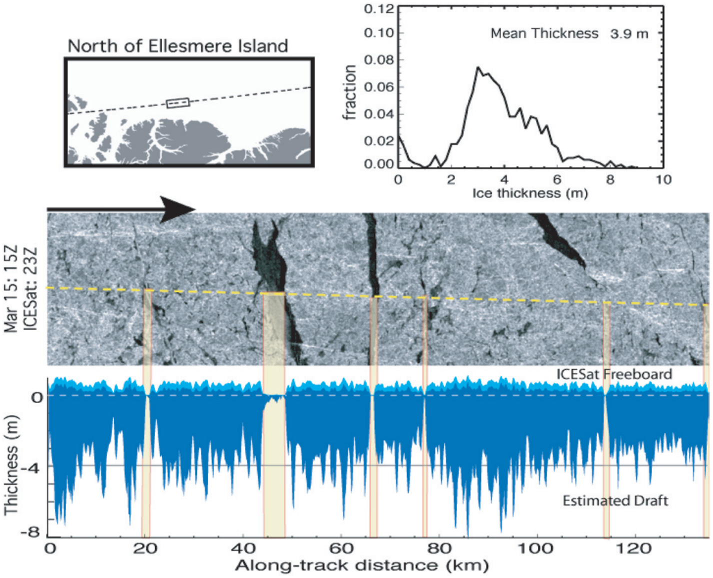
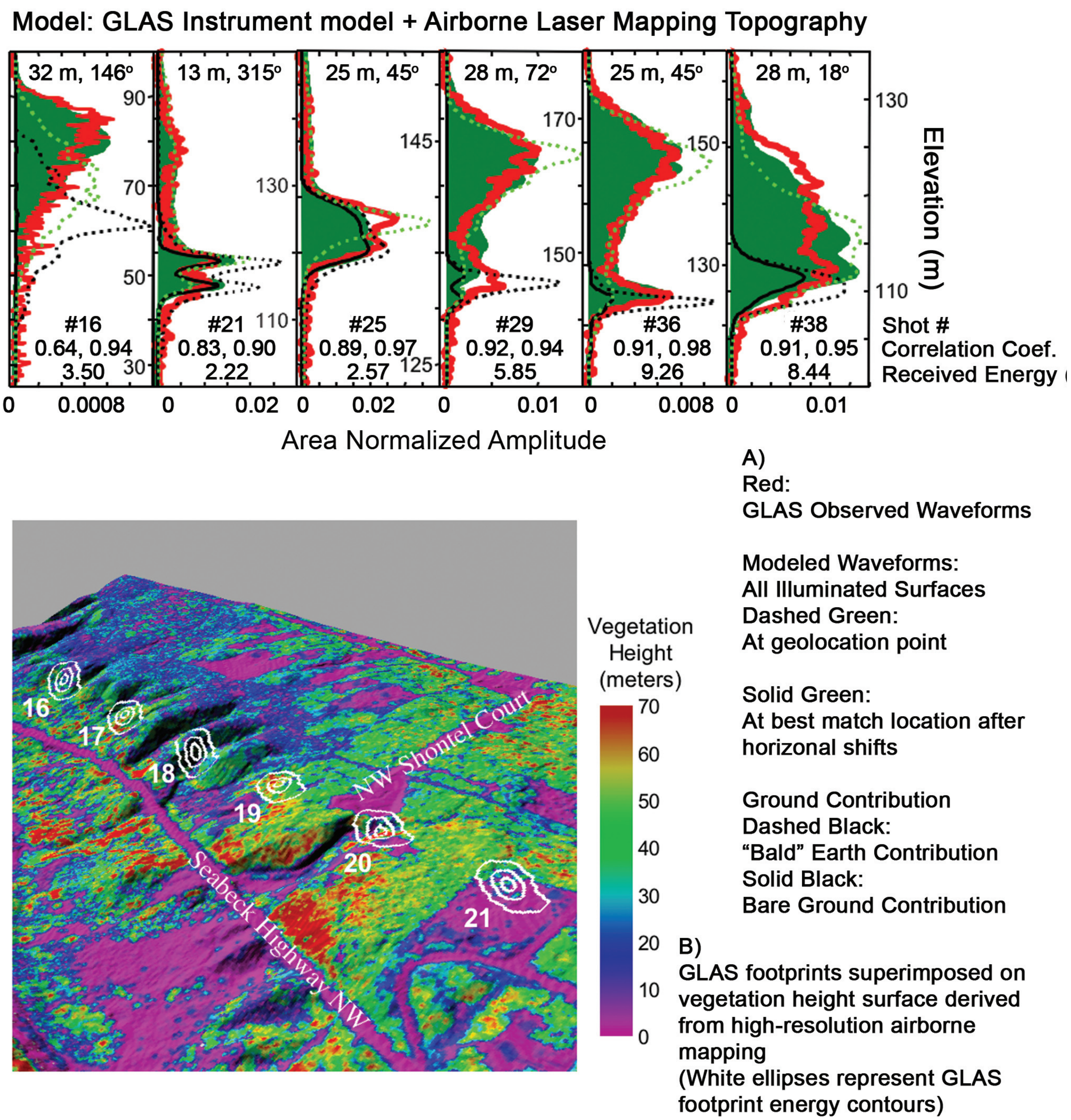


Figure 3. Near-coincident ICESat and RADARSAT observations of the sea ice cover north of Ellesmere Island. The ICESat track (dashed yellow line) is overlaid on the RADARSAT imagery. Thin ice in open leads is used as a sea surface reference. The ICESat profile is then converted to thickness by assuming hydrostatic equilibrium. The mean thickness over the 160 km transect is 3.9 m (figure courtesy of Ron Kwok).



A)
Red:
GLAS Observed Waveforms

Modeled Waveforms:
All Illuminated Surfaces
Dashed Green:
At geolocation point

Solid Green:
At best match location after horizonal shifts

Ground Contribution
Dashed Black:
"Bald" Earth Contribution
Solid Black:
Bare Ground Contribution

B)
GLAS footprints superimposed on vegetation height surface derived from high-resolution airborne mapping
(White ellipses represent GLAS footprint energy contours)

Figure 4. ICESat Waveform modeling in vegetated landscapes. GLAS received waveforms from vegetated terrain, representing the height distribution of backscattered light reflected from canopy surfaces and the underlying ground where it was illuminated by the ~65 m diameter laser pulse (top). Comparisons of GLAS waveforms (red curves) to simulated waveforms generated using height resolution airborne topography data from the Kitsap Peninsula (Washington State), and an accurate GLAS instrument model, have validated ICESat elevation products and footprint geolocation in forested areas. Dark green curves represent the contribution from all illuminated surfaces, at the mission geolocation for the GLAS footprints (dashed green) and after shifting the footprint location in the horizontal directions for best correlation match between observed and modeled waveform (solid green). The dashed black curves represent the "bald" Earth contribution, while solid black curves illustrate the contribution of the bare ground. Optimal shift values are shown in magnitude and azimuth at the top for every waveform. Shot number, correlation coefficients before and after best match geolocation, and received energy in femto-Joules are shown at the bottom. The lower left panel shows the contours of laser energy for six GLAS footprints (white, for 12%, 50%, and 88% of the transmit pulse peak energy) superimposed on high-resolution airborne laser altimeter mapping of ground elevation, where color corresponds to canopy height (Harding and Carabajal 2005).

scheduling of targets-of-opportunity observations; the time and attitude maneuvers required to reach an off-nadir target affects much of the orbit, impacting acquired observations elsewhere on the orbit, and affecting other research targets along the nominal tracks. A more agile spacecraft would diminish the impact on data acquisitions around targets of opportunity. In addition, the achieved cross-track variations from reference tracks were approximately ±100 m (1 σ) compared to a preflight expectation of ±35 m. Nevertheless, this capability has enabled analysis of ice sheet elevation changes that have been critical to mission success in light of the reduced periods of laser operations. For ICESat-II, pointing to a cross-track variation with an accuracy of approximately ±30 m (1 σ) should be achievable globally with improvements in the command storage, attitude control system (ACS), and orbit prediction.

Different requirements among disciplines regarding the optimum laser footprint size: The goal for ICESat-I was to use a circular, 70-m diameter laser footprint. Based on limited modeling of ice sheet small-scale topographic roughness in the form of wind-generated sastrugi, 70 m was thought to be best suited to avoid aliasing (Figure 6). As implemented, however, the first and second lasers on ICESat-I generated variably shaped and elliptical footprints that measured approximately 100 m × 50 m in diameter. The third laser exhibited a more nearly circular footprint, but with a diameter of only about 50 m. For vegetation, because of the mixing of ground relief and vegetation structure in the observed waveforms, the ICESat-I footprints lead to vegetation canopy heights with an uncertainty of ±5 m. If instead, a 25-m spot size is used, this uncertainty can be reduced to ±1 m.

For sea ice freeboard measurements, detection of leads is required to determine the ocean reference level. As discussed in the sea ice section, a tradeoff was considered at the workshop between smaller footprints that would provide better sampling of smaller leads having thin ice or open water entirely across the footprint, versus larger footprints that would give a higher probability of sampling some portion of leads within the footprint.

Similarly, because of its value in separating ground and canopy components within the waveforms, the solid Earth/hydrology option would also like a 25-m footprint, thus permitting more accurate determination of ground control points for the generation and validation of digital elevation models (DEMs). Hydrologic considerations also favor a smaller spot size for observations of small inland water bodies, and of river slopes.

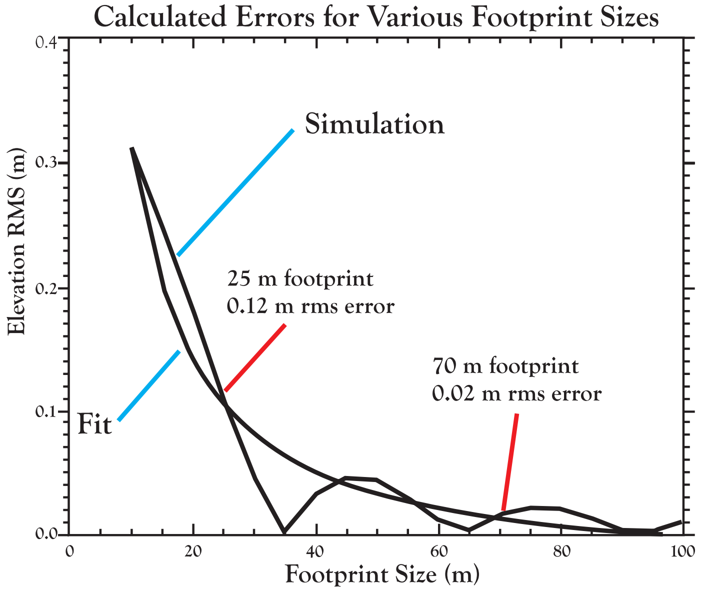


Figure 6. Typical sampling errors caused by ice-sheet surface roughness based on an analytical model of sastrugi heights and wavelengths. The sampling error scales with footprint diameter (D) by between 1/D and 1/D^2, and increases by a factor of 6 as D decreases from 70 m to 25 m, which would require 36 times more samples to achieve the same accuracy for spatially averaged elevation changes (figure courtesy of Jay Zwally).

Different requirements among disciplines for along-track footprint spacing: ICESat-I is operating at 40 Hz with 170-m footprint spacing, trading density of sampling along-track for laser life (by minimizing the number of pulses). Because analyses show that interpolation errors at the 150-m scale remain small over most of the ice sheets, separation at these scales is sufficient.

There is more interest in ensuring longer laser life than in reducing the separation between laser shots. The scales of variability for vegetation, solid Earth sea ice, and hydrology, however, are often smaller and as such, these interests would be better served with denser along-track sampling. The tradeoffs between sampling density and laser life are an important consideration in the mission design.

Saturation: Specular and quasi-specular targets, such as the open water areas in rivers, lakes, and sea ice leads and other highly reflective surfaces, can cause saturation of the GLAS detectors. This limits the use of returns from smooth targets, thus a greater detector range and better gain control system is considered an important upgrade for ICESat-II.

Advantages of simultaneous imagery: For many local applications of ICESat-I data, one of the first requirements for interpretation of the profile or waveform data is a visible-band or near-infrared band image. Because of the effects of clouds and their rapid motion, it can be difficult to obtain data from the same day from the MODIS[6] sensors, and acquisitions of ASTER[7] or Landsat data are too infrequent for close comparison in time. The advantage of coincident imagery applies to all science applications, and to quality control the data (e.g., cloud and aerosol effects, pointing control, and surface conditions, such as snow cover on land and melt water on ice sheets).

Mission lifetime: There was general agreement at the Workshop that a 5-year mission is needed to achieve the necessary level of scientific understanding of ice changes as opposed to the 3-year mission lifetime that was costed by the Decadal Survey for ICESat-II and all the other missions it considered. For ICESat-II, the choice of a five-year mission is based on a number of observed time scales in the Earth system, for example the 3–5 year cycle of recent glacier calvings-accelerations-restabilizations in southeastern Greenland, observations of subglacial lake fill-drain cycles, and ENSO[8] variations and their effects on forest canopy.

Engineering improvements: The most important improvement needed is in laser life, because this drives much of the planned sampling. A doubling in laser life could enable either a doubling of mission life or a doubling of sampling on the surface, or some combination of the two. Additional improvements are needed in areas such as

- More controls on the alignment of the beam to avoid clipping,
- More robust attitude control to reduce uncertainties in spot locations and elevation retrievals,
- Reduced field of view (FOV) to reduce forward-scattering effects, and
- More controls on such factors as the laser output energy to enable a tuning of parameters and more flexibility in the mission implementation.

2. Assessment of Scientific and Societal Benefits of the ICESat-II Mission

2.1 Ice Sheets

"Will there be catastrophic collapse of the major ice sheets, including Greenland and West Antarctica and, if so, how rapidly will this occur? What will be the time patterns of sea level rise as a result?" (Decadal Survey)

"The poorly understood dynamic response of the ice sheets to climate change is one of the major sources of uncertainty in forecasts of global sea level rise." (Decadal Survey)

"The ice sheets of Antarctica and Greenland could raise sea level greatly. Central parts of these ice sheets have been observed to change only slowly, but near the coast rapid changes over quite large areas have been observed. In these areas, uncertainties about glacier basal conditions, ice deformation and interactions with the surrounding ocean seriously limit the ability to make accurate projections." (Intergovernmental Panel on Climate Change [IPCC] 2007)

If the Greenland and Antarctic ice sheets were to disappear completely, enough fresh water would be released to raise global sea level by 65 m. Although sea level changes also occur in response to melting of the smaller glaciers, as well as from thermal expansion of the ocean, all the glaciers in the world contain less than ~0.5 m of sea level equivalent and the ability of the ocean thermal expansion to contribute to rapid sea level rise is limited. In contrast, because the ice sheets contain so much ice and are potentially unstable, they have the potential to make large and rapid contributions to sea level rise. Each year, the ice sheets exchange about 8 mm/yr of global sea level equivalent with the ocean, so that even small changes in this rate of mass exchange are significant. New studies show that the ice sheets are responding much faster and more strongly than previously anticipated (Alley et al. 2007, and Truffer and Fahnestock 2007).

Moreover, the recent IPCC Summary for Policy Makers made clear that the lack of our understanding of the ice

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[6] MODIS: Moderate Resolution Imaging Spectroradiometer

[7] ASTER: Advanced Spacebourne Thermal Emission and Reflection Radiometer

[8] ENSO: El Niño Southern Oscillation

sheet behavior and its rapid response to present-day climate conditions severely limits our ability to predict the ice sheet contributions to sea level in the coming decades. As a result, observing the behavior of the ice sheets and understanding the mechanisms that control their changes is crucial to determining their present and future contributions to sea level. Because these changes and the mechanisms that control them are manifest in the topographic variations in the ice sheet surface, the ICESat-II mission is specifically targeted at quantifying these changes and providing insight into their underlying causes. Sustained long-term observations are critical to understanding the current and future behavior of the ice sheets.

Regarding the specific behavior of Antarctic and Greenland ice sheets, first, the Antarctic ice sheet divides into two great ice masses, East and West Antarctica, each with different characteristics. The largest, East Antarctica, has displayed considerable stability even between glacial and interglacial periods, while West Antarctica and its northern appendage, the Antarctic Peninsula, have experienced large and repeated changes in volume. On the Antarctic Peninsula, large floating ice shelves have suddenly disintegrated, causing feeding glaciers to accelerate 100s of percent in 2 years (Scambos et al. 2003, Scambos et al. 2004, and Rignot et al. 2004). In West Antarctica, discharging glaciers along almost the entire Amundsen Sea coast are accelerating and thinning without the loss of its narrow fringing ice shelves (Thomas et al. 2004). Similar behavior is seen in more isolated areas of East Antarctica (Shepherd et al. 2002). For ICESat-II, observations of these changes will require a dense ICESat-II track coverage.

Changes in the West Antarctic ice sheet with its equivalent of 5 m of sea level change are of particular concern, because the ice sheet rests on a soft till bed, which lies far below sea level. Despite the fact that the ice sheet is well below freezing and experiences very little surface melt, its bed structure may make it susceptible to dynamic instabilities (Bindschadler 1998, Oppenheimer 1998, and Bentley 1997). Another major feature of the Antarctic ice sheet, and in particular West Antarctica, is that the ICESat-I data shows the existence of widespread and active systems of subglacial lakes and streams (Fricker et al. 2007). The source of this subglacial water is the water generated by geothermal and frictional heating. The new subglacial lakes were observed because the ice surfaces inflate as subglacial lakes fill, and deflate as they drain. ICESat-I, therefore, is providing revolutionary new information on the presence and movement of subglacial water that influences the rates of ice discharge through lubrication of the ice–bed interface.

Second, although the Greenland ice sheet is only about 1/9th as large as the Antarctic ice sheet, it may be more vulnerable to climate warming because unlike Antarctica, summer melting occurs over much of its surface. In summer, this melting manifests itself in the form of lakes on the surface, which drain rapidly to the bottom of the ice sheet through deep vertical tunnels called "moulins." The resultant mass balance of the ice sheet is the difference between the annual snowfall and the combined loss from melting and iceberg calving. For 1961–2003, the recent IPCC 2007 Working Group report indicates that the Greenland Ice Sheet had a negative mass balance and lost ice at a rate of 20 km^3/yr (0.05 mm/yr contribution to sea level). For the more recent period of 1993–2003, this rate increased substantially to 90 km^3/yr (0.21 mm/yr). After 2003, several published results indicate the annual mass loss is now somewhere between 120–220 km^3/yr (0.3–0.55 mm/yr). While these contributions represent a relatively small fraction of the current rate of present sea level rise, the increase by roughly 0.5 mm/yr over a period when mean summer temperatures in Greenland have risen by about 1°C is cause for concern in the face of much greater potential future warming and the potential instability of the Greenland Ice Sheet.

While ICESat-II provides valuable information about changes in the surface characteristics of the interior ice sheet, understanding the details of outlet glacier elevation change requires complementary observations of ice flow characteristics. These are best obtained by Interferometric Synthetic Aperture Radar (InSAR) observations such as those advocated in the DESDynI mission and those provided by international partners. Additional velocity measurements can be achieved by feature tracking in visible imagery. Additional detailed elevation data in the outlet glacier trunks should be provided by airborne laser altimetry, as is currently the case.

A primary purpose of ICESat-II will be the determination of interannual and long-term changes in polar ice-sheet mass, the causes of changes in mass balance (polar precipitation, ice melting, or ice flow acceleration/deceleration, accumulation variations), and the impact of these changes on global sea level. Changes in ice mass are caused by an imbalance between the ice mass input (snowfall, condensation, and occasional rainfall) and output (evaporation, melt runoff, iceberg discharge, and snow drift removal). Conventional methods of studying ice sheet mass balance examine the difference between the mass input and output terms, but significant errors in these quantities have limited determinations to about 25%

(Warrick et al. 1996), equivalent to 2 mm/yr of sea level change. This exceeds the magnitude of sea level rise during the 20th century (Miller and Douglas 2004). From 1993–2006, however, measurements of sea level from the TOPEX/Poseidon[9] radar altimeter show a rise of 3.36 ±0.41 mm/yr over the 14-year period from 1993–2007, and with a relative increase in the global mean sea level trend of 1.5 ±0.7 mm/yr in the latter seven years (Beckley et al. 2007).

2.2 Sea Ice and Polar Oceanography

"High accuracy altimetry will also prove valuable for making long-sought repeat estimates of sea ice freeboard and hence sea ice thickness change, which is a parameter used to estimate the flux of low salinity ice out of the Arctic basin and into the marginal seas. As yet, altimetry is the best (and perhaps only) technique for making this measurement on basin scales and with seasonal repeats. This is particularly important for climate change studies because sea ice areas and extents have been well observed from space since the 1970s and have been shown to have significant trends, but sea ice thicknesses do not have such a record." (Decadal Survey)

2.2.1 Science Priorities for Sea Ice

There are three science priorities for sea ice:

1) Improve current knowledge of mean and variability of the ice thickness distribution of the polar oceans,

2) Provide long-term monitoring to determine trends in ice thickness, and

3) Refine the estimates of sea ice outflow into the Northern Atlantic.

This section divides into two parts. The first describes the measurement of sea ice thickness using lidar data; the second discusses the retrieval of sea surface height and its importance to the determination of polar ocean circulation.

2.2.2 Sea Ice Thickness

Trends and variability in sea ice thickness, along with the sea ice areal extent, are important indicators of the state of the ice cover and climate of the polar regions and are critical for understanding the ice–ocean–atmosphere interactions that comprise a fundamental aspect of the Earth's climate system. Because of a dearth of thickness measurements, there are large uncertainties in current knowledge of the volume and mass balance of the Arctic and Antarctic sea ice cover. At present, altimetric freeboard is perhaps the best measurement from which basin scale estimates of sea ice thickness can be derived. Freeboard, as measured by ICESat-I is the vertical distance between the local sea surface and the air–snow interface, or from very young ice, the air–sea ice interface. Because of snow loading on the sea ice, in the conversion of freeboard to ice thickness, it is also necessary to estimate the snow layer thickness. Thus, snow depth is an ancillary measurement that is crucial for accurate estimation of ice thickness.

Kwok et al. (2004, 2006, and 2007) demonstrated that ICESat-I profiles can provide estimates of the freeboard of the air–snow interface. Furthermore, this freeboard is sensitive to seasonal changes associated with snow accumulation and ice growth. From freeboard measurements of the snow surface, the use of snow depth from climatology and from snow precipitation from meteorological fields provides promising estimates of ice thickness. Ongoing investigations are improving on, and providing validation to, these estimates; however, the current ICESat-I operational scenarios that are designed to extend the laser lifetime do not allow a thorough examination of the full potential of these freeboard measurements.

In contrast to ICESat-I, ICESat-II will provide uninterrupted coverage of the Arctic and Southern Oceans. The denser temporal sampling will be essential in monitoring the annual development and decay of the snow and ice covers (i.e., freeboard) and allow the application of seasonal constraints in the thickness estimation process. Because there is a large snow signal in the ICESat freeboard and the changes in freeboard over thick multiyear ice are due mostly to precipitation, the time-varying freeboard should contribute to the snow–ice thickness retrieval: snowfall tends to occur in episodic storms while ice growth is more steady and slower in time.

2.2.3 Sea Surface Height and the Geoid

The advantages of knowing sea surface height, or absolute elevation of the sea surface, is not as important when freeboard is the only desired retrievable. Because of the information it provides about circulation of the Arctic Ocean, sea surface height is of great interest. The high latitude coverage of ICE-Sat-I and -II provides a valuable opportunity to improve knowledge of the geoid at high latitudes.

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[9] TOPEX/Poseidon: Topography Experiment/Poseidon

The orbit inclinations of dedicated oceanographic missions like TOPEX and Jason have limited their sampling of the polar oceans. Nevertheless, carefully selected altimetric returns of the sea surface from the radars on the Earth Resources Satellite (ERS)/Environmental Satellite (Envisat) have produced, a fairly consistent depiction of the geoid and the variability of the sea surface. Investigations using the decade-long moderate resolution ERS altimetry have contributed to improvements in the Arctic gravity field and an understanding of the variability of the sea surface height of the Arctic Ocean. This will be continued with CryoSat-2.

The unique high-resolution profiles of ICESat-I have already contributed to the refinement of the Arctic geoid. A new marine gravity field of the Arctic has been constructed by combining new GRACE and ICESat-I observations with earlier compilations of airborne, surface, and submarine gravity data from the Arctic Gravity Project (Forsberg and Skourup 2005). The launch of ICESat-II will offer continuous high-resolution observations of the time-varying sea surface. Over the ice-covered ocean, sea surface height is a by-product of the freeboard retrieval process. The mapping of ICESat-II will be extremely useful for resolving the spatial and temporal variability of the Arctic Ocean sea surface at length scales that are complementary to those from radar altimeters.

ICESat-II will be capable of addressing the science objectives of improving the description of the Arctic Ocean surface topography (i.e., the mean sea surface), the mean dynamic topography (MDT) and the marine geoid. The mean dynamic topography of the Arctic Ocean is the difference between the mean sea surface and the geoid. The dynamic topography, a direct consequence of the ocean circulation, of the Arctic basin has large uncertainties, as mentioned earlier, because of the lack of dedicated oceanographic missions. To contribute to the understanding of the polar oceans, it is recommended that sea surface height be incorporated as a key ICESat-II measurement objective to the extent that it does not compromise the ice measurements, which are the primary objective of the ICESat-II mission.

2.3 Accuracy and Precision Requirements for the Ice Sheets and Sea Ice

The following precision and accuracy specifications encompass the full-range of requirements for the anticipated ice sheet and sea ice studies. For mean elevations derived from individual laser footprints, the requirement is for an absolute accuracy of ±5 cm on 0° slopes increasing to ±20 cm on 2° slopes (primarily determined by ice sheet studies) and a satellite-to-surface range precision of ±2 cm (primarily determined by sea ice studies). Implicitly included in these specifications is a radial orbit accuracy of 2 cm and knowledge of the laser pointing to ≤ 2 arcsec, which is equivalent to knowledge of the laser footprint location to ≤ 6 m horizontally on the surface. Other implicit characteristics of the measurement are a laser footprint diameter of about 70 m with a footprint spacing of 140 m, although sea ice freeboard can also be determined with a 25-m spot size.

These specifications represent a nominal improvement for ICESat-II compared with ICESat-I, which had a goal of ±10 cm accuracy on a 0° slope increasing to ±20 cm on 1° slopes. Analysis of ICESat-1 data over ice sheets demonstrates that its goal is being achieved for the best-calibrated data sets. Analysis of data over both ice sheets and sea ice has also demonstrated a satellite-to-surface range precision of ±2 cm, which exceeds the preflight goal of ±10 cm, and has been an important additional capability for the extraction of accurate sea ice freeboard heights.

These accuracy specifications can also be derived from the principal scientific objective of ICESat-II, which is the measurement of seasonal, interannual changes and long-term trends in ice surface elevation, from which changes in ice thickness and mass balance can be derived. At the highest level, an accuracy requirement of ±0.2 cm/yr over the entire ice sheet corresponds on average to approximately 1% of the annual mass exchange. It also corresponds to a global sea level rise of 0.1 mm/yr sea level equivalent, which is about 3% of the current rate of sea level rise. Average elevations and their associated accuracies are derived from analysis of large numbers of elevation measurements at individual laser footprints. Such analyses of ICESat-I data demonstrates that multiyear trends in ice elevation can be derived with accuracies approaching ±0.2 cm/yr.

For ICESat-II, significant improvements in capability will also come from the continuous laser operations, which will enable better characterization of seasonal and interannual elevation changes and their spatial distributions. For averages over 50 × 50 km^2, the improved capabilities should provide annual accuracies of ±1 cm/yr, and for the seasonal cycle, an accuracy of ±2 cm (or ±10%).

2.4 Vegetation Three-Dimensional Structure, Biomass, and Disturbance

"The horizontal and vertical structure of ecosystems is a key feature that enables quantification of carbon storage, the effects of

disturbances such as fire, and species habitats. The above ground woody biomass and its associated below ground biomass store a large pool of terrestrial carbon. Quantifying changes in the size of this pool, its horizontal distribution, and its vertical structure resulting from natural and human-induced perturbations such as deforestation and fire, as well as the recovery processes, is critical for quantifying ecosystem change." (Decadal Survey)

"How will the boreal forest shift as temperature and precipitation change at high latitudes? What will be the effect on animal migration patterns and invasive species?" (Decadal Survey)

Accurate estimates of terrestrial carbon storage are required to

- Determine its role in the global carbon cycle;
- Estimate the degree that anthropogenic disturbance (i.e., land use/land cover change) is altering that cycle; and
- Monitor mitigation efforts that rely on carbon sequestration through reforestation.

Lidar remote sensing, from airborne or satellite platforms, has a unique capability for estimating forest canopy height; this has a direct and increasingly well-understood relationship to aboveground carbon storage (Lefsky et al. 2005). Through measurement of canopy height, ICESat-II has the potential to provide such information globally (Figure 7).

2.4.1 Science Overview

The Earth's carbon cycle controls both the amount of carbon stored on land and in the oceans, and the distribution of the important greenhouse gases CO_2 and methane in the atmosphere. Because carbon in forest canopies represents about 85% of the carbon in the Earth's aboveground biomass, the terrestrial biosphere plays a significant role in the carbon cycle (Olson 1983). A major source of uncertainty in global carbon budgets comes from the large errors in the current estimates of these terrestrial carbon stocks (IPCC 2001, and Canadell et al. 2007). Disturbances of the forest by natural phenomena, such as fire or wind, as well as by human activities, such as logging and the subsequent forest regrowth, complicate the quantification of carbon storage and release. The resulting spatial and temporal heterogeneity of terrestrial biomass and carbon in vegetation makes it very difficult to estimate terrestrial carbon stocks and quantify their dynamics. Measurements of vegetation three-dimensional (3D) structural characteristics over the Earth's land surface are needed to estimate biomass and carbon stocks and to quantify biomass recovery following disturbance. These measurements include vegetation height; the vertical profile of canopy elements (i.e., leaves, stems, and branches); and/or the volume scattering of canopy elements. Such measurements are critical for reducing uncertainties in the global carbon budget.

Vegetation height profiles and recovery patterns from natural and anthropogenic disturbances are also required to assess ecosystem health and to characterize habitat. The 3D structure of vegetation provides habitats for many species and is a control on biodiversity. Canopy height and structure influence habitat use and specialization, two fundamental processes that modify 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.

New or expanded measurements of vegetation 3D structure will facilitate research on two fundamental components of this question:

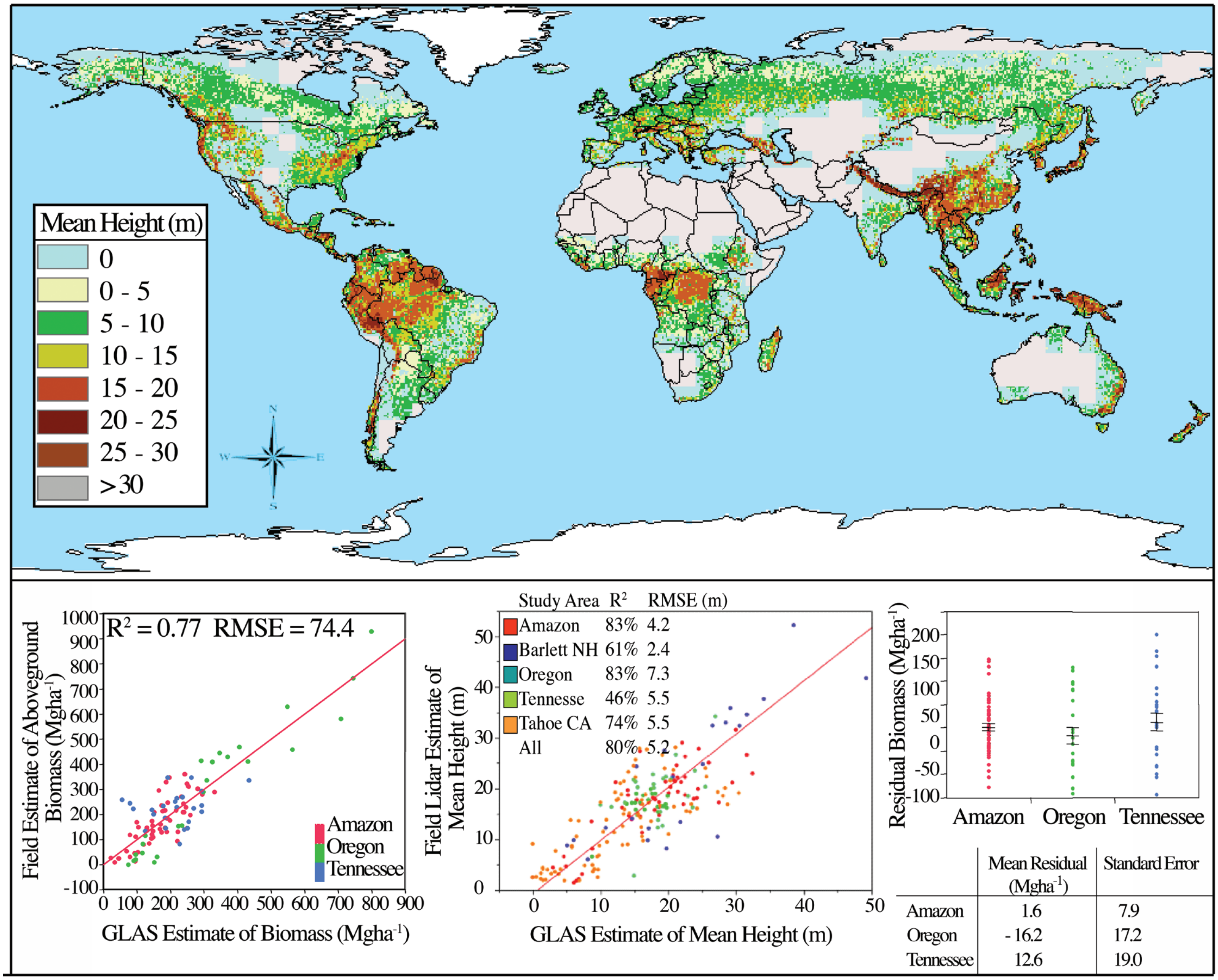
1) carbon in aboveground vegetation; and
2) ecosystem properties (i.e., structural indicators of ecosystem function, habitat, and biodiversity).

A mission designed to measure vegetation 3D structure, biomass, and its response to disturbances will enable critical estimates of changes in vegetation carbon stocks, thereby substantially reducing uncertainties about major factors affecting atmospheric concentrations of CO_2 and CH_4. New understanding of relationships between vegetation structure and underlying processes, especially that driven by human and natural disturbances, will enable more effective management and utilization of natural resources and will likely lead to the discovery of the fundamental processes that control biodiversity.

With the proper satellite operational characteristics, described below, ICESat-II can significantly improve existing knowledge of how much carbon is stored globally in vegetation.

2.4.2 Science Measurement Requirements

The vegetation measurement requirements have been established through the recommendations of vegetation structure workshops, findings of a recent NASA Biodiversity, Terrestrial Ecology, and Applied Sciences Joint Science Workshop, and the Decadal Survey. Recently, in support of NASA's advanced mission concept studies, a Vegetation Structure Science Working Group held regular teleconferences to discuss



	Mean Residual (Mgha^{-1})	Standard Error
Amazon	1.6	7.9
Oregon	- 16.2	17.2
Tennessee	12.6	19.0

Figure 7. GLAS measurements of tree height and biomass estimates. Global ICESat average tree height estimates from GLAS waveform data (top). The correlation between GLAS tree height estimates and those obtained at field sites in the Amazon, Bartlett forest in New Hampshire, Oregon, Tennessee, and Tahoe in California (bottom left), show R^2 values between 46% and 83%, with RMSE estimates between 2.4 and 7.3 m. Biomass estimates for three of the field sites (tropical broadleaf forest in Brazil, temperate needle leaf forest in Oregon, and temperate broadleaf forest in Tennessee) show an R^2 of 0.77, with an RMSE of 74.4 Mg ha^{-1} (Lefsky et al. 2007).

science objectives that produced the following requirements:

- Measurements over Earth's terrestrial ecosystems; statistically rigorous sampling of height and profiles and/or contiguous global coverage over a 3-year period;
- Vegetation height and profiles—Maximum vertical height measurement accuracy ~1 m, vertical resolution of canopy profile, 2–3 m, 25 m spatial resolution or better in a sampling mode;
- Aboveground biomass and changes including disturbance;
- Spatial resolution ~100 m to 1 km for contiguous biomass;

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[10] Hectare

- Within pixel accuracy ±10 tonne or 20% (whichever is greater) at a 1 ha[10] spatial resolution for forest biomass;
- Changes at a scale of 1 km with a precision of 2–4 tonne $\mathrm{ha^{-1}\,yr^{-1}}$;
- Revisit time, i.e., monthly to seasonal; and
- Measurement techniques to reduce the height measurement uncertainty resulting from topographic slope.

With the proper laser spot size and laser pointing capability, ICESat-II will potentially satisfy many of these requirements. This is a lidar sampling mission, however, and will therefore not meet the requirement for contiguous global coverage at a one hectare resolution. In the section immediately below, ICESat-II capabilities are described in the context of vegetation science needs.

Other current space-borne instruments do not quantify vegetation 3D structure with the spatial resolution, temporal repeat, or geographic coverage required for accurate global biomass estimation and disturbance mapping. For example, MODIS and Landsat do not measure vertical structure and do not provide a basis for biomass estimates beyond the land-cover categories that can be used to extend *in situ* plot-based measurements across landscapes. The lidar technology is the only one that can accurately determine the vertical canopy height required to improve biomass estimates from orbit.

2.4.3 ICESat-II Capabilities and Vegetation Requirements

Analysis of ICESat-I lidar data has demonstrated that for individual footprints, canopy height can be estimated with a root-mean-square error (RMSE) of ±5 m, and aboveground biomass with an RMSE of 50–75 $\mathrm{Mg\,ha^{-1}}$ (25–30% of mean predicted value). Characterizing a homogeneous region with multiple footprints could further reduce RMSE by as much as the square root of the number of footprints. For example, if 200 cloud-free footprints could be acquired within each 25 × 25 $\mathrm{km^2}$ grid cell on land (1/4° resolution), and ancillary data such as Landsat could be used to develop a stratified sampling strategy with a stratum variance of 100 $\mathrm{Mg\,ha^{-1}}$, the RMSE of the biomass estimate could be as small as 10–20 $\mathrm{Mg\,ha^{-1}}$. However, height estimation biases have been observed at some sites that would degrade accuracy within the grid cells.

Based on ICESat-I results, it appears that with ICESat-II as currently configured, a 0.25° resolution gridded global land biomass product might be possible once per year with a 91-day orbit or for even smaller grid cells with a 183-day orbit. With a 3-year mission, the contribution to atmospheric carbon flux from interannual variations in above-ground biomass from disturbance could potentially be measured to accuracies significantly better than current ground-based estimates. With an extended 7-year mission, ecosystem dynamics could potentially be monitored from disturbance through early stages of succession to assess the effects of vegetation recovery on global carbon sinks.

It should be noted, however, that while the ICESat-II capabilities will satisfy some of the vegetation science objectives, a design with footprint size and a PRF similar to ICESat-I will not meet a significant fraction of the stated vegetation requirements for biomass inventories, habitat, and biodiversity studies. Given the proposed orbit, a single-beam configuration, and a 50 Hz pulse repetition rate, the data acquired is only about 10% of that called for to meet vegetation science requirements. The height accuracy of ±5 m that is achievable with a 70-m footprint would not be sufficient to accurately measure low biomass and short stature forests, such as woody encroachment, and much of the boreal forests, both believed to play important roles in the land carbon sink. The vegetation science community has determined that satisfying these more stringent requirements requires that ICESat-II measure canopy heights to ±1 m accuracy, achieve 10 $\mathrm{Mg\,ha^{-1}}$ RMSE biomass accuracies within 1 km grid cells over land, even for "rare" cover types (<1% area fraction). Finally, ICESat-II coverage of the landscape is too coarse to resolve fine scale processes at the 1-ha area important for ecosystem dynamics characterization.

Possible accommodations were discussed that could improve the situation. For example, to reduce height and biomass estimation errors, a smaller lidar footprint of 25 m or less is needed. This concept of adding a smaller footprint beam to the ICESat-I lidar was discussed and viewed favorably by the vegetation scientists present. There was also discussion of pointing the lidar off-nadir a few degrees (off nadir pointing at 1.5° will permit coverage at 2 km at the equator over 5 years) to fill in measurements between the repeat orbit tracks required by the cryosphere science goals. Though the amount of data would still only be 10% of the full vegetation requirements, these two accommodations would improve accuracy for the gridded 0.25° and regional level biomass inventories.

2.5 Solid Earth

2.5.1 Elevation Measurements and Digital Elevation Models (DEMs)

Accurate elevation profiles, even at coarse along-track resolution, contribute to a number of the Solid Earth objectives related to natural hazards as described in Solid Earth Science Working Group (2003). A primary ICESat-I contribution to solid Earth studies has been in the identification of elevation biases in DEMs such as 90-m near global land Shuttle Radar Topography Mission (SRTM) DEM. The main contribution of ICESat-I for solid Earth purposes has been in the calibration and validation (Cal/Val) of the SRTM and other DEMs (Figure 8). This work has been of three related types:

(1) Independent assessment of the accuracy of DEMs in order to define their random and systematic error characteristics; by knowing those characteristics, the DEMs can be used for purposes for which their accuracy is appropriate. Furthermore, these errors can be linked to terrain land cover and relief characteristics. For SRTM, whose elevation is the radar phase center, this assessment is especially important because ICESat-I can be used to determine the height of the SRTM elevation within the vegetation canopy in forested regions. There is close correlation between the SRTM phase center elevation and the centroid of the GLAS waveform (the "average" elevation of surfaces illuminated by the laser pulse) (Carabajal and Harding 2005).

(2) Correction of systematic data errors in DEMs, improving their utility for detection of elevation change observed by differencing DEMs obtained at different times, and other applications where accurate representations of Earth topography are required. For example, relationships established between DEM errors and land cover and relief characteristics can be used to correct DEM elevations before inferences are drawn from the data. In addition, the SRTM DEM has elevation undulations at 100s of kilometer spatial scales with amplitudes as large as 5 m. ICESat-I data can document the structure of these undulations, which can then be removed from the DEM.

(3) Use of the ICESat data as ground control points in the production of DEMs, either by stereo photogrammetric or interferometric SAR techniques (Atwood et al. 2007).

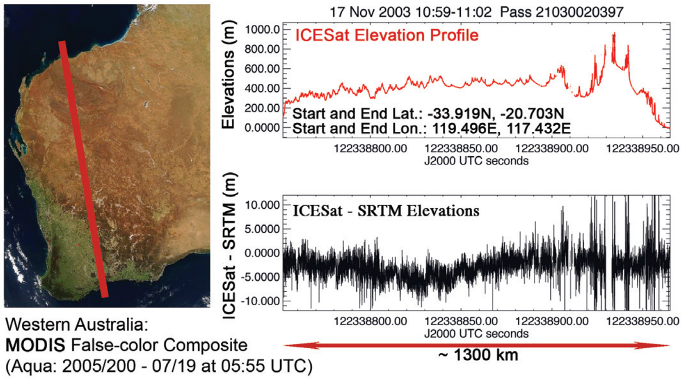

Figure 8. ICESat's high accuracy elevation measurements provide a globally distributed set of ground control points for validation and calibration of DEMs, such as that produced by the Shuttle Radar Topography Mission (SRTM). On the right, the ICESat elevation profile and corresponding elevation differences between individual ICESat laser footprints and corresponding SRTM DEM elevations are plotted for an ICESat track across western Australia. The profile location is shown on the left plotted on a MODIS composite image. The negative-biased elevation differences reveal that the SRTM DEM is biased high relative to an absolute datum by several meters, on average, in this region. This would introduce errors when using the SRTM data for coastal hazard modeling purposes. In addition, the along-profile variations reveal undulating elevation errors in the SRTM DEM at the 100s of kilometer length scale and ~5 m amplitude. The comprehensive ICESat coverage across the continents can be used to correct long-wavelength DEM errors, providing globally-consistent elevation data referenced to an absolute datum (figure courtesy of Claudia Carabajal).

ICESat-I related studies contribute to another of the key SESWG questions: How do tectonics and climate interact to shape Earth's surface and create natural hazards? ICESat-derived elevations, in combination with historical DEMs, have been used to document ice volume change in the mountain glaciers in Alaska (Sauber et al. 2005, and Muskett et al. 2007). The large ice changes documented in these and other studies cause stress changes large enough to influence the timing of earthquakes (Sauber and Molnia 2004).

Although some attempts have been made to directly observe land surface elevation change from repeated ICESat tracks, to date, these results have been of limited value. In spite of providing a very accurate estimate of elevation on a footprint-by-footprint basis, their value is best exploited when used in combination with other data sets. Because land topography varies at very short wavelengths and because of the undersampled ICESat-I profiles, even when "precisely" repeated, are usually displaced cross-track by 10s to 100s of meters, it is very hard to differentiate elevation change from simple elevation differences between profile locations. However, the value of accurate and globally consistent topographic data, in particular in areas that are difficult to access by other means, remains an important component which complements other observations needed.

When used to produce high-resolution DEMs, laser altimetry makes extremely important contributions to solid Earth science. This is done now with scanning airborne laser altimeters and which may be done in the future from space, as recommended by the National Research Council (NRC) Decadal Survey in the form of the Lidar Surface Topography (LIST) mission.

2.6 Hydrology

From the perspective of surface hydrology, the ICESat-II sensor, with its focus on ice sheets and terrestrial biomass, will be monitoring relatively slowly changing surface processes. Because of this, the sampling design will be characterized by observation repeat frequencies on the order of weeks to months, although flexible pointing capability may permit more frequent observations over a few designated targets.

Consequently, the types of surface hydrologic processes that can be addressed with the ICESat-II sampling configuration will be those with comparatively slower time scales. They include the dynamics of principally i) stored liquid water in the forms of lakes, reservoirs, and wetlands, and ii) stored frozen water over land including snow pack and ice. If repeat observations are made on the order of several days, ICESat-II can also monitor iii) river height and discharge from large basins on the basis of observations of water level and slope, and surface knowledge about the river bedforms.

These three types of observations have immediate societal relevance in that they will contribute to improved knowledge of global water cycle science and also enhance decision making in a number of applications including water resources, agriculture, disaster management, and public health. US Department of Agriculture (USDA) accuracy requirements for lakes monitoring include near-real time observations needed (1 week) at 10 cm vertical accuracy for large lakes, 25 cm for long-term trends, or for those reservoirs undergoing large (greater than 5 m) seasonal amplitude variations will partly be satisfied by ICESat-II observations. Observations of flood events, however, that require observation repeat frequencies on the order of several times per day, will not be likely with ICESat-II.

2.7 Atmosphere

The atmospheric lidar measurements on ICESat-I are already followed by another NASA instrument (CALIOP[11] on CALIPSO[12]) and an ESA mission in development that includes cloud and aerosol laser profiling from space. ICESat-II is directed toward surface measurements and does not have a currently stated atmospheric objective. However, the ICESat-II instrument capability as now defined will have at least the atmospheric profiling capability of the ICESat-I 1064-nm channel, therefore, the following questions need to be addressed:

- What would be the value and what would be the best approach by NASA to maximize the scientific return and cost effectiveness of the observations?
- How will the ICESat-II atmospheric measurements complement the many other NASA and international missions making cloud and aerosol measurements?

Even if the mission is limited to the measurements demonstrated by the GLAS 1064 nm data on ICESat-I, the mission will still detect and profile 80–90% of all the cloud and aerosol layers that the more sensitive 532-nm channel detected in the GLAS data. The detection of cloud and aerosol layers by the GLAS 1064-nm channel independently has been shown to be better, and more consistent, than most passive cloud retrievals. In addition, it also uniquely provides the height distribution of the clouds. Significant applications, such as polar clouds and haze, global pollution aerosols, planetary boundary layer height, global cloud change monitoring, and others can be observed by the 1064-nm channel. A particular issue unique to the ICESat-II potential for cloud measurements are the changes in polar clouds associated with the reduction in Arctic ice cover.

Other than polar clouds, the data will also provide a major part of the global atmospheric observations that were the basis for the CALIPSO mission, such as global height distribution of aerosol and subvisual clouds. The sensitivity will be at least sufficient to profile all scattering layers down to an optical thickness of 0.1. The 94° orbit again introduces the limitation of non-simultaneity with passive sensors on sun synchronous

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[11] CALIOP: Cloud-Aerosol Lidar with Orthogonal Polarization

[12] CALIPSO: Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations

platforms. There is, however, a phased repeat of crossing time with seasonal cycle, and for high latitudes all orbits overlap. For applications related to polar climate change, observations can be readily merged.

In addition, use of the direct atmospheric measurement to clear and correct surface altitude errors caused by multiple scattering in clouds and aerosol layers was a significant part of the plan for altimetry accuracy on ICESat-I. The correction for surface altitude from atmospheric propagation effects must also be addressed for ICESat-II.

3. ICESat-II Science Questions/ Objectives

The ICESat-II community consists of researchers focusing on the following components of the Earth System: ice sheets, sea ice, vegetation, solid Earth, land hydrology, and atmosphere. The critical scientific and societal-benefit questions raised by these communities at the Workshop follow, listed by discipline.

3.1 Ice Sheets

The Ice Sheet Working Group posed the following science questions for ICESat-II to address:

- How are the volumes of the Greenland and Antarctic ice sheets and other smaller ice masses changing, and what is their impact on sea level rise?
- What are the detailed changes of the more dynamic areas of the ice sheets?
- What changes are occurring at the floating ice shelf and ice tongue fronts and how do they propagate to the interior ice sheet?
- What effect does subglacial water storage and release have on ice flow? How much water moves between Antarctic subglacial lakes and what is the total water budget?
- How do small-scale (few-kilometer) undulations, dunes, and glaze regions affect the distribution of snow accumulation?

ICESat-II is expected to operate continuously, and will therefore acquire a much denser grid of elevations over the ice sheets while still periodically repeating the 33-day track of ICESat-I. The continuous operation of ICESat-II will include the combination of the following two orbit phases:

(a) Mapping pattern with an annual phase that will provide dense track spacing, and

(b) A shorter repeat-track phase with a seasonal or semi-annual repeat pattern.

The combination of these patterns will make four kinds of observations for ice sheet science:

1) Detailed surface mapping—The dense spacing of the ICESat-II mapping phase will provide more details and more accurate DEMs, mapping the catchment basins, undulations, and outlet glaciers in greater detail.

2) Long-term repeat measurements of elevation change—The seasonal repeat-track pattern will provide year-round seasonal coverage of the changes in the interior of the Greenland and Antarctic ice sheets, as well as some measurements of the critical outlet glaciers through periodic off-pointing. The repeat tracks and crossovers provide a valuable retracing of the tracks and crossovers acquired by ICESat-I. The combination of the ICESat-I and ICESat-II records will provide an ~15-year record of changes in ice sheet elevations.

3) Mapping of active Antarctic subglacial lakes—The repeat-track phase of ICESat-II will allow further study of subglacial lakes, and may lead to the discovery of additional lakes. In particular, the possibility will exist of understanding on a year-round basis, the flow of water between these lakes. Current inventories state the total number of large lakes at approximately 150, but recent results from ICESat-I and ERS radar altimetry show that the number is much higher, and that water movement occurs between lakes. Because some of these lakes underlie and may lubricate important outflow glaciers, this information is essential to understanding Antarctic ice dynamics.

4) Snow accumulation rates—The repeat-track phase of ICESat-II will permit a much better quantification of the seasonal cycle of accumulation, and of the local redistribution of snow.

3.1.1 Ice Sheet Science Priorities for ICESat-II

i) Improve current knowledge of ice sheet volume change and of how these changes are related to environmental change with a goal of **improving the predictive capability of ice sheet and glacier numerical models**.

ii) Establish and monitor the long-term mass balance of the ice sheets and glaciers as a means of **assessing the contribution of the cryosphere to sea level rise**.

An emphasis on i) leads to a strong mission priority towards denser coverage, because it is clear from aircraft and surface investigations that important, poorly understood processes at the margins of the ice sheets (where track separation is large) greatly and rapidly control the mass balance of large catchment areas. Such studies further support the requirement for an agile spacecraft, which will be necessary to obtain measurements of specific processes (ice shelf breakup, glacier surge, melt season ablation).

Considerations of ii) leads to a requirement for seasonal (or similar) repeat measurements so that annual variations in the mass flux of the ice sheet can be better constrained and removed from the long-term trend. This further supports GRACE–ICESat-I combined determinations of mass balance change. It also leads to support for occasional very-high-density coverage for baseline DEMs at higher detail.

Ultimately, these considerations need to be weighed against each other in the context of mission priorities to determine the optimum operating scenario.

3.2 Sea Ice

- What are the thickness distributions of Arctic sea ice, and how are they changing?

For sea ice, the Arctic summer ice cover in particular is undergoing a serious decrease in its areal extent. Changes in thickness, however, are less certain, although a broad trend towards significant thinning is indicated. As the Decadal Survey states, “*High accuracy altimetry will also prove valuable for making long-sought repeat estimates of sea ice freeboard and hence sea ice thickness change, which is a parameter used to estimate the flux of low-salinity ice out of the Arctic basin and into the marginal seas. As yet, altimetry is the best (and perhaps only) technique for making this measurement on basin scales and with seasonal repeats.*”

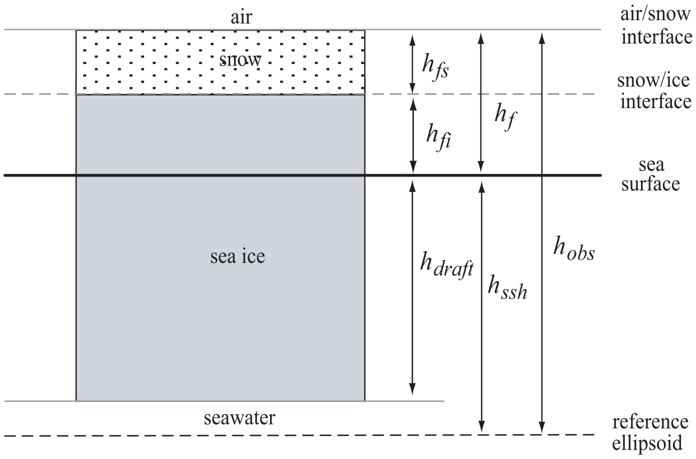

Figure 9. The snow (h_{fs}) and ice (h_{fi}) components of the total freeboard (h_f), from which thickness can be estimated. That portion of the sea ice below the sea surface is h_{draft}, the elevation of the sea surface from the reference ellipsoid is h_{ssh}, and the elevation measured by ICESat is h_{obs} (figure courtesy Ron Kwok).

The ICESat-II lidar measurements however, provide only part of the solution for the measurement of ice thickness. As Figure 9 shows, sea ice has a ‘layer cake’ structure, with a snow layer lying above an ice layer. The mass of the snow weighs down the underlying ice, so that the freeboard, or height between the open water surface and the snow surface, depends on both the snow and sea ice thicknesses, as well as on the densities of the two materials. Because the laser measures only the height of the snow surface relative to the height of an open water surface, to determine the ice thickness the freeboard of the sea ice/snow interface must also be determined, a challenge not mentioned in the Decadal Survey.

There are several solutions to this problem. First, Kwok et al. (2007) estimated the snow layer thickness, both from climatology, and from ECMWF[13] snowfall. The snowfall method depends on tracking the motion of the floe field, then overlying the ice floes with the geographically specific precipitation. From comparison of the ice thicknesses and snow depths observed by ICESat-I with those measured by a NOAA[14] ice-thickness buoy and field observations, Kwok et al. (2007) showed that the snow depths are within several centimeters and the thicknesses are within 0.5 m, or within 25%, of the observed.

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[13] ECMWF: European Centre for Medium-Range Weather Forecasts

[14] NOAA: National Oceanic and Atmospheric Administration

Second, because a satellite radar altimeter penetrates through the snow and is reflected from the snow–ice interface, the altimeter can measure the sea ice freeboard, but not the snow surface freeboard. Because the lidar measures the first return surface elevation, a combination of satellite radar and lidar can measure both the air–snow and snow–ice freeboards. This suggests that the sea ice thickness measurements could benefit significantly by combining laser altimetry measurements with nearly coincident radar altimetry observations. Efforts should be made to identify such complementary radar altimetry measurements in the time frame of the ICESat-II. *A strategy to determine the best approach to estimate snow loading for conversion of sea ice freeboard to ice thickness is critically needed.*

3.3 Vegetation

- What is the global distribution of carbon stored in the above- ground biomass of forests?

For vegetation, the measurement of the relative height between the laser reflection from the canopy and the reflection from the ground through gaps in the canopy provides an estimate of canopy height. For the ICESat-I laser, with its nominal surface spot size of approximately 65 m, the measurements yield canopy height with an accuracy of ±5 m, and estimates of above-ground biomass with errors of 25–30%. This capability permits useful regional (i.e., county or province) level biomass surveys. Smaller-scale biomass assessments require greater accuracy. Using conservative assumptions, a <25-m footprint would reduce the canopy height error to ±1 m, and the above-ground biomass error to 10% with sufficient sampling density. The Vegetation Working Group prefers a footprint with a less than 25-m diameter, and the ability to point the laser off track less than 2°, to fill in gaps in land coverage and increase sampling density.

3.4 Solid Earth/Hydrology

- Given that ICESat-I provides, and ICESat-II *will* provide, a global set of land elevation data referenced to an absolute datum, how is land elevation changing? What can elevation changes occurring near volcanoes and tectonic boundaries tell us about future natural hazard events in these regions?
- Are there changes in fresh water land storage and runoff? What is the inventory of land storage of water, and how does it change seasonally and interannually? What effect is climate change having on water storage in various regions of the Earth?

The most important ICESat-I contribution to solid Earth/hydrology is that it provides, relative to a global reference datum, accurate heights of the land and water surfaces that are used to calibrate and validate elevations derived from other techniques, and to measure surface change along profiles. All working groups suggest that ICESat-II should be designed to be more agile than ICESat-I with an improved pointing accuracy, so that the satellite can follow, on a repeat basis, elevation changes associated with natural hazards such as the pre-eruptive dome inflation at Mount St. Helens, and precursor vertical movements near earthquakes (Figure 10). The lidar observations can also be used to observe long wave post-glacial rebound signals, and to observe fault zones that are not visible in InSAR.

For hydrology, ICESat-I data has measured the slope of the Mississippi River (Figure 11). Smaller spot sizes with higher pulse-repetition rates provide more detail on smaller rivers. This information, combined with the surface-measured river bed-form measurements, would allow estimates of the river flow rates from space. Furthermore, ICESat-I global water stage measurements have shown to be invaluable where station data are not available. Nominal ICESat-I observations have been used to monitor the water levels at the largest reservoir in the world in China (Three Gorges Dam, on the Yangtze River, Figure 12). These observations have been used to validate GRACE estimates of mass changes due to the impoundment of the reservoir through time.

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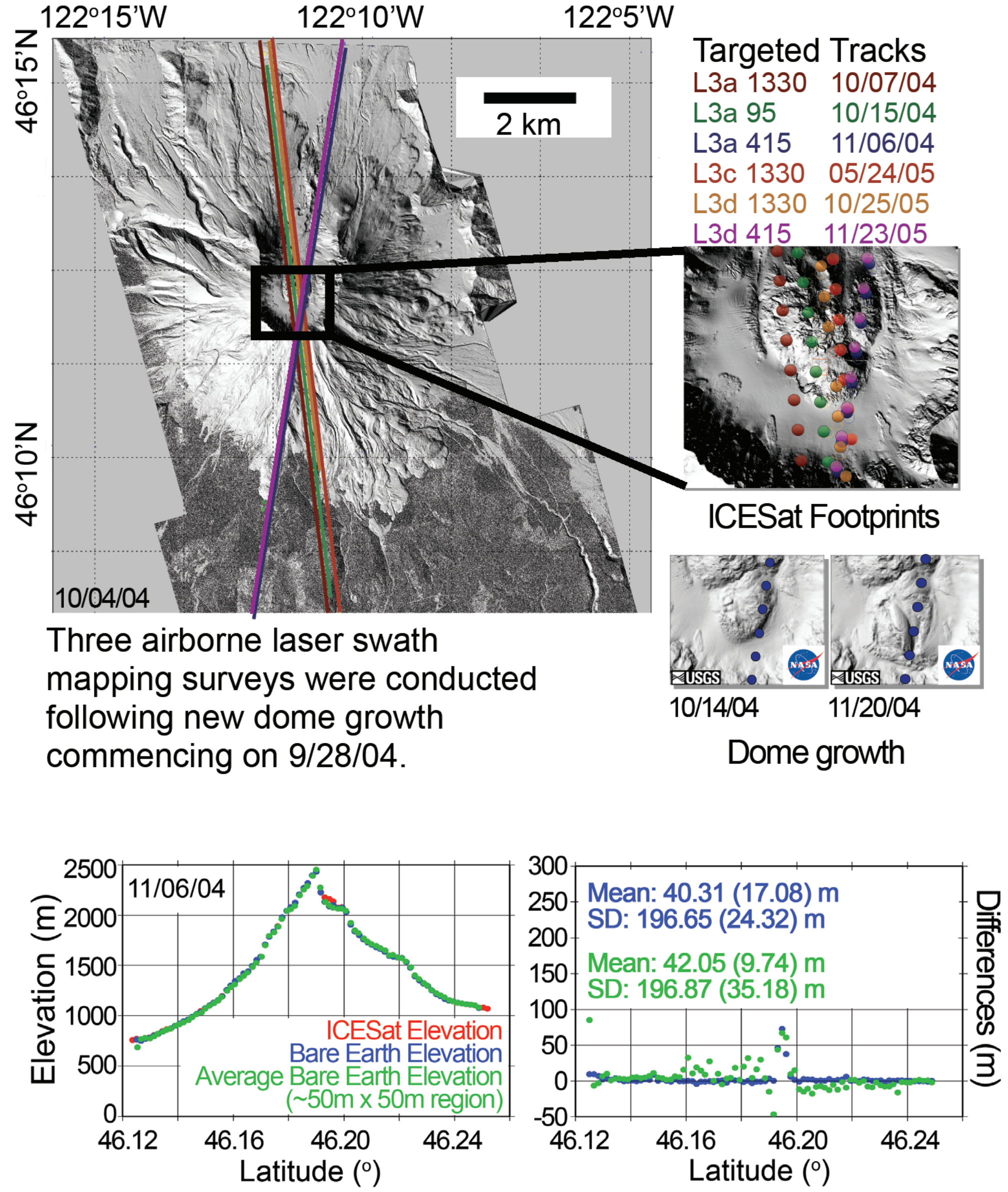

Figure 10. Elevation changes due to natural hazards: Monitoring the volcanic dome growth of Mt. Saint Helens, Washington State. ICESat's off-pointing capability allows the observation of targets of opportunity (TOOs) with an accuracy of 50 m ±150 m (3 σ). After the onset of St. Helens' activity, ICESat was able to monitor the dome growth. ICESat targeted profiles for 2004 and 2005 are shown superimposed on high-resolution airborne laser swath mapping topography (top), taken on October 4, 2004. The inset shows a close up of the dome region and the ICESat footprints for the shown profiles, over USGS airborne photos of the dome taken on October 14 and November 10, 2004, following the onset of activity. The bottom figure shows an ICESat elevation profile taken on November 6, 2004 (red dots), along with the "bare Earth" elevation profile (blue) and the average "bare Earth" elevations for a 50 m × 50 m region (green). ICESat elevation differences with airborne mapping are shown on the right, along with mean and standard deviation values for the dome region. These elevation profiles provide the first profiler laser altimeter measurements of a deforming volcano from space (Carabajal et al. 2005).

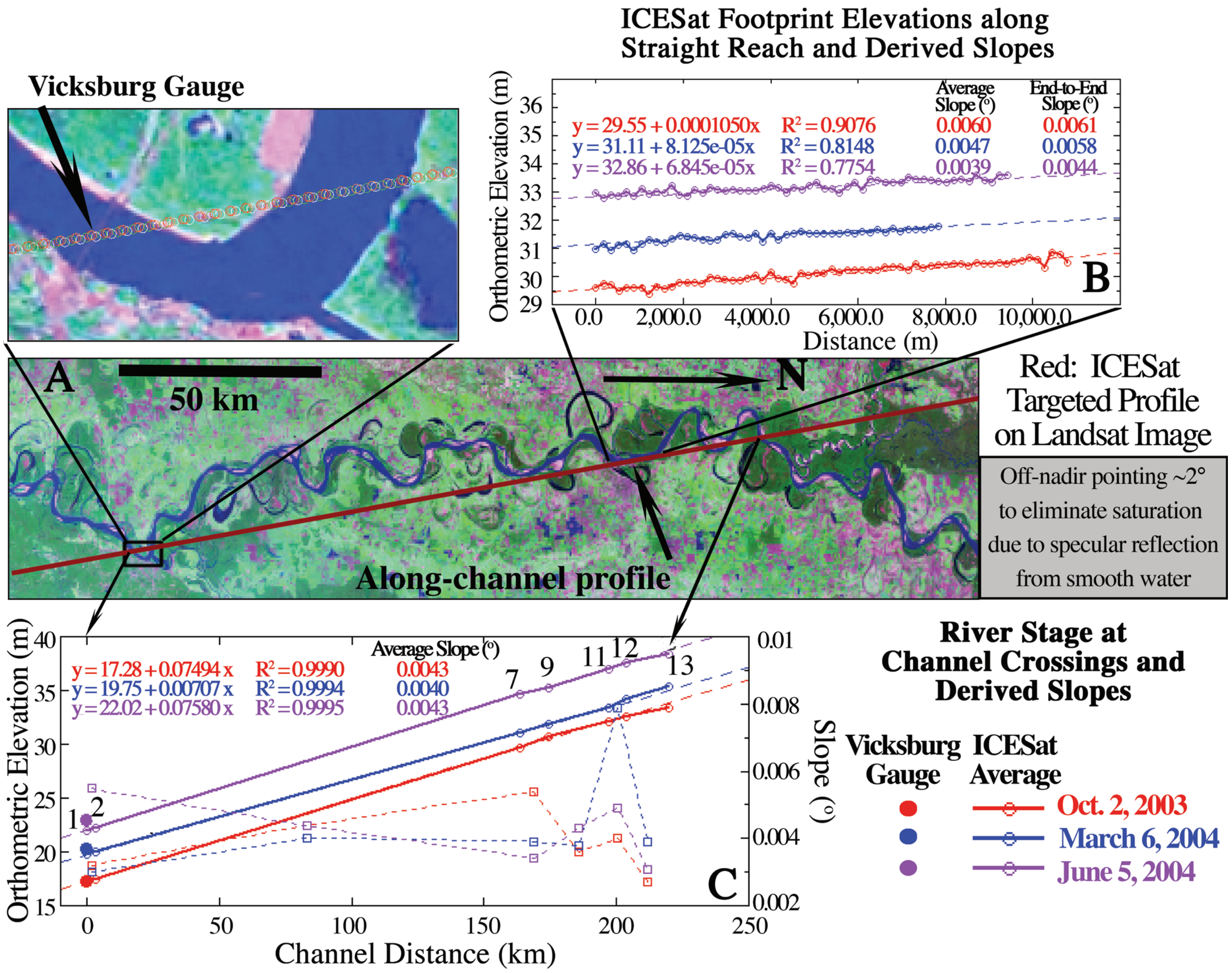

Figure 11. River stage (water surface height) and slope for three ICESat profiles targeted to cross the lower Mississippi River at multiple locations. Middle: a Landsat TM false color image in which water appears blue with the location of the targeted profile superimposed (red). Top right: individual footprint elevations (circles) along a channel segment and the derived local river surface slope (dashed lines). Bottom: river elevations where crossed by the ICESat profiles (pluses), the derived average surface slope of the river between Vicksburg, MS (inset, top left) and the Arkansas River (dashed line), and the river height recorded by the gauge station at Vicksburg at the time of the ICESat overpasses (filled circles). River targeted profiling by ICESat-I provides river stage and slope measurements for water discharge, demonstrating the potential of these type of observations for hydrological applications (Harding and Jasinski 2004).

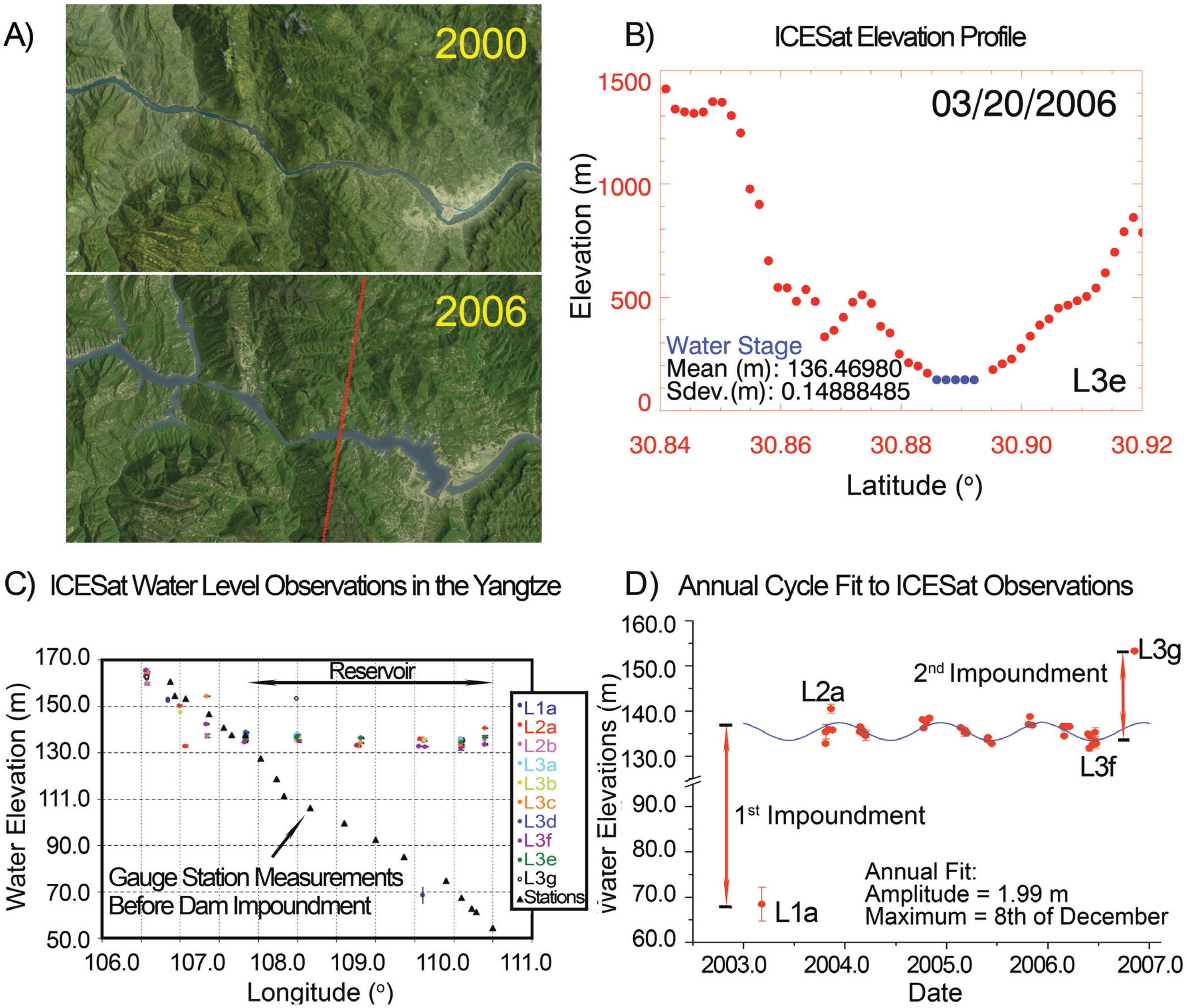

Figure 12. Monitoring the impoundment of the Three Gorges Reservoir (TGR). Figure 12A shows two images taken by ASTER on July 17, 2000 and May 14, 2006, respectively. In 2000, the dam construction was underway; by mid-2006, construction of the main dam was completed and the reservoir had filled, extending more than 2 miles (3 km) upstream. Figure 12B shows an example of an ICESat-1 elevation profile close to the TGD taken on March 20, 2006 (L3e campaign), along the red ground track shown in Figure 12A. ICESat observations show that the reservoir levels had reached 136.47 m (±0.149 m), compared with 55 m before impoundment. Figure 12C compares the surface gauge station elevation measurements before the reservoir was filled (black triangles), with the average ICESat measurements of water levels measured during the various campaigns, showing different levels of the impoundment. Figure 12D shows the fit of the annual cycle to the ICESat-1 time series, as well as the impoundment heights. Fluctuations in reservoir levels are caused by the variability associated with hydroelectric power generation. Images created by Jesse Allen, Earth Observatory, using ASTER data made available by NASA/GSFC/MITI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team. (Carabajal et al. 2006).

changes due to the change in water volume with time (Carabajal et al. 2006)

3.5 Atmosphere

- How are the distribution of atmospheric clouds and aerosols changing, especially at high latitudes?

Lidar profiling of clouds from space by ICESat-I, as continued by the CALIPSO mission, gives essential observations of the global distribution of cloud and aerosol that are not provided by passive sensors. The lasers contribute in two ways: (1) the cloud and aerosol height distribution are measured, and (2) much thinner optical scattering layers are detected. As demonstrated by the existing ICESat-I and CALIPSO missions, these measurements provide a unique input to passive observations and climate models, and over time, show the response of cloud and aerosol distributions to changing climate. These observations are needed over the long term, and must be made in a consistent manner. Because a lidar system capable of high precision surface ranging is also of sufficient power and aperture to profile a significant fraction of the global cloud and aerosol distribution, cloud and aerosol signals obtained from ICESat-II can address important climate questions.

Few atmospheric science objectives are more important than the long term monitoring of changes in polar cloud cover. As shown in Spinhirne et al. (2005) and in Figure 13, a large fraction of polar cloud cover is missed in passive sensing (e.g., satellite visible-infrared, or thermal, images), and passive-based cloud height observations are even less accurate. Because the albedo of clouds and snow are nearly identical, it is almost impossible to accurately retrieve polar clouds from passive visible-infrared sensor observations. If the Arctic sea ice area continues to decrease in summer, the increase in open water area should be associated with large changes in cloudiness. The results from ICESat-I show that existing passive cloud retrievals are not adequate to observe cloud changes in the Arctic and Antarctic with the necessary detail and accuracy.

The importance of Arctic clouds is that they have large climatic feedback effects. These feedbacks occur at both the longwave and shortwave parts of the surface energy balance spectrum, although the primary effect may be at the longwave, because it operates all year. While CALIPSO and CloudSat are currently providing a great deal of excellent data, both missions are expected to end before the time of an ICESat-II launch. Based on the present rate of change in Arctic ice cover and atmosphere aerosol loadings, large changes in cloud and aerosols are expected in the coming decade. Therefore, observations of clouds and atmosphere from ICESat II will be important for climate models and forecasts—not just in the Arctic, but worldwide. NASA should exploit this value of the mission investment.

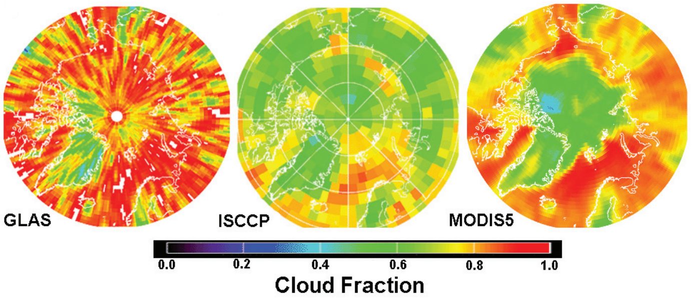

Figure 13. The comparison of the total fraction of clouds detected in the Arctic for October 2003 from GLAS to results for the same period for the International Satellite Cloud Climatology Project and the current MODIS cloud retrieval. The greater sensitivity and discrimination of the laser sensing results in much greater detection for clouds of optical thickness less than 0.2 (figure courtesy of James Spinhirne).

4. Synergistic Missions and Observations Needed to Fulfill the Science Objectives

What other measurements are necessary to achieve the mission science?

The Workshop identified several measurements, synergistic missions and other observations to fulfill the ICESat-II science objectives. Some of these were recognized to be critical to the mission, in that they were required to produce the ICESat-II elevation data products at the level of ICESat-I accuracy. For example, to obtain the desired accuracy in Precision Orbit Determination (POD) and laser pointing accuracy, or Precision Attitude Determination (PAD), the mission will require the support of the geodetic networks used in orbit determination. Other related satellite observations that support the ICESat-II objectives differ among the disciplines.

4.1 Critical Measurements for Generating ICESat-II Data Products

Critical measurements include the following:

- Meteorological data from the National Center for Environmental Predictions (NCEP) provides atmospheric pressure models for the tropospheric and the inverse barometer correction;

- Solar flux measurements (ground-based at a network of stations) used in the POD provided by the NOAA Space Environment Center;
- Continued support by NASA of the International GPS Service (IGS) that maintains the global network of GPS stations, used in the POD;
- Continued support of the International Earth Rotation System (IERS) and the International Terrestrial Reference Frame (ITRF);
- Continued support of the International Laser Ranging Service (ILRS), which provides the Satellite Laser Ranging (SLR) observations used to validate the ICESat POD; and
- Support of the International Celestial Reference Frame (ICRF) used for POD and PAD.

4.2 Other Supporting Measurements and Missions

4.2.1 Ice Sheets

The complementary satellite, and other observations, that can improve interpretation of ICESat-II data over ice sheets include a number of aspects:

InSAR will provide measurements of ice velocity to provide high resolution, contemporaneous ice flow velocity measurements to get a better understanding of surface processes. This is critically important for the narrow outflow glaciers. The current and future sources for such measurements are expected to be RADARSAT-1[15], RADARSAT-2, TerraSAR-X[16], TanDEM-X[17], Envisat, ALOS/PALSAR[18] (L-Band), and the DESDynI mission.

A **GRACE follow-on mission** will give improved estimates of mass and volume changes for the ice sheets. Over the ice sheets, the simultaneous operation of ICESat-I and GRACE permits improvement in the measurements of post-glacial rebound, and allows conversion of the GRACE-determined changes in ice mass measurements to the ICESat-I–determined changes in ice volume. Thus, there would be great value to having the GRACE-II mission overlap in time with ICESat-II.

Visible satellite imagery with medium resolution (250 m): The ICESat-II science requires ongoing acquisition of images for data interpretation. For example, because the NSIDC[19] 2002 Mosaic of Antarctica (MOA) played a significant role in discovering water movement through the subglacial lakes, scientists need to ensure that VIIRS[20] can produce a similar product for ICESat-II. Images at this resolution also assist in the interpretation of ice shelf rifts and calvings, ice sheet dunes, grounding line changes, and icebergs. High radiometric sensitivity is key to extracting important information from moderate resolution sensors over ice sheets. High resolution (15–30 m) visible imagery e.g., ASTER, or its equivalent, for producing stereo DEMs for understanding ice sheet and glacier dynamic and surface processes, and surface feature tracking. Both medium and high resolution images can support DEM generation from laser altimetry through photoclinometry ('shape from shading'). Note that for ICESat-I, acquisition of high-resolution image data close in time to specific laser profiles has been difficult.

CryoSat-2 radar altimeter for providing independent estimates of elevation change. CryoSat-2 is currently a three-year mission scheduled for launch in 2009, with a nominal 3-year lifetime. ESA missions, however, have consistently exceeded their lifetimes, and CryoSat-2 will carry sufficient fuel for a six-year lifetime, or until 2015.

Airborne laser altimetry for providing detailed measurements of changes along major outlet glaciers that are of a geometry, scale, and orientation that is not fully captured with the ICESat-II mission. Such measurements would support detailed modeling of outlet glacier flow processes.

Cal/Val: The ice sheet program will need airborne and *in situ* data for calibration of range, pointing, and other parameters

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[15] RADARSAT: Radar Satellite

[16] TerraSAR-X: A German Earth observation satellite that uses an X-band SAR

[17] TanDEM-X: TerraSAR-X add-on for Digital Elevation Measurement

[18] ALOS/PALSAR: Advanced Land Observing Satellite/Phased Array type L-band Synthetic Aperture Radar

[19] NSIDC: National Snow and Ice Data Center

[20] VIIRS: Visible Infrared Imager Radiometer Suite

such as reflectivity, roughness, firn compaction, surface melt, and blowing snow. In addition, the possibility should be considered for a Research and Applications (R&A) program for Cal/Val related research.

There are other complementary observations that would facilitate interpretation of the ICESat-II observations, but they are not at the level of missions or Cal/Val efforts that would typically be within NASA's domain. These would include GPS and seismic measurements to improve the Post Glacial Rebound/Glacial Isostatic Adjustment (PGR/GIA) correction and understanding of these dynamic processes; measurements of ice sheet thickness to facilitate ice sheet and outlet glacier modeling; and historic accumulation rates, such as those obtained from ice cores and ice penetrating radar observations.

4.2.2 Sea Ice

ICESat-II will contribute significantly to the Decadal Survey goal of understanding the response of the sea ice cover to local and global climate by providing long-sought estimates of thickness. To meet the goals of sea ice science, the following program is recommended:

- Plan coordinated airborne and field programs for the validation of ice thickness determined from ICESat;
- Assess the sources of snow depth and its spatial distribution to determine the best suitable for use in converting freeboard to ice thickness;
- Characterize and understand the differences between the thickness estimates from ICESat-I, and Envisat/ERS-1 and -2 altimeters.

Some of this work is already in progress. Because ICESat-II will follow, and perhaps overlap, the CryoSat-2 mission that carries the SIRAL altimeter, the importance of the cross-comparison/calibration of the ice thickness records from the two altimeters should be stressed; consistent observations of sea ice thickness from the two instruments and those of ERS-1, -2/Envisat should allow for a two-decade record of ice thickness estimates.

For sea ice science, uncertainties in snow loading introduce large errors in the retrieval of ice thickness. It is clear that the non-simultaneous radar or lidar measurements (e.g., from CryoSat-2 and ICESat-II) may be useful, but still not the best for snow depth estimation—radar echoes are from the snow–ice interface, while lidar returns are from the air–snow interface. The sea ice breakout group recommended that a combined radar–lidar instrument be explored for obtaining estimates of snow depth by obtaining a radar for ICESat-II through a partnership with an international agency that would be interested in these simultaneous observations.

Because ESA has invested significantly in sea ice thickness retrieval from radar altimeters (CryoSat-1 and -2, Envisat, and ERS-1 and -2), it would be worth approaching ESA to see if they could provide a Ku-band radar altimeter to the ICESat-II platform. In addition to that of sea ice, a radar–lidar combination could also contribute to a wide range of other science disciplines e.g., snow cover on land, as well as addressing the penetration issue over ice sheets. Such an instrument could contribute significantly to the advancement of earth science. In addition to snow depth, and from field studies with multi-agency and international support, the following field measurements are also important:

- Measurements of Arctic and Antarctic snow and sea ice densities will improve the accuracy of the freeboard and ice thickness determinations;
- Better observations of the polar sea surface height and tides will improve the geoid accuracy.

Prior to the launch of ICESat-II, the following opportunities involving ICESat-I, Envisat, and CryoSat-2 should be explored:

- Validation of the lidar/radar procedure by pointing the ICESat-I lidar to the Envisat or CryoSat-2 ground track for coincident snow/ice thickness estimates;
- Analysis of currently available ICESat-I and satellite radar data, to further our understanding of the efficacy of combined lidar/radar observations for snow depth estimation; and
- Analysis of airborne radar/lidar measurements coincident with spaceborne altimetry.

4.2.2.1 Supporting Imagery and Analyzed Fields

If snow thickness is determined by other sources of satellite data or by precipitation, then Lagrangian tracking of the ice floes will be required. This requires determination of the ice kinematics from high-resolution SAR imagery. The ice concentration fields, as provided by high-resolution NIR, scatterometer and high resolution, passive microwave data, are also important in the validation and verification of the ice thickness estimates. Finally, for sea surface height, an improved Arctic geoid from GOCE[21] is also needed.

4.2.3 Vegetation

Existing and future remote sensing data sources could potentially be combined with ICESat-II canopy height measurements to enhance carbon science and allow extrapolation of ICESat-II measurements to finer scales with higher accuracy. These ancillary data sources include:

- Land cover maps at 30-m spatial resolution (Landsat equivalent);
- Cover type: for example, evergreen (e.g., broadleaf, needleleaf), broadleaf deciduous, and so forth;
- Biophysical characteristics: cover density, crown and stand morphology;
- Topography: a global topography data set such as that derived from TanDEM-X is required to compensate for surface slopes in the observed fields;
- Vegetation phenology observations, which are seasonal changes in land cover such as flowering or leaf production, are derived from MODIS or VIIRS;
- Land use history of successional status;
- Data to drive and validate the carbon flux and succession models;
- VIIRS products to relate interannual variations in global areas of fire disturbance to changes in atmospheric CO_2 concentrations;
- Access to data from the Orbiting Carbon Observatory (OCO) and successor satellites, where these missions provide a “top-down” inference of regional carbon flux to understand source-sink mechanisms;
- Access to ALOS-PALSAR/InSAR and PALSAR dual polarization data to develop techniques for height and direct biomass inference.

4.2.3.1 A Research and Applications (R&A) Program

The Vegetation Working Group expressed the concern that their technology readiness for extrapolating lidar samples to finer landscape scales for carbon flux and succession modeling is low with unknown risk. The use of ICESat-II measurements in conjunction with the above ancillary data to extend canopy height and biomass estimates beyond the ICESat-II lidar samples requires further research and development. Thus, a robust R&A program will be essential to develop and validate techniques to extend lidar height information to finer scales using InSAR, SAR, and passive optical images. This program could be done jointly with the DESDynI mission, and would include the following:

- Aircraft campaigns across, and within, key biomes to develop and validate algorithms using the above sensors;
- Development and maintenance of airborne lidar instruments and access to commercial data sets;
- Augmentation of the number and distribution of field sites with *in situ* characterization;
- Collaboration with international flux sites to obtain data to force and validate the carbon flux and succession model;
- Standardized protocols for, and data access to, the network of field plots that will be observed with ICESat-II.

4.2.3.2 Calibration and Validation (Cal/Val) for Vegetation Research

A Cal/Val component for the ICESat-II vegetation component is critical. Existing ground plots are of little use for the ICESat-I GLAS validation because it is unlikely that they would be co-located and co-registered with a GLAS pulse; therefore, ground plots need to be established as part of an ICESat-II vegetation component. It is strongly recommended that standardized protocols for establishing ground plots be developed and that these be made available to the greater community. A coordinated global ground plot activity should be considered. Additionally, it is strongly recommended that a Cal/Val program of airborne lidar campaigns be established, also using standardized measurement protocols to the extent possible.

4.2.4 Solid Earth/Hydrology

The measurements and network infrastructure needed to fulfill the solid Earth and hydrology science objectives largely

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[21] GOCE: Gravity field and steady-state Ocean Circulation Explorer (ESA)

overlap with those needed by the other disciplines. Several auxiliary data sets of interest include those discussed in detail in the ice sheets, sea ice, and vegetation sections. Measurements that help improve accurate geolocation of the altimetry measurements are critical. Precise location, or precise orbit determination (POD), and pointing or precise attitude determination (PAD), are required for generating accurate elevation data products to support solid Earth and hydrology objectives.

Complementary satellite missions

SAR: The TanDEM-X Mission, due to launch in late 2008, with a polar synchronous orbit at 514 km and an 11-day repeat cycle, will fly in close formation with TerraSAR-X, launched in July 2007. These will provide accurate, consistent, high precision, global DEM products. The ICESat-II observations can contribute to assessing the accuracy of those data sets, and well as improving them when used as geodetic control points.

The CryoSat-2 Interferometric SAR (InSAR) mode, which is used over the steeply sloping ice-sheet margins, small ice caps, and areas of mountain glaciers, will provide a valuable data set when combined with ICESat-II altimetry, especially in the vicinity of plate boundaries.

The DESDynI mission will address major questions in the areas of plate-boundaries deformation, land-surface evolution, ice dynamics, volcanism, and mantle dynamics. Data products from this mission, especially if flying in the same time frame, will contribute a valuable complementary data set to the ICESat-II observations. Although global/regional DEMs are not planned as an output of the mission, those produced as the result of the DESDynI mission could be used in combination with ICESat-II altimetry. Conversely, the ICESat-II altimetry can improve the quality of the InSAR DEMs by provision of accurate ground control.

The ESA mission Sentinel-1 satellite will carry a C-band SAR, which should address the issue of data continuity for C-band SAR data after Envisat. The Sentinel-1 satellite is planned for launch in 2011 before the end of Envisat.

Visible/infrared (VIR): The Sentinel-2 satellite will continue the provision of the high-resolution VIR currently being provided by data from the SPOT or Landsat series of satellites, ensuring continuity of data availability. Sentinel-2 and -3 will cover the land surface requirements at a lower spatial resolution and high revisit optical imaging, and will ensure continuity of MERIS[22]-Envisat and SPOT[23]/AVHRR[24] observations. Other VIR missions important to the success of the land measurements include ASTER and VIIRS.

Gravity measurements: ICESat-II observations that are simultaneous with a GRACE follow-on mission are highly desired, because accurate determination of the Earth's gravity field over a wide range of spatial scales is fundamental to understand the structure and dynamics of the solid Earth. Gravity, combined with accurate topography, can help resolve the compositional, thermal, and mechanical structure of the deep crust and upper mantle, and help elucidate aspects of the plate tectonics processes and their surface manifestation when earthquakes and volcanic eruptions occur. The ESA GOCE mission, scheduled for launch in 2008, will enhance scientific knowledge of the Earth's gravity field and geoid by orders of magnitude. GOCE data will have many uses, such as probing hazardous volcanic regions and bringing new insight into ocean behavior. Although this 2-year mission will not be flying at the same time as ICESat-II, ICESat-II would still benefit from the improved gravitational potential, especially as it pertains to improved orbitography, and more accurate determination of orthometric elevations needed for solid Earth/hydrology studies.

Complimentary data

Surface and airborne observations: High resolution DEMs from airborne lidar scanning systems and from *in situ* stations are required for Cal/Val of ICESat-II land products.

Global Circulation Models (GCMs): Current GCMs are key in aiding the interpretation of the various contributions of the hydrology components to the mass/equivalent water elevation changes induced by the hydrology. ICESat-II lidar measurements can validate water elevation changes. In addition, atmospheric circulation models provide an ideal environment for testing the importance of critical processes in a controlled fashion. Furthermore, regional topography can be embedded within the GCM to provide high resolution of the topographic forcing. In the case of GCMs, the models are not supporting the interpretation of ICESat-II measure-

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[22] MERIS: Medium Resolution Imaging Spectrometer

[23] SPOT: Système Pour l'Observation de la Terre (French remote sensing satellite)

[24] AVHRR: Advanced Very High Resolution Radiometer

ments, but rather ICESat-II would be supporting the GCM improvement and validation.

4.2.5 Atmosphere

Ancillary meteorological data: The retrieval of both surface ranging and aerosol and cloud backscattering data require the atmospheric temperature/pressure and humidity profiles. The temperature and humidity are necessary to calculate the optical path length through the atmosphere. The temperature/pressure profile is needed to calculate the molecular scattering cross section to calibrate and correct particle cross section. Surface wind speed is needed to derive ocean reflectance for several applications. Thus, for the data processing of the current mission, the meteorological output from NOAA operational weather models is a routine input and will be a required ancillary input for ICESat-II.

Airborne and surface site validation: Aircraft intercomparison experiments were used for ICESat-I to validate data. Routine comparison to ground-based Aerosol Robotic Network (AERONET) sites has been important to verify optical thickness measurements. Similar observations would be required for ICESat-II.

VIR (visible/infrared) imagery: In general, it is considered valuable if the lidar profiling of cloud and aerosol are combined directly with 2D images. The combination of the cloud and aerosol vertical structure with the horizontal structure from VIR images provides a 3D view of the atmosphere. There are dedicated missions, such as the ESA Earthcare program, which are based on the concept of combined active and passive observations of clouds including lidar and radar. Intermediate to a dedicated multisensor mission and an independent lidar profiler, the addition of an infrared (IR) radiance measurement is of particular value in combination with lidar cloud profiling, because it allows retrieval of cloud IR emissivity. For aerosol retrievals, the addition of visible spectral measurements also enhances the lidar measurements. To a degree, and especially for the polar regions, the ancillary spectral images can be merged from existing platforms. The merger with passive data for some applications has been readily accomplished for GLAS data, but of course the coverage and temporal coincidence has limits.

Signal depolarization: Measurement of lidar signal depolarization has an important application toward discrimination of the ice/water phase of cloud particles and some inference of particle shape. In and of itself, the radiative and dynamical properties of clouds are related to the measured phase, with the ice–water phase being particularly valuable. The calculation of the surface range delay correction is sensitive to particle shape, in addition to particle size, and the layer optical thickness. For this and other reasons, observations of signal depolarization could improve surface applications. It should be studied to determine whether there would be a significant advantage to a signal depolarization channel.

5. Spacecraft and Instrument Improvements for ICESat-II

To maximize the ability of ICESat-II to achieve its science objectives, what modifications should be made to the ICESat-I concept?

As part of the ICESat-II mission, the Workshop recommends that NASA examine the following issues and potential formulation studies.

5.1 Orbit, Track Spacing, and Repeat Period

To allow continuity with the existing ICESat-I track lines, there is a strong interest in repeating the ICESat-I 33-day tracks, which sets the orbit inclination. There was general agreement that ICESat-II be placed into an identical orbit as ICESat-I, with the 91-day seasonal orbit strongly recommended, utilizing the same ground tracks as ICESat-I. Once ICESat-II is launched, this orbit choice would provide the potential for a 15-year time series of laser observations. This orbit has a 25-km spacing at the equator that with off-track pointing, satisfies all disciplines, and contains the present 33-day cycle as a subcycle.

The consensus items of the ice sheets panel regarding orbit issues are as follows:

- The early mission testing might repeat the 8-day pattern of the ICESat-I initial Cal/Val phase for a calibration period of about 32 days and for analysis of elevation changes since 2003 along those tracks.
- The primary science mission should repeat the 91-day repeat pattern of ICESat-I including the 33-day subcycle for comparison with ICESat-I data, which approximately triples the spatial coverage, and provides up to four samples per year of each ground track for studies of seasonal cycles.

- The breakout group suggested that early in the mission, the satellite map one 183-day pattern of ground tracks. This would be accomplished by departing from the standard 91-day repeat tracks for one 91-day cycle to map a set of tracks that are shifted and interleaved with the standard pattern. (return to the following prose) This would provide a denser spacing for DEM mapping.

These recommendations lead to ICESat-II operating in two phases 1) a mapping phase with dense track spacing (183-day repeat period), and 2) a repeat-track phase with a seasonal or semi-annual repeat pattern (91-day repeat period).

Significantly increased spatial density of tracks over land, as required by the vegetation community, can be accomplished over time by the systematic off-nadir pointing capability demonstrated by ICESat-I. Figure 14 illustrates the track spacing (between adjacent ascending or descending track pairs), which could be achieved over time by cross-track pointing.

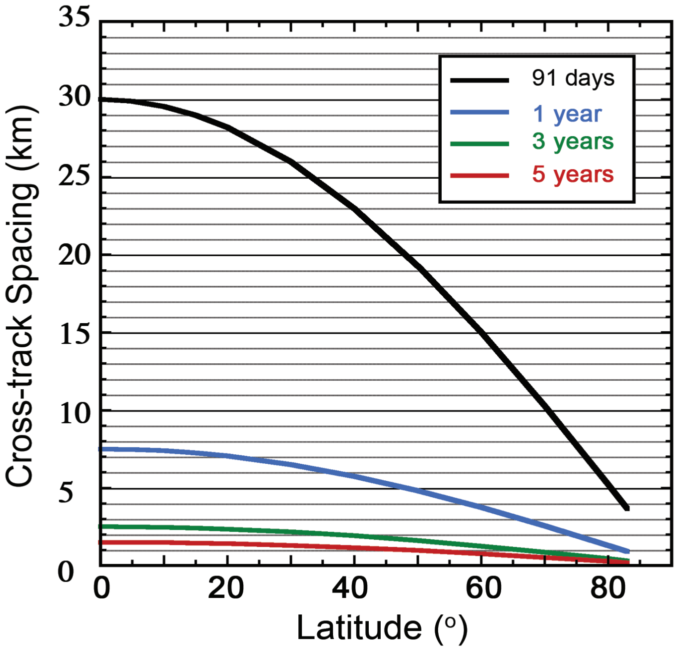

Figure 14. Track spacing (between ascending or descending track pairs) as a function of latitude achieved over time using cross-track pointing to uniformly distribute the tracks. The colors and inset box give the orbit repeat period (figure courtesy of David Harding).

5.2 Laser Spot Diameter and Spot Separation

The Workshop found that a major issue was the diameter of the laser spot size on the Earth's surface; the ice sheet community favors larger spot sizes, on the order of 50–70 m in order to sample over scales larger than the small roughness elements of the ice sheet. This issue is similar to the requirement of ocean radar altimetry, which uses a pulse-limited footprint size on the order of a kilometer to average over the roughness of ocean waves. The results of an analysis (Figure 6) presented at the workshop shows how the sampling error due to small-scale surface roughness (wind-driven sastrugi and melt features) increases as the diameter of the footprint decreases.

For sea ice, a tradeoff was considered at the Workshop between smaller footprints that would provide better sampling of smaller leads having thin ice or open water entirely across the footprint versus larger footprints that would give a higher probability of sampling some portion of leads within the footprint. Detection of leads is required to determine the ocean reference level for the sea ice freeboard measurements. For a diameter of 70 m versus 25 m, eight times as much lead area would be sampled for any given pulse-repetition frequency. In addition, ICESat-I has only a limited capability to utilize the large difference in reflectivity between the darker areas of open water or grey thin ice in leads and the brighter adjacent areas of thicker ice. For ICESat-II, however, improvements in the automatic gain control, dynamic range, and reflectivity calibration of the signal detection system will enable better detection of the height level of the thin ice and open water in a lead, even if only a portion of the lead is sampled. Therefore, a larger diameter such as 50–70 m is favored for sea ice, although 25 m will probably yield satisfactory results.

At the same time, the vegetation community requires smaller spot sizes that are less than or equal to 25 m, because larger spots smear out the detail in the canopy structure, and on sloped terrain, mix the canopy and ground return signals and cause errors due to waveform spreading. The ICESat-I nominal 65-m footprint is estimated to retrieve canopy height to an accuracy of 5 m, as opposed to the estimated 1-m accuracy of a 25-m footprint. As a result, the vegetation community strongly favored a 25-m or less spot size, with which the solid Earth community concurred.

Given these conflicting requirements, the Workshop recommends the following additional studies related to the footprint size requirements:

1. **An additional ice sheet roughness study using Airborne Topographic Mapper (ATM) data from overflights of Greenland**—The purpose of this study would be to further investigate whether the

70-m spot size could be reduced without increasing the error associated with the small-scale roughness of the ice sheet. As discussed below in Section 5.4, this study should be done in combination with a study of the atmospheric range delay associated with forward scattering, which increases with spot size.

2. **Modification of the receiver sensor**—The Workshop recommended a study of whether the receiver in the telescope could be modified into an annulus such that it could receive the return from both the 25-m and 70-m spot size. Initial analysis of this concept suggests some significant challenges. If the energy distribution within the spot size is modeled as a gaussian with a width at two standard deviations of 70 m, then the central 25-m diameter circle contains only 22.5% of the energy. This results in a configuration that either provides laser energy that is too low in the 25-m footprint to meet the stated requirements, or it increases the overall laser energy to a level that will compromise laser life. Given that the gaussian assumption is only a rough approximation, this issue needs further analysis.

3. **Footprint requirements for vegetation and land topography**—Documentation is needed of how these requirements were derived and their sensitivities to deviations from the stated 25-m requirement.

4. **Along-track sampling**—Another issue was the separation of spots on the ground. The Workshop recommended additional investigation and documentation of the requirements of the respective communities and the analysis for the different disciplines of the trade space between the along-track sampling considerations and laser lifetime requirements. The ice sheet community recommended a 140-m separation (50 Hz PRF), to meet the ice requirements, reduce the total number of shots fired, and reduce the number of lasers needed on the instrument for a particular mission lifetime. The scales of ice sheet variability are such that interpolation over these distances is sufficient, and the lower the PRF, the longer the laser lifetime. The choice of the 170-m spacing (40 Hz PRF) for ICESat-I was selected on the basis of an analytical study using ATM data over Greenland. A crossover analysis of ICESat-I data versus spacing (170 m and greater) supports the preflight analysis showing that the additional reduction in interpolation error at smaller spacings would be small. In contrast, some members of the vegetation community strongly requested contiguous footprints to capture the horizontal spatial inhomogeneity, while others stated that contiguous footprints were not essential for studies such as large-scale biomass estimates. The fundamental trade is one between optimizing sampling density (for a portion of the vegetation science community) and maximizing laser life. **Investigation of the trade space between these two considerations for the different disciplines should be carried out.**

5.3. Spacecraft Agility, Pointing Control, and Accuracy

The two issues on which all groups agree concern spacecraft agility and pointing accuracy.

5.3.1 Agility

The working groups agreed that they would like a more agile pointing of the lidar on ICESat-II, so that it can quickly execute off-nadir pointing to targets-of-opportunity (TOO) and for pointing to 100 km segments of tracks acquired by other satellites, such as CryoSat and Envisat. ICESat-I requires 10-min for TOO targeting, which means that 40° of latitude, or 4,500 km of orbit length, or 10% of an orbit is affected by this operation. Compared to this performance, ICESat-II should be able to point up to ±5° off-nadir in the cross-track direction in no more than 60 s (allowing 30 s from the reference track to point at the TOO and 30 s back to the reference track pointing; the distance covered in 30 s is approximately 2° of latitude). A special TOO maneuver, not performed during ICESat-I, but very desirable for ICESat-II is a “dwell” maneuver whereby precision pointing maintains the laser fixed on a location on the Earth’s surface for up to 2 s. This dwell maneuver would be used for pointing at Cal/Val sites and to densely sample point locations.

Examples of such point locations include determination of elevation changes due to natural hazards such as volcanoes, landslides and surging glaciers. This dwell pointing should be achievable over a range of attitudes from nadir to ±5°. As for other TOO events, the pointing time should not exceed 60 s to depart from, and return to, the normal reference track. Cross-track pointing accuracy to the specified TOO targets should be ±30 m (1σ). For pointing that follows the nadir tracks of other satellites, the path followed by the laser pointing must be able to diverge from the ICESat-II nadir track at rates of 5° of cross-track pointing per 10° of latitude, reaching a maximum cross-track angle of 15°. As an example, to follow CryoSat nadir tracks requires cross-track pointing of 4° at 60° latitude, and 12° at 80° latitude.

5.3.2 Pointing Accuracy

Compared to ICESat-I, and to achieve more accurate repeat profiling of reference tracks, the spacecraft pointing capabilities for ICESat-II should be improved. For ice sheets, improved pointing will reduce the uncertainty in the ice sheet elevations introduced by the cross-track surface slope. In addition, for land topography and vegetation, improved pointing will provide observations along exact repeat ground tracks, and by sampling along uniformly spaced ground tracks, well-sampled grids of topography and biomass. Specifically, ICESat-II should have an Attitude Control System (ACS) capable of precision pointing of the laser to pre-specified reference tracks with a cross-track accuracy of ±30 m (1σ), as compared to the ±100 m (1σ) capability achieved by ICESat-I. Precision pointing to the repeat orbit reference tracks, or to tracks that are parallel to but offset from the reference tracks, should be able to be done continuously and globally at off-nadir angles up to 3° with a cross-track accuracy of ±30 m (1σ). Because of command storage limitations, ICESat-I only implemented reference-track pointing at polar latitudes and only while pointing near-nadir. This limitation should be overcome with ICESat-II.

5.4 Atmospheric Effects, Range Delay, and the Accuracy of Ice Sheet and Sea Ice Retrievals

There was considerable discussion at the workshop about the Survey's recommendation to delete the green laser channel used for more sensitive cloud and aerosol measurements, and the impact of forward scattering on the ice measurements. The effect of forward scattering by clouds and aerosol to stretch laser pulses and the resulting bias error for surface altimetry are an issue for the accuracy of ice sheet change detection. Atmospheric scientists stated that the green channel was a requirement for ICESat-I both for the scientific value of the atmospheric measurements, and to enable corrections of significant surface altitude errors due to forward scattering in clouds and aerosols. They also stated that a similar capability for ICESat-II would be required to meet the most stringent of the surface altitude requirements. For ICESat-II, however, because the green channel would require approximately 50% more laser power and increases the complexity of the laser and the detector system, the Decadal Survey concluded that a single channel NIR laser would be sufficient.

Forward scattering of the laser light from clouds and aerosols increases the path length, thus making the surface appear farther from the satellite. For ICESat-I, if filtering and corrections were not done, calculations and data analysis show that the stretching of a laser pulse by cloud-induced forward scattering gave bias errors on order of a meter. Calculations, as in Duda et al. 2001 and Mahesh et al. 2002, show that the GLAS 532-nm channel as designed could be used to sufficiently clear data of clouds such that the requirement of ±1.5 cm per year surface altitude change detection could be realized. As Section 2.3 describes, the precision and accuracy requirements for ICESat-II are stringent, with for example, a requirement for an absolute single-shot accuracy of ±5 cm on 0° slopes. As Figure 15 shows for Antarctica, for the 532-nm ICESat-I channel for the combined effect of clouds and blowing snow, the average bias error for surface altitude is on order of several tens of centimeters. Analysis of the 1064-nm data alone shows that the residual accuracy imposed by undetected cloud scattering is at the decimeter, not centimeter, level. Because seasonal and interannual variability in clouds and blowing snow are substantial, errors in surface altitude result. This suggests that to obtain the desired level of accuracy for the ICESat-II mission, it may be necessary to employ more than just the 1064-nm channel.

There are changes that can be implemented on ICESat-II to reduce the cloud scattering bias. The forward scattering effect can be in some cases made smaller by reducing the telescope field of view (FOV). If the FOV is small enough, then most of the forward scattered photons from the surface will not return to the receiver. For cloud/fog scattering that occurs close to the surface, however, the typical situation with the largest impact, the reduction of this effect can be minimal. The size of the current GLAS receiver FOV is approximately 360 m. The inclusion of an active beam steering mechanism to ensure that the laser beam is aligned with the center of the receiver FOV, will allow the FOV for a 70-m footprint to be reduced to about 100 m. The inclusion of an active beam steering mechanism to ensure that the laser beam is aligned with the center of the receiver FOV, will allow the FOV for a 70-m footprint to be reduced to about 100 m, which would reduce the maximum path length for forward scattering by about a factor of 10. The 1064-nm channel can also be improved to allow somewhat better cloud detection. Modeling studies are required to determine how effective the improvements would be. Overall, there is a need for a robust and proven approach to correct the atmosphere propagation errors to the accuracy

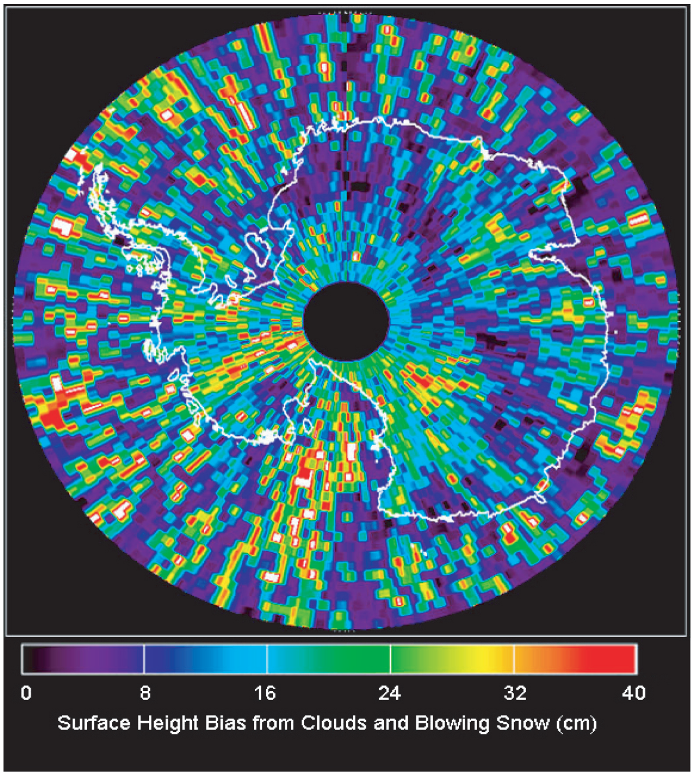

Figure 15. The calculated average cloud and blowing snow range bias from atmospheric scattering using the GLAS 532-nm data of October 2003. The small scale variability is related to the limited sampling for the nadir-only coverage. The large scale results show that this bias is important if centimeter-level height changes are to be measured (figure courtesy of James Spinhirne).

required for the surface measurement goals.

In summary, short of having a means to correct for forward scattering, there are two recourses:

- Make the FOV sufficiently small so that forward scattering effects and range delay are small enough to meet mission requirements; the assumption that the proposed 100-m FOV is sufficiently small is inadequate. Analysis is required here.
- Have a reliable means of knowing which shots are affected by forward scattering and edit them out (e.g., tails on the waveform and/or intensity of the return and/or detection of clouds and aerosols with 1064-nm atmospheric data).

The second approach describes the situation for ICESat-I. The problem with this approach is that about half the surface returns are discarded, seriously affecting the ability to do change detection. This means that ICESat-I employs a laser altimeter with enough energy to "burn through" the clouds, where half that data is then thrown out. Given this situation, the workshop recommends that a study be done of the dependence of forward scattering and range delay on FOV and spot size. For completeness purposes, this study should be done in combination with the surface roughness studies.

5.5 Unbiased Elevation Retrievals for Specular Water Surfaces

ICESat-I did not have a measurement requirement for the elevation accuracy of the smooth water surfaces that are typical of inland water bodies and open leads in sea ice. When observed at or near-nadir, the intense specular reflection from smooth water saturates the ICESat-I receiver and the resulting returns are severely distorted. The ranges retrieved from these saturated returns have delay errors as large as several meters, yielding elevations significantly below the true water surface. Based on laboratory calibration data, range corrections for saturated returns have been developed for ICESat-I. For smooth water returns severely distorted by saturation, however, these corrections are accurate only at the several decimeter level. This accuracy is insufficient for retrieving sea ice thickness that requires measuring the elevation of the water surface in open leads and for surface water hydrology objectives, including water storage in lakes, reservoirs, and river discharge.

ICESat-II retrievals of the elevations of specular water surfaces should be as accurate as those achieved for ice and snow surfaces. This could be accomplished in several ways, including a larger receiver dynamic range and/or slightly increased off-nadir pointing. In order to avoid detector damage from specular reflections observed perpendicular to a smooth water surface, ICESat-I acquires reference track data with a nominal laser off-nadir pointing angle of 0.3°. A small increase in this off-nadir angle would further reduce the intensity of the return from specular surfaces. Data acquired by ICESat-I from smooth water surfaces over a range of off-nadir pointing angles through clear atmospheric conditions should be evaluated in order to quantify the relationship between pointing angle and return intensity, thus providing the necessary information to guide the ICESat-II design. A larger dynamic range for the receiver should be implemented, for example, by using a detector with a larger number of recording bits, improving the amplifier design, or using a split-signal approach in which received pulse energy is optically split into high- and low-energy channels that are separately detected and recorded as waveforms.

5.6 Complementary Radar Altimetry with ICESat-II Sea Ice Measurements

The determination of sea ice thickness is one of the three major Decadal Survey goals for ICESat-II. Because of the diminishing sea ice area in the Arctic, it is important to provide systematic measurements of ice thickness, so that the loss of sea ice volume can be determined, and the ocean–ice–air interactions can be examined. The Sea Ice Working Group recommends that NASA look into how to best achieve coordinated measurements with radar altimetry, such as CryoSat or other future radar altimetry sensors. This could be achieved by near-coincident data collection from a separate radar altimetry mission, or it could be achieved by adding a radar altimeter, such as the CryoSat SAR Interferometric Radar Altimeter (SIRAL) to the ICESat-II mission. The former is entirely dependent on the particular space-based radar systems that the international partners fly. The latter would require a partnership with ESA, and would add cost and complexity to the mission, but it would achieve coincidence of measurement. In either case, the combination of radar and laser altimetry, whether on the same platform or not, should improve the sea ice thickness measurements desired by the Decadal Survey.

5.7 Addition of an Imager

The Ice Sheet Working Group expressed an interest in mounting on the satellite an imager, which would be centered on the boresight of the ICESat-II laser. This instrument would acquire imagery of the laser path at the same time as the laser is fired, to provide information on time-dependent variables such as blowing snow or clouds. This imager would have three major applications:

1) Confirming the geolocation of the laser footprint,

2) Assisting in the interpretation of the return laser signal by identifying the nature of the backscatter source, and

3) Providing additional information for the extraction of geophysical information from the laser signal.

At the ICESat-II workshop, presentations of ICESat-I data from every discipline, with the exception of atmosphere, showed plots of the ICESat-I ground tracks superimposed on a visible image acquired by an instrument on another spacecraft at a different time (usually MODIS). The speed of the movement and evolution of clouds prevents this approach in atmospheric science. The collocation of the ICESat-I data with satellite imagery can be a tedious and time-consuming process, which for ICESat-II, could be greatly simplified and improved for many applications if an imager were part of the spacecraft payload. The imager should be able to resolve features that are smaller by at least a factor of two than the laser footprint. The image swath width should be wide enough to allow unambiguous identification of features that determine the laser backscatter (minimum of 15 km). The spectral requirements include red and near-infrared bands for terrestrial biomass applications, and red-green-blue for true-color imagery (or a single panchromatic band) for studies of the cryosphere and atmosphere.

6. Summary

On June 27–29, 2007, the NASA-sponsored ICESat-II Workshop convened at the BWI Holiday Inn in Linthicum, Maryland. The purpose of the workshop was to provide a forum for the science community to discuss the ICESat-II mission recommended by the Decadal Survey; assess its suitability for achieving science objectives across a variety of disciplines (ice sheets, sea ice, vegetation, solid Earth, hydrology, and atmospheric sciences); and identify important considerations required to maximize its ability to achieve its mission objectives as stated in the Decadal Survey.

In the breakout sessions and throughout the workshop, the community showed great enthusiasm for an ICESat-II mission. All the groups identified scientific goals of high importance that could be achieved with an ICESat-II mission that is broadly similar to the ICESat-I design. Moreover, all groups expressed a strong interest in minimizing the observational gap between ICESat-I and ICESat-II and ensuring that ICESat-II has the capability of operating for a minimum of five years. The community is eager to support NASA in taking the steps to advance the ICESat-II concept to formulation. As the above sections shows in detail, the conclusions and recommendations of the workshop are as follows:

1. **Orbits**—There was general agreement that ICESat-II be placed into an identical orbit to ICESat-I, with the 91-day seasonal orbit strongly recommended, utilizing the same ground tracks as ICESat-I. Once the satellite is launched, this would provide the potential for a 15-year time series of laser observations. Such an orbit has a 25-km spacing at the equator, with the present 33-day observation period as a subcycle.

2. **Spacecraft agility**—The working groups agreed that they would like a more agile pointing of the lidar instrument on the satellite. This would be used for repeat targeting of land targets such as volcanoes, rivers and reservoirs, and for off-track pointing to provide 2-km lidar track spacing at the equator to satisfy the vegetation sampling density requirement.

3. **Questions about the laser spot size diameter and spot separation**—One major point of discussion concerned the diameter of the laser spot on the Earth's surface. The ice sheet and sea ice communities favored a 70-m spot diameter to meet their requirements and optimize the number of shots required to achieve the required noise level; whereas the vegetation community felt that this spot diameter would not provide sufficient accuracy to satisfy their canopy height measurement requirements. They strongly favored a 25-m spot size, with which the solid Earth community concurred. The ice sheet community also favored a 140-m shot separation (50 Hz) to preserve laser life and because the scales of variability does not require any more dense sampling; whereas the vegetation community favors a more dense sampling to capture the ecosystem structure at a higher spatial resolution.

Because of these differences, the Workshop recommended that an additional analysis of the noise introduced to the ice measurement by reduction of the laser footprint diameter be carried out to quantify the impact on the ice objectives. In addition, the impact on vegetation science of footprints with diameters greater than 25 m needs to be quantified so the trades can be appropriately considered. With respect to pulse separations, the impact on vegetation science of pulse separations that are greater than 25 m needs to be quantified and considered in the context of the implications for laser life associated with a higher pulse-repetition frequency. In the event that high laser reliability can be ensured, the benefits and costs to ice science of increased sampling density should be examined. Finally, and as discussed further in the next paragraph, because reduction of the spot size requires a smaller receiver FOV, which can reduce the forward scattering correction, the footprint size study needs to be done in parallel with a study of the effect of spot size and FOV on forward scattering and range delay.

4. **Atmospheric range delay**—For ICESat-II, the Decadal Survey recommended dropping the green 532-nm channel on ICESat-I, and using only the 1064-nm channel. The importance of the green channel is that it improves the calculation of the atmospheric range delay caused by forward scattering. Because ICESat-II lacks this channel, the possibility of modifying the instrument to reduce range delay must be examined. These potential modifications include reducing the telescope FOV, the possibility of having a more sensitive 1064-nm channel, and examining of the value of adding the green channel.

5. **An annular sensor in the receiver**—Again for the spot size, the Workshop recommends a study to explore the possibility of modifying the receiver into an annulus such that it could receive the return from both the 25-m and 70-m spot size; this potential modification needs careful investigation.

6. **Coordinating ICESat-II sea ice measurements with complementary radar altimetry**—The Sea Ice Working Group recommends that NASA look into how to best achieve coordinated measurements with radar altimetry to complement the lidar measurements over sea ice. This could be achieved by near-coincident data collection between ICESat-II and a separate radar altimetry mission flown by one of the international partners.

7. **An international partnership radar on ICESat-II**—In the event that the coordinated measurement strategy does not work, the Workshop recommends that the goal of coincident lidar–radar sea ice observations be achieved by adding a radar altimeter, such as the CryoSat SAR Interferometric Radar Altimeter (SIRAL) to the ICESat-II mission. This ESA instrument would provide data of significance to both agencies.

8. **A vegetation R&A program**—The vegetation breakout group expressed the concern that their technology readiness for extrapolating lidar samples to finer landscape scales for carbon flux and succession modeling, is low with unknown risk. The use of ICESat-II measurements in conjunction with the above ancillary data to extend canopy height and biomass estimates beyond the ICESat-II laser samples requires further research and development. Thus, a robust R&A program will be essential to develop and validate techniques to extend lidar height information to finer scales using InSAR, SAR, and passive optical images. Such a program could be done jointly with the DESDynI team members.

9. **Addition of an imager to ICESat-II**—The Ice Sheet Working Group expressed an interest in placing an imager on the satellite to acquire imagery of the laser path at the same time as the laser is fired, to unravel time-dependent variables such as blowing snow or clouds. It would also benefit vegetation studies by recording vegetation structure at the shot location.

In summary, the Workshop made clear the depth and breadth of community support for the ICESat-II mission across a range of science disciplines, and the strong interest in an early launch with a minimum five-year mission life. The ability of the profiling laser capability to open up the third dimension of geophysical observation with unprecedented detail represents a significant advance in Earth remote sensing. Although there are some fundamental differences in the optimum measurement sampling interests among disciplines, the workshop participants made recommendations to help address the extent to which those incompatibilities can be resolved. Ultimately, the ICESat-II mission will clearly provide tremendous breakthroughs in the scientific understanding of the Earth's ice cover, as well as provide valuable scientific information that will complement other measurements across a wide range of other disciplines.

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Appendix A: Workshop Attendees

Chuck Athas	Sigma Space
Brooks Atkinson	Ball Aerospace
Rich Barney	NASA Goddard Space Flight Center
Robin Bell	Columbia University
Robert Bindschadler	NASA Goddard Space Flight Center
Charon Birkett	ESSIC
Lahouari Bounoua	NASA Goddard Space Flight Center
Anita Brenner	SSAI
Jamie Britt	NASA Goddard Space Flight Center
Lisa Callahan	NASA Goddard Space Flight Center
Claudia Carabajal	Sigma Space /NASA GSFC
L. DeWayne Cecil	NASA Headquarters
Christine Chiu	NASA Goddard Space Flight Center
Josefino Comiso	NASA Goddard Space Flight Center
Bob Connerton	NASA Goddard Space Flight Center
Laurence Connor	NOAA Laboratory for Satellite Altimetry
Bryant Cramer	NASA Headquarters
Beata Csatho	University at Buffalo
Curt Davis	University of Missouri
John DiMarzio	SGT, Inc.
Katelyn Dolan	NASA Goddard Space Flight Center [Intern]
Andrea Donnellan	Jet Propulsion Laboratory
Ralph Dubayah	University of Maryland
Fernando Echavarria	U.S. State Department
Joe Famiglietti	NASA Goddard Space Flight Center
Sinead Farrell	NOAA
Douglas Fowler	University of Colorado
Tony Freeman	Jet Propulsion Laboratory
Helen Amanda Fricker	Scripps Institution of Oceanography
Randall Friedl	Jet Propulsion Laboratory
Jim Golder	SIgma Space
Shahid Habib	NASA Goddard Space Flight Center
Dorothy Hall	NASA Goddard Space Flight Center
Forrest Hall	UMBC /NASA Goddard Space Flight Center
David Harding	NASA Goddard Space Flight Center
Peter Hildebrand	NASA Goddard Space Flight Center
Brian Holz	Ball Aerospace & Technologies Corporation
Huw Horgan	Penn State University
Yongxiang Hu	NASA Langley Research Center
Fred Huemmrich	University of Maryland Baltimore County
George Hurtt	University of New Hampshire
Eric Ianson	NASA Headquarters
Michael Jasinski	NASA Goddard Space Flight Center
Martin Jeffries	NSF
Jack Kaye	NASA Headquarters
Josef Kellndorfer	The Woods Hole Research Center
Dan Kimes	NASA Goddard Space Flight Center
Robert Knox	NASA Goddard Space Flight Center
William Krabill	NASA Goddard Space Flight Center
Nathan Kurtz	JCET
Ron Kwok	Jet Propulsion Laboratory
John LaBrecque	NASA Headquarters
Seymour Laxon	University College London
Michael Lefsky	Colorado State University
Jun Li	SGT
Eric Lindstrom	NASA Headquarters
Craig Lingle	University of Alaska Fairbanks
John Loiacono	NASA Goddard Space Flight Center
Scott Luthcke	NASA Goddard Space Flight Center

Robert Mackey	Lockheed Martin
Hank Margolis	Laval University/UMBC-GEST
Alexander Marshak	NASA Goddard Space Flight Center
Chreston Martin	NASA Wallops
Seelye Martin	NASA Headquarters
Anthony Martino	NASA Goddard Space Flight Center
Jeff Masek	NASA Goddard Space Flight Center
David McAdoo	NOAA
Pamela Millar	NASA Goddard Space Flight Center
Peter Minnett	University of Miami
Reginald Muskett	University of Alaska Fairbanks
Mark Neal	ITT Corporation
Steven Neeck	NASA Headquarters
Ross Nelson	NASA Goddard Space Flight Center
Wenge Ni-Meister	Hunter College of The City University of New York
Stephen Palm	SSAI
Claire Parkinson	NASA GSFC
John Petheram	Lockheed Martin
Joe Pitman	Lockheed Martin Space Systems
Jon Ranson	NASA Goddard Space Flight Center
Jeanne Sauber	NASA Goddard Space Flight Center
Ted Scambos	NSIDC / University of Colorado
Bob Schutz	University OF Texas at Austin
Bernard Seery	NASA GSFC
Olga Sergienko	ORAU / NASA Goddard Space Flight Center
Aurelie Shapiro	World Wildlife Fund
Edwin Sheffner	NASA Ames Research Center
C. K. Shum	Ohio State University
Christopher Shuman	UMBC GEST
Joseph (Jay) Skiles	NASA Ames Research Center
Jay Smith	NASA Goddard Space Flight Center
James Spinhirne	NASA Goddard Space Flight Center
Konrad Steffen	University of Colorado
Julienne Stroeve	NSIDC
Vijay Suchdeo	Sigma Space
Tim Urban	University of Texas
Diane Wickland	NASA Headquarters
Warren Wiscombe	NASA Goddard Space Flight Center
Hongjie Xie	University of Texas at San Antonio
Yuekui Yang	NASA Goddard Space Flight Center
Taehun Yoon	SUNY Buffalo
Qingyuan Zhang	UMBC /NASA Goddard Space Flight Center
Jay Zwally	NASA Goddard Space Flight Center

Appendix B: List of Papers from the GLAS GRL Special Issue

(*Geophysical Research Letters*, Volume 32, No. 21, 22, and 23, 2005)

Abshire, J.B., X. Sun, H. Riris, J.M. Sirota, J.F. McGarry, S. Palm, D. Yi, and P. Liiva, 2005: Geoscience Laser Altimeter System (GLAS) on the ICESat Mission: On-orbit measurement performance. *Geophys. Res. Lett.*, **32**, L21S02, doi:10.1029/2005GL024028.

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