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The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2): Science requirements, concept, and implementation

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A B S T R A C T

The Ice, Cloud, and land Elevation Satellite (ICESat) mission used laser altimetry measurements to determine changes in elevations of glaciers and ice sheets, as well as sea ice thickness distribution. These measurements have provided important information on the response of the cryopshere (Earth's frozen surfaces) to changes in atmosphere and ocean condition. ICESat operated from 2003 to 2009 and provided repeat altimetry measurements not only to the cryosphere scientific community but also to the ocean, terrestrial and atmospheric scientific communities. The conclusive assessment of significant ongoing rapid changes in the Earth's ice cover, in part supported by ICESat observations, has strengthened the need for sustained, high accuracy, repeat observations similar to what was provided by the ICESat mission. Following recommendations from the National Research Council for an ICESat follow-on mission, the ICESat-2 mission is now under development for planned launch in 2018. The primary scientific aims of the ICESat-2 mission are to continue measurements of sea ice freeboard and ice sheet elevation to determine their changes at scales from outlet glaciers to the entire ice sheet, and from 10s of meters to the entire polar oceans for sea ice freeboard. ICESat carried a single beam profiling laser altimeter that produced ~70 m diameter footprints on the surface of the Earth at ~150 m along-track intervals. In contrast, ICESat-2 will operate with three pairs of beams, each pair separated by about 3 km cross-track with a pair spacing of 90 m. Each of the beams will have a nominal 17 m diameter footprint with an along-track sampling interval of 0.7 m. The differences in the ICESat-2 measurement concept are a result of overcoming some limitations associated with the approach used in the ICESat mission. The beam pair configuration of ICESat-2 allows for the determination of local cross-track slope, a significant factor in measuring elevation change for the outlet glaciers surrounding the Greenland and Antarctica coasts. The multiple beam pairs also provide improved spatial coverage. The dense spatial sampling eliminates along-track measurement gaps, and the small footprint diameter is especially useful for sea surface height measurements in the often narrow leads needed for sea ice freeboard and ice thickness retrievals. The ICESat-2 instrumentation concept uses a low energy 532 nm (green) laser in conjunction with single-photon sensitive detectors to measure range. Combining ICESat-2 data with altimetry data collected since the start of the ICESat mission in 2003, such as Operation IceBridge and ESA's CryoSat-2, will yield a 15+ year record of changes in ice sheet elevation and sea ice thickness. ICESat-2 will also provide information of mountain glacier and ice cap elevations changes, land and vegetation heights, inland water elevations, sea surface heights, and cloud layering and optical thickness.

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1. Introduction

ICESat was the first spaceborne laser altimetry mission for Earth science and was in operation from 2003 to 2009 (Schutz et al., 2005). Because of laser lifetime issues, ICESat's collection strategy was changed from continual operation to 30 day campaign periods two to three times each year. Despite this campaign mode operation, it was a very successful mission that enabled estimates of the overall mass change of the Greenland and Antarctic ice sheets, as well as the regional changes that illuminate the underlying processes (Pritchard et al., 2009; Zwally et al., 2011 and 2015; Sørensen et al., 2011; Sasgen et al., 2012, Csatho et al., 2014, Khan et al., 2014).

One of the key findings of ICESat was that some outlet glaciers around the margins of these ice sheets are losing more mass quicker than expected (e.g., Pritchard et al., 2009; Zwally et al., 2011). Investigations using ICESat data resulted in the discovery and subsequent mapping of sub-glacial lakes in Antarctica (Fricker et al., 2007; Smith et al., 2009) and the improvement of tide models under ice shelves (Padman et al., 2008; Ray, 2008). ICESat altimeter data have been used to deconvolve ice and solid earth mass change signals for the Gravity Recovery and Climate Experiment (GRACE) data over Antarctic ice sheets (Gunter et al., 2009; Groh et al., 2012). Furthermore, ICESat observations provided a comprehensive assessment of ice shelf thinning in Antarctica and subsequent links to dynamic thinning of grounded tributaries (Pritchard et al., 2012).

Outside of the ice sheets, ICESat data played a critical role in resolving mass changes of mountain glaciers and ice caps (Moholdt et al., 2010; Gardner et al., 2011; Gardner et al., 2012; Moholdt et al., 2012) that were determined to have contributed one third of total sea level rise observed over ICESat's period of operation (Gardner et al., 2013). Glacier thickness changes from ICESat observations served as a basis to derive the first spatially resolved mass budget over the entire Hindu Kush–Karakoram–Himalaya region (Kääb et al., 2012), the peripheral glaciers, and ice caps of Greenland (Bolch et al., 2013).

ICESat also demonstrated that it is possible to extract sea ice freeboard, thickness, and volume from laser altimetry (e.g. Kwok et al., 2009; Farrell et al., 2009; Kurtz and Markus, 2012). Freeboard is the height of the snow or ice surface above the local sea surface. Sea ice thickness can be derived from freeboard by assuming local hydrostatic balance and with assumptions or estimates of sea ice and water densities as well as snow load on top the ice floes (see, for example, Kwok et al., 2009, Connor et al., 2013, Farrell et al., 2015).

Time series of inter-annual variation and mission-length trends in sea ice thickness for the entire Arctic and Southern Oceans could be calculated. Recent observations of Arctic sea ice coverage from satellite passive microwave data show that record or near-record lows in ice extents occurred in the years 2005–12. In September 2012, the summer ice extent reached another record minimum of 3.6×10^6 km^2 which was 2.2×10^6 km^2 or 30% less than the record set seven years earlier in September 2005. With this record, seasonal ice now covers more than half of the Arctic Ocean. Results from ICESat showed that over the 5 years (2004–2008) for which we have ICESat data the overall sea ice thickness of the Arctic Ocean multiyear ice decreased by 0.6 m, and >40% of the thick multiyear ice was lost (Kwok et al., 2009). Over decadal time scales, the combined record of submarine and ICESat thickness estimates suggest that winter thickness in the central Arctic has thinned from 3.64 m in 1980 to 1.75 m by 2009 (Rothrock et al., 2008; Kwok and Rothrock, 2009). Extending the ICESat time series with more recent observations from CryoSat-2 shows that ~1500 km^3 of winter (February/March) sea-ice volume has been lost from the Arctic Ocean during the last decade between 2003 and 2012 (Laxon et al., 2013). As a result, there is a reversal in both the volumetric and areal contributions of the multiyear and seasonal ice to the total volume and area of the Arctic Ocean ice cover. While thinner, seasonal ice is common in the peripheral seas and ice margins, the Arctic ice cover has clearly shifted to a regime where seasonal ice is now also prevalent in the interior of the Arctic Ocean. With a diminishing multiyear ice cover and thinner ice a significant fraction of the Arctic Ocean is now exposed to the atmosphere during the summer. For the coming decade, thickness estimates are needed for improved subseasonal-to-seasonal forecasts and refined projections of future climate patterns. ICESat also allowed for the first time a rough estimate of sea ice volume of the Antarctic sea ice cover (Kurtz and Markus, 2012).

Utilizing ICESat sea surface height measurements from leads across the Arctic sea ice pack, together with contemporaneous radar altimetry measurements from Envisat, Farrell et al. (2012) described the first mapping of the Arctic Ocean mean dynamic topography using satellite-only data. These sea surface height measurements were also used to derive a high-resolution, satellite-only marine gravity field model of the Arctic (McAdoo et al., 2013).

ICESat also enabled the estimation of global vegetation heights (e.g. Harding and Carabajal, 2005; Lefsky et al., 2007), global sea level anomaly and mesoscale variability features (Urban and Schutz, 2005), coastal ocean, ocean island and inland hydrology applications (e.g. Urban et al., 2008), as well as atmospheric characteristics (Spinhirne et al., 2005). Lefsky (2010), Simard (2011), and Los et al. (2012) generated global canopy height maps using ICESat in combination with other remote sensing data. Since ICESat digitized and recorded the full temporal profile of the received energy, additional research efforts were focused on analyzing specific waveform metrics to determine topographic characteristics and vegetation structure (e.g. Neuenschwander et al., 2008).

Despite ICESat's success the science community identified some limitations that prohibited the full exploitation of the dataset for scientific applications, particularly for determining change in the cryosphere. Therefore, different needs, requirements, and potential designs were discussed for an ICESat follow-on mission (Abdalati et al., 2010). It was concluded that to understand the governing processes that drive the large-scale changes in glacier and ice sheet elevation and sea ice thickness, changes in elevation should be monitored on a seasonal basis for the lifetime of the mission with improved spatial resolution beyond the observations provided by ICESat. Since the greatest elevation changes are known to occur at the glaciers along the margins of Greenland and Antarctica, there were added complications to the ICESat collection strategy in terms of deconvolving elevation change from surface slope and surface roughness. A single beam laser such as ICESat was not able to separate slope effects from true elevations changes on an orbit-by-orbit basis and thus many years of data were needed to separate these two effects (Howat et al., 2008; Pritchard et al., 2009; Moholdt et al., 2010). Improved spatial resolution and the ability to measure the cross-track slope were a critical consideration when developing the ICESat-2 mission. The multi-beam instrument design, smaller footprint, and the ability to resolve rougher terrains, would enable more accurate mountain and peripheral glacier mass balance measurements, allowing for improved quantification of land ice contributions to present-day sea level rise.

Similarly, a smaller footprint size, or rather higher spatial resolution, with increased spatial sampling intervals, will also enhance sea surface height and sea ice freeboard retrievals, and subsequently sea ice thickness calculations. While ICESat's campaign mode allowed the monitoring of inter-annual changes in sea ice thickness, monthly maps of sea ice thickness are needed to better understand freeze and melt processes as well as delineate dynamic versus thermodynamic sea ice thickening.

It was also determined that ICESat-2 should collect data over the mid- and lower-latitudes for land and ocean areas utilizing an operational off-nadir pointing capability in order to generate an optimized (non-repeat) collection of measurements for canopy heights that will contribute to the generation of a global carbon inventory assessment. Such an inventory is critical for understanding the global carbon budget.