IceBridge Science Requirements Summary (for inclusion in body of the Project Plan)

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Research on the polar ice cover is guided by the societal needs to: (1) understand glaciers and ice sheets sufficiently to estimate their current and predicted contribution to local hydrology and global sea-level rise; and (2) understand sea ice sufficiently to predict its response to and influence on global climate change and biological processes as well the impact of changing sea ice on Arctic operations. Furthering that understanding motivates a set of well documented, high level scientific inquiries including:

- Will there be catastrophic collapse of the major ice sheets, including those of Greenland and West Antarctica and, if so, how rapidly will this occur? (NRC, 2007, p. 2)
- What will be the time patterns of sea-level rise as a result of ice sheet change (NRC, 2007, p. 27)
- How can the incorporation of ice sheets into climate models be improved (NRC, 2007, p. 287)
- How can the contribution of ice sheets to sea-level change be estimated better (NRC, 2007, p. 287)?
- What is the interaction between sea ice, climate, and biological processes (NRC, 2007, p. 287)?

IceBridge will compile a unique knowledge base necessary to answer these questions by addressing four strategic measurement objectives:

1. Make airborne altimetry measurements over the ice sheets and sea ice to extend and improve the record of observations begun by ICESat.
2. Link the measurements made by historical airborne laser altimeters, ICESat, ICESat-2, and CryoSat-2 to allow accurate comparison and production of a long-term, ice altimetry record.
3. Monitor key, rapidly changing areas of ice in the Arctic and Antarctic to maintain a long term observation record.
4. Provide key observational data to improve our understanding of ice dynamics, and better constrain predictive models of sea level rise and sea ice cover conditions.

Consequently, our sampling methodology will concentrate on selected regions of the ice sheet where measurement continuity and process understanding can be best addressed. We will optimize data collections to take advantage of the unique capabilities of IceBridge platforms and instrument suites. Implementing this methodology means we can complement the synoptic scale goals better achieved by satellites.

By successfully reaching the strategic objectives, IceBridge will strive to achieve four significant scientific goals:

Goal 1. Document volume changes over the accessible domain of the Greenland and Antarctica ice sheets between Icesat-1 and Icesat-2. A particular focus will be to document rapid changes. Icebridge will answer: how have the ice sheet volumes (areas accessible by a/c) changed during these 5 years?

Goal 2. Document the thickness of glacier beds and other geophysical properties to better interpret volume changes measured with laser altimetry and to enable more realistic simulations of ice sheet flow with numerical models. IceBridge will answer: how are the ice sheets likely to change in the future?

Goal 3. Document the spatial and interannual changes in the mean sea ice thickness and the thickness distribution in the Arctic and Southern Oceans between ICESat-1 and ICESat-2, in support of climatological analyses and assessments.

Goal 4 Improve sea ice thickness retrieval algorithms by advancing technologies for measuring sea ice surface elevation, freeboard, and snow depth distributions on sea ice.

Table W summarizes the threshold requirements that OIB must satisfy. The table combines both terrestrial and marine ice requirements and all have equal priority. Table X summarizes the prioritized baseline line science requirements that must be achieved by a multiyear, airborne measurement program designed to addresses the above objectives and reach the major scientific goals. To that end, the list is composed of relatively well established, essential parameters such as repeat measurement of ice surface topography, ice elevation change, ice thickness, glacier bed topography, snow thickness on sea ice, a first order description of bathymetry in front of tidewater glaciers and underneath ice shelves. There are also projected requirements in table Y that include a set of important parameters that could reasonably be but are not yet realized on an operational basis because of insufficient data to develop a vetted, standardized measurement methodology (for example, measuring the changing distribution of subglacial water; large scale measurements of surface accumulation rate; subglacial geothermal heat flux). Similarly, the science requirements include geographic objectives that are demonstrably in reach of manned aircraft in the time frames consistent with previous airborne programs in the polar regions. There are also spatial and temporal requirements that are highly desirable but which likely would require different platforms and operational strategies to achieve. Quoted measurement accuracies represent uncertainties of 1 standard deviation about the mean.

The science requirements also draw on publications that summarize community consensus on important variables and their measurement sensitivities (ISMASS, 2004; NRC, 2007, IGOS, 2007, ISMASS, 2010). The scientific basis for these requirements is contained in Appendix Z.

Table W Operation IceBridge Threshold Science Requirements

1.	Measure annual changes in glacier, ice cap and ice sheet surface elevation sufficiently accurate to detect 0.15 m changes in uncrevassed and 1.0 m changes in crevassed regions along sampled profiles over distances of 500 m.
2.	Make sea ice surface elevation measurements with a shot-to-shot accuracy of 5 cm, assuming uncorrelated errors.
3.	Make sea ice elevation measurements of both the air-snow and the snow-ice interfaces to an uncertainty of 3 cm, which enable the determination of snow depth to an uncertainty of 5 cm.
4.	Acquire annually, near-contemporaneous, spatially coincident ice elevation data with ESA's Cryosat for underpasses in the Arctic and Antarctica. Coordinate with ESA in situ validation campaigns as possible.
5.	Conduct one campaign in the Arctic and one campaign in the Antarctic each year

*Table **X** Operation IceBridge Baseline Science Requirements*

*Table **X.1** Baseline Science Requirements for Ice Sheets*
1. Measure surface elevation with a vertical accuracy of 0.5 m or better.
2. Measure annual changes in ice sheet surface elevation sufficiently accurate to detect 0.15 m changes in uncrevassed and 1.0 m changes in crevassed regions along sampled profiles over distances of 500 m.
3. Measure ice thickness with an accuracy of 50 m or 10% of the ice thickness, whichever is greater.
4. Measure free air gravity anomalies to an accuracy of 0.5 mGal and at the shortest length scale allowed by the aircraft
5. Acquire annually, near-contemporaneous ice elevation data with ESA's Cryosat for underpasses across Greenland and Antarctica. Flight segment should span ESA SARIN and LRS mode boundaries. Coordinate with ESA in situ validation campaigns as possible.
6. Remeasure annually Antarctic and Greenland surface elevation along established airborne altimeter and ICESat underflight lines that extend from near the glacier margin to near the ice divide.
7. Collect elevation data so that the combined ICESAT-1-OIB sampling provides an elevation measurement within 10-km for 90% of the area within 100-km of the edge of the continuous Greenland Ice Sheet, as well the Antarctic Amundsen Sea Coast and Peninsula.
8. Measure ice thickness, gravity, surface, and bed elevation along central flowlines of the outlet glaciers in Greenland with terminus widths of 2 km or greater[1]. Measurements should extend at least 1.5 times farther than predicted outlet glacier valley dimensions. Repeat surface elevation measurements as practical.
9. Measure once, ice thickness, surface, and bed elevation across-flow transects at 3- and 8-km upstream of the terminus for each glacier in (8). Repeat surface elevation measurements as practical.
10. Measure once Greenland ice sheet elevation and ice thickness about four, nearly continuous close loops approximately about the 1000, 2000, and 2500 ice sheet elevation contours.
11. Measure ice thickness, elevation, gravity and magnetic anomalies over 10 Greenland glaciers[2] and 15 Antarctic glaciers[3] that are rapidly changing now or are likely to change in the next 10 years. Coverage should extend from the terminus to the elevation where velocities are about 50 m/yr. Over the fast flowing deep troughs, the grids must have 5-km spacing or better, with 10-km or better spacing on the surrounding regions of the lower catchment. Cycle through the glacier list for the duration of IceBridge.
12. Measure once ice thickness, surface elevation, gravity anomalies within 3 km of the Antarctic Ice Sheet Grounding line and along a second line located 10 km upstream of the grounding line.
13. Measure once surface elevation, ice thickness and seabed bathymetry beneath selected Antarctic Ice Shelves[4], along Greenland Fjords[5] where we will collect a line along the center of the fjords and three lines across (one at the sill, one near the middle, and one near the glacier front) and beneath Greenland Ice Tongues[6].
14. Acquire repeat radar, basal-echo-amplitude data with a relative radiometric calibration of 3 dB over 200 km for investigation of the changing distribution of subglacial water.
15. Acquire submeter resolution, stereo color imagery covering laser altimetry swaths

Table X.2 Baseline Glaciers and Ice Caps Requirement
1. Annually to semi-annually collect LiDAR swath data along the centerlines of major Gulf of Alaska glacier and icefield systems, repeating previous IceSAT measurements and airborne laser altimetry centerline profiles[7].
2. Make annual repeat measurement of surface elevation on select Alaskan Glaciers
3. Make ice elevation, ice thickness and gravity measurements on Canadian Ice Caps at least twice during the IceBridge program. Coverage should be based on previous airborne campaigns and leverage against ESA supported in situ Cryosat validation activities.
4. Make ice elevation, ice thickness and gravity measurements on selected ice caps and alpine glaciers around the Greenland Ice Sheet. Repeat the elevation measurements at least once during the IceBridge program[8].

Table X.3 Baseline Requirement for Sea Ice
SI 1. Make surface elevation measurements of the water, ice, or snow with a shot-to-shot independent error of less than 10 cm and correlated errors which contribute less than 1 cm to the mean height error in either sea surface or sea ice elevation. The spot size should be 1 m or less and they should be spaced 3 m or less. SI 2. Make elevation measurements of both the air-snow and the snow-ice interfaces to an uncertainty of 3 cm, which enable the determination of snow depth to an uncertainty of 5 cm. SI 3. Provide annual acquisitions of sea ice surface elevation in the Arctic and Southern Oceans during the late winter along near-exact repeat tracks in regions of the ice pack that are undergoing rapid change. Flight lines shall be designed to ensure measurements are acquired across a range of ice types including seasonal (first-year) and perennial (multiyear) sea ice to include, as a minimum: *Arctic* a. At least two transects to capture the thickness gradient across the perennial and seasonal ice covers between Greenland, the central Arctic, and the Alaskan Coast. b. The perennial sea ice pack from the coasts of Ellesmere Island and Greenland north to the pole and westward across the northern Beaufort Sea. c. Sea ice across the Fram Strait and Nares Strait flux gates. d. The sea ice cover of the Eastern Arctic, north of the Fram Strait. *Antarctic* a. Sea ice in the Weddell Sea between the tip of the Antarctic Peninsula and Cape Norvegia. b. Mixed ice cover in the western Weddell Sea between the tip of Antarctic Peninsula and Ronne Ice Shelf. c. The ice pack of the Bellingshausen and Amundsen Seas.
SI 4. Include flight lines for sampling the ground tracks of satellite lidars (ICESat-1 and ICESat-2) and radars (CryoSat-2 and Envisat). In the case of CryoSat-2, both IceBridge and CryoSat-2 ground tracks should be temporally and spatially coincident whenever possible. At

least one ground track of each satellite should be sampled per campaign.
SI 5. Conduct sea ice flights as early as possible in the flight sequence of each campaign, prior to melt onset.
SI 6. Collect coincident natural color visible imagery of sea ice conditions at a spatial resolution of at least 10 cm per pixel to enable direct interpretation of the altimetric data.
SI 7. Conduct sea ice flights primarily in cloud-free conditions. However data shall be retained under all atmospheric conditions with a flag included to indicate degradation or loss of data due to clouds.
SI 8. Make full gravity vector measurements on all low-elevation (< 1000 m) flights over sea ice to enable the determination of short wavelength (order 10 to 100 km) geoid fluctuations along the flight track to a precision of 2 cm.
SI 9. Actively seek out and coordinate with field campaigns that are consistent with IceBridge project objectives.
SI 10. Make available to the community instrument data on sea ice surface elevation and snow depth within 3 months of acquisition and derived products within 6 months of data acquisition.

Table Y Projected Science Requirements on Future IceBridge Development

Table Y.1 Projected Ice Sheet Science Requirements on Future IceBridge Development

1.	Measure surface snow accumulation rate with an accuracy of 4 cm/yr averaged over 25 km square areas in dry snow regions with annual accumulation in excess of 10 cm/yr.
2.	Measure the distribution and changing distribution of subglacial water over 5 km square areas.
3.	Seasonally remeasure surface elevation on select Greenland and Antarctic Glaciers using UAVs.
4.	Estimate relative spatial changes in subglacial geothermal heat flux using ice thickness, gravity and magnetic data.
5.	Remeasure ice sheet surface elevation at the locations of ICESat detected subglaical lakes located beneath West Antarctic Ice Streams and outlet glaciers draining into the Ross Ice Shelf. Measure with accuracy of 10 cm and at least once during the IceBridge mission using UAVs.
6.	Measure free air gravity anomalies to an accuracy of 0.5 mGal and a wavelength of 2.5km
7.	Acquire photogrammetrically calibrated, stereo, color imagery covering laser altimetry swaths and adjacent areas for creating DEMs and orthophotographs with submeter resolution and accuracy.
8.	Collect elevation data so that the combined ICESAT-1-OIB sampling provides an elevation measurement withing 10-km for 90% of the area within100-km of the edge of the continuous Greenland Ice Sheet as well as the Antarctic grounding line.

Table Y.2 Projected Sea Ice Science Requirements on Future IceBridge Development

SIP 1. Improve sea ice baseline requirement 1 to make surface elevation measurements with a shot-to-shot accuracy of 5 cm (versus 10 cm), assuming uncorrelated errors.

SIP 2. Extend sea ice baseline requirement 3 to other regions of the Arctic and Southern Oceans:

Arctic (to better constrain estimates of sea ice volume change)

a. North Pole region
b. Southern Beaufort Sea, west of Banks Island
c. Sea ice along the east coast of Greenland
d. Southern Chukchi Sea north of Bering Strait
e. Davis Strait
f. Lancaster Sound and other parts of the Canadian Archipelago

Antarctic (to better understand the process of sea ice formation and snow accumulation)

a. Ross Sea
b. Surveys of areas of polynya formation, over and downwind of the polynya
c. Surveys of areas where katabatic winds may deposit abundant snow.

SIP 3. Collect thermal images for a swath that, as a minimum, covers the LVIS data swath with a resolution of 0.5 m or better, and are calibrated to brightness temperature with an accuracy of 0.1K.

SIP 4. Improve sea ice baseline requirement 6 to collect coincident digital *stereo* imagery of sea ice conditions at a spatial resolution of at least 10 cm (versus 20 cm) per pixel, at a vertical resolution of 20 cm, to enable direct interpretation of the altimetric data and provide a complimentary surface digital elevation product.

SIP 5. Operation IceBridge shall support the validation of operational sea ice analysis and forecast products by providing estimates of sea ice freeboard within 1 week of data acquisition and estimates of sea ice thickness within 2 weeks of data acquisition.

Footnotes

1. For a list of Greenland outlet glaciers see Moon and Joughin (2007)
2. The targeted list of Greenland glaciers includes but is not exclusive to: Petermann, Humboldt, 79 North, Zaceriea (NE IceStream), Store, Rinks, Jacobshavn, Eqalorutsit kangigdlit sermiat, Nordboggletscher, Helheim, Daugaard-Jensen
3. The list of Antarctic Glaciers includes but is not exclusive to: Pine Island, Thwaite, Crane, Rutford, Lambert, Toten, Mertz, Shirase, Recovery, Jutulstraumen, David, Byrd, Nimrod, WAIS Ice Streams.
4. The list of ice shelves includes but is not exclusive to: Getz, Dotson, Crosson, Thwaites, Pig, Cosgrove, Abbot, George VI, Larsen C, Venable, Cook, Moscow, Totten, Riiser Larsen, Fimbul, West, Shackleton.
5. The list of fjords includes but is not exclusive to: Nordre Sermilik, Kangiata (Nuuk), jakobshavn, Torssukataq, Ummanaq (3 fjords), Upernavik, and the mini fjords in Melville bay should be pursued based on the 2010 results, Ingelfield Bredening (north thule) and Humboldt Heimdal Fj.,

Bernstorft Fj., Gylden love fj., Helheim, Kangerlugssuaq, Vestfjord, Daugaard Jensen, Keyser Franz Joseph Fj., Borfjorden (Storstrommen).

6. The list of ice tongues includes but is not exclusive to: Peterman, 79 north, and Zacheriae Glaciers.

7. Targeted glaciers include but ar not exclusive to the Columbia-Tazlina system, the Bering-Bagley system, the Seward-Malaspina system, the Yathse, Guyot, Tyndall and Tsaa tidewater glaciers in Icy Bay, the Yakutat Icefield, Glacier Bay's Grand Plateau, Fairweather, Grand Pacific, Margerie, Brady, Carroll, and Muir glaciers, and finally the Stikine, Juneau, Nabesna and Harding Icefields.

8. Coverage will be selected to be representative for varying climate zones and priority will be given to ice caps and alpine adjacent to rapidly changing ice sheet regions. Suggested regions: Sukkertoppen Iskappe, Disko Island, North Ice Cap, Kronprins Christian Land, Renland Iskappe.

9. References included in the appendix.