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Operation IceBridge

Level 1 Science Requirements

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1. IceBridge Program Overview and IceBridge Science Team

NASA has established the Operation IceBridge program (OIB) which is mandated to fulfill the following **observational goals**:

- P1. Make airborne altimetry measurements over the ice sheets and sea ice to extend and improve the record of observations begun by ICESat.
- P2. 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.
- P3. Monitor key, rapidly changing areas of ice in the Arctic and Antarctic to maintain a long term observation record.
- P4. 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.

In addition, OIB has the following **technical goal**:

- P5. Adapt existing instruments for airborne remote sensing of ice by unmanned aerial systems such as NASA's Global Hawk.

The IceBridge Project is directed from NASA's Goddard Space Flight Center. There are separate management functions for IceBridge Instruments, logistics, data management, and science. The five programmatic goals listed above provide general scientific direction for the project. Specific direction is provided by the IceBridge Science team (IST). The team has **three tasks mandated by the Program** (see OIB Science Team Terms of Reference Document, 2010):

1. Final development of the IceBridge Science Definition Document and Level-1 Scientific Requirements Document
2. Evaluation of the IceBridge mission designs in achieving the goals defined by the Science Definition Document and Level-1 Scientific Requirements Document as requested by the NASA Program Scientist; and
3. Support to the IceBridge Program Scientist, Project Scientist, and Project Manager in the development of the required analyses, documentation, and reporting during the IceBridge mission..

In addition, the science team, in collaboration with the instrument teams, will ensure the fidelity of the data products delivered to the public. This includes thorough documentation and access to level 1 data and corrections (e.g. geophysical corrections, trajectory, orientation, ranging) so as to provide a strong basis for future investigation and for improvement of the instrument level 2 products (e.g. footprint surface elevation).

This document addresses the first science team task to establish Level-1 science requirements. The science team adopted the following strategy for completing this task. First, the team articulated broad scientific goals or themes addressing Greenland and Antarctica ice sheets and sea ice and also glaciers in Alaska and ice caps in the Canadian Arctic. The goals then flowed into a set of more specific questions that could be addressed with the IceBridge data suite. The science questions were then linked to a set of observational goals, which are themselves driven by a set of specific measurement requirements. Science requirements (both measurement accuracy and geography requirements) are detailed in Section 5 of this report. Justification for many of the requirements parameters are reviewed in Section 6. (section 6 is not included in this document)

Note that the science themes, questions and measurement plans are important, ambitious and wide ranging. Consequently, the science community beyond just the IST is envisioned as active participants using the IceBridge data suite to address these questions. Two important functions of the IST are to engage the external community when developing data acquisition plans and to assure that the data set is as complete and as accurate as possible in order to facilitate broad and aggressive use by the science community. The team must walk the boundary between making recommendations on prudent and somewhat cautious use of the resources while at the same time anticipating the likelihood of new scientific investigations relying on a rich and cutting edge data set.

2. IceBridge Science Goals

At the highest level, the IceBridge data set will help address the following science goals (numerals in parentheses refer to Program Objectives of section 1.0).

Goal 1:
Document volume changes over the accessible domain of the Greenland and Antarctica ice sheets between ICESat and ICESat-2. A particular focus will be to document rapid changes. IceBridge will answer: how have the ice sheet volumes (areas accessible by aircraft) changed during these 5 years? (P1, P2))

Goal 2:
Document glacier ice thickness, basal characteristics 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? (P3, P4)

Goal 3:
Document the spatial and inter-annual changes in the mean sea ice thickness and the thickness distribution in the Arctic and Southern Oceans between ICESat 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.

Note that IceBridge data cannot be used solely to tackle these important questions. Other data (for example, ice sheet surface velocity, sea ice deformation and motion data) must come from other sources. However, IceBridge surface elevation, surface elevation change, and ice thickness data are essential ingredients needed to resolve these questions. Moreover, some of the measurements (swath altimetry and ice sounding radar) are only implementable on airborne platforms at present.

3. IceBridge Science Questions

Several specific science questions flow from the IceBridge science goals. This increasing level science specificity will be used to establish quantitative measurement requirements. Shown in parentheses is the traceability from the science goal to each question.

Ice Sheets

IQ1. *Where are glaciers continuing to thin and where may they be slowing/ thickening (G1)*

IQ2. *What are the major forces and mechanisms causing the ice sheets to lose mass and change velocity, and how are these processes changing over time? (G2)*

- *How do the ice sheet/glacier surface topography, bed topography, bed geology, ice shelves/tongues, and grounding line configurations affect ice dynamics?*
- *How far inland are the effects of coastal thinning transmitted and by what physical processes?*
- *How far downstream do changing processes near the ice divide (changes in snow accumulation, divide migration) effect glacier flow?*
- *What is the important scale for measuring geophysical parameters so as to substantially improve modeling fidelity?*
- *Where is the sub-glacial water produced and where is it going?*

IQ3. *How do ocean, sea ice, ice sheet interactions influence ice sheet behavior (G2)*

- *How does the bathymetry beneath Arctic fjords and Antarctic ice shelves influence ocean/ice sheet interactions and ice sheet/glacier flow dynamics?*

IQ4. *What are yearly snow accumulation/melt rates over the ice sheets? (G1)*

- *How do changing accumulation rates (and hence near surface densities and firn structure) impact altimetry measurements?*
- *What are the surface-melt flow-patterns and how do they change with time?*

Sea Ice

SQ1. *How are the physical characteristics of the sea ice covers changing (e.g. strength, thickness, snow depth, sea ice age)?*

SQ2. *What level of accuracy in ice thickness observations is desirable for climate forecast; Operational forecast? Climate/operational?*

SQ3. *What is the optimal configuration of instruments to remotely measure:*

- *Sea-ice freeboard, as a function of sea-ice elevation and sea surface elevation (via leads)*
- *Snow depth*
- *Sea-ice thickness (as derived from sea-ice freeboard and snow depth)*
- *Surface roughness (distinction of ice types, changes in ridge characteristics due to ice dynamics, relating melt point coverage to snow depth)*
- *Change in floe size and lead width distribution (affects ice albedo feedback)*

SQ4. *What is the optimal configuration of an Arctic sea ice observing network? Antarctic?*

- *How can data from in situ, airborne, submarine and satellite platforms, each with a unique spatial and temporal signature, be effectively combined?*
- *Are there locations that should be specifically monitored to aid in the observation and prediction of ice volume (e.g. monitoring sea-ice flux through Fram Strait)?*

SQ5. *How does snow depth impact melt pond formation? What is the relationship between snow and ice roughness?*

SQ6. *How is momentum being transferred between the ice and atmosphere? Ice and ocean?*

4. IceBridge Dataset Requirements

The IceBridge data set will have the following attributes based on the programmatic goals (section 1.0).

- DR1. Provide a dataset for cross-calibration and validation of ice-sheet elevations from satellite lidars (ICESat, ICESat-2, DESDynI-LiDAR) and radars (CryoSat-2 and Envisat). (P1,2,3)
- DR2. Provide a dataset for improving and linking ICESat and ICESat-2 ice-sheet elevation time series, including better characterization of ICESat errors. (P1,2)
- DR3. Provide a data set for investigating critical ice sheet processes (P3,4)
- DR4. Provide a dataset for improving and comparing numerical models of ice-sheet dynamics, especially precise maps of the bed beneath glaciers and coarse maps of the sea bed beneath ice shelves. (P3,4)
- DR5. Provide a dataset for improving instrument simulation and performance analysis in support of future missions, such as ICESat-2 and DESDynI-LiDAR. (P1,2)
- DR6. Collaborate with field programs that will enhance interpretation of ice bridge data. (P4)
- DR7. Provide a timely, well documented dataset for easy use by the science community. (P3,4)
- DR8. The data set should complement the ongoing and planned programs of international partners (P2).

Programmatic goal P5 (UAV and advanced aircraft) does not trace into these data set requirements nor the baseline science requirements (section 5). However the issue of advanced systems and sensors is partly addressed in the projected science requirements.

5. IceBridge Science Requirements

The IceBridge science requirements must satisfy NASA's established programmatic goals to provide for measurement continuity between ICESat and ICESat-2, measurement comparison and continuity between ICESat/Cryosat-2/ICESat-2 to create a decade long change record of ice sheet and sea ice characteristics, monitor rapidly changing areas of the Arctic and Antarctic, improve understanding of ice dynamics, and to provide data necessary to improve predictive models. Specific science requirements (both measurement and geographic constraints) are presented in this section. Measurement accuracy and geographic requirements are culled from the literature and are also based on the measurement parameter analyses presented in section 6. – (note: we don't include section 6 here).

The **Threshold Science Requirements** listed below combine both terrestrial and marine ice requirements and all have equal priority.

The **Baseline Science Requirements** listed below 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.

Projected Science Requirements, listed below, include a set of important parameters that could reasonably be sampled in the future 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 sub-glacial water; large scale measurements of surface accumulation rate; and sub-glacial 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 presented in section 6. (note: we don't include section 6 here).

Threshold Science Requirements

T1. Measure annual changes in glacier, ice cap and ice sheet surface elevation sufficiently accurate to detect 0.15 m changes in un-crevassed and 1.0 m changes in crevassed regions along sampled profiles over distances of 500 m.

T2. Measure sea-ice surface elevation with a shot-to-shot accuracy of 10 cm, assuming uncorrelated errors (SI 1.), and measure air-snow and the snow-ice interface elevation to an uncertainty of 3 cm, to enable the determination of snow depth on sea ice to an uncertainty of 5 cm (SI 2.), which together will enable the annual estimation of the springtime sea-ice thickness over broad regions of the Arctic and Antarctic ice packs to an uncertainty of 50 cm or better.

T3. Acquire annually, near-contemporaneous, spatially coincident ice elevation data with ESA's CryoSat-2 for underpasses in the Arctic and Antarctic. Coordinate with ESA in situ validation campaigns as possible.

T4. Conduct one campaign in the Arctic and one campaign in the Antarctic each year.

Baseline *Science Requirements*

Ice Sheets

IS1. Measure surface elevation with a vertical accuracy of 0.5 m or better.

IS2. Measure annual changes in ice sheet surface elevation sufficiently accurate to detect 0.15 m changes in un-crevassed and 1.0 m changes in crevassed regions along sampled profiles over distances of 500 m.

IS3. Measure ice thickness with an accuracy of 50 m or 10% of the ice thickness, whichever is greater.

IS4. Measure free-air gravity anomalies to an accuracy of 0.5 mGal and at the shortest length scale allowed by the aircraft.

IS5. Acquire annually, near-contemporaneous ice elevation data with ESA's CryoSat-2 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.

IS6. Re-measure 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.

IS7. Collect elevation data so that the combined ICESat-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.

IS8. 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.

IS9. 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.

IS10. Measure once Greenland ice sheet elevation and ice thickness about four, nearly continuous closed loops approximately about the 1000, 2000, and 2500 ice sheet elevation contours.

IS11. 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.

IS12. 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.

IS13. 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].

IS14. 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 sub-glacial water.

IS15. Acquire sub-meter resolution, stereo color imagery covering laser altimetry swaths

Glaciers and Ice Caps

IC1. 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].

IC2. Make annual repeat measurement of surface elevation on select Alaskan Glaciers.

IC3. 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-2 validation activities.

IC4. 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].

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 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.

<u>Projected</u> Science Requirements

Ice Sheets

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 sub-glacial water over 5 km square areas.

3. Seasonally re-measure surface elevation on select Greenland and Antarctic Glaciers using UAVs.

4. Estimate relative spatial changes in sub-glacial geothermal heat flux using ice thickness, gravity and magnetic data.

5. Re-measure ice sheet surface elevation at the locations of ICESat detected sub-glacial 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 sub-meter resolution and accuracy.

8. Collect elevation data so that the combined ICESAT-1-OIB sampling provides an elevation measurement within 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.

Sea Ice

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 on the Requirements

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, Zachariae (NE Ice Stream), Store, Rinks, Jacobshavn, Eqalorutsit Kangigdlit Sermiat, Nordboggletscher, Helheim, Daugaard-Jensen.
3. The list of Antarctic Glaciers includes but is not exclusive to: Pine Island, Thwaites, Crane, Rutford, Lambert, Totten, Mertz, Shirase, Recovery, Jutulstraumen, David, Byrd, Nimrod, Siple Coast Ice Streams.
4. The list of ice shelves includes but is not exclusive to: Getz, Dotson, Crosson, Thwaites, Pine Island, Cosgrove, Abbott, 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 of Thule) and Humboldt, Heimdal Fjord, Bernstorft Fjord, Gyldenlove Fjord, Helheim, Kangerlugssuaq, Vestfjord, Daugaard Jensen, Keyser Franz Joseph Fjord, Borfjorden (Storstrommen).
6. The list of ice tongues includes but is not exclusive to: Peterman, 79° North, and Zachariae 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, Margerite, 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.