NASA Operation IceBridge
Level-1 Science Requirements and Scientific Basis

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1. Program Overview and the Science Team

NASA established Operation IceBridge (OIB) and mandated it to fulfill the following programmatic (**P**) 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 inter-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.*

OIB is directed by a Project Science Office (PSO) based at NASA's Goddard Space Flight Center. There are separate management functions for OIB science, logistics, instruments and data management. The five programmatic goals listed above provide general scientific direction. Specific direction is provided by the OIB Science Team (OIB-ST), which has the following three tasks mandated by the Program:

ST1	*Finalize development of the OIB Science Definition Document and Level-1 Scientific Requirements document.*
ST2	*Evaluate OIB mission designs in achieving the goals defined by the Science Definition Document and Level-1 Scientific Requirements document.*
ST3	*Support the OIB Program Scientist and Project Science Office in the development of the required analyses, documentation, and reporting during the mission.*

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

This document addresses the first science team task to establish Level-1 science requirements. The OIB-ST adopted the following strategy for completing this task. First, the OIB-ST articulated broad scientific goals or themes addressing Greenland and Antarctic ice sheets, Arctic and Antarctic sea ice, Alaskan glaciers and Canadian Arctic ice caps. These goals then flowed into a set of more specific questions that could be addressed with the OIB instrument suite. These 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 document.

Note that the science themes, questions and measurement plans are important, ambitious and wide-ranging. Consequently, the community of scientists beyond just the OIB-ST is envisioned as an active participant in using OIB data to address these questions. Two important functions of the OIB-ST are to engage the external community when developing data-acquisition plans and to assure that the datasets are as complete and as accurate as possible to facilitate broad and ambitious use by the relevant community of scientists, including those conducting other field campaigns. The OIB-ST must walk the boundary between making recommendations on prudent and somewhat cautious use of limited resources, while simultaneously anticipating the likelihood of new scientific investigations relying on rich and cutting-edge datasets.

2. Science Goals

At the highest level, OIB datasets will help address the following science goals (**G**; parentheses refer to programmatic goals in Section 1):

G1	*Document volume changes over the aircraft-accessible portions of the Greenland and Antarctic ice sheets during the period between the ICESat and ICESat-2 missions. A particular focus will be to document rapid changes. OIB will answer: How have the ice-sheet volumes within areas accessible by aircraft changed during this period? (P1, P2)*
G2	*Document glacier and ice-shelf thickness, ice-shelf bathymetry, snow accumulation-rate variability and other geophysical properties to better interpret volume changes measured with laser altimetry and to enable more realistic simulations of ice-sheet flow and mass balance with numerical models. OIB will help answer: How are the ice sheets likely to change in the future? (P3,P4)*
G3	*Document spatial and interannual changes in the mean sea ice thickness in the Arctic and Southern Oceans in the period between ICESat and ICESat-2, in support of climatological analyses and assessments.*
G4	*Improve sea ice thickness retrieval algorithms by advancing technologies for measuring sea ice surface elevation, freeboard and snow depth over sea ice in the Arctic and Southern Oceans.*

Note that OIB data alone cannot answer these important questions. Supporting data must come from other sources (e.g., ice-sheet surface velocity, sea ice deformation and motion data).

However, OIB surface elevation, surface-elevation change, and ice-thickness data are essential information needed to resolve these questions. Moreover, some of the measurements are presently implemented on airborne platforms only (swath altimetry and radar sounding).

3. Science Questions

Several specific science questions flow from the OIB science goals. This increasing level of specificity is used to establish quantitative (**IQ**) measurement requirements (parentheses refer to science goals in Section 2):

Ice sheets

IQ1	*Where are glaciers continuing to thin and where are they 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 ice sheet/glacier surface topography, bed topography, 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 affect ice-sheet evolution (e.g., changes in snow accumulation, divide migration)?*
IQ3	*How do the oceans, sea ice, and ice sheets interact, and how do these interactions ultimately 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 Arctic and Antarctic sea ice changing (e.g., thickness, snow depth, age)? (G3)*
SQ2	*What level of accuracy in ice thickness observations is desirable for climate or operational forecasts? (G3)*
SQ3	*What is the optimal temporal and spatial sampling strategy for extensive airborne observations of Arctic and Antarctic sea ice? (G4)* • *How can sea ice data from OIB airborne platforms be most effectively combined with data from in situ, submarine and satellite platforms?* • *Are there sea ice physical characteristics or locations that should be specifically monitored to best aid in the future observation of ice thickness with ICESat-2 (e.g., snow thickness in the Fram Strait)?*
SQ4	*What is the optimal instrument configuration to measure the following sea ice properties remotely: sea ice freeboard, snow depth, sea ice thickness, surface roughness and sea ice/lead distributions? (G4)*
SQ5	*What is the relationship between sea ice surface roughness and the thickness of any overlying snow? (G4)*

4. Dataset Requirements

OIB datasets will have the following attributes (**DR**), based on the programmatic goals (Section 1):

DR1	*Provide a dataset for inter-comparison of ice-sheet elevations from laser (ICESat, ICESat-2) and radar (CryoSat-2, Sentinel-3) satellite altimeters. (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 dataset for investigating critical ice-sheet processes. (P3,4)*
DR4	*Provide a dataset for improving and validating numerical models of ice-sheet dynamics, especially precise maps of the bed beneath glaciers and coarse maps of the bathymetry 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. (P1,2)*
DR6	*Collaborate with field programs that will enhance interpretation of OIB data. (P4)*
DR7	*Provide a timely, well-documented dataset for easy use by the science community. (P3,4)*
DR8	*Provide data to complement the ongoing and planned programs of international partners. (P2)*

5. Science Requirements

As summarized above, OIB science requirements must satisfy NASA's established programmatic goals to provide measurement continuity between ICESat and ICESat-2, to provide measurement comparison and continuity between ICESat/Cryosat-2/ICESat-2, to create decadal records of ice-sheet and sea ice characteristics, to observe rapidly changing areas of the Arctic and Antarctic, to improve our understanding of ice dynamics, and to provide data necessary to improve predictive numerical models. Specific science requirements, including both measurement and geographic constraints, are presented in this section. Measurement accuracy and geographic requirements are based on peer-reviewed studies.

Table 1 summarizes the threshold requirements that OIB must satisfy. This table combines both land and sea ice requirements, and all have equal priority. Tables 2.1, 2.2 and 2.3 summarizes the prioritized baseline science requirements that must be achieved by a multi-year airborne campaign designed to address 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, and a first-order description of bathymetry in front of tidewater glaciers and underneath ice shelves. Tables 3.1 and 3.2 show projected requirements that 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 (e.g., large-scale measurements of surface melt, runoff or surface accumulation rate). 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 one standard deviation about the mean.

These science requirements also draw on publications that summarize the scientific community consensus on important variables and their measurement sensitivities (ISMASS, 2004; NRC, 2007; IGOS, 2007; ISMASS, 2010).

Table 1. Threshold Science Requirements

T1	*Measure annual changes in glacier, ice-cap and ice-sheet surface elevation with sufficient accuracy to detect 15-cm changes in un-crevassed and 100-cm 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 (SI1), and measure air-snow and 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 (SI2), which together will enable the annual estimation of the springtime sea ice thickness over broad regions of Arctic and Antarctic sea ice to an uncertainty of 50 cm or better.*
T3	*Acquire annual, near-contemporaneous and spatially coincident ice elevation data with ESA's Cryosat-2 for underpasses in the Arctic and Antarctica. Coordinate with ESA in situ validation campaigns as possible.*
T4	*Conduct one campaign in the Arctic and one campaign in the Antarctic each year.*

Table 2.1. Baseline Science Requirements for Ice Sheets

IS1	*Measure surface elevation with a vertical accuracy of 10 cm*
IS2	*Measure annual changes in ice sheet surface elevation with sufficient accuracy to detect 15-cm changes in un-crevassed and 100-cm 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 sub-meter resolution, stereo color imagery covering laser altimetry swaths*
IS6	*Measure repeat* Antarctic and Greenland surface elevation profiles along established airborne altimetry and ICESat/ICESat-2 ground tracks, and in support of other altimetry missions †*
IS7	*Measure ice thickness in Greenland and Antarctica to support interpretation of the ICESat, OIB and ICESat-2 elevation records, the NISAR mission, and other cryospheric objectives*
IS8	*Measure surface elevation along central flowlines of outlet glaciers constraining 80% of the ice discharge from the Greenland Ice Sheet[1,2]**
IS9	*Measure cross-transects of ice thickness, surface, and bed elevation upstream of the terminus of glaciers constraining 80% of the ice discharge from the Greenland Ice Sheet[1,2]*
IS10	*Measure cross-transects of ice thickness, surface elevation, gravity anomalies upstream of the grounding line of select Antarctic glaciers[3]*

IS11	*Measure surface elevation, ice thickness and sea floor bathymetry beneath select Antarctic ice shelves[4], adjacent continental shelves, and along select Greenland fjords[5]*
IS12	*Acquire near-surface radar data to document spatial patterns of snow accumulation with a vertical resolution of 10 cm or better*
IS13	*Acquire radar-sounding data to measure changes in ice-shelf thickness with a precision of 5 m or better per time interval along select ice shelves in Antarctica and floating ice tongues in Greenland[4,6]*
IS14	*Collect seasonal changes (spring vs. fall) in surface elevation in Greenland to detect 15-cm changes in un-crevassed areas and 100-cm changes in crevassed regions along sampled profiles over distances of 500 m*

* Baseline missions established for Greenland and Antarctica
† Cryosat-2, Sentinel-3.

Table 2.2. Baseline Requirements for Glaciers and Ice Caps

IC1	*Annually to semi-annually collect laser altimetry 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 Arctic ice caps at least twice during OIB. Coverage should be based on previous airborne campaigns and in support of CryoSat-2 in situ validation activities*
IC4	*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 OIB[8]*

Table 2.3. Baseline Requirements for Sea Ice

SI1	*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 that 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.*
SI2	*Make elevation measurements of both the air–snow and the snow–ice interfaces to an uncertainty of 3 cm, which enables the determination of snow depth to an uncertainty of 5 cm.*
SI3	*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 (multi-year) sea ice to include, as a minimum:* ***Arctic*** • *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.* • *The perennial sea ice pack from the coasts of Ellesmere Island and Greenland north to the pole and westward across the northern Beaufort Sea.*

	Arctic (continuing from page 6) • *Sea ice across the Fram Strait and Nares Strait flux gates.* • *The sea ice cover of the Eastern Arctic, north of the Fram Strait* ***Antarctic*** • *Sea ice in the Weddell Sea between the tip of the Antarctic Peninsula and Cape Norvegia.* • *Mixed ice cover in the western Weddell Sea between the tip of Antarctic Peninsula and Ronne Ice Shelf.* • *The ice pack of the Bellingshausen and Amundsen Seas.*
SI4	*Include flight lines for sampling the ground tracks of satellite laser altimeters (ICESat and ICESat-2) and radars (CryoSat-2 and Sentinel-3). In the case of CryoSat-2, both OIB 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.*
SI5	*Conduct sea ice flights as early as possible in the spring flight sequence of each campaign, prior to melt onset.*
SI6	*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 altimetry data.*
SI7	*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.*
SI8	*Make full gravity vector measurements on non-repeat, 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.*
SI9	*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 3.1. Projected Ice Sheet Science Requirements on Future OIB Development

ISP1	*Measure isochronal layering in the snow and firn with an accuracy of 4 cm in dry snow regions with annual accumulation rate in excess of 20 cm yr–1 water equivalent.*
ISP2	*Acquire photogrammetrically calibrated, stereo color imagery covering laser-altimetry swaths and adjacent areas for creating digital elevation models and orthophotographs with sub-meter resolution and accuracy.*
ISP3	*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 margin of the Greenland Ice Sheet and the grounding line of West Antarctica.*

Table 3.2. Projected Sea Ice Science Requirements on Future OIB Development

SIP1	*Improve SI1 to make surface elevation measurements with a shot-to-shot accuracy of 5 cm (versus 10 cm), assuming uncorrelated errors.*
SIP2	*Extend SI3 to other regions of the Arctic and Southern Oceans:* ***Arctic*** *(to better constrain estimates of sea ice volume change)* • *North Pole region* • *Southern Beaufort Sea, west of Banks Island* • *Sea ice along the coast of Greenland* • *Southern Chukchi Sea north of Bering Strait* • *Davis Strait* • *Lancaster Sound and other parts of the Canadian Archipelago* ***Antarctic*** *(to better understand the process of sea ice formation and snow accumulation)* • *Ross Sea* • *Surveys of areas of polynya formation, over and downwind of the polynya* • *Surveys of areas where katabatic winds may deposit abundant snow*
SIP3	*Collect thermal images for a swath that, as a minimum, covers the laser altimetry data swath with a resolution of 0.5 m or better, and are calibrated to brightness temperature with an accuracy of 0.1K.*
SIP4	*OIB shall support the validation of operational sea ice analysis and forecast products by providing estimates of sea ice freeboard within one week of data acquisition and estimates of sea ice thickness within two weeks of data acquisition.*

Footnotes on 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, Zachariæ, Store, Rinks, Jakobshavn, Eqalorutsit Kangigdlit Sermiat, Nordboggletscher, Helheim, Daugaard-Jensen.
3. The list of Antarctic glaciers includes but is not exclusive to: Pine Island, Thwaites, Smith, Fleming, Crane, Evans, Mertz, Recovery, Jutulstraumen, David, Byrd, Nimrod, WAIS Ice Streams.
4. The list of ice shelves includes but is not exclusive to: Getz, Dotson, Crosson, Thwaites, Pine Island, Cosgrove, Abbot, George VI, Larsen C, Venable, Cook, Moscow, Fimbul.
5. The list of fjords includes but is not exclusive to: Nordre Sermilik, Kangiata (Nuuk), Jakobshavn, Torssukataq, Ummanaq (three fjords), Upernavik, and mini fjords in Melville Bay, Humboldt, Heimdal Fj., Bernstorft Fj., Gyldenlove fj., Helheim, Kangerlugssuaq, Vestfjord, Daugaard Jensen, Keyser Franz Joseph Fj., Borfjorden (Storstrømmen).
6. The list of ice tongues includes but is not exclusive to: Petermann, 79 North, and Zachariæ.
7. Targeted glaciers include but are not exclusive to the Columbia-Tazlina system, the Bering-Bagley system, the Seward-Malaspina system, the Yahtse, 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.