NASA's Operation IceBridge (OIB) Mission
Midterm External Review Report

Submitted to NASA HQ, April 2014

Prepared by the OIB Midterm external Review Team (OIB-MRT)

Beata Csatho (Chair), University at Buffalo, Buffalo, NY, USA, bcsatho@buffalo.edu

Land Ice

Helen Fricker (co-chair), Scripps, UCSD, La Jolla, CA, USA, hafricker@gmail.com

Alex Gardner, Clark University, Worchester, MA, USA, AGardner@clarku.edu

Ian Howat, OSU, Columbus, OH, USA, ihowat@gmail.com

Erik Ivins, NASA/JPL, Pasadena, CA, USA, erik.r.ivins@jpl.nasa.gov

Sea ice

Richard Moritz (co-chair), University at Washington, Hawaii, USA, dickm@snark.apl.washington.edu

Hajo Eicken, University of Alaska, Fairbanks, AL, hajo.eicken@gi.alaska.edu

Christian Haas, York University, Toronto, Ontario, Canada, haasc@yorku.ca

Julienne Stroeve, University of Colorado, Boulder, CO, USA, stroeve@kryos.colorado.edu

Leif Toudal Pedersen, Danish Meteorological Institute, Copenhagen, Denmark, ltp@dmi.dk

Land-Ice Group (LIG)[1] Report

Summary

The OIBMR-T LIG has conducted an extensive review of all aspects of the land-ice component of the Operation Ice Bridge mission (OIB), including the goals and the level-1 science requirements. The primary motivation behind OIB was the identified need to bridge the ice sheet altimetry record between ICESat and ICESat-2 missions. The OIBMR-T LIG concludes that OIB has made excellent progress in establishing an extended altimetry record of polar ice sheets and glaciers and it is on target to accomplish its main scientific objectives, and has proven to be much more valuable than originally anticipated. OIB has evolved into a complementary, not substitute, observing platform to satellite laser altimetry, measuring critical geophysical properties of glaciers and ice sheets that currently cannot be measured from space, e.g. ice sheet bedrock topography, basal and englacial characteristics and other crucial geophysical parameters, all of which are required for improving understanding of ice dynamics and for the development of 3-D time-dependent numerical ice-flow models.

The OIBMR-T has made several recommendations that would further strengthen the OIB mission as it moves into the second phase, summarized below:

- Revisit the science requirements so that the list is more concisely and clearly defined;
- Revisit flight-planning priorities to enhance the capabilities of OIB to act as a bridge between satellite altimetry missions and to allow for cross-calibration between the altimeters;
- Include additional instruments for retrieval of snow radiative transfer properties critical for characterizing scattering of 532nm wavelength laser altimeters and atmospheric forcing at the surface and for improved photogrammetric mapping of glacier topography;
- Publication of key review papers documenting the mission and its observing capabilities.

The discontinuation of OIB would leave a large gap the observational record of ice sheet properties required to further understand glacier and ice sheet response to external forcing and their consequence for sea level change. ***The OIBMR-T LIG recommends that efforts are made to secure funding for the continuation of OIB for at least the next decade.***

1. OIB Land Ice Goals and Accomplishments

The primary goal of OIB was to bridge the gap in the modern laser altimetry record, which started with historical airborne laser altimeters, such NASA's Airborne Topographic Mapper (1993-present), and then continued with satellite laser altimeters ICESat-1 (2003-2009) and ICESat-2 (2017-2020). As recent observations of dramatic changes challenged the traditional view of slowly evolving ice sheets and revealed the complexity of ice sheet response to climatic forcing, an improved understanding of processes controlling ice sheet mass balance became critically important for predictions of ice sheet mass loss and related sea level rise, and this is now a central goal of NASA's Cryospheric Sciences Program. By quantifying the spatio-temporal evolution of ice sheet surface elevation, repeat laser altimetry allows assessment of the contributions of secular, inter-decadal and inter-annual variability in snow accumulation, surface-melt and ice flow dynamics and their impact on mass balance. Only *uninterrupted monitoring* of land ice provides a multi-decadal record of change, and the *continuous nature* of such observations is critical. Thus, the temporal 'gap' in the comprehensive satellite laser altimetry coverage between ICESat and ICESat-2 was a major concern. In 2008, OIB was conceived to bridge this gap, and the primary concept was to use airborne instruments for continuous monitoring of elevation change.

---

[1] The OIB-MRT Land Ice Group: Helen Fricker, Beata Csatho, Alex Gardner, Ian Howat, Erik Ivins

Since it is not possible for an airborne mission to fully reproduce the spatial and temporal coverage of a satellite, due to fundamental limitations in spatial and temporal sampling density, the primary focus of OIB was on areas already known to be undergoing rapid changes, including the coastal regions of the Greenland Ice Sheet, Alaska, Arctic Canada as well as Antarctic outlet glaciers in the Amundsen Sea Embayment and on the Antarctic Peninsula. OIB has successfully extended the time series in these key regions. Additionally, by 2011 all the altimetry data had been collected for constructing improved Digital Elevation Models (DEMs) of land ice surfaces in steep coastal regions where existing DEMs have large errors (Greenland, Amundsen Sea Embayment and Antarctic Peninsula).

The airborne platforms of OIB offer capabilities to measure ice thickness, stratigraphy and near-surface ice and snow properties, which cannot be measured from space. Therefore, OIB provides unique and important observations that have improved our understanding of ice-sheet mass balance and ice dynamics, resulting in more robust constraints for predictive models of sea level rise. OIB observations have lead to improved bedrock maps, grounding line positions and ice thickness measurements. The compilation of the new Antarctic bed topography (Bedmap-2) was made possible by extensive collection of radar depth-sounding by OIB and is a major step toward improving estimates of Antarctica's ice discharge. The use of gravimeters on OIB flights has allowed data to be acquired for construction of more accurate bathymetric maps near the grounding line, a critical product for reconstructing the geometry of major flux gates that discharge land ice across the grounding line. OIB gravity and magnetics have provided new bathymetry for over many Greenland fjords and some of the major West Antarctic ice shelves and ice streams. Improved knowledge of the bathymetry in Antarctica over the Larsen and Abbott ice shelves and at the grounding lines of Thwaites and Pine Island glaciers has provided new insights into the stability of these systems***.***

Complementing its overarching goals, OIB uses different ice penetrating radar systems to investigate the subglacial environment and near surface firn-structure. These observations are critical for better characterizing the role of liquid water in controlling ice flow and mass balance. For example, these observations helped in the mapping of vast liquid water aquifers within the Greenland ice sheet. The observations also reveal the details of englacial stratigraphy, a data set that may be important for future ice model flow reconstructions.

Benefits of continued OIB measurements and related modeling activity

- OIB altimetry observations will continue to extend ice sheet and glacier elevation change records and provide enhanced resolution and improved accuracy.
- OIB altimetry observations will allow for cross-calibration between ICESat, ICESat-2 data and CryoSat-2 altimetry.
- OIB altimetry observations will provide accurate ground control information to register high-resolution, repeat aerial and satellite stereo imagery (e.g., DigitalGlobe's WorldView satellites) suitable for deriving high-resolution and high-accuracy DEMs.
- OIB observations will enable characterization of the evolving state of the ice sheets through assimilation into numerical ice sheet models.
- OIB will map snow accumulation that is needed for validation of regional and global climate models and for determining firn-compaction rates.
- OIB observations will support the reconciliation of bathymetry and bed mapping at the position of outlet glacier grounding line, thus establishing a map of the Earth's solid rock surface free of artificial discontinuities. This is critical for improved ice sheet models.

2. Summary of IceBridge User Survey

The OIBMR-T prepared a User Survey for the community that was sent out to users of IceBridge data via Cryolist in October 2013. The Survey asked questions related to IceBridge coverage, instrumentation and sampling, data access and distribution, presentations and publications and success and future of IceBridge. The Survey yielded 32 complete responses (21 from land-ice users). The results, provided in the Appendix, are summarized as follows:

- 63% think that the coverage is adequate for their research
- 75% think that key regions were missed
- 94% think no region was oversampled
- 66% think the temporal sampling is adequate
- 50% have no recommendation for improving sampling strategies
- 91% think OIB is collecting the right type of data for their science
- 81% think no instruments should be added
- 91% find the data easy to use and think there is sufficient information and support
- 94% think IceBridge should continue at least a year past ICESat-2 launch (and 75% think it should go for longer).

The main points emphasized in the detailed requests for future OIB land-ice observations were as follows:

- Broader coverage of the ice sheets to better assess the overall mass balance of the ice sheet and better tie in a time-series between ICESat and ICESat-2.
- A focus on the Antarctic grounding line, in its entirety.
- Spatial sampling could be improved; data along grid patterns would be more beneficial compared to flying single lines along glaciers.
- Use of swath mode for glacier terminus width would improve both the coverage but also make the data more useful as glaciers advance/retreat.
- Better coverage of large glacier systems (outside the ice sheets).

3. Recommendations for further enhancing OIB outcomes

3.1 OIB Science Goals and Requirements

To satisfy NASA's programmatic goals, OIB defined 19 baseline science requirements and 4 threshold requirements for land ice. To meet the requirements for altimetry change detection OIB should 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 repeated OIB flight lines over distances of 500 m. With careful consideration to flight planning, along-track elevation changes can be interpolated to determine total volume changes of ice sheets and glaciers, which is relevant to understanding how glaciers respond to ocean and atmospheric forcing and the role the play in present rates of sea level rise. Science requirements call for measurements of surface and bed topography/bathymetry along loops enclosing the higher elevation part of the GrIS and following the Antarctic Ice Sheet grounding line. OIB also established detailed observational requirements for characterizing glaciers, ice shelves and ice caps and provided a list of recommended targets (regions that were known to be changing). OIB has made excellent progress in fulfilling most of these science requirements, as summarized in Section 1. However, some of the requirements appear to be unrealistic and it is likely that they will not be met by the end of first phase of the OIB mission, due to the inherent limitation in spatio-temporal coverage by an airborne mission.

As OIB moves into its second phase, the OIBMR-T LIG believes that the mission would benefit from a thorough review of its science requirements based on the better-known logistical limitations of the airborne campaign and rapid developments in sensor technology since the mission began. Some science requirements are repetitive and could be combined, while others seem unrealistic and could be removed completely. In particular, the OIBMR-T LIG recommends re-evaluating the requirements for characterizing Greenland and Antarctic outlet glaciers and ice shelves (Baseline Science Requirements IS8, IS9, IS11 and IS13), prioritizing the target regions (IS8, IS9, IS13) and reducing the number of glaciers selected for detailed monitoring (IS11). The OIBMR-T LIG also suggests including new targets as aircraft logistics and NASA programmatic goals allow, including selected ICESat-2 ground tracks and large and rapidly changing non-polar glacier systems. Finally, OIBMR-T LIG recommends re-evaluating the requirement to monitor the changing subglacial water distribution ('warm ice') from repeat radar, basal-echo-amplitude data (IS14). The required accuracy (3dB) is unachievable over most of the ice sheet with the current OIB instrumentation, as uncertainties of that magnitude across the distances specified (200 km) have been known to occur even in regions where dielectric attenuation is well constrained.

Recommendations:

1) Revisit the land-ice science requirements and streamline them so that they are more concisely and clearly defined;

2) Include the following new targets as aircraft logistics and NASA programmatic goals allow: (i) selected ICESat-2 ground tracks on the ice sheets over a range of conditions i.e. elevation/melt/roughness; and (ii) infrequent coverage of other large and rapidly changing non-polar glacier systems, especially when logistically straightforward.

3) Re-evaluate the requirement to monitor the changing subglacial water distribution ('warm ice') from repeat radar, basal-echo-amplitude data.

3.2 Altimeter validation and cross-calibration

Extending the altimetry record of ICESat and linking the interrupted ice altimetry record of ICESat (2003-2009), ICESat-2 (2017-) and ESA's CryoSat-2 (2010 to present) requires careful planning of flight lines and comparison of elevation estimates from different altimeters carried by each mission. ICESat carried a 1064 nm waveform laser altimeter and ICESat-2 will carry a photon-counting 532 nm laser altimeter. The OIB laser altimeters are the Airborne Topographic Mapper (ATM; 532 nm with fine footprint and no waveform provided) and the Land, Vegetation and Ice Sensor (LVIS; 1064 nm with large footprint and waveform provided). Past OIB efforts have coordinated closely with ESA and university-led ground campaigns to compare ATM elevations with those derived from CryoSat-2 radar returns, but the OIBMR-T LIG concluded that not enough effort has been made to ensure cross-calibration of elevations over land ice.

It is important to investigate the probable biases introduced by differences in snow and ice via multiple scattering at 532 nm and 1064 nm wavelengths. Absorption by ice varies significantly between these wavelengths and the mean scattering path length is dependent on snow grain shape and size and the frequency of cracks and bubbles within ice, both of which can vary significantly in space and time. Ice has very low absorption at 532 nm, such that changes in the scattering properties of the ice will alter the photon return time. At 1064 nm ice has much higher absorption and thus gives a truer surface reflection. The addition of a small footprint 1064 nm laser altimeter with similar characteristics as the ATM and mounted on the same platform should allow OIB to characterize the 532 nm penetration bias. This is of high importance for identifying biases between ice and snow elevations acquired using 532 nm and 1064 nm laser altimeters and for improving the overall accuracy of ICESat-2 elevations. Because fresh snow is highly scattering (i.e. a short mean photon path length within the snowpack at both wavelengths), elevation biases between 532 nm and 1064 nm laser altimeters will likely only be of significance (~ >1 cm) over ice and aged snow surfaces. The OIBMR-T LIG recommends that a validation campaign to quantify volume scattering is planned for the Greenland Ice Sheet during summer when the widest range of snow and ice conditions can be sampled. Characterization of the multiple-scattering bias would require that both a 532 nm and a 1064 nm laser altimeter to be installed on the same platform (see Section 3.4.2). Including an imaging spectrometer as part of the instrument suite would be helpful in characterizing target optical characteristics that are relevant to scattering of the laser beam (see Section 3.4.3).

More generally, the OIBMR-T LIG has identified a need to validate OIB elevation products over a wider range of snow/ice conditions and surface textures to ensure direct comparability between products and to better characterize uncertainties in derived elevation for real-world conditions. Of particular concern are differences in elevations determined from laser altimeters with varying illumination footprints, wavelengths, and range identification algorithms. To ensure direct comparability between elevations derived from different instruments is recommended that a targeted validation campaign be organized to collect simultaneous measurements of ice elevation using the various OIB altimeter systems (ATM, LVIS, and a 1064 nm laser altimeter with similar characteristics as the ATM sensor), over a wide range of ice surface: Bare ice, fresh snow, lakes, crevasses, firn, and large grain melting snow.

The OIBMR-T LIG **recommends the implementation of coordinated and simultaneous validation campaigns on common and different platforms for altimeter cross-calibration, as follows**:

1) **Additional work should be done to ensure direct comparability between elevations retrieved from the different satellite and airborne altimeters.**

2) Validation campaign for Greenland Ice Sheet in summer to sampled a variety of snow and ice conditions to quantify the volume-scattering bias, flying both a 532 nm and 1064 nm laser altimeter simultaneously, and an imaging spectrometer if possible.

3) **Design targeted validation campaigns to quantify range uncertainties and biases for each of the OIB laser altimetry systems for glacier surfaces of varying roughness, slope and surface optical properties, and to better characterize the firn-densification process**.

To act on these recommendations, was suggested that OIB consider the coordination of a no-cost Announcement of Opportunity to support targeted field programs to improve altimeter cross-calibration.

3.3 Flight planning

OIB is tasked with extending the ICESat mission, providing continuity with ICESat-2, and monitoring select regions of interest, such as rapidly-changing outlet glaciers. This list of tasks is likely to result in conflicting schedules due to the trade-off between higher spatio-temporal sampling (best for improved processes understanding) and broader coverage (best of estimating regional volume change and sea level contribution). For example, more ICESat lines can only be flown at the expense of reduction in outlet glacier surveys. The task of the OIB ST is to balance these goals to maximize science return in accordance with the OIB science questions and logistical constraints. Overall, the OIBMR-T LIG concluded that OIB has done an excellent job in mission planning to balance these various complex and competing goals. However, the OIBMR-T LIG suggests that the flight planning priorities should be revisited within logistical limits and has identified two key ways in which flight planning can be improved as OIB moves into the second phase:

3.3.1. Mechanism for soliciting input from broader cryospheric community

Since OIB is a NASA-directed mission, no formal system is established for soliciting community input into the planning process for collection of observations over land ice. OIB holds annual mission-level town hall meetings at the Fall Meeting of the American Geophysical Union. While valuable, these meetings are largely informational and provide little opportunity for community input. To ensure broad representation, OIB ST members are selected as representatives of various parts of the cryosphere community to ensure that all focus areas are considered in planning. There is, however, the perception of imperfect syncing of this general mandate and the influence of OIB ST members, in their roles as individual investigators, in selecting flight lines.

The OIBMR-T LIG believes that both the policy and mechanisms for planning and coordination can be improved with respect to actuating the OIB flights with fieldwork or other data collection programs and staying rigorously directed toward the science goals. In at least a couple of cases, grants were awarded that included OIB over-flights, but there was no system for including this into the OIB ST input. Such a process will be critical for coordinating data collection with validation/calibration studies, including firn-compaction measurements.

Recommendation: OIB adopt a more transparent method for selecting and coordinating land-ice flight lines during future OIB campaigns. An example would be to hold semi-formal planning meetings amongst PIs to discuss flight planning.

3.3.2 Balance between local (rapid dynamics) and regional data-continuity flight patterns.

The OIB ST has taken the approach of identifying the most critical and/or scientifically relevant ICESat lines for surveying at frequencies determined by the temporal scale of change. Long-established, pre-OIB flight lines on and around outlet glaciers have been re-surveyed, maintaining those multi-decadal time series, while coverage in scientifically important areas, such as the northwest and southeast coasts of Greenland, have been greatly expanded.

There is, however, strong consensus that OIB has likely oversampled some outlet glaciers, and other rapidly changing regions at the expense of broad spatial measurements that are needed to characterize decadal to century timescale responses of the ice sheet and to determine regional-scale changes in ice sheet volume. **Recommendation: OIB should place more emphasis on acquiring broader-scale coverage.**

3.4 Instrumentation

The OIBMR-T LIG considered the full suite of instrumentation being flown by OIB and examined which of these instruments were underutilized, which ones could be replaced, and also what additional instruments could be added. The usefulness of the magnetometer was examined, as was the Digital Mapping System. Instruments that we believe could be added are a 1064 nm laser altimeter and alternative instrumentation for imaging bedrock in warm, crevassed ice.

3.4.1 Magnetometer justification

The OIBMR-T LIG raised questions as to the benefit of routinely including the magnetometer in the suite of OIB instrumentation. After discussions with OIB scientists, it seams that the magnetometer makes the inclusion of new instrumentation more difficult because their installation requires a re-calibration of the magnetometer. The magnetometer has had relatively few downloads from NSIDC (<50) and, to our knowledge, there are no published results that use the data. We acknowledge the useful role it has in delineating sedimentary from igneous, metamorphic and higher density bedrock types in support of gravity data interpretation.

3.4.2 Addition of a 1064 nm laser altimeter

Characterization of the multiple-scattering bias over a range of ice conditions (Seciton 3.2) would require that both a 532 nm and a 1064 nm laser altimeter to be installed on the same platform.

Recommendation: a conventional 1064 nm laser altimeter with similar characteristics as the ATM be mounted on the same platform as the ATM during the suggested validation campaign.

3.4.3 Addition of a visible/NIR imaging spectrometer

The surface energy balance plays a critical role in the mass budget of glaciers and ice sheets. One of the primary energy terms contributing to melt is the absorption of shortwave radiation, which is greatly modulated by surface optical properties (reflectance). OIB provides a unique platform to characterize the surface optical properties of snow and ice with low atmospheric interference. With minimal additional cost, OIB could include an imaging spectrometer that would allow for the simultaneous measurement of reflectance, surface effective grain size, and characterization of trace light absorbing impurities. Such measurements would also be highly valuable for determining the surface radiation budget and characterizing the snow optical properties relevant to the multiple scattering of laser altimeters. One instrument that is ideally suited for this application is NASA's Airborne Visible / Infrared Imaging Spectrometer (AVIRIS) that is already being flown over snow as part of JPL's Airborne Snow Observatory. Inclusion of such an instrument would greatly enhance the science outcomes of the mission. **Recommendation: include an imaging spectrometer (ideally AVIRIS) as part of the OIB instrument suite.**

3.4.4 Re-evaluate the Digital Mapping System (DMS)

The DMS camera has proven to be more challenging than originally anticipated and very few elevation models have been derived from the data. This is in large due to unanticipated changes in the focal length of the camera system with changes in temperature. A post-acquisition independent bundle adjustment is of limited benefit as it is poorly constrained by a lack of across track imagery. Therefore, the construction of high accuracy DEMs require the ATM data for control. This means that the DMS is able to add additional resolution to the ATM elevation observations but without maintaining its independence. Replacement with a relatively inexpensive photogrammetric camera would remove many of the issues experienced by the DMS and would allow for independent and automated DEM and orthophoto production. **Recommendation: re-evaluate the inclusion of the DMS and explore the option of replacing it with a photogrammetric mapping camera with more stable lenses and camera properties.**

3.4.5 Addition of a low-freauency radar or seismic methods for improved bed retrieval

Retrieving bed topography under crevassed, temperate and polythermal ice typical for southern Greenland and Alaska outlet glaciers, has continued to be a major challenge for the radar depth sounder that is currently flown as part of the OIB suite of instruments. The problem is significant enough that OIB might consider alternatives to the current flight radar system strategies. To overcome this, the OIBMR-T LIG **recommends that the OIB SDT explore the following**:

- low frequency radars, perhaps gaining insights from those successfully deployed in Alaska
- alternative methods, for example seismic and electromagnetic imaging methods; much effort has been made through NSF to develop innovative seismic instrumentations for measuring ice thickness, bathymetry and sub-ice sediment thickness.

3.5 Data Usability and Accessibility

An OIB Data Management plan (DMP) was released in May 2013 that gives OIB data standards, including submission schedules, production, formatting and documentation. Data formatting and documentation is primarily the responsibility of the individual instrument teams, with the NSIDC responsible for compiling the provided information into a standard metadata/documentation format and posting the data for distribution. In addition, OIB has funded the creation of an interactive web data portal for browsing/locating OIB data. Due a large volume of recent deliveries to the NSIDC from the instrument team and reformatting to comply with new NASA standards (as described below), there is a significant back log in data and documentation availability on the NSIDC website. Therefore, the panel is unable to fully assess the data accessibility, quality and utility, data delivery schedule or the adequacy of the documentation, at this time and some of the recommendations below may be obsolete. **Recommendation: the OIB SDT conduct regular and frequent reviews of data usability and accessibility as these new products become available**.

3.5.1 Data Formatting

Data formatting has presented a major challenge for OIB. OIB data have been distributed in a wide range of formats that are legacies of pre-OIB operations, and this practice continues today. Even some single datasets, such as the ATM QFIT data, are quite often inconsistently formatted between different campaigns (although we note that these data are being comprehensively reformatted as part of the NASA Earth Science Division (ESD) mandate, see below). The use of non-standard formats, some of which require specialized commercial software such as Matlab or IDL, poses a significant barrier to use. This has been one of the most easily identified, and significant, flaws in the OIB mission implementation to date.

NASA ESD has adopted new, stringent standards for data formatting (see https://earthdata.nasa.gov/data/standards-and-references/data-format-standards). According to the OIB DMP: “Operation IceBridge data product formats, with the exception of Level 0 or raw data, shall conform to one of the NASA ESD approved Data System standards.” While some instrument teams have embraced these formats, others plan to continue with their non-standard legacy formats, as given in the current DMP. This was facilitated by the fact that no data formatting standards were given in the OIB instrument team NRA.

While the OIBMR-T LIG recognizes that adopting new formats and reformatting old data represents a substantial, and largely unfunded, burden on the instrument teams, we consider that such standardization is essential and should be a priority for OIB, possibly through the granting of devoted funds to third parties and in collaboration with NASA data records programs such as MEaSURES and ACCESS. Such a formatting standardization is a worthwhile investment to facilitate use of OIB data and its long-term usefulness. This reformatting could be conducted as part of larger OIB data quality review. **Recommendation: OIB should set aside funds to ensure that all OIB data adheres to ESD approved Data System standards.**

3.5.2. Data quality control

Data quality control has been the sole responsibility of the individual OIB instrument teams and data quality is inadequately documented. Importantly, there is no clearly-defined mechanism in place to ensure data conforms to the requirements. For example, in OIBMR-T LIG discussions the DMS L3 DEMs were repeatedly singled out as having particularly poor accessibility and documentation. DMS-generated elevation data is difficult to use, is only available in 2011, and has not been validated. Also, there is inadequate documentation about their generation. **Recommendation: the OIB ST should be tasked with ensuring that data providers/producers provide adequate quality assessments of all data products released by the OIB project**. Some specific recommendations should be formulated and implemented by the data experts themselves.

Finally, the OIBMR-T LIG recommends that more effort be put into educating end-users on data use, such as webinars that discuss the collection of data by OIB, issues with the instruments, data formats and parameters. Although experienced investigators may be less likely to use these, they would be good tools for helping students get familiar with the data. Standardization of formats will have a multiplying effect: end-users themselves will more easily educate collaborators, and even potential new adopters of the data.

3.6 Reporting of OIB Results

Data collected by the OIB mission has resulted in an impressive number of high-quality and high-impact publications. There are, however, a lack of overview publications documenting the mission and its sensor capabilities that could stimulate a broader use of OIB data. The OIBMR-T recommends that the OIB ST initiate publication of key review papers documenting the mission and its observing capabilities.

4. Summary of OIBMR-T LIG Recommendations

OIB Science Goals and Requirements

- Revisit the land-ice science requirements and streamline them so that they are more concisely and clearly defined.

Validation and cross-calibration

- Implement coordinated and simultaneous validation campaigns on common and different platforms for altimeter cross-calibration
- Design calibration experiments to compare elevations between altimeters and for different snow and ice conditions to ensure direct comparability between elevations retrieved from the different satellite and airborne altimeters.
- Design targeted validation campaigns to quantify range uncertainties and biases for each of the OIB laser altimetry systems for glacier surfaces of varying roughness, slope and surface optical properties, and to better characterize the firn-densification process.

Flight planning

- Adopt a more transparent method for selecting and coordinating land-ice flight lines during future OIB campaigns.
- Place more emphasis on acquiring broader-scale coverage.

Instrumentation

- Include a conventional 1064 nm laser altimeter with similar characteristics as the ATM to be mounted on the same platform as the ATM during the suggested validation campaign.
- Include the AVIRIS spectrometer as part of the OIB instrument suite
- Re-evaluate the inclusion of the DMS and explore the option of replacing it with a photogrammetric mapping camera with more stable lenses and camera properties.
- Explore alternative methods for imaging the bedrock for warm, crevasse ice, e.g. low frequency radars, and alternative methods (seismic and electromagnetic imaging methods)

Data format and quality

- OIB SDT should conduct regular and frequent reviews of data usability and accessibility as new OIB data products become available.
- OIB should set aside funds to ensure that all OIB data adheres to ESD-approved Data System standards.
- SDT should ensure data quality of all data products released by the OIB project.

Reporting

- Publication of key review papers documenting the mission and its observing capabilities.

Sea Ice Group (SIG)[2] Report

The OIBMR-T SIG reviewed the goals and level-1 science requirements (L1SR) of Operation IceBridge (OIB) and evaluated how OIB's activities and products have addressed the goals relevant to sea ice and marine snow cover at the mid-term of the program. The evaluation and recommendations comprise this report to the OIB Program Manager, Science Team and Project Office.

1. Summary

The mandated programmatic goals and broad scientific goals of OIB are important and appropriate. Progress toward the goals is substantial at the mid-term of the program. OIB has produced and made available estimates of sea ice thickness and snow depth that are being used by the research community to document changes in the state of the marine cryosphere, understand the physics of sea ice and snow, improve predictive models, and improve methods of remote sensing. At least 23 OIB-related articles concerning sea ice and marine snow cover have been published since 2010.

Important problems remain to be addressed fully, including:

- Understanding the snow radar returns and the accuracy of estimates of snow thickness.
- Expanding seasonal and spatial coverage of OIB measurements over sea ice.
- Clarifying how the L1SR follow from the OIB Observational and Science Goals.
- Enhancing opportunities for community input on instrumentation and flight lines.
- Merging snow depth and ice thickness observations from ICESat, IceBridge, CryoSat-2, ICESat-2 and other airborne and in-situ measurements programs for application to climate research and forecasting.
- Implementing uniformity of OIB data formats to increase use by the research community.

The SIG recommends the following actions, listed in priority order, for the second half of OIB:

(1) *Establish a working group charged with estimating snow depth and errors, from snow radar, altimeter, and other remote and in-situ measurements and models.*

(2) *Pursue additional opportunities to expand the seasonal and spatial coverage of OIB sea ice and snow measurements, and strengthen connections between OIB and in-situ measurement programs.*

(3) *Update the L1SR document and clarify how the baseline requirements follow from the science goals, especially the goals related to climate dynamics and forecasting.*

(4) *Formally establish the annual open meeting to enhance the effectiveness of input to OIB from the sea ice/snow research community on flight lines, instruments, data access and other topics.*

(5) *Establish a working group charged with estimating sea ice thickness and errors from altimeter, radar and other remote and in-situ measurements and models, spanning the ICESat-ICESat2 era.*

---

[2] The OIB-MRT Sea Ice Group: Richard Moritz, Hajo Eicken, Christian Haas, Leif Toudal Pedersen, Julienne Stroeve

OIB is well-positioned to increase NASA's leadership role in the community of researchers studying sea ice and marine snow cover, both nationally and internationally, and in partnership with other agencies.

2. OIB Accomplishments

In assessing the achievements of the program, it is well to recall that OIB was focused originally on land ice, but expanded to address sea ice in response to urgent needs arising from rapid summer ice loss in the Arctic. OIB has accomplished much concerning sea ice and snow cover during its first half and the SIG commends the achievements of OIB participants. Highlights include:

- OIB demonstrated that airborne observations of sea ice thickness can be used as initial conditions to improve the skill of April-to-September predictions by numerical ice/ocean models.
- OIB data have played the leading role in documenting changes in the Arctic marine cryosphere since the dramatic ice loss of 2007. First-year ice (FYI) continues to grow to approximately 2 meters maximum thickness despite the diminished growth season, and average ice thickness has decreased slightly since 2009 in the FYI-dominated Beaufort and Chukchi Seas. Multi-year ice (MYI) continues as the dominant ice type in the central Arctic Ocean and north of Greenland.
- OIB data have demonstrated that the snow cover over FYI is thinner than and inconsistent with the Warren climatology, but the climatology remains reasonable over the MYI regions. The overall increase of FYI area during 2007-2013 implies a 45% decrease of total snow volume.

To increase the impact of this report, the SIG decided to invest most of its time and resources on problems that remain to be addressed fully, and to summarize only briefly the many other important accomplishments of OIB as follows:

- Scientific justification and implementation of the L1SR.
- Community access to OIB data products via NSIDC.
- Expanded Arctic coverage in the Beaufort and Chukchi Seas.
- Expanded Antarctic coverage in the Ross Sea.
- Implementation of a "quick-look" product for seasonal predictions.
- Development and application of the snow radar.
- Development of collaborations with ESA, CSA, CryoSat-2, Polar6, BROMEX, SAMS, BAS, NRL.
- Gathering community input at annual workshops.
- Adding the KT-19 radiometer to OIB missions to detect leads and automate the DMS analysis.
- Increasing the operational time window for OIB sea ice observations in spring.
- Implementing educational outreach.

The list of sea ice-related publications on the OIB website, augmented by Web of Science search results for "sea ice" and "IceBridge", includes 23 publications since 2010. The OIB quicklook product has been valuable to the efforts of the international seasonal sea ice prediction network, with impacts beyond those evident in the publication record.

3. Results of the OIBMR-T survey

The OIBMR-T designed, publicized and conducted a survey requesting input from researchers with interests in OIB. The survey resulted in 32 responses, 12 of which were concerned with sea ice. The tradeoffs and competition between spatial coverage and temporal coverage came through loud and clear, with some respondents advocating the importance of repeat flightlines in every year, and others advocating the importance of covering different regions at the expense of gaps in the time series in a single region. Not surprisingly, no respondent thought sea ice has been oversampled by OIB. Several respondents indicated the importance of extending the temporal coverage, especially in the Arctic, to two phases of the annual cycle: the end-of-winter maximum and end-of-summer minimum in sea ice thickness. Another theme that came through strongly was the importance of coordinating OIB's sea ice sampling plans with: (a) CryoSat-2 over passes, (b) In-situ measurement campaigns, e.g. drifting ice station(s) where snow cover and ice thickness are studied in detail, (c) Overflights by other airborne projects, including EM sensors, other LIDAR, or both. Suggestions related to (c) include flying the EM sensor on OIB flightline(s) to get co-located, simultaneous data, and flying EM and LIDAR sensors in regions not covered by OIB to get broader spatial sampling, or to get a phase of the annual cycle not captured by OIB. Greater coordination between OIB and other projects, both airborne and in-situ was advocated.

4. Important Problems

Notwithstanding the significant progress of OIB to date, there are important problems that remain to be addressed fully by the program, as discussed in this section.

a. OIB Goals, Science Questions and the L1SR

The SIG reviewed the document "Level 1 Science Requirements" produced by the GSFC Cryospheric Sciences Laboratory and dated 27 January, 2012. The document lists five observational goals (OG) mandated by the program, and four broad science goals (SG) developed by the IceBridge Science Team (IST). The IST also identified ten science questions, eight dataset requirements, four threshold science requirements, twenty nine baseline science requirements, and thirteen projected science requirements.

The OG relevant to sea ice (P1-P4) are sufficient, appropriate and ambitious in the contexts of completed, ongoing and planned altimeter missions of NASA and ESA, and NASA's role in documenting, understanding and predicting the state of the cryosphere. The SG relevant to sea ice (SG3 and SG4) are clearly important in the context of climate dynamics, given the choice of altimetry as the primary method of measurement in the program. Six of the ten science questions (SQ1-SQ6) are relevant to sea ice and its snow cover. These questions are connected to the OG and SG, but not in a unique way, i.e. given the OG and SG, other questions of similar importance could be stated. SQ2 and SQ3 concern the accuracy of ice thickness observations and the optimal configuration of remote sensing instruments, respectively, needed to support climate dynamics and forecasting. These questions are fundamental to evaluating the progress and outcomes of OIB, as well as ICESat and ICESat-2. Therefore the connections between SQ2 and SQ3 and the more detailed L1SR threshold and baseline requirements are of particular importance. Although the distinction between threshold (e.g. T2) and baseline (e.g. SI1) science requirements is not defined, the respective requirements for maximum sea ice elevation error (< 10cm) and maximum snow depth error (< 5cm) are the same. The relationship between these requirements, the science questions and the science goals is not sufficiently clear. The statement at the beginning of L1SR Section 5

"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)"

does not fully inform as to how the stated requirements follow from considerations of climate dynamics and forecasting. To answer SQ2 and SQ3, temporal (e.g. inter-seasonal, inter-annual) sampling requirements would have to be addressed in addition to measurement accuracy and spatial sampling.

In the fields of climate dynamics and forecasting, sea ice is characterized by statistics defined as averages over some space/time domain. For example, SG3 refers specifically to the spatial and temporal variations of the mean sea ice thickness and the sea ice thickness distribution. It follows that quantitative measures of progress relevant to the science goals should include estimated errors of the sample mean thickness and sample thickness distribution. The requirements imposed on the errors would follow from the particular problem, e.g. what is the maximum error in sample mean thickness for which inter-annual differences in mean thickness can be resolved? Such errors depend on both measurement errors and sampling errors. Therefore, to make a connection between SG3 and the maximum allowable measurement error, it is necessary in principle to know what spatial and temporal domain is represented by the statistics, and to estimate the number of statistical degrees of freedom available from the IceBridge (and, as appropriate, CryoSat-2) measurements in the domain, and the variability of the (true) un-averaged ice thickness within the domain. Depending on these parameters, the contribution of measurement error to errors in the sample mean may range from insignificant to dominant. It is especially important to distinguish mean measurement error (bias), which cannot be reduced by averaging, from random variability of the measurement error. The L1SR document lacks information needed to make the connection between error thresholds of statistics relevant to problems of climate dynamics and forecasting on the one hand, and measurement error requirements, e.g. as stated in SI1 and T2.

The connections among goals, science questions, sampling errors and measurement errors are also fundamental to the problem of bridging the gap between ICESat and ICESat-2 using data from OIB and other sources. Because OIB is constrained by funding, aircraft, logistics and weather to acquire data during a small fraction of each year along mostly sparse flight lines, other data are needed to bridge the gap. The only datasets with near-continuous space/time coverage are those from CryoSat-2, and the reliability of CryoSat-2 ice thickness retrievals is still being evaluated. It would be useful to see more in the L1SR regarding the role of OIB in this connection, e.g. the balance between OIB providing data that, in their own right, are useful when averaged over time and space scales relevant to climate and forecasting, and OIB providing data and analysis that improve the accuracy of CryoSat-2 retrievals which then provide the needed spatial and temporal coverage of thickness statistics. This balance is expected to have an impact on the requirements for the accuracy and spatial/temporal coverage of OIB measurements.

b. The snow radar signals

The primary instrument in OIB is the Airborne Topographic Mapper (ATM), a conical-scanning optical LIDAR that operates at a wavelength of 532 nm. The ATM produces data from which the elevation of the top surface of the sea ice/snow system is estimated. Over polar oceans, the primary purpose of ATM and satellite-borne altimeters is to produce data from which sea ice thickness may be estimated accurately for climate and forecasting applications. To convert elevation to thickness it is essential to have estimates of snow depth, snow density and ice density. Snow depth has the largest impact, and in this application has been estimated from climatology, from physical snow models driven by meteorological analysis data, and from in-situ and remote measurements by instruments other than the LIDAR altimeters. Ice type information from passive and active (scatterometer and SAR) satellite microwave measurements is also used to distinguish between regions of thin and thick snow and to evaluate the validity of snow climatologies.

An important difference between OIB and previous sea ice altimetry programs is the nearly co-located, simultaneous radar backscatter measurements by the nadir-looking, ultra-wideband, frequency-modulated, continuous wave "snow radar" operating in the frequency range 2-8 GHz (S and C bands) with corresponding wavelengths 15cm to 3.8cm. Typically, the snow radar return signal exhibits one or two distinct peaks that may be identified with the arrival of the return from the snow/ice (or air/ice) interface (*si*), and the air/snow (*as*) interface. In principle, if the ranges from the radar to *si* and *as* can be estimated from the radar signal with sufficient accuracy relative to local sea level, it is possible to calculate the freeboard of the sea ice and the depth of the snow from the radar signal alone. The difference in range between *si* and *as* also provides a measure of snow depth, irrespective of whether either range can be referenced accurately to sea level, in which case the radar-determined snow depth may be combined with the ATM-determined elevation to estimate the freeboard of the sea ice.

Problems arise in attempts to use the snow radar data as sketched in the previous paragraph because:

- The ATM and snow radar have finite horizontal footprints of different size (~1m & ~15m, resp.)
- The center locations of the ATM and radar footprints differ.
- Ice and snow interface elevations vary spatially within the footprints.
- Uncertainties in physical properties of the snow, e.g. layering, radar wave propagation speed.
- Uncertainties associated with the retrieval of interface ranges from the peaks in the radar signal.
- Absence of one or both peaks in many radar return signals.
- Uncertainties in how the retrieved interface ranges are related to snow depth in the footprint.
- Ambiguity between ice surface roughness and snow surface returns.

(e.g. Kwok, JGR 2011; Kurtz, The Cryosphere, 2013). Addressing these problems is complicated further by the fact that the OIB snow radar is regarded as an experimental instrument, and has undergone significant modifications after each OIB campaign.

Sturm's (JGR, 2002) analysis of in-situ snow depth measurements during April-May, 1998 near the SHEBA station shows that variability of 10-25cm on horizontal scales of 1-10m is not uncommon, and the mean and standard deviation of snow depth vary significantly among the ice classified as "smooth", "refrozen melt ponds", "hummocky" and "deformed". So during spring, 10-25 cm may be typical of the random difference between the true snow depth at the center of the ATM footprint and the snow depth in the nearest (overlapping) radar footprint. This raises the question "What aspects or measures of the true snow depth distribution in the radar footprint correspond to the estimated range difference *as* minus *si*?" If this difference corresponds to the *mean* within-footprint snow depth, then ATM elevations averaged over the radar footprint would provide a consistent basis for using the radar snow depth to estimate average freeboard. However, because the radar return signal likely results from a mixture of (near) specular reflection and scattering, it may be that the peak(s) in the return signal correspond to within-footprint surfaces with particular orientations relative to the radar beam. Nevertheless, analyses of spatial and temporal variations of snow depth based on the OIB snow radar data have been published, as estimated by different algorithms and with different results. The algorithms screen the data, eliminating measurements for which the chosen algorithm cannot retrieve *as* and *si* consistently. Much of the screened data is "deformed ice" so that results have to be qualified as applying only to some portion of the overall ice cover. Therefore it is important to understand and define the preferential sampling of different ice and snow configurations, and to assess the impact on estimating climate parameters, such as the large-scale mean sea ice thickness.

Even though OIB produces measurements for estimating snow depth, this information will be lacking once OIB is concluded, and at present, away from OIB flightlines. To retrieve freeboard and thickness, e.g. from CryoSat-2 and ICESat-2 measurements, other methods must be used to estimate snow depth and snow loading, e.g. climatology, and snow models. Therefore it is important to use OIB data to develop satellite remote sensing methods to quantify marine snow cover. Such methods could be based on passive microwave observations such as AMSR-E/AMSR-2, L-band SMOS/SMAP measurements etc. In this connection it would be useful to fly an AMSR-type microwave radiometer with the snow radar to investigate empirical relationships between brightness temperatures and snow parameters in a more controlled environment than combining satellite PMR data with 20km footprint with meter scale airborne data.

In light of the importance of snow depth, and the problems cited, additional effort is warranted to better understand the radar return signals and their relationship to the elevation and snow depth within the radar footprint. Progress in this area would be enhanced by bringing together the expertise and experience of the snow radar instrument team, users of the snow radar data who are knowledgeable in radar remote sensing (e.g. scattering physics, radar phenomenology and algorithm development), and researchers knowledgeable in the morphology, statistics and physical properties of sea ice and its snow cover. Such an effort would also be helpful in evaluating potential sources of bias in radar-derived snow-depth records due to systematic differences in snow dielectric properties that affect radar wave propagation, absorption and backscatter. Dielectric properties are strongly affected by the presence of salt in the snow pack which may differ substantially between ice types and region.

c. Snow depth, rough ice and the conversion of elevation to thickness

Estimates of the mean thickness of sea ice are essential to climate dynamics and the sea ice physics relevant to forecasting. Distributions of sea ice thickness over a given area are typically right-skewed with a long tail comprising ice that has been ridged to thicknesses greater than the thickness achievable by thermodynamic growth acting alone. It follows that the ridging process and the resulting deformed ice are vital determinants of the mean thickness. ICESat, OIB, CryoSat-2 and ICESat-2 would make great contributions to climate dynamics and forecasting if they yielded accurate estimates of mean sea ice thickness in all kinds of sea ice. To accomplish this requires estimates of snow depth for the intermediate step of converting measured elevation to freeboard. Parameters derived from ancillary information (e.g. estimates of the covariance of freeboard and draft from in-situ and remote measurements, published statistics of variations in sea ice density, effects of uncertainty in the densities of ridge keels and sails) are needed to convert freeboard to thickness.

Because OIB has acquired a large volume of nearly simultaneous, co-located ATM and snow radar data, it is positioned uniquely to contribute to the problem of converting elevation to thickness, and the contributions ought to have major impacts on the analysis of ICESat, CryoSat-2 and ICESat-2 measurements. To fully realize this potential, OIB needs to address the estimation of snow depth, or at least the estimation of average snow loading, over horizontal areas on length scales for which the ATM can provide unbiased estimates of average elevation. Key problems specific to understanding the snow radar return signal were indicated previously in section (4b), but there are broader problem areas in which OIB can play an important, and perhaps leadership, role, viz. defining where and when direct measurements by altimeters can provide estimates of snow depth useful for estimating the mean and other statistics of sea ice thickness, coordinating in-situ snow measurements with OIB overflights, modeling snow depth in relation to atmospheric forcing and ice/snow morphology, assessing estimation of snow depth from other satellite and airborne sensors (present and future), and bringing together researchers with a variety of snow and ice expertise to accelerate progress.

Progress has been greatest in estimating average snow depth over “smooth” sea ice (although definitions of “smooth” may vary among researchers and applications). The problems of in-situ measurements, remote retrieval of air/snow and snow/ice interfaces, freeboard-to-thickness conversions and spatial averaging are all simplest for this morphological class. Additional work on the smooth ice case is needed to beef up estimates of errors in area-averaged snow depth estimates on length scales useful for elevation-to-thickness conversion, and to compare effectively the in-situ and snow radar estimates of snow depth with the results of models that will be needed for the ICESat-2 era. Experience has shown that it is very challenging, even in smooth ice, to plan and conduct in-situ experiments in which measurements of snow depth are made at positions that are identical to the positions sampled by the snow radar and the ATM. Also challenging is to make in-situ measurements that can be averaged in a manner consistent with the altimeter data, to provide effective comparisons with individual or averaged airborne measurements, and with the results of snow depth models. In this connection it behooves OIB to reach out proactively to the community of researchers planning and conducting in-situ measurement programs and snow depth modeling projects, and to entrain expertise that facilitates addressing the problem across all its facets: in-situ measurements, airborne measurements, satellite measurements, retrieval of snow and ice variables, the use of models and climatology, and the conversion of elevation to thickness.

All of the snow-on-sea ice problems cited previously are exacerbated in “deformed” sea ice. Elevation and snow depth vary on horizontal length scales as small as a few centimeters, often in a chaotic manner. Surface variations in such ice are complicated by discontinuities in air/snow and snow/ice interfaces, and by overlapping blocks and plates that constitute multiple interfaces at a single horizontal location. In deformed ice, acquiring in-situ measurements of sufficient number and kind to yield accurate area averages poses a daunting problem. Signals returned to the ATM and snow radar may be very difficult to interpret, as they result from scattering by surfaces with highly variable orientations and dielectric properties. In this context, OIB is well-positioned to better define how past, current and planned altimetry missions can contribute to knowledge of mean sea ice thickness, including limits on when and where altimeter data are useful. By bringing together researchers with a variety of expertise in the context of the big-picture problem of estimating average ice thickness, with a focus on the elevation-to-thickness conversion, OIB can help characterize and clarify what ice “types” can be measured effectively by altimeters, what ice “types” are being missed, and how to improve approaches to merging altimeter and other data to account for the effect of the omissions on the mean and other statistics of thickness.

A key factor in this context is a better overall evaluation of sources and magnitudes of errors and biases that affect estimates of the snow and ice properties discussed above. Meeting some of the L1SR requires a better characterization of uncertainties in the data than is currently the case. This problem also directly affects the overarching goal of obtaining long-term, climate data-record type data sets for sea ice volume. While it is unreasonable to expect the OIB Science Team to complete such efforts, the Science Team can serve as a catalyst for directed research that addresses these issues and generates results that can in turn improve OIB sea ice data products. The need for such efforts has been demonstrated in a number of recent publications, such as a study by Zygmuntowska et al. (The Cryosphere Discussions, 2013) that attempted to identify key sources of error in altimeter-derived ice thickness.

d. Bridging ICESat, IceBridge, CryoSat-2 and ICESat-2

A fundamental objective that motivates the ICESat, OIB, CryoSat-2 and ICESat-2 missions is to establish accurate, time-continuous estimates of the mean and other statistics of sea ice thickness that resolve e.g. inter-regional variations, annual cycles, inter-annual variability and multi-year trends over the ice-covered oceans of both hemispheres during nearly two decades. Achieving this objective will require analysis to support merging of datasets that derive from different instruments, with different resolutions, algorithms and space-time coverage. In the more specific context of OIB, a major objective is to "bridge the gap" in coverage between ICESat and ICESat-2, which, because of the relatively sparse space-time coverage of OIB missions, requires analysis of CryoSat-2 data. The mid-term of OIB is an appropriate time to devote additional effort to bring together key OIB participants and other researchers who are and will be using the data to study the variability of sea ice thickness in the context of climate and forecasting.

e. OIB data formats and the usage of OIB datasets

There has been a wide-range of data formats used in OIB data sets, including ASCII text, binary, GeoTIFF, Matlab, HDF, NetCDF, CSV and ICARTT as well as different formats for browse images (i.e. JPEG and PNG). Flightlines may be reported in Shapefiles or KML format. Some products even have a summary report in PDF format. Formatting details also vary within format types and within datasets for some OIB binary and ASCII datasets. Usually this occurs when the data provider implements the IceBridge data standards for the most recent campaign. In this case, the data exist in multiple formats until the provider back processes the data from previous campaigns.

The myriad of data formats has made it difficult for users of the OIB products to use the data. The problems are known and are being addressed by the OIB Science Team and Project Office. Currently the final format of data products is being formalized through the data management plan, with input by NASA's Earth Science Division and Information System (ESDIS) and OIB management. The emphasis is to facilitate use of OIB data products, and all OIB data except Level 0 (raw data) must conform to one of the ESDIS approved standards (see http://earthdata.nasa.gov/data/references/data-format-standards). Once the format is decided upon the data format is to be kept consistent for all future deliveries. Going forward, this should stabilize data formats and increase the usability of OIB data sets.

There remains the problem of some older data in one format and newer data in a different format. To resolve this problem, the data providers have to reformat and redeliver these legacy products. Some data providers have reformatted legacy products, others have yet to do so, and data providers lack funding to carry out this task, which has put NSIDC in a difficult position regarding implementation of the new standards.

There is also a plan to make the data available through the Earth Observing System Data and Information System (EOSDIS) Core System (ECS) to facilitate use of the OIB data portal and provide more comprehensive metadata. However, ECS is designed for satellite-borne missions rather than airborne missions and it is unclear if this is the best method for providing OIB data to users. Ideally the OIB data formats would be compatible with those of other altimeter missions (e.g. ICESat, ICESat-2 and CryoSat-2), and OIB datasets would include error information important to modelers.

The following recommendations are specific to OIB datasets and data management:

1) Implement a plan for reprocessing the remaining legacy products.
2) Assure that OIB data formats are compatible with those of ICESat, ICESat-2 and CryoSat-2.
3) Evaluate how to enhance the use of OIB data by modelers.
4) Evaluate how ECS can better support OIB, and airborne missions generally.

f. Community input

In the first half of its expected duration, OIB has established a solid track record of information exchange between program participants (e.g. the IST and the OIB Project Office (OPO)) and sea ice/snow researchers outside the program (e.g. current and prospective users of OIB data). Input on the utility of IceBridge sea ice products has been gathered via 1-day 'workshops' held annually in conjunction with IceBridge Science Team Meetings. This input has, for example, influenced the design of flightlines, facilitated collaborations within and outside the OIB team, and planted the seed for the quick look product. The SIG commends the IST on these activities, and recommends that they be continued and enhanced. The following activities would facilitate the process: (a) formally establish the workshop as an annual, recurring opportunity for information exchange between OIB and the broader sea ice research community; (b) announce the time, location, purpose and format of the workshop well in advance, and in lists, publications, websites etc. that reach the vast majority of interested researchers outside of OIB; (c) take a fresh look at the timing of the meeting to maximize its effectiveness on planning, e.g. by the instrument teams and the flightline planners; (d) review the stated purpose of the workshop and, as appropriate, clarify what kinds of input are sought, who within OIB will review the input, how the input may be used, and how and to what extent workshop participants can follow the processing of the input by the IST and the OPO. This SIG sees this as tweaking, rather than overhauling, the already-successful annual workshops related to OIB sea ice, to increase interest, participation and use of OIB data by the broader community, and to enhance availability of relevant new information to the IST and OPO.

5. Recommendations

The working groups recommended here need not be limited to members of the IST, OPO and OIB-funded investigators. Indeed it will be helpful to entrain expertise to take advantage of measurements and research supported by other U.S. and non-U.S. agencies. The working groups will be most effective if they have a definite charge and have to report back on a regular schedule to project management, e.g. the IST and/or the Program Manager. In all cases, one purpose of the working groups is to enhance communication among instrument, remote sensing scientists, modelers, in-situ measurers and data users in the context of common goals and objectives, within a relatively narrow focus.

It is recommended that OIB establish a working group charged with estimating snow depth from altimetry, snow radar, other remote and in-situ measurements and models. This working group should include members of the OIB instrument teams and science team, together with the ICESat-2 science team, CryoSat-2 researchers and researchers conducting in-situ measurements relevant to OIB. It is recommended that this working group address the problem of better understanding the snow radar signals.

OIB is encouraged to pursue additional opportunities to expand the spatial and seasonal coverage of OIB sea ice and snow measurements, and to strengthen connections between OIB and in-situ measurement programs. In particular, in the Arctic it is important to have data at the end of the melt season, as well as at the end of the growth season. Also, in both hemispheres, it is important for OIB to enhance and forge new connections with other airborne and in-situ measurement programs to better address issues of coverage, data inter-comparison, and validation. Potential mechanisms to link field observations and obtain guidance on expanded spatial coverage include communication with the research community through entities such as the Climate and Cryosphere (CliC) working group on arctic sea ice, the international sea ice prediction network (SIPN) and the annual OIB sea ice workshop.

It is recommended that the IST update the L1SR document and clarify the connections between climate dynamics and forecasting and the baseline requirements. It would be especially useful to understand how the requirements posed by particular problems, such as estimating inter-annual variability and multi-year trends, and initializing inter-seasonal forecasts by ice/ocean models, translate into specifications of spatial and temporal coverage and error variances of sample statistics derived from OIB data, and how these specifications are related to the requirements for measurement errors. For instance, how do such requirements translate into minimum coverage and maximum sampling error thresholds for the mean and modal sea ice thickness and snow depth, the open water/thin ice fraction, and the thickness distribution? This information would be helpful in evaluating progress and outcomes of OIB relative to the broad goals, and understanding how the baseline requirements for measurement accuracy, spatial resolution and flight lines flow from these goals. Results of ice/ocean modeling studies ought to play a significant role in the identification of essential variables and estimation errors that are required for climate dynamics and forecasting.

It is recommended that OIB formally establish an open annual workshop to facilitate input to OIB from the sea ice research community on flight lines, instruments, data access and other topics relevant to OIB. Building on useful past efforts, the meeting's purpose, format and follow-up process should be documented clearly and well-publicized. The meeting should be conducted at a time and place that facilitates participation by current and prospective users of OIB datasets, and effective use of the input, e.g. to support activities of the instrument teams and flightline planners.

It is recommended that OIB establish a working group charged with estimating sea ice thickness from altimetry, snow radar, and other remote and in-situ measurements and models. This working group should include members of the OIB instrument teams and science team, together with the ICESat-2 science team, CryoSat-2 researchers and researchers conducting in-situ measurements relevant to OIB. This group should address how OIB is contributing to the bridging of ICESat-CryoSat-2-ICESat-2, e.g. are there sufficient OIB flightlines that coincide with CryoSat-2 passes and in-situ field measurements? This working group should address the problem of merging snow depth and ice thickness observations from ICESat, IceBridge, CryoSat-2, ICESat-2 and other airborne and in-situ measurements programs for application to climate research and forecasting. Therefore much of its work would follow that of the snow depth working group. However, this working group should be implemented immediately to consider flightline compatibility with CryoSat-2 and in-situ measurements.

It is recommended that OIB program management, Science Team and Project Office address the data management and formatting recommendations that appear at the end of section 4e.