Operation IceBridge

Data Products in relation to Level 1 Science Requirements

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Summary

Data Products necessary to meet Level 1s, but that are not delivered yet to NSIDC: bathymetry, distribution of subglacial water, dh/dt of ice surface elevation, radar ice surface elevation (Ku-band radar), short wavelength (order 10 to 100 km) geoid fluctuations from gravity measurements

Data products not included in current Level 1s: sea-ice thickness, gridded bedrock elevation.

Recommended Actions:

- Need to clarify who will provide snow-thickness over sea ice (currently developeded by Project Science Office, but CReSIS is funded to provide).
- Need to determine who will produce gridded bedrock elevation models (CReSIS, NSIDC, or Project Science Office).
- Need to determine who will produce dh/dt (currently NSIDC, based on Csatho et al algorithm).
- LDEO needs to provide bathymtery estimates to NSIDC (my understanding is they are funded to provide this product).
- Need to determine feasilibility and product development for short wavelength (order 10 to 100 km) geoid fluctuations. This is proprietary processing by Sander Geophysics and has been advertised by LDEO that they can provide.
- Need to clarify who will product maps of subglacial water. (R. Bell funded to do this as part of IST proposal?). Product development is very unclear.
- Need to revise Level 1 Science Requirements to better reflect data product requirements.

Color code for Level 1 – Data Product Matrix

green	Existing data products are sufficent. No action required.
yellow	Required product is under development.
red	Product development has not yet started or some other red flag issue that needs attention.

Operation IceBridge Threshold Science Requirements				
	Data Product Requirements			
Level 1 Science Requirement	**Available L1B and L2 IceBridge Products**	**Data Product Requirements**	**Remaining Issues assossiated with Production**	**Producer Organization**
T1: Measure annual changes in glacier, ice cap and ice sheet surface elevation sufficiently accurate to detect 0.15 m changes in uncrevassed and 1.0 m changes in crevassed regions along sampled profiles over distances of 500 m.	Along-track ice-surface elevations from ATM, LVIS, UAF and UTIG laser altimeter measurements	Produce along-track and gridded annual ice surface elevation changes (dh/dt).	Need to start working on along-track products.	NSIDC based on B. Csatho's algorithm development. Currently only available for Greenland. Depending on the complexity responsibility may be transferred to the Project Science Office.
T2: Make sea ice surface elevation measurements with a shot-to-shot accuracy of 5 cm, assuming uncorrelated errors.	Along-track ice-surface elevations from ATM, LVIS, UAF and UTIG laser altimeter measurements	No data product required other than existing L1B and L2 products.	Need to add sea ice thickness measurements to Level 1 science requirements. Sea-ice thickness data are not required to meet threshold requirements.	Instrument teams.
T3: Make sea ice elevation measurements of both the air-snow and the snow-ice interfaces to an uncertainty of 3 cm, which enable the determination of snow depth to an uncertainty of 5 cm.	Along-track geolocated snow radar data.	Need to produce snow thickness layer (two-way tavel time) and transfer into calibrated and validated snow thickness measurements.	Calibration and validation requires access to ground truth data and can only follow a comprehensive analysis of these data sets.	Too many at the moment. In the long run, this should either be provided by CReSIS as part of the snow radar L2 product or being produced by the Project Science Office. Need to develop a project-wide plan soon.
T4: Acquire annually, near-contemporaneous, 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.	Along-track ice-surface elevations from ATM, LVIS, UAF and UTIG laser altimeter measurements	Radar ice surface elevation measurements from Ku-band radar. Project Scientist is working with ESA/CryoVEx to facilitate joint analysis of CryoVEx/IceBridge data for cal/val and science products.	Requires access to proprietary data sets and likely long wait time before analysis is completed. Large number of players involved.	Radar ice surface elevation measurements from Ku-band radar should be produced by CReSIS. Alternatively, the Project Science Office will have to provide.
T5: Conduct one campaign	Existing L1B and L2	No specific data product required	None.	Instrument teams.

in the Arctic and one campaign in the Antarctic each year	products from all instruments.	other than existing L1B and L2 products.		
Note: Level 1 data products have to be produced for all data sets and campaigns, including UAF, UTIG and U Colorado led data collection efforts. So far almost all method development efforts focus only on data collected by the P-3 and the DC-8.				

Baseline Science Requirements for Ice Sheets				
Level 1 Science Requirement	**Available L1B and L2 IceBridge Products**	**Data Product Requirements**	**Remaining Issues assossiated with Production**	**Producer Organization**
IS1: Measure surface elevation with a vertical accuracy of 0.5 m or better.	Along-track ice-surface elevations from ATM, LVIS, UAF and UTIG laser altimeter measurements	No data product required other than existing L1B and L2 products.	None	Instrument teams
IS2: Measure annual changes in ice sheet surface elevation sufficiently accurate to detect 0.15 m changes in uncrevassed and 1.0 m changes in crevassed regions along sampled profiles over distances of 500 m.	Along-track ice-surface elevations from ATM, LVIS, UAF and UTIG laser altimeter measurements	Produce along-track and gridded annual ice surface elevation changes (dh/dt).	Need to start working on along-track products.	NSIDC based on B. Csatho's algorithm development. Currently only available for Greenland. Depending on the complexity responsibility may be transferred to the Project Science Office.
IS3: Measure ice thickness with an accuracy of 50 m or 10% of the ice thickness, whichever is greater.	Along-track ice thickness measurements from CReSIS MCoRDS and UTIG HiCARS radar sounders.	No data product required other than existing L1B and L2 products.	None	Instrument teams
IS4: Measure free-air gravity anomalies to an accuracy of 0.5 mGal and at the shortest length scale allowed by the aircraft.	Along-track and gridded free-air anomalies from Sander Geophysics.	No data product required other than existing L1B and L2 products.	None	Instrument teams
IS5: Acquire annually, near-contemporaneous ice elevation data with ESA's Cryosat for underpasses across Greenland and Antarctica. Flight segment should span ESA SARIN and LRS mode boundaries. Coordinate with ESA *in situ* validation campaigns as	Along-track ice-surface elevations from ATM, LVIS, UAF and UTIG laser altimeter measurements.	Radar ice surface elevation measurements from Ku-band radar. Project Scientist is working with ESA/CryoVEx to facilitate joint analysis of CryoVEx/IceBridge data for cal/val and science products.	Requires access to proprietary data sets and likely long wait time before analysis is completed. Large number of players involved.	Radar ice surface elevation measurements from Ku-band radar should be produced by CReSIS. Alternatively, the Project Science Office will have to provide.

possible.				
IS6: Remeasure annually Antarctic and Greenland surface elevation along established airborne altimeter and ICESat underflight lines that extend from near the glacier margin to near the ice divide.	Along-track ice-surface elevations from ATM, LVIS, UAF and UTIG laser altimeter measurements.	No data product required other than existing L1B and L2 products.	None	Instrument teams
IS7: Collect elevation data so that the combined ICESAT-1-OIB sampling provides an elevation measurement within 10-km for 90% of the area within 100-km of the edge of the continuous Greenland Ice Sheet, as well the Antarctic Amundsen Sea Coast and Peninsula.	Along-track ice-surface elevations from ATM, LVIS, UTIG laser altimeter measurements.	No data product required other than existing L1B and L2 products.	None.	Instrument teams
IS8: Measure ice thickness, gravity, surface, and bed elevation along central flowlines of the outlet glaciers in Greenland with terminus widths of 2 km or greater[1]. Measurements should extend at least 1.5 times farther than predicted outlet glacier valley dimensions. Repeat surface elevation measurements as practical.	Existing L1B and L2 products from ATm, LVIS, and MCoRDS , and gravity instruments.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
IS9: Measure once, ice thickness, surface, and bed elevation across-flow transects at 3- and 8-km upstream of the terminus	Existing L1B and L2 products from ATm, LVIS, and MCoRDS instruments.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams

for each glacier in (8). Repeat surface elevation measurements as practical.				
IS10: Measure once Greenland ice sheet elevation and ice thickness about four, nearly continuous close loops approximately about the 1000, 2000, and 2500 ice sheet elevation contours.	Existing L1B and L2 products from ATm, LVIS, and MCoRDS instruments.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
IS11: Measure ice thickness, elevation, gravity and magnetic anomalies over 10 Greenland glaciers[2] and 15 Antarctic glaciers[3] that are rapidly changing now or are likely to change in the next 10 years. Coverage should extend from the terminus to the elevation where velocities are about 50 m/yr. Over the fast flowing deep troughs, the grids must have 5-km spacing or better, with 10-km or better spacing on the surrounding regions of the lower catchment. Cycle through the glacier list for the duration of IceBridge.	Existing L1B and L2 products from ATm, LVIS, and MCoRDS , and gravity instruments.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
IS12: Measure once ice thickness, surface elevation, gravity anomalies within 3 km of the Antarctic Ice Sheet Grounding line and along a second line located 10 km	Existing L1B and L2 products from ATM, LVIS, and MCoRDS , and gravity instruments.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams

upstream of the grounding line.				
IS13: Measure once surface elevation, ice thickness and seabed bathymetry beneath selected Antarctic Ice Shelves[4], along Greenland Fjords[5] where we will collect a line along the center of the fjords and three lines across (one at the sill, one near the middle, and one near the glacier front) and beneath Greenland Ice Tongues[6].	Existing L1B and L2 products from ATM, LVIS, and MCoRDS , and gravity instruments.	Estimating bathymetry from gravity inversion is under development.	LDEO is funded to provide bathymetry to NSIDC. So far no data has been delivered.	Instrument teams
IS14: Measure changing distribution of subglacial water over regions of rapidly flowing ice and distribution of subglacial water over interior cold ice.	Existing L1B and L2 products from MCoRDS.	Echo strength and basal reflectivity. Need temperature, and chemistry data from ice sheets and crystal fabrics to estimate absorption rate of radar waves in ice.	Product development has not yet started. Science requirement was seen as very controversial by the science team. Reliable methods to image subglacial water from radar do not exist.	Product development and responsibilities are unclear.
IS15: Acquire submeter resolution, stereo color imagery covering laser altimetry swaths.	Existing L1B and L2 products from DMS instrument.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
Note: There is no Level 1 Science Requirement that requires gridded bedrock elevation data for either catchment wide areas such as Russell Glacier or ice-sheet wide. These products are targeted at accomplishing the science goals rather than meeting level one requirements. If we produce them this needs to be fixed.				

Baseline Science Requirements for Glaciers and Ice Caps				
Level 1 Science Requirement	**Available L1B and L2 IceBridge Products**	**Data Product Requirements**	**Remaining Issues assossiated with Production**	**Producer Organization**
IC1: Annually to semi-annually collect LiDAR swath data along the centerlines of major Gulf of Alaska glacier and icefield systems, repeating previous ICESat measurements and airborne laser altimetry centerline profiles[7].	Existing L1B and L2 products from UAF LiDAR instrument.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
IC2: Make annual repeat measurement of surface elevation on select Alaskan Glaciers.	Existing L1B and L2 products from UAF LiDAR instrument.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
IC3: Make ice elevation, ice thickness and gravity measurements on Canadian Ice Caps at least twice during the IceBridge program. Coverage should be based on previous airborne campaigns and leverage against ESA supported *in situ* CryoSat-2 validation activities.	Existing L1B and L2 products from ATM, LVIS, and MCoRDS , and gravity instruments.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
IC4: Make ice elevation, ice thickness and gravity measurements on selected ice caps and alpine glaciers around the Greenland Ice Sheet. Repeat the elevation measurements at least once during the IceBridge program[8].	Existing L1B and L2 products from ATM, LVIS, and MCoRDS , and gravity instruments.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
Note: need to determine if we want dh/dt products for IC1, IC2, and IC4 from UAF LiDAR data.				

Baseline Science Requirements for Sea Ice				
Level 1 Science Requirement	**Available L1B and L2 IceBridge Products**	**Data Product Requirements**	**Remaining Issues assossiated with Production**	**Producer Organization**
SI1: Make surface elevation measurements with a shot-to-shot accuracy of 5 cm, assuming uncorrelated errors.	Existing L1B and L2 products from ATM, LVIS, snow-radar.	No specific data product required other than existing L1B and L2 products.	None	Instrument teams
SI2: Make elevation measurements of both the air-snow and the snow-ice interfaces to an uncertainty of 3 cm, which enable the determination of snow depth to an uncertainty of 5 cm.	Existing L1B and L2 products from ATM, LVIS, snow-radar.	Need to produce snow thickness layer (two-way tavel time) and transfer into calibrated and validated snow thickness measurements.	Need to clarify who will provide snow thickness measurements: CReSIS or Project Science Office. Calibration and validation requires access to ground truth data and can only follow a comprehensive analysis of these data sets.	CReSIS and Project Science Office
SI3: Provide annual acquisitions of sea ice surface elevation during the late winters of the Arctic and Southern Oceans along near-exact repeat tracks, to within 500 m of the previous years' flight tracks, in regions of the ice pack that are undergoing rapid change. Flight lines shall be designed to ensure measurements are acquired across a range of ice types including seasonal (first-year) and perennial (multiyear) sea ice to include, as a minimum: Arctic	Existing L1B and L2 products from ATM and LVIS laser altimeters.	No specific data products required other than existing L1B and L2 products.	None	Instrument teams

a. At least two transects to capture the thickness gradient across the perennial and seasonal ice covers between Greenland, the central Arctic, and the Alaskan Coast. b. Perennial sea ice pack from the coasts of Ellesmere Island and Greenland north to the pole, and westward across the northern Beaufort Sea. c. Sea ice across the Fram Strait and Nares Strait flux gates. d. Sea ice covers of the Eastern Arctic North of the Fram Strait. Antarctic a. Weddell Sea ice between the tip of the Antarctic Peninsula and Cape Norvegia. b. Mixed ice cover in the western Weddell between the tip of Antarctic Peninsula and Ronne Ice Shelf. c. The ice pack of the Bellingshausen and Amundsen Seas.				
SI4: Include flight tracks for sampling the ground tracks of satellite lidars (ICESat-1 and ICESat-2) and radars (CryoSat-2	Along-track ice-surface elevations from ATM, LVIS, UAF and UTIG laser altimeter measurements	Radar ice surface elevation measurements from Ku-band radar. Project Scientist is working with ESA/CryoVEx to facilitate joint analysis of CryoVEx/IceBridge	Requires access to proprietary data sets and likely long wait time before analysis is completed. Large number of players involved.	Radar ice surface elevation measurements from Ku-band radar should be produced by CReSIS. Alternatively, the Project Science Office will

and Envisat) and, in the case of CryoSat-2, both IceBridge and CryoSat-2 ground tracks should be temporally and spatially coincident whenever possible. At least one ground track of each satellite should be sampled per campaign.		data for cal/val and science products.		have to provide.
SI5: Conduct sea ice flights as early as possible in the flight sequence of each campaign, preferably prior to melt onset.	N/A	N/A	N/A	N/A
SI6: Collect coincident natural color visible imagery of sea ice conditions at a spatial resolution of at least 20 cm per pixel to enable direct interpretation of the altimetric data.	DMS L1B and L2 data products	No specific data products required other than existing L1B and L2 products.	None	Instrument team
SI7: Conduct sea ice flights primarily in cloud-free conditions, and data shall be retained under all atmospheric conditions, such that a flag shall be included to indicate degradation or loss of data due to clouds.	Need flag!	Need to produce a cloud flag.	**Level 1 Science requirements is inconsistent with DMS data acquisition strategy, which only stores data in cloud-free conditions. This needs to be resolved.**	Need to clarify who will determine cloud flagging for DMS, ATM, and LVIS data. This was part of the deliverables for the Instrument Summit but no instrument team has provided data files.
SI8: Make full gravity vector measurements on all low-elevation (< 1000 m) flights over sea ice, to enable the determination	Free-air gravity anomalies.	Geoid undulations along flight tack.	Proprietary data processing by Sander Geophysics. Data product is still under development.	Instrument teams

of short wavelength (order 10 to 100 km) geoid fluctuations along the flight track to a precision of 2 cm.				
SI9: Actively seek out and coordinate with field campaigns that are consistent with and advance IceBridge project objectives to extend and improve the record of observations begun by ICESat related to sea ice thickness and snow depth retrievals.	Existing L1B and L2 products from ATM, LVIS, snow-radar.	Stricktly speaking no specific data products are required other than existing L1B and L2 products.	Weak link to sea-ice thickness product and snow depth.	Instrument teams and Project Science Office
Note: Sea-ice thickness product should be added to level 1 baseline science requirements				