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Digital Terrain Mapping of Petermann Ice Island Fragments in the Canadian High Arctic

A. L. Forrest^{1*}, A. K. Hamilton², V. Schmidt³, B. E. Laval², D. Mueller⁴, A. Crawford⁴,
S. Brucker⁵, and T. Hamilton⁵

1. Civil Engineering, University of California Davis Tahoe Environmental Research Center,
Incline Village, NV, USA

2. Civil Engineering, University of British Columbia, Vancouver BC, Canada

3. Center for Coastal Ocean Mapping, University of New Hampshire, Durham, NH, USA

4. Geography and Environmental Studies, Carleton University, Ottawa ON, Canada

5. Ocean Mapping Group, Department of Geodesy and Geomatics Engineering., University of
New Brunswick, Fredericton NB, Canada

* alforrest@ucdavis.edu

Understanding subsurface shape, topography and roughness of icebergs and ice islands (large tabular icebergs) in the Canadian High Arctic is limited by a paucity of underwater ice terrain data. This information is critical for calibrating operational iceberg drift and deterioration models that aim to mitigate hazards to shipping and the offshore petroleum industry. Observations beneath icebergs and ice islands have been limited in part by the associated risks operating in close proximity to unstable targets and an inability to map the underside of the ice. In this work, we use a combination of three-dimensional digital terrain mapping sonar systems, including an interferometric sonar mounted on a small Autonomous Underwater Vehicle (AUV), to map portions of the sidewalls and the underside of Petermann Ice Island (PII) fragments in Lancaster Sound and Baffin Bay. The complete perimeter of a small free-drifting ice island fragment named *Berghaus* (0.13 km²; up to 131 m thick), was mapped with surface vessel multibeam sonar and volume and mass estimated. Portions of the sidewalls of the free-drifting PII-Ba (15 km²; up to 106 m thick) and the grounded fragment PII-B (90 km²; up to 102 m thick) were also mapped with surface vessel sonar. Subsurface roughness is compared between the three ice islands and shows relatively smooth surfaces at the scales analyzed (20 cm to 5 m). PII-Ba was

surveyed with a remotely operated vehicle (ROV) that revealed widespread 'scallop' concavities on the order of 5–10 cm down the full depth of the sidewall. A small AUV, *UBC-Gavia*, was used to map a roughly 700 m × 500 m portion of the underside of PII-B and combined with a surface vessel sidewall survey produced a 3D terrain map of the underwater portion of the ice island. A highly eroded ice wall is revealed, showing a pronounced ice skirt indicative of intense surface wave erosion. The draft of the ice island increased from 30 m at the edge to 50 m at the furthest extent of the survey beneath the ice island with a relative uniform basal topography. While only a partial survey could be completed due to the vast size of the ice island, this work demonstrates a unique application of AUVs to contribute to improved understanding of the roughly 9/10ths of the ice that lies below the ocean surface. The ultimate goal of this project, to understand ice island drift and *in situ* melt and deterioration processes will require knowledge of the original glacier topography (pre-calving) and a re-survey of the ice islands over time, along with measurements of the external forcing on the fragments. Here we focus on the digital terrain mapping data which will provide the baseline for further studies and help improve operational iceberg drift and deterioration model parameterization of underwater shape, topography and surface roughness.

1. Introduction

The trajectory and distribution of icebergs and ice islands is directly relevant to the operational mandates of the Canadian Ice Service (CIS) and the International Ice Patrol. In turn, this information is used by the shipping, fishing, tourism and offshore petroleum industries to mitigate ice hazards. Affected by recent and projected climate changes, calving rates of tidewater glaciers and ice shelves are increasing dramatically (Mueller et al., 2008; Peterson, 2005) at a time of increased Arctic marine traffic creating an increased demand for ice hazard information. Operational models of iceberg drift and deterioration are based on a paucity of observational data, primarily from the East Coast of Canada (Bigg et al., 1997; Kubat et al., 2005; Kubat et al., 2007) with little observational data of Arctic icebergs. Drift models are especially sensitive to iceberg shape, which governs drag from ocean currents and wind, and present models may not account for the substantially different shape of ice islands (very large tabular icebergs) compared to smaller icebergs. Deterioration of icebergs is driven by wave erosion, calving, buoyant vertical convection, forced convection, and solar radiation, as well as calving due to internal stresses and capsizing due to instability (Savage, 2001). To refine these models and validate them ice islands in Arctic waters it is critical to observe the drift and melt/deterioration of ice islands *in situ*.

On August 5, 2010 a 250 km² fragment of the Petermann Glacier in northwest Greenland calved from the terminus and drifted into Nares Strait. This fragment, named the Petermann Ice Island (PII), then split into two pieces, PII-A (85 km²) and PII-B (160 km²) which subsequently drifted south in the Baffin Current and continued to break into smaller pieces. The Canadian Ice Service tracked PII-A during its rapid drift south along the east coast of Canada until it disintegrated off the coast of Newfoundland in October 2011. The ice island received international media attention due to the potential risk it posed to offshore petroleum platforms. PII-B remained in the Canadian Arctic for a much longer period of time. PII-B calved a daughter ice island, PII-Ba (28 km²) in October 2010, and several smaller fragments, including one nicknamed *Berghaus* (0.13 km²) targeted in this study. PII-B eventually became grounded off the east coast of Baffin

Island in March 2011. The vast size of the PII fragments results in an enormous ice mass with a relatively shallow draft (~40 m to 100 m); this poses a significant risk to offshore platforms that are usually protected from massive icebergs by being situated in shallow waters (~80 m deep). Larger ice islands are tracked with beacons and satellite imagery, however smaller daughter icebergs continually calved off the larger ice islands pose an increasing risk to ship traffic. Previous mapping efforts of icebergs have largely been conducted using surface vessel side-scan sonar, however this method is not suitable for surveys under large ice islands and new technologies must be adapted to investigate basal ice topography.

Autonomous Underwater Vehicles (AUVs) allow the exploration of the water column that was previously logistically or physically impossible to access. A prime example of this, and one that has been receiving increased attention as the technology becomes more robust, is the exploration of ice-covered waters. These include everything from shorefast lake-ice (Forrest et al., 2008) to drifting sea-ice (Doble et al., 2009; Wadhams 2011) to ice shelves (MacPhail et al., 2009) and glacial tongues (Stevens et al., 2011). Due to the inherent unstable nature of icebergs, there have been limited application and success using autonomous technologies around icebergs (Bachmayer et al., 2007; Kimball and Rock, 2009). Free-drifting icebergs also present significant navigational challenges for AUV surveys due to the constantly rotating and translating frame of reference.

Under-ice exploration requires the development of the platform, autonomous strategy, and the associated scientific payload. While temperature and conductivity measurements have been collected for the past 30 years (Hayes and Morrison, 2002), the development of mapping and imaging sonars are in their relative infancy. The first AUV-based application of sidescan sonar imagery of arctic pack ice was in February 2002 in East Greenland with a Martin 150 AUV (Wadhams et al., 2004). The first AUV-based three-dimensional images of under-ice topography, as collected with an upward-looking swath sonar mounted on the Autosub AUV in August 2004 (Wadhams et al., 2006). One of the additional challenges unique to icebergs is trying to characterize both the relatively flat bottom topography and the steep sidewalls.

This work uses a combination of an upward-looking interferometric swath bathymetric sonar on a *Gavia* AUV in conjunction and a sideways mounted Kongsberg EM3002 multibeam sonar on the surface support vessel to characterize three Petermann Ice Island fragments off the coast of northern Baffin Island. Working within the logistical constraints of being based on the Canadian research icebreaker CCGS *Amundsen*, we were required to select a variety of targets rather than staying in one location. The following section presents the three study locations and the characteristics of each ice island. Specific methodology developed to conduct the ice surveys are then detailed. Mapping results from each of the ice islands is subsequently detailed. Finally, conclusions are drawn regarding how this work could be improved in the future.

2. Study Location

All of the surveys that were conducted in this study were based from the CCGS *Amundsen* as part of the larger Canadian ArcticNet program created to study the impact of climate change in coastal Canadian Arctic. The two legs of the cruise that included the presented survey work were from July 18–Aug. 5, 2011 (from Quebec City, PQ to Pond Inlet, NU) and Oct. 3–Oct. 29, 2011 (from Kugluktuk, NWT to Quebec City, PQ; Fig. 1). During the July leg, a small tabular ice

island fragment, nicknamed *Berghaus*, was surveyed in Lancaster Sound just north of Pond Inlet, NU. In the interim between the two legs, this smaller piece had broken apart and so the return mission was to survey a portion of both the larger fragments PII-Ba and PII-B located off the coast of Baffin Island (Fig. 1).

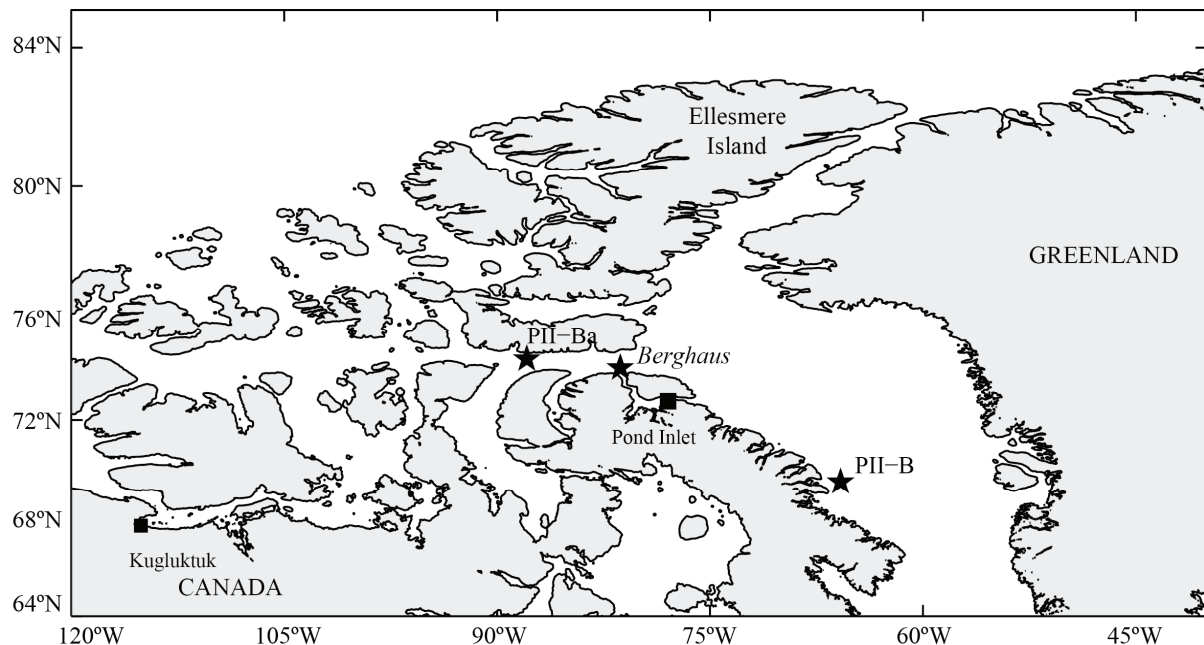


Figure 1. Map of the Canadian Arctic Archipelago with Petermann Ice Island fragments PII-Ba, *Berghaus* and PII-B locations at the time of survey identified.

Berghaus and PII-Ba were both free-drifting at the time of each survey. Measured rotation for both fragments was minimal ($<1^\circ$ over the duration of each survey) while the drift rates of 0.5–0.6 km/hr required careful survey planning. In contrast, the fragment PII-B was grounded on a shallow seabed rise on the coast of Baffin Island. As will be discussed, these relatively shallow depths were also a challenge for AUV mission planning but much less so than dealing with a drifting frame of reference.

3. Methodology

UBC-Gavia, the University of British Columbia AUV, was used for these surveys in a similar configuration to previous under-ice applications (Doble et al., 2009). Unlike those previous deployments, which used a Kearfott T-24 Inertial Navigation System (INS) and a 500 kHz GeoAcoustics GeoSwath Plus phase measuring sonar, the vehicle was configured with a 468 kHz SWATHplus phase measuring sonar and relied on dead-reckoning for navigation. The operating frequency of this unit provides 20 cm resolution in the final acoustic backscatter mosaic and then 0.5–1 m resolution in the associated final gridded bathymetric products. Additional scientific payload included a dual-frequency high-resolution side-scan sonar (220/990 kHz Imagenex), a Conductivity-Temperature-Depth sensor (SBE49, Seabird Electronics), an acoustic Doppler current profiler (DVL/ADCP, RD Instruments), and an optical backscatter sensor to measure chlorophyll-a, turbidity and colored dissolved organic matter (Ecopuck, Wetlabs). As configured, the vehicle was 3.2 m in length, 0.2 m in diameter and ~80 kg dry weight in air. Only the

SWATH_{plus} data is discussed here. The relatively small AUV was deployed by hand from a 10 m landing craft launched over the side of the *CCGS Amundsen*. The surface vessel team consisted of three AUV engineers, a multibeam sonar technician and three Coast Guard personnel for vessel navigation.

Operations in July 2011 focused on running the AUV inverted and tethered as had been done previously (Doble et al., 2009). As a result of the length of the tether, missions were programmed to be less than 1000 m in total length (500 m away and return from the surface support vessel). Although the vehicle successfully dove and operated normally during the test operations, the trials were unsuccessful at reaching full operating depth and getting underneath *Berghaus*. One of the encountered problems was the ability to communicate with the inverted vehicle between missions (as the wireless network communications tower was submerged on the surface in inverted mode). In order to improve chances of success in October 2011 the Swath_{plus} module was re-engineered to have the transducers upward facing while the vehicle was in an upright orientation.

The University of New Brunswick's Kongsberg EM3002 (300 kHz) multibeam system was pole mounted on the port side of the surface support vessel. At the bottom of the pole a 40° elbow adapter was fit as the mount for the EM3002 transducer. This angle allowed the system to view from the water free-surface on the port side, to 25 degrees past nadir on the starboard side of the vessel. A Coda Octopus F185 attitude and positioning system provided attitude and a GPS baseline derived heading. A C&C Technologies C-Nav 2000 GPS system exported Real Time GYPSY corrections to the F185 unit. A pole mounted AML Oceanographic SVP&T surface sound speed sensor delivered updates to the multibeam system throughout the survey. CTD casts collected on site were utilized during post processing to correct for refraction. The free-drifting fragments (*Berghaus* and PII-Ba) were undergoing both translation and rotation so GPS tracking beacons were deployed on the icebergs during each sonar survey to correct the sonar position data in post-processing.

Subsurface roughness of the sidewall of the ice islands was calculated from the EM3002 multibeam data using a semi-variogram method where the variability in surface topography normal to the average wall slope is plotted as a function of length-scale. A representative patch of multibeam sonar data was selected from a straight section of the ice island wall (avoiding abrupt corners). A roughness semi-variogram was calculated for length-scales between 20 cm to 5 m in both vertical and horizontal directions. A semi-variogram was calculated for 100 m² sliding windows (50% overlap between adjacent windows) then averaged over all windows across the entire section.

The submerged face of PII-Ba was visually surveyed using a Seamor 300F Remotely Operated Vehicle (ROV) equipped with a Sony FCBIX11A color video camera and two 50 Watt LED spotlights. Real-time video (460 TV lines) was transmitted through a 300 m fiber optic tether to a surface display and recorded to a laptop computer. The ROV was piloted down the vertical face of the ice island from the surface to the maximum draft of the ice island. An attempt to pilot underneath the ice island was unsuccessful due to a loss of communication with the ROV due to an electrical fault in the power supply. Time constraints and technical issues prevented ROV surveys of the other ice islands.

4. Results and Discussion

4.1 Berghaus

The first fragment targeted for survey was nicknamed *Berghaus*, and was selected from an aerial reconnaissance on July 30, 2011 (81°12'W, 74°6'N; Fig. 2a). The ice island width ranged from 190–260 m and length ranged from 260–460 m. Freeboard estimates made from the surface vessels ranged from 18–25 m. Several attempts were made to run the AUV underneath the iceberg; however, as a result of technical difficulties, none were successful. Although *Berghaus* wasn't rotating significantly during the 12-hour sampling window ($<1^\circ$), it was drifting significantly ($0.5\text{--}0.6\text{ km hr}^{-1}$). This made it difficult to plan missions for the AUV as transects positions continuously needed to be readjusted in mission planning software. Also, as this survey was being conducted mid-summer, the sidewall of the ice island was calving overhanging fragments every 20–30 minutes making it risky for the surface support vessel to get close. Evidence of a recent calving event can be seen by the debris in the water to the left side of the ice island (Fig. 2a).

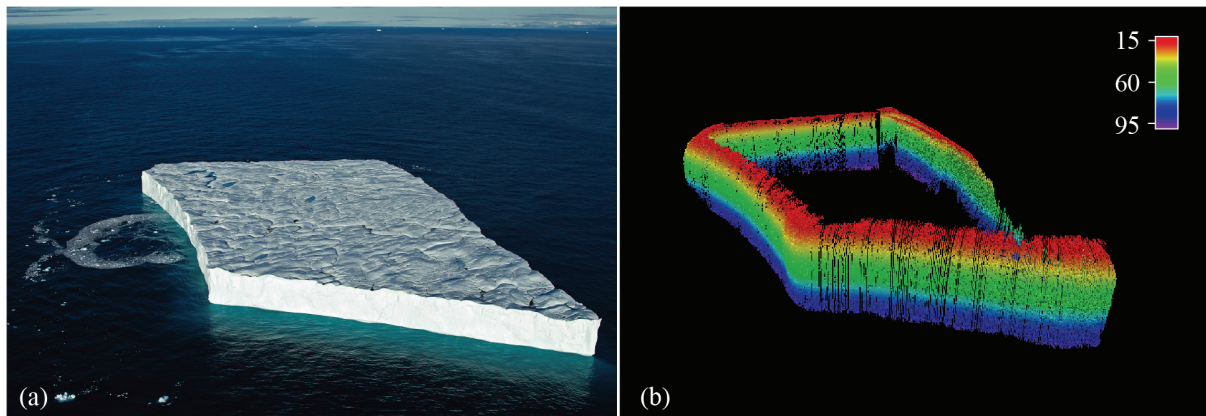


Figure 2. Surveys of *Berghaus* as viewed from (a) aerial photography of the sail (Photo courtesy of Jean-Jacques Pangrazi) and (b) corrected EM3002 multibeam sonar data of the sidewalls of the keel (Image created in FledermausTM).

In the remaining time in the sampling window, a circumnavigation of *Berghaus* was conducted at a standoff distance of 75–125 m in the surface support vessel in order to collect EM3002 multibeam data (Fig. 2b). Each of datasets took 30–45 minutes to collect and so the drift needed to be corrected during post-processing. There are also gaps in the data where the surface vessel was too far away from the iceberg (Fig. 2b; the right side of the image). The data shows near vertical walls extending down to just over 104 m depth. The measured ice draft was observed to be nearly uniform all the way around the fragment. These values were much greater than was originally expected by the team and posed a significant challenge for the planned AUV surveys. Four point thickness measurements were collected from the surface of the iceberg using ground penetrating radar (GPR) and ranged from 124–131 m. The agreement of the multibeam derived draft and freeboards estimates ($104\text{ m multibeam draft} + 24\text{ m freeboard} = 128\text{ m total thickness}$) with the GPR total thickness estimates suggest that this fragment had relatively flat topography on the underside. Assuming an average draft of 104 m and freeboard of 24 m with a horizontal top surface we can calculate an approximate volume of *Berghaus* of $13.72 \times 10^6\text{ m}^3$ and assuming a density of 0.9 kg/m^3 gives a total mass of $12 \times 10^9\text{ kg}$ (12 million tonnes).

4.2 Petermann Ice Island – Ba

The second fragment, PII-Ba (Fig. 3), was surveyed on Oct. 13, 2011 in Lancaster Sound ($87^{\circ}54'W$, $74^{\circ}15'N$). With surface dimensions of $6\text{ km} \times 2.5\text{ km}$, this free-drifting fragment was significantly larger than *Berghaus*. This surface area of PII-Ba was much larger than could be completely surveyed in the time available so a 400 m long section was mapped for comparison. Fig. 3 shows the CCGS *Amundsen* holding station in the vicinity of the survey section.



Figure 3. Aerial view of ice fragment PII-Ba with the CCGS *Amundsen* shown holding station near the wall where the survey was being conducted (Photo courtesy of Jessy Barrette – INRS-ETE).

As a result of the elevated sea-state, limited time on station and other logistical constraints the AUV could not be deployed to conduct an under-ice survey. Instead, EM3002 data was collected and compared with an image survey conducted with the ROV. Two passes in front of the wall were conducted with the multibeam at a similar stand-off distance of 75–125 m as was used in the *Berghaus* survey. The results (Fig. 4a) show the wall extending down to ~ 75 m water depth, although acoustic return from the bottom edge are variable. Once the multibeam survey was completed, the ROV was then deployed to conduct a vertical survey of the wall from surface to the bottom edge of the ice island (76 m). The captured images show widespread "scalloped" concavities $O(5\text{--}10\text{ cm})$, uniformly distributed down the entire depth of the wall (Fig. 4b). These "scallop" features are indicative of ice with air bubbles melting underwater (Josberger, 1980), and the lack of periodic parallel "flutes" or "grooves" indicate the melting occurs under variable flow conditions.

The "scalloped" features cannot be resolved by the multibeam survey as their associated length scales are smaller than the resolution (20 cm) of the sonar system. The distinct bottom edge of the ice island observed in the ROV image survey indicates that the multibeam survey was not

properly characterizing the bottom ice edge. A combination of signal attenuation and shading of the ice edge could explain the variability of bottom edge detection. The multibeam survey shows some vertical grooves in the ice wall (e.g. boxed region in Fig. 4a) that may be associated with melt channels or underwater ice calving, but the incomplete survey prevents conclusion on their origin.

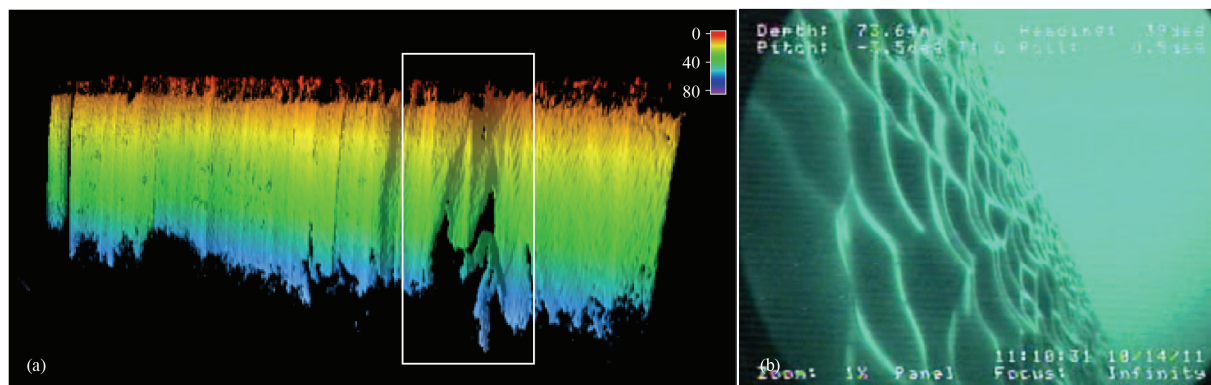


Figure 4. Surveys of PII-Ba as viewed from (a) corrected EM3002 multibeam sonar data of a 400 m long section of the sidewall (vertical exaggeration of 6 times; depths ranging from near surface (red) to ~75 m (blue); image created in Fledermaus™) and (b) underwater imagery collected with an ROV showing the 5–10 cm scallop features indicative of subsurface melt.

4.3 Petermann Ice Island – B

The third fragment, PII-B, was mapped on Oct. 22, 2011 off of the east coast of Baffin Island, just south of Clyde River (65°48'W, 69°37'N). This fragment was larger than the previous two fragments (11.6 km × 7.9 km) and had been grounded in place since March 2011. Bathymetric charts and a survey in the area by the CCGS *Amundsen* showed water depths of 80–200 m. From satellite imagery the ice island showed slight rotation around a pivot point near the centre of the ice island, indicating the grounding point was localized at the center of the island. The relatively low freeboard at the ice edge (4–8 m) indicated there the ice was afloat and relatively thin near the edge and there was sufficient water depth to run AUV transects for a distance under PII-B. A 500 m section of the ice island edge was mapped with surface vessel sonar and AUV mission were planned to start in this region. Four AUV missions were run under the ice island at a depth of 60 m, the longest transect running 700 m under the ice. The surface vessel sonar and AUV sonar datasets were combined to show the full three-dimensional nature of the ice fragment (Fig. 5). The 3D terrain map shows the ice island is shaped similar to an ice shelf or glacier tongue, the thicker region nearer the grounding point (not shown in Fig. 5; the grounding point would be several kilometers inland from the edge) gradually tapering to a relatively thinner and more highly eroded floating ice edge. AUV transects revealed the basal topography to be relatively uniform across the survey region, with ice draft increasing from ~30 m depth at the ice edge to a depth of 50 m at 700 m inward from the edge. A surface based GPR thickness measurements of 73 m, obtained a kilometer further inland from the end of the AUV transects suggests the ice island gradually increasing in thickness toward the center at this location. The geometry of the sidewall edge is much more complex than in either of the two previous fragments. In contrast to

Berghaus and PII-Ba, which had nearly vertical, straight sidewalls, PII-B shows numerous undulations and embayments. These features may be the result of PII-B being subject to increased wave erosion due to being grounded and exposed to the open waters of Baffin Bay, as well as increased surface and sub-surface melt as a result of its more southerly latitude.

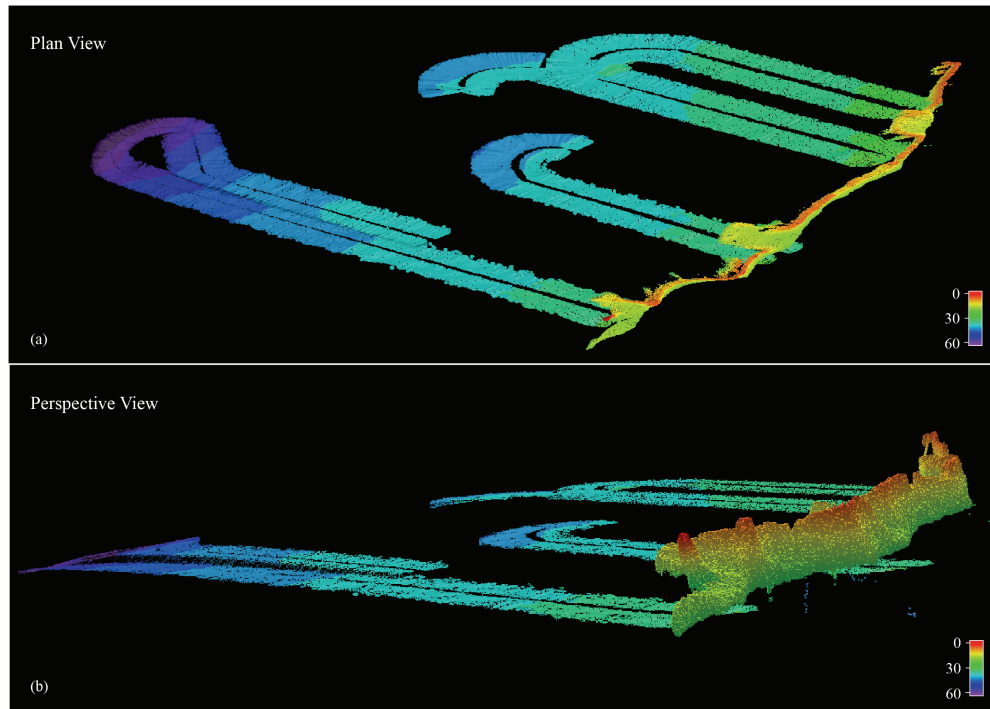


Figure 5. Survey of PII-B as viewed in (a) plan view and (b) perspective view from corrected, AUV-based interferometric sonar data of the underside of the ice and of the sidewalls of the ice fragment collected with the EM3002 system (vertical exaggeration of 6 times; (Image created in FledermausTM).

4.4 Comparison of Roughness and Topography

Results of the preliminary roughness analyses of the ice island walls are shown in Fig. 6. The semi-variograms show all ice islands had relatively smooth submerged surfaces at the length scales analyzed (0.2 m to 5 m), with PII-Ba showing a maximum roughness variance of 0.2 m^2 at the 5 m length scale. PII-B showed the least variance in the horizontal ($<0.02 \text{ m}^2$), suggesting it had a very smooth surface at these scales (a perfectly smooth surface would have zero variance), while PII-Ba had the least variance in the vertical. *Berghaus* showed relatively uniform variance in both horizontal and vertical directions ($\sim 0.8 \text{ m}^2$ on average at all scales). The lack of a significant peak in variance at any specific length scale indicates the surfaces are relatively uniform in nature, with no regular periodic patterns such as parallel flutes or grooves. However, the authors caution that this is a preliminary analysis and the results should be viewed as such. A quantitative roughness analysis of the AUV transect under PII-B has not yet been completed as there are sonar artifacts from AUV performance that need to be corrected. We aim to further develop the roughness analysis across all length scales and using the AUV sonar data from under PII-B, with the ultimate goal to relate roughness to skin friction water drag.

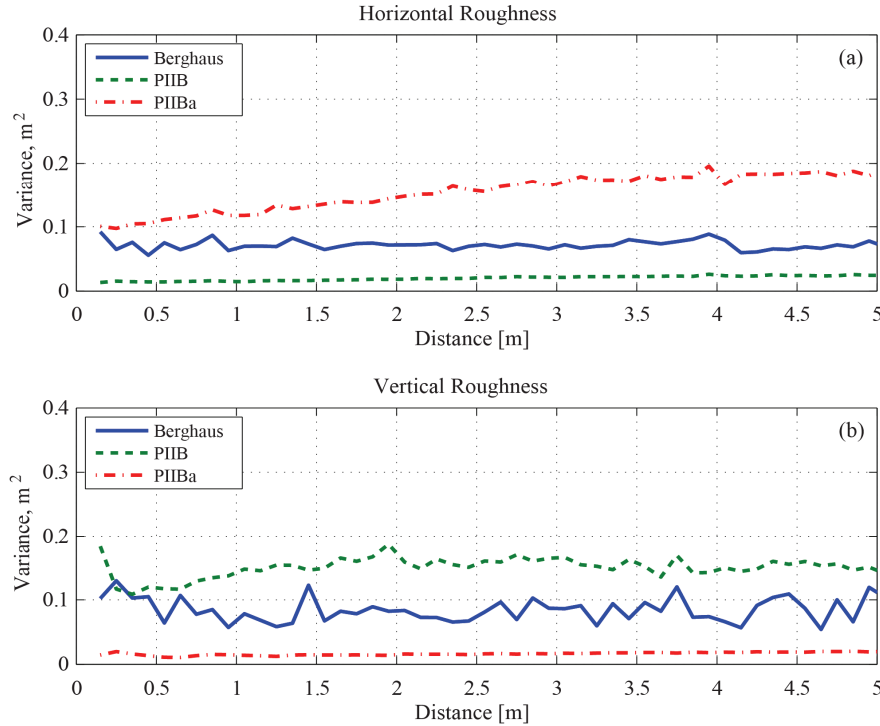


Figure 6. Roughness variance for *Berghaus*, PII-B and PII-Ba in the horizontal direction and vertical direction. Variance is calculated normal to the local plane of the ice wall.

5. Conclusions and Recommendations

This work represents a significant advance for using small AUVs to map the underside of ice islands, which could now be extended to various under-ice applications such as icebergs, ice shelves and glacier tongues. The two biggest challenges encountered were the ability to plan missions for a drifting reference frame and limited time on-site as the study was opportunistic and therefore time was limited at each station. While it is possible to correct for the former challenge in post-processing, the latter can only be dealt with by changing the paradigm of the study. If a similar study were to be repeated, it would benefit from focusing an entire cruise to iceberg or ice island studies allowing for greater time on site. As well, small AUVs, such as *UBC-Gavia*, can also be effectively deployed through ice holes from a winter ice camp enabling year-round studies.

The ultimate goal of this project, to completely map an ice island and track its drift and deterioration over time was not met due to a combination of logistical (e.g. the rapid demise of *Berghaus*) and technical (e.g. AUV navigational issues) challenges. However, as an opportunistic pilot project it has proved useful in providing detailed 3D terrain maps of ice island keels, rare datasets that will improve our ability to model drift and deterioration. This information is becoming increasingly important as ice islands, including fragments of PII-B are, at the time of writing, continuing to drift south toward trans-Atlantic shipping lanes and off-shore petroleum platforms.

The next phase of this research will be to place the ice island topography data presented here in a larger context to better understand the external forcings acting to control the drift and

deterioration of the ice islands. To do this, we collected several concurrent datasets including: ice island drift tracks over several months; surface ablation and total ice thickness from each island; *in situ* meteorological data (wind velocity, solar irradiance, surface temperatures, surface ice ablation, etc.) at *Berghaus* over 6 weeks; conductivity-temperature-depth (CTD), current velocity and nutrient profiles around the ice islands; and horizontal CTD/optical backscatter/current velocity AUV transects under PII-B. These datasets will be the focus of future publications. The mapping datasets presented in this paper contribute rare observations of ice island subsurface topography, improving our understanding of ice island keel shape and surface roughness.

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