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Through-ice AUV deployment: Operational and technical experience from two seasons of Arctic fieldwork

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ABSTRACT

Detailed sea ice draft mapping was recently accomplished in the Beaufort Sea, north of Alaska, in 2007 and in the Lincoln Sea, north of Canada's Ellesmere Island, in 2008 using a small (3 m long, 20 cm diameter), man-handleable *Gavia* AUV incorporating an inertial navigation system and a 500 kHz phase-measuring swath sonar. The topography of specific ice features was mapped across 80 m-wide swaths by performing repeated runs in the vicinity of access holes drilled in the sea ice. The paper discusses the technical and operational developments undertaken to successfully accomplish the missions, including test deployments in a frozen Canadian lake prior to each Arctic deployment. Example data are shown and accuracy issues discussed.

1. Introduction

The technology of operation of autonomous underwater vehicles (AUVs) in ice-covered waters has developed over a long period with the initial work being related to military needs.

The first under-ice AUV was funded by the Office of Naval Research, was called UARS (Unmanned Arctic Research Submersible) and was first deployed in the Beaufort Sea in 1972. It required the use of a gantry for lowering it through a 4 m hole in the ice, as it weighed 410 kg. It was equipped with three narrow-beam upward sonars and succeeded in obtaining data at ice island T-3, in the Beaufort Sea (Francois and Nodland, 1972). Bowen and Topham (1996) mounted an upward-looking sonar on an ROV to build up a digital elevation map (DEM) of a Beaufort Sea first-year ice ridge in April 1991. The vehicle was piloted along 32 tracks from two deployment holes, to cover an area of 150×300 m. An under-ice AUV was not used again until the winter Lead Experiment (LeadEx) in 1992, in the Beaufort Sea (Morison and McPhee, 1998). This was a very light (9.6 kg) small vehicle which carried a CTD and was launched and recovered from a lead, homing to an acoustic beacon before recovery in a net. The Canadian Defence Research Establishment (Atlantic) used the very large (10.7 m length, 8600 kg) Theseus AUV for cable-laying in the Arctic in 1996 (Ferguson et al., 1999), launching the vehicle from the bay in which the 2008 experiments by the authors, described below, took place. Hayes and Morison (2002) used a REMUS-derived AUV to measure turbulent fluxes of heat, salt and momentum and ice draft profiles during the SHEBA project in 1997–8, and single-beam upward sonar data were collected in the Antarctic from the UK Autosub vehicle (Brierley et al., 2002) in 2001.

Systematic ice mapping by AUV began in February 2002, when a Maridan Martin 150 AUV was used in the Greenland Sea (Wadhams et al., 2004), equipped with a Tritech SeaKing 675 kHz sidescan sonar, a CTD and an ADCP. The sidescan sonar generated imagery of first- and multi-year ice floes in the marginal ice zone of the winter polar pack ice, while the upward channel generated a profile of ice draft. Previous sidescan sonar data under-ice had been obtained only from manned submarines (Wadhams, 1978, 1988). The final step was to obtain full three-dimensional mapping capability, and this was achieved in August 2004 using the Autosub II vehicle off NE Greenland, equipped with a Kongsberg EM2000 multi-beam sonar (Wadhams et al., 2006). More than 450 track-km of data were obtained. The same vehicle later collected data under the Fimbul ice shelf in Antarctica (Nicholls et al., 2006) before being lost there for reasons which remain unknown, despite an extensive post-event investigation (Strutt, 2006).

2. Small AUVs as a solution to the through-ice problem

Recently, development has accelerated because of scientific concerns about ice thinning, the commercial need to extract oil and gas from ice-covered waters and increasing concerns with regards to sovereignty issues in Polar regions. For large-scale, basin-wide surveys of the ice underside in Arctic waters there is still no substitute for military submarines (Wadhams, 2000), which have yielded valuable information

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on the statistical nature of the ice bottom and the changing thickness due to global warming (Rothrock et al., 1999; Wadhams and Davis, 2000).

There is however an increasing need for specific surveys of ice regimes associated with oil extraction–e.g. the pile-up of ice rubble against offshore platforms; scouring of the seabed by ice ridges; entrapment of spilt oil by ice (Wilkinson et al., 2007)–and for multi-sensor surveys of ice types such as ridges to infer their dynamics and thermodynamics. For these applications an AUV is ideal as it can follow a programmed track and can work in areas where the use of manned vehicles is logistically difficult or operationally dangerous. In particular, an AUV small enough to be launched through an ice hole is a significant asset, since this gives a greater flexibility of operation.

This paper describes the development and field deployments of such an AUV–the *Gavia* vehicle, manufactured by Hafmynd ehf–at two ice camps in the Arctic Ocean, the first as part of the Applied Physics Laboratory Ice Station (APLIS) in the Beaufort Sea, during April 2007, and then as part of the European DAMOCLES (Developing Arctic Modelling and Observation Capabilities for Long-term Environmental Studies) programme, this time north of Canadian Forces Station Alert, in the Lincoln Sea in April/May 2008. Both Arctic deployments were preceded by ice camps at Pavilion Lake, B.C., Canada, carried out in February (2007 and 2008).

The scientific objectives of the Pavilion Lake ice camps were to investigate temperature variations at fixed depths in the water column using a CTD mounted onboard the vehicle. Concurrent measurements of the ice-cover explored the relationship between ice and snow coverage and non-uniform mixing within the lake resulting from radiative penetrative convection in late winter/early spring. This is part of an ongoing study to understand small scale mixing processes within the lake on a seasonal time scale.

Scientific interests during the Arctic deployments focused on the use of a swath sonar to measure ice draft along the vehicle track. Both Arctic campaigns obtained co-incident measurements of snow+ice thickness and snow+ice freeboard using a helicopter-borne electromagnetic induction system (HEM) (Haas et al., 2006; Haas et al., 2008) and a scanning laser profilometer mounted on a Twin Otter aircraft (Hvidegaard and Forsberg, 2002). The 2008 deployment also included a downward-looking radar, similar to that to be flown on Cryosat-2 satellite to be launched in March 2009. Extensive *in situ* validation of snow thickness and ice thickness were also performed with around 200 holes drilled during each campaign. The goal of these deployments was to increase our understanding of the freeboard–draft–thickness relation in advance of space-based ice thickness determination. Scientific results will be detailed in forthcoming publications. Sonar imaging from the first experiment is shown in Wadhams and Doble (2008) while the focus of the work presented here is the development of the technology by which the results were achieved.

3. The *Gavia* vehicle

The *Gavia* vehicle can be configured according to the mission requirements, with twist-lock modules fitting together in any convenient order and communicating over an internal Ethernet network. Various oceanographic modules have been developed for the vehicle, including CTD and optical sensors. A swath-sounding sonar has been integrated, providing the possibility to map under-ice topography in detail for the first time and providing the impetus for a programme of Arctic deployments.

The vehicle was designed to be used with its various sensors pointing downwards, at the seafloor, while mapping under-ice terrain requires the instruments to look upwards at the ice underside. The AUV was therefore ballasted with an appropriate external keel to invert the vehicle. The control software adjusted to this situation automatically, inverting the control inputs accordingly.

The sonar is a development of the GeoSwath™ phase measuring unit, produced by GeoAcoustics of Great Yarmouth, UK. It was originally designed as a 125 or 250 kHz unit, for use from small boats for surveying seafloor bathymetry. A 500 kHz unit was produced for AUV/ROV use and has been used for various seafloor surveys to date (e.g. Kennedy, 2005). The sonar has one transmit and four receive elements/side, angled at 30° from the horizontal. Phase delays between receivers are used to calculate the angle of returns and travel time gives the range to each reflector. Fig. 1 shows the general arrangement. Unlike multi-beam units, there is no set number of beams for which returns are calculated: the data consist of an arbitrary number of angle/range pairs 'per ping'. This results in a very high data density, usually of over 5000 points/ping, and a very wide swath width in comparison with multi-beam systems. GeoAcoustics quote a swath width of up to 12 times water depth, though we found that the spreading of draft solutions with range became unacceptably high beyond a horizontal range of approximately 40 m either side of the vehicle, when running at 20 m depth (i.e. four times water depth). This may be related to the increasing slant range at this relatively deep running depth—the attenuation coefficient for a 500 kHz signal is around 100 dB km^{-1}, in addition to spreading considerations. The minimum data density occurs directly above the vehicle, since a flat reflector is effectively all at the same range, giving only one angle. Significant relief along the centreline will be well-imaged, however, since many different ranges are present.

Navigation presents the greatest challenge for AUV deployments under a heavy ice cover, given the difficulty of locating and recovering a vehicle should it not return to the deployment hole, and the impossibility of obtaining GPS fixes under-ice, in contrast to open-water operations. These field trials were conducted with a Kearfott IN-24 inertial navigation system (INS) coupled, via a Kalman filter, to a RDI Navigator 1200 kHz Doppler velocity log (DVL) which tracked the progress of the vehicle along the underside of the ice. This ice-referenced frame of the DVL is essential, since we are only interested in the vehicle's position with respect to the ice (and especially with respect to the recovery hole), rather than true geographic co-ordinates. The GeoSwath™ unit uses attitude data from the INS to convert the transducer-relative range/angle/amplitude points to geographic co-ordinates during post-processing.

The vehicle carried a 4 mega-pixel still camera in the nose module, firing 4 frames/second, looking upwards at the ice underside. The camera's field-of-view is 60°, giving a frame width of approximately 25 m and allowing continuous photo-mosaics to be assembled along the vehicle track. The vehicle also carries a strobe flash unit for use with the camera, consisting of 16 high-intensity LEDs mounted in a faired pod.

The nose module also contains a forward-looking collision-avoidance sonar. This was disabled during under-ice work, as the vehicle would tend to 'see' the underside of the ice when pitching up

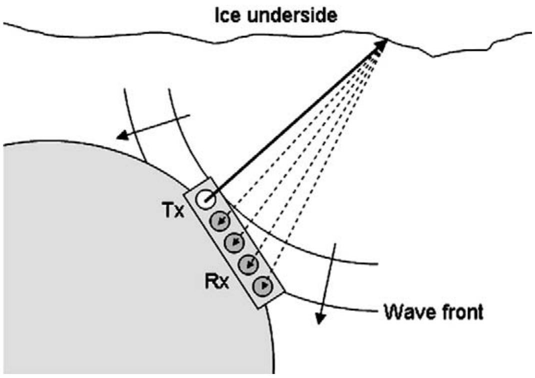

Fig. 1. Schematic showing operation of the phase measuring sonar, mounted on the AUV hull and insonifying the underside of the ice from the transmit element (Tx). The reflected wave front passes each of the four receive elements (Rx) at a slightly different time (i.e. phase), allowing the angle to the reflecting point to be calculated. The time between transmission and reception gives the range to that same point.

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(either during a buoyant rise or a programmed change to a shallower running depth), causing it to reverse the propeller and abort the mission. Running depth was thus planned to avoid the deepest expected features in the area. Features in the areas studied were not expected to be deeper than around 15 m, therefore this requirement did not conflict with the need to run relatively shallow to maintain adequate insonification of the ice—GeoAcoustics quote a maximum water depth of 50 m for the 500 kHz system for seabed surveys, for which we would expect the contrast in acoustic impedance to be greater than for the ice–water interface.

The vehicle was also fitted with external acoustic transponders. These included a Datasonics LXT system (17–23 kHz), loaned by the Applied Physics Laboratory, University of Washington for the APLIS deployment. A 73 kHz acoustic tag was installed in the conning tower to provide range to the vehicle (~500 m) for the work near Alert, tracked with a Datasonics hydrophone system. *Gavia*'s on-board acoustic modem (LinkQuest UWM2000H) could also be interrogated for range, using a similar modem lowered into the deployment hole, connected to a laptop computer. As a redundant system, a COTS 457 kHz avalanche transceiver was installed in the buoyancy module during the lake trials. The range and direction provided by a similar hand-held transceiver allowed the vehicle position to be determined to within an accuracy of 3 to 4 m while it was at rest on the underside of the ice cover. Although not used for the majority of the sea ice trials, several runs were conducted during work in 2008, which confirmed a similar precision in determining the vehicle's position under first-year sea ice (*c*.1.6 m thick). Though such devices are often used to locate moorings once they have been released in ice-covered seas, this success was unexpected, given the fact that the transceiver was housed within a sealed aluminium module, combined with the relatively high salinity of first-year sea ice.

Other equipment mounted on the command module included a 2.4 GHz WiFi antenna for communication with the mission-controlling laptop, a GPS antenna and an Iridium satellite antenna for communications in its normal free-surface mode.

Fig. 2 shows a photograph of the vehicle in the ice hole. The vehicle is shown in its running position for upward-looking, under-ice work with the various modules and components identified.

4. Technical development

4.1. Pavilion 2007

Prior to the first deployment in the ice-covered ocean, trials were conducted under lake ice at Pavilion Lake, British Columbia, Canada (50°52′N, 121°44′W). This relatively small and shallow lake (less than 6 km^2, maximum depth 61 m) provided a benign environment to explore the problems and limitations of the vehicle's under-ice use. The site is a long-term study area for the Pavilion Lake Research Study, of which the Environmental Fluid Mechanics group in the Civil Engineering Department of the University of British Columbia (UBC-EFM) is a member. The UBC-EFM group uses their own *Gavia* vehicle (*UBC-Gavia*) for limnological investigations there (Forrest et al., 2007). Trials were conducted using *UBC-Gavia*, with various other modules (GeoSwath™, INS) brought over by *Gavia* technical staff, who also attended.

The aim, from the point of view of preparing for Arctic Ocean operations, was the development and testing of: (1) launch and recovery techniques; (2) inverted operation of the vehicle; and (3) navigation methods under-ice.

Trials were conducted from 18–23 February 2007, when the ice thickness on the lake was around 40 cm. The ice was undeformed, though displayed extensive and ongoing cracking from diurnal temperature variations. There was very little snow, as elevated temperatures and intermittent rain in the previous weeks had melted the usual 5 cm snow cover. The thin, snow-free ice meant that the strobe lights of the vehicle could easily be seen through the ice during the hours of darkness, allowing it to be visually tracked during relatively shallow missions (<10 m) and located in the event of an aborted mission when the vehicle would come to rest against the underside of the ice.

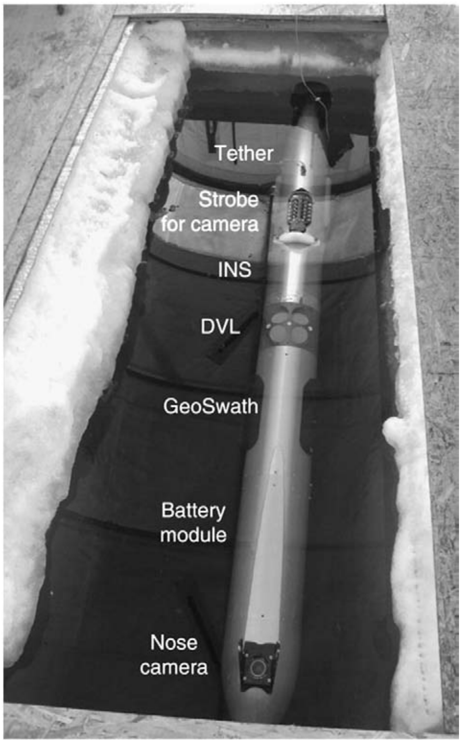

Fig. 2. The *Gavia* AUV, ballasted for upward-looking operation, in the deployment ice hole. Various module functions are indicated. The vehicle is 2.9 m long in this configuration and 20 cm in diameter.

Operations were conducted from a 3 × 1 m hole cut through the ice. The large hole allowed the AUV to be floated horizontally and facilitated ballasting and pre-flight preparation. The mild meteorological conditions (−10 °C during the night to +5 °C during the day and low winds) meant that work could be conducted outside reasonably comfortably and without concern for ice formation on the vehicle. The thin ice (and hence low draft) allowed the vehicle to be hand-launched from beside the ice hole. The tail of the vehicle was simply held out of the water until the mission was executed and the propeller was in operation. The AUV was then released on a diving path to begin its turn onto mission track.

The planned deployment in the Arctic entailed deployments through ice with significant draft (>1.5 m), however, and thus a weighted release system was also tested. A 2.5 kg lead weight was attached to an eye at mid-length on the vehicle via a release shackle, operated by a second line. The vehicle was lowered to below an ‘arming depth’ (15 m), the weight released (and pulled out of the hole) and the vehicle allowed to float up to a ‘trigger depth’ (10 m) at which point the mission was executed. This allowed the vehicle to be horizontal in the water and at depth before mission execution, cutting the time to reach the survey line and hence optimising the data gathering potential of the mission.

Missions always terminated at some distance from the actual hole and thus some method of recovering the vehicle to the hole was required. Divers were present at the lake, engaged in unrelated tasks, but mobilisation of these resources would have required considerable time and effort. When the vehicle was not running inverted, the fresh lake ice allowed WiFi communications to be established with the AUV floating directly beneath the ice, since the communications tower was then in direct contact with the ice underside. It proved quite possible

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to pilot *Gavia* back to the recovery hole using a laptop computer to command propeller and rudder controls, with the vehicle sliding along beneath the ice and using the strobe lights as reference. The same luxury is not available when operating under sea ice, of course, due to its salt content.

Once inverted (i.e. tower down), the water depth between the tower and ice prevented WiFi communication. The vehicle was then recovered using a SeaBotix LBV ROV, provided by Roper Resources of Victoria, British Columbia. This operated on a 150 m tether and was fitted with a small manipulator arm, which grabbed a short weighted line hung from the mid-length of the AUV for this purpose. The vehicle was successfully recovered several times using this system, even at the limit of the ROV's tether range. More distant recoveries of an inverted vehicle would have required the time-consuming drilling of a recovery hole, however, and in the interests of maximum engineering development, further inverted tests were made using a tether line attached to the mid-length of the AUV, with which the vehicle was pulled back to the hole after a mission.

Inverted running tests produced many interesting problems, including the software interface between GeoSwath and *Gavia*, which prevented any under-ice data acquisition during these first tests. Navigation using the INS without DVL input was poor, with the vehicle returning up to 50 m from the hole even after very short runs. The DVL unit rotated its horizontal reference frame when inverted, giving erroneous results, and was thus unable to constrain the INS drift. In contrast, with the vehicle running tower-up and close enough to the lake bottom (<30 m altitude), the DVL-INS combination was sufficiently accurate to allow extended missions. The AUV was seen to pass directly under the deployment hole on several occasions, though the best final position achieved was around 10–20 m from the hole.

UBC-Gavia can also navigate acoustically, using two or more transponders lowered through the ice, communicating with the acoustic modem fitted to the vehicle's command module. This “long baseline” (LBL) system was trialled using two LinkQuest TrackLink 1500 transponders (wideband, 27–45 kHz) placed around 600 m apart. This was expected to provide the best navigational accuracy under-ice, but the trials proved otherwise. Acoustic fixes were intermittent and runs were often conducted without a single acoustic fix being obtained. Reflections from the lake bottom, shore and ice were all suggested as possible causes. The limited time window to interrogate the transponders was another possible factor contributing to the poor acoustic performance, since the role of the on-board acoustic modem is split between communications and positioning.

In the case of an aborted mission, the strategy of a ‘fallback’ mission was developed, to be executed either when the original mission aborted or when it was completed, with the vehicle programmed to return to the deployment hole. Though successful at mission end (i.e. with minimal position error), return to the hole was clearly more problematic if the position accuracy had exceeded the specified threshold, which was the main cause for aborting missions.

The experience highlighted the need for extensive development before the AUV could be expected to return reliably to a small recovery hole in the ice. Major hardware fixes were precluded since only 5 weeks remained before the 2007 Beaufort Sea deployment, but extensive software changes were implemented; specifically with regard to the DVL and GeoSwath interface problems.

4.2. APLIS 2007

The next under-ice deployment was during the Applied Physics Laboratory Ice Station (APLIS), in the Beaufort Sea, north of Prudhoe Bay, Alaska (approximately 73°N, 145°W), from 4–13 April 2007. The demonstration *Gavia* was leased from the manufacturers for the project. The experiments formed part of the SEDNA (Sea Ice Experiment: Dynamic Nature of the Arctic) project led by University of Alaska, Fairbanks (UAF); a multi-sensor survey of the region around the camp originally established by the Arctic Submarine Laboratory, San Diego, as a base for acoustic experiments with US and British submarines. The AUV measurements thus benefited from multiple validation studies by other sensors including a submarine sonar survey of the site carried out in March 2007 aboard HMS *Tireless*.

The ice-covered Arctic Ocean represents a significantly more challenging environment for AUVs than lakes as it is effectively ‘boundless’ both in horizontal extent and in depth. The ice concentration in the deployment area was almost 100%, consisting of dominantly first-year ice (modal thickness ~1.7 m) with a significant multi-year fraction (modal thickness ~2.9 m) and a 20–30 cm deep snow cover. All of these factors dramatically reduce the chances of recovering a lost AUV compared to the lake environment. Additionally, the ice generally moves at a significant velocity—the camp moved 48 km WSW during the AUV operations at a mean velocity of 0.07 ms^{-1} and a maximum of 1.22 ms^{-1}. Any navigation method must therefore be referenced to the ice, rather than geographic or GPS co-ordinates, eliminating dead-reckoning as a navigation strategy.

With this in mind, and given the performance of the various navigation methods at Pavilion Lake, the decision was taken to run the AUV with a tether. Though this severely limited the autonomous nature of the AUV, the swift and guaranteed recovery of the vehicle significantly accelerated the development process, while enabling the scientific ice mapping objectives which motivated the deployment to be completed.

Two sites were selected for the AUV experiments. The first was a region of first-year ice, which did not contain well-defined ridges, but was mainly undeformed ice with some thickness variability due to single blocks. The second site was close to a first-year ridge observed to have formed 8 days before initial vehicle deployment. This was a much more complex topography, and the subject of intense surface studies by the UAF group.

Access to the underside of the ice was gained through a 3×1 m hole, prepared by a hot water drill feeding a 1 m diameter circular ring. The resulting 1.8 m thick cylindrical plugs were removed using a large tripod and winch. A heated canvas hut mounted on a sled was placed over the hole to allow operations to be carried out in comfort and to keep equipment, including the AUV, reasonably warm. Though the vehicle does not contain any wet cavities which would sustain damage in freezing conditions, it would be inadvisable to place a vehicle cooled to the ambient −15 °C back into the water, given the potential for subsequent ice formation, for instance on the directional control fins. To keep the hole ice-free during operations, a ducted fan was mounted in the roof of the hut, blowing warm air from the roof through a 10 cm diameter flexible conduit to just above the water surface in the hole. This was largely successful, though approximately 1 cm of ice did still form on the hole overnight which required clearing every morning, due largely to an imperfectly-sealed gap between the operations hut and the ice.

Mission profiles were created and uploaded remotely through the programming interface via the WiFi link with the vehicle. The significant draft of the ice floe (1.6 m) meant that the surface launch technique used at Pavilion Lake was not appropriate and the depth-triggered release technique was used exclusively. The vehicle then began the mission, diving to its target depth (usually 20 m) while performing a best approach to the target line. This method proved very successful and easy to use.

Missions terminated at a waypoint beneath the hole at running depth, where the vehicle would then rise. As experience was gained, this waypoint was progressively adjusted in an effort to compensate for the vehicle being under way when reaching the waypoint, allowing it to ‘coast’ forwards to the expected location of the recovery hole.

A 400 m, 2 mm diameter Kevlar line was attached to an eyelet mid-way along the vehicle body, to minimise the effect on the turning and diving capability of the AUV. The line was chosen to be slightly

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negatively buoyant, allowing it to sink away from any possible snags on the ice underside. The line was led back to a spool topside at the deployment hole, which was allowed to run freely during the mission.

Inverting the vehicle was achieved by fixing external lead ballast to the hull. The majority of this (4 kg) was carried on two rails below the GeoSwath™ module with minor weights screwed to pre-tapped holes in the modules, to achieve a submerged positive buoyancy of around 0.5 kg.

4.2.1. Level ice site

Seven runs were performed at the first test site, in level first-year ice. Operations focused on software development for successful under-ice, inverted operation. Many software defaults, though perfectly adequate for the usual open-water mode of operation, caused missions to abort in an under-ice environment.

The relatively level first-year ice was also used to ground-truth the GeoSwath™ drafts, drilling 110 holes on a grid covering the surveyed region at 10 m spacing. Exact matching of drill holes to AUV mapped data is not feasible, thus the cross-correlation function between drilled and sonar-derived drafts was matched, requiring an adjustment of −14 cm (i.e. reduced sonar draft) to bring the two data sources into agreement. This was checked on later runs with respect to a thin, very flat, refrozen lead, with consistent results.

Depth control during these missions demonstrated a similar level of precision to that experienced in the Pavilion Lake trials, namely to within ±5 cm of the depth setpoint. Navigational accuracy was poor, however; the vehicle typically returning to within 20–30 m from the hole having executed a 200 m out-and-return pattern. The DVL system failed to achieve a consistent ‘lock’ on the ice (very few velocities of the vehicle with respect to the ice were obtained) and thus did not constrain the INS's normal position drift to any appreciable degree. The failure of one of the four DVL beams probably exacerbated this problem. The INS itself did not perform as well as expected, showing considerable position drift until forced to assimilate a constant GPS position (input via WiFi). This was subsequently ascribed to a faulty accelerometer in the unit, following its return to the manufacturers for repair. Navigation quality therefore was not sufficient to enable overlapping swaths to be co-located without recourse to manual alignment (rotation and translation) during post-processing, performed in the Matlab environment.

Missions became more ambitious until the vehicle became lodged in a ridge 354 m from the hole. The vehicle had continued to pull tether line beyond expectations during the mission (subsequently attributed to operator error in programming a waypoint) and was therefore held on the line until the mission aborted (expected position exceeded a threshold error from actual position). The vehicle then floated up to rest in the ridge and could not be pulled back to the hole. Range was determined using both the LXT transponder and the vehicle's onboard acoustic modem. This mode of communication was used to determine the vehicle depth (7 m) and pitch (20° down), though commanding the propeller using the modem was unsuccessful in freeing the vehicle. It was freed by tying a 2.5 kg weight onto the end of the line, then adding a further 300 m of line. This had the effect of pulling the line and vehicle downwards and free of the ridge, allowing the vehicle to be pulled back to the hole along the bottom of the ice without further incident, happily avoiding having to employ the diving team.

4.2.2. Ridge site

Operations were then moved to the main site of interest—the recently-formed ridge. A similarly-sized hole had been previously prepared, and the ridge profile had been investigated by APL divers, who reported a maximum draft of 8 m.

The LBL system was tested at this site, to determine whether the problems observed during the Pavilion Lake deployment had resulted from reflections from the nearby lake bed and shore. The LBL system was intended to provide a moving frame of reference as required for operations in drifting ice. LinkQuest™ UWM2000H transponders were lowered through holes in the ice to a depth of 15 m. Separation between transponders was 620 m and they were 311 m and 356 m from the deployment hole. The base line was perpendicular to the ridge, chosen so the vehicle could not cross the line during any planned mission: with only two transponders, the position solution is not unique, but mirrored across the baseline.

Though reliable positions were obtained in the hole every 7–8 s, solutions during missions were intermittent and of poor quality, causing large jumps in the calculated position. The transponders were then lowered to 35 m, to be well clear of any possible acoustic obstructions (e.g. ice keels), but no improvement was seen. This failure was attributed to multi-path reflections from the ice. From these two studies, it was initially concluded that the problem was not related to the topography, since the very flat ice of Pavilion Lake caused similar problems. A lower-frequency system would probably be beneficial for under-ice work although the physical size of the larger sonar transponder in such a small vehicle would be problematic. Navigation by the LBL system was then abandoned and the INS/DVL system was used for the remainder of the operations.

A pattern of runs were then performed to cover the region of interest, initially spaced at 60° around a complete circle, then interleaved at 30° offset. Twenty one runs were performed in the remaining 2 days of the camp.

Fig. 3 shows an underwater photograph, taken by University of Washington divers, illustrating the steepness of the ridge face and the character of the blocks (size, orientation) making up the ridge. Fig. 4 shows a short extract of sonar draft data from the same feature. Several interesting features are apparent in the swath. The structure of the main ridge is clear, with the blocky topography apparently reproduced satisfactorily, even given the very difficult acoustic environment that the terrain represents. Acoustic shadowing is evident in the bottom-right-most section of the ridge, where the angle of the topography prevents the sonar illuminating the far side of the feature. The ridge is surrounded by FY ice (modal draft 1.60 m). A thinner, re-frozen lead (modal draft 0.48 m) can be seen bottom-centre of the swath, with a narrow crack and a detached piece of FY ice embedded within it. This crack was also evident on the surface, and was measured (manually) to be around 20 cm wide, giving an idea of the feature size resolution available with the GeoSwath system: though the feature is sub-bin-scale, its contribution to the draft statistics will reduce the weighted mean value for that bin. The centreline of the swath is indicated by a line of disrupted drafts, a result of the data density at zenith as previously discussed (see § 3).

Fig. 3. Diver photograph showing the steepness and blocksize of the main study ridge at APLIS (Photograph courtesy of Mitch Osborne, University of Washington).

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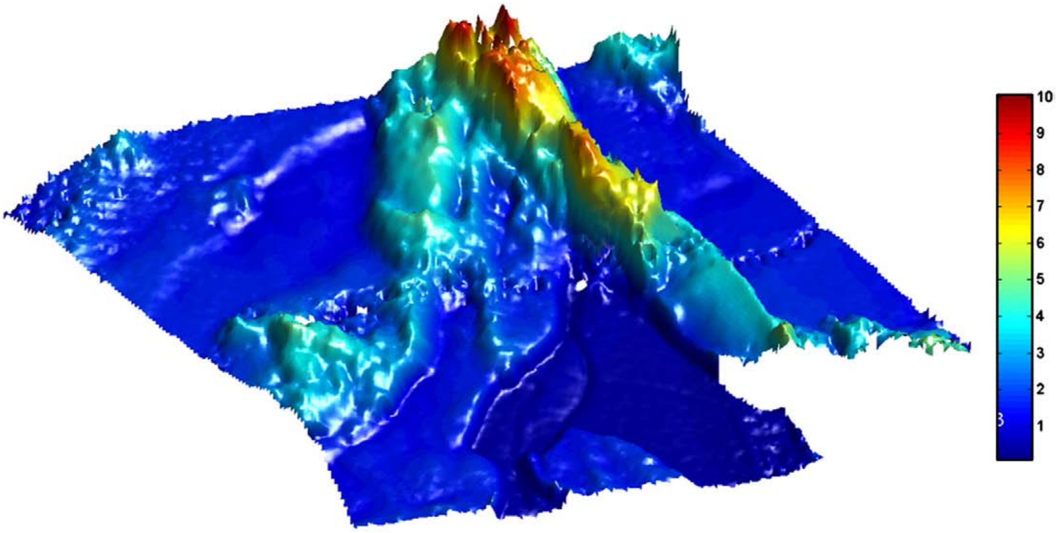

Fig. 4. Sonar swath showing part of the main study ridge at APLIS. Colour scale indicates draft in metres—maximum is 9.75 m in this figure. The vehicle travelled from right-to-left in this image, and was still diving to its operational depth as it passed under the ridge. The swath is 80 m-wide (40 m either side of the centre line) and approximately 100 m long. The AUV was running at 15 m depth, *i.e.* approximately 13 m below the level ice. Bin size in the image is 0.5×0.5 m, with around 20 individual range/angle solutions contributing to each bin in a weighted mean scheme. Vertical exaggeration is two times.

The draft error was investigated in terms of the draft difference between two points (i.e. using all the valid range/angle solutions, rather than binned data) over a small (5×5 m) area, sampling various topographic types. Results are shown in Fig. 5, plotted against the distance between points (separation). Ice from the very flat refrozen lead shows no relation between separation and draft difference, being constant at around 30 cm and suggests that the instrument error for an individual range/angle solution is ±15 cm. Results for the ridge region show a steeply-increasing draft difference with separation, as might be expected from a relatively planar slope. They-intercept (*i.e.* the draft difference between almost co-incident points), where instrument error again dominates, has the same value as measured for the refrozen lead, confirming the instrument error *for an individual range/angle solution* as ±15 cm. The rubble field data (not shown in Fig. 4) shows a higher difference value for neighbouring points than expected from instrumentation error alone, indicating that the variation in draft of neighbouring points for such features dominates the noise floor of the unit, being in this case around 55 cm. This is consistent with the rough and chaotic topography there. Choosing a bin size of 0.5×0.5 m results in around 20 values contributing to each bin, which reduces the error in a single bin value by a factor of $\sqrt{20}$ (*i.e.* ±3 cm for binned values), which is an acceptable value for the purposes of this study.

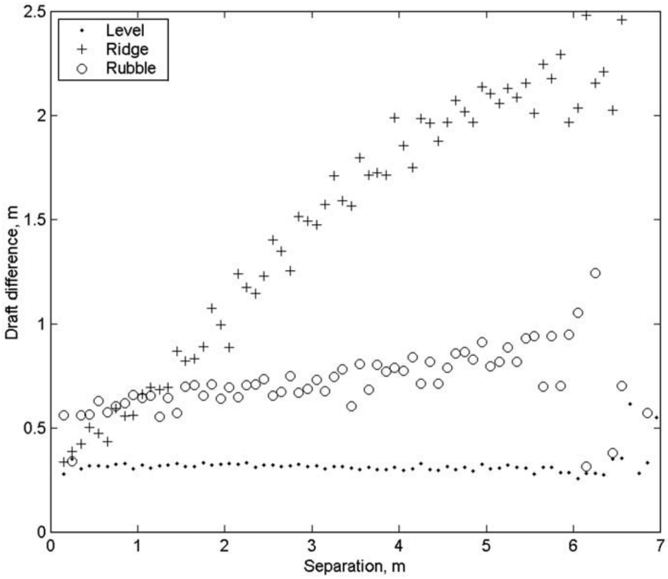

Fig. 5. The draft difference between points of varying horizontal separation, for three 5×5 m areas within one swath. The analysis uses all valid range-angle solutions, i.e. unbinned data. Sub-samples are chosen to cover (◆) level FY ice; (+) the slope of a FY ice keel and (○) a FY ice rubble field.

The example illustrates the fact that bin dimensions should be optimised for the ice type expected. If the ice to be surveyed were very flat and a very accurate estimate of draft was required, the bin size can be increased to produce the precision required. Conversely, if the ice is very rough, then little is gained by having larger bins, and higher *xy* resolution can be achieved without detriment to the precision of measured draft.

The standard error of the mean (SEM) is also used to determine the reliability of data within a bin (Hiller and Hogarth, 2005). This is given by the square root of the variance of the binned values, divided by the square root of the number of samples. For the bins in the three areas mentioned above, the mean SEMs over the 100 bins making up the 5×5 m region were 3.3, 9.1 and 12.7 cm, respectively. The role of the divisor is important in determining these figures however-due to the varying success of the GeoSwath in obtaining valid range/angle solutions in the areas, average bin populations varied between 25 (refrozen lead) and 7 (rubble field).

4.3. Pavilion 2008

On 15–24 February 2008, *UBC-Gavia* was deployed at the same approximate location in Pavilion Lake as the previous winter season. In the same approach taken in the previous two deployments, a 3×1 m hole was cut through the relatively uniform ice cover (thickness around 50 cm) using a combination of chainsaw and ice drill.

Engineering objectives included: (1) homing to an acoustic beacon and net recovery of the vehicle; (2) refinement of the LBL navigation system; (3) refining deployment techniques from the ice hole; and (4) locating and recovering the vehicle from a remote site from the deployment hole. INS and GeoSwath™ modules were unavailable for this deployment, as they had been committed to other projects.

The strategy used for acoustic homing was a development of the fallback missions introduced in 2007. Once the mission objectives were completed, the fallback mission called for the vehicle to target the

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LinkQuest™ UWM2000H transponder, lowered into the recovery hole for that purpose. A simple range-based scheme was used, dictated by the single transponder on-board the vehicle which precluded assessment of the bearing to the recovery hole. The vehicle ran at a specified depth in a straight line, interrogating the in-hole transponder for range. If that range increased from the previous fix (a 15 s refresh rate), the vehicle would turn by a user-specified angle and continue along the new trajectory. Also introduced was a timeout that, if the target were not achieved in a specified amount of time, this fallback mission would also be aborted leaving the vehicle to rise to the surface.

Initial runs turned out to be quite unsatisfactory, as the vehicle would tend to overshoot the target and then continue to wander around the hole at a considerable distance. A number of trials were conducted varying turn angles, vehicle speed and refresh rate before the optimum settings were found. These were a 120° turn angle, 1.2 m s^{-1} vehicle speed and 6 s refresh rate. The vehicle would then reliably return to a net (2×6 m) moored at the deployment hole, within 3.5 min of mission completion approximately 400 m away. Although further development is required, this technique promises to be highly effective for further under-ice work.

Further testing of the LBL navigation system was then conducted with no acoustic homing programmed for the missions. The transponders were lowered to a depth of 20 m at a distance of 209 and 212 m from the hole. As at APLIS, the baseline was established to be perpendicular to the planned missions. The shorter baseline was designed to improve the system's performance. Configuration files were changed for these runs to ensure that the vehicle only interrogated the LBL transponders (and not the acoustic modem). Finally the refresh time was left at 6 s from the homing experiments.

These changes resulted in dramatically improved navigational performance, only generating one or two erroneous fixes/600 m of operation. These bad fixes caused the vehicle to deviate from the correct track, though the planned line was regained once a subsequent correct fix was obtained. A final software refinement to reject non-physical jumps in position is required. Once demonstrated, the vehicle was able to perform six missions between 1 and 2 h duration, returning to within 10 m of the recovery point on each occasion. A final, 5 h mission demonstrated the same proficiency. Used in conjunction with an INS, this system has the potential to allow untethered operations in drifting ice.

An alternative method of launching missions was next trialled, releasing the vehicle from the line with acoustic communications. This procedure involved lowering the vehicle on a weighted line with a releasable shackle. The mission would then be executed through the acoustic communications link and the motion of vehicle would release the line. For these tests, the on-board acoustic modem was configured to only interrogate the in-hole acoustic transceiver and not the LBL transponders as it had in the previous experiments. Tests were hampered by poor high-frequency communications with the vehicle (sending commands), however, despite having successful low-frequency communications (ranging). This was attributed to the control software and is undergoing continued investigation.

4.4. Alert 2008

The most recent deployment took place from an ice camp on fast ice just north of Canadian Forces Station Alert, on Canada's Ellesmere Island (82° 33.01′N, 62° 34.42′W), at the beginning of May 2008, this time using the *UBC-Gavia* vehicle and renting the INS/GeoSwath combination from Hafmynd. In contrast to the relatively elaborate facilities at APLIS, the camp was pared to the minimum required to work in safety and comfort, namely a heated working tent (a Weatherhaven 12′×20′ tunnel tent) and one sleeping tent for three persons. A 3×1 m hole was made with a hot water drill, as before, though this time using a 1 m long straight cutter, dividing the ice into blocks before removing them with skidoo and an A-frame (see Verrall (2001) for this technique).

The camp was deployed from the shore by skidoo, since attempts to land on the floe by Twin Otter were unsuccessful due to the roughness of the sastrugi. Three aircraft loads would have been sufficient. The camp was situated on a large undeformed pan of first-year ice, 1.6 m thick, adjacent to a large multi-year floe. Deformed ice, characterised by large isolated ice blocks–presumably formed when the MY floe collided with the fast ice–constituted the interface between the two ice types. Apart from simplifying logistics, the fast nature of the ice allowed easy co-registration of AUV, *in situ* and airborne measurements. A series of calibration lines were set out across the area with ground-truth holes drilled at 5 m intervals, measuring draft, freeboard and snow thickness. These served to validate the AUV draft measurements, as well as overflights by HEM, laser and, for the first time, airborne ASIRAS radar instruments, as part of the EU DAMOCLES project and the European Space Agency CRYOVEX programme.

Operations at the camp lasted less than a week, dictated by a combination of access to Alert and aircraft availability. An extensive development programme was therefore precluded and gathering the science data was the priority. Additionally, the rental agreement for the INS and GeoSwath units required the vehicle to be operated on a tether, as before. Valuable experience was gained at high latitude, however.

Foremost among concerns for this deployment was the performance of the INS at such high latitudes. Initial alignment of the INS is achieved by conducting either a moving base alignment (fixed error) or a stationary alignment (fixed time). Standard operating protocol for *Gavia* is to perform the moving base alignment. Position drift was high (~20 m min^{-1}) once the alignment was complete, however, and appeared to be randomly oriented. A stationary alignment, with an increased alignment time, gave better results with initially minimal drift. Drift after even a very short, tethered, mission was similar to that seen with the moving base alignment, however. No DVL lock was obtained and this was later traced to a broken connection inside the RDI unit. Reviewing the navigation logs, the system appeared to perform well for the first 2–3 min of a run before significant position jumps and drift began to occur. It was therefore necessary to perform a new alignment after every mission and this slowed down operations considerably. The position jumps only occurred when the GeoSwath module was connected, however, pointing to some mis-interaction between the two units rather than a fault in the INS itself. A total of 24 missions were run during the period—16 with the GeoSwath sonar, four with a Seabird CTD fitted and four with an externally mounted hyperspectral radiometer to examine the horizontal variation of transmitted light intensity beneath sea ice.

It had been intended to test the LBL and homing system in conjunction with the INS, following the successful developments with the stand-alone acoustic system at Pavilion Lake earlier in the year. The time-consuming nature of the repeated INS alignments and other problems did not allow sufficient time for these tests, however, and these will be pursued at the next opportunity.

5. Future developments

The primary objective for future deployments is to allow the vehicle to run untethered at very high latitude, restoring its autonomy. Apart from the terms of rental agreements, the main factors preventing untethered, longer-range, deployments are navigation and reliability issues. The small physical size of *Gavia* precludes the mounting of the low-frequency acoustic transceivers which would considerably aid under-ice operations, either for the DVL, LBL or acoustic communications paths. The experience in Pavilion 2008 suggests that these problems are not insurmountable, however, given adequate development of position filtering algorithms to reject non-physical position jumps.

Once the vehicle is adequately navigated within an acoustic array, the issues of reliability—aborting a mission and being unable to successfully

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return to the hole become more tractable. The GeoSwath unit presents particular problems in this regard, since the considerable overhead on *Gavia's* main CPU occasionally generates spurious errors, causing missions to abort unexpectedly, and is a possible cause of the navigation position jumps. The INS/DVL combination has had faults on both Arctic deployments, limiting evaluation of its performance at high latitude.

Our experience has shown that a running depth of 20–25 m is best for the GeoSwath system, allowing the vehicle to avoid most ice features while retaining a reasonable insonification of the ice undersurface. The vehicle did pass very close to the bottom of the deepest ice keels, however, and a considerable degree of acoustic shadowing was therefore observed. Since the collision-avoidance sonar was disabled (to avoid false triggering on rising to the surface), the AUV also risks impacting deeper keels at running speeds. It would therefore be advantageous to implement a 'terrain following' path, where the vehicle follows deep topography downwards, maintaining a constant clearance. *Gavia* is able to dive at around 30° down, which is sufficient for many ice keels. The very steep face seen in the APLIS study appears to be quite unusual. A submarine sonar study of 729 keels showed that 90% had slope angles in the range 8° to 36°, with a mode of 18° and a mean of 23° (Davis and Wadhams, 1995). Terrain following is already implemented for following seafloor features, so this should not require significant effort in software terms.

The small diameter of the *Gavia* vehicle (40 cm from the top of communications tower to the bottom of the hull) in principle allows its deployment vertically through a much smaller hole than employed to date, further simplifying the logistics required to operate in a 100% ice cover. Such a method does complicate mission set-up (ballasting) and recovery, however, and further experience is necessary before this is implemented.

6. Conclusions

A small AUV coupled with a swath sonar system has great potential to enhance our understanding of under-ice topography in areas where it is impractical to deploy large, ship-based vehicles. The most recent deployment has demonstrated that such a system can be successfully deployed using minimal logistical effort. The very compact GeoSwath and Kearfott instruments allow accurate characterisation of ice features in a man-handleable package, though navigation challenges related to high latitude operations and the high-frequency acoustic devices dictated by such a small vehicle, remain.

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