Surveying the underside of an Arctic ice ridge using a man-portable AUV

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In April 2007 a man-portable Gavia underwater vehicle was deployed to perform high-resolution bathymetric surveys of the underside of the Arctic ice cap at the SEDNA ice camp in the Beaufort Sea. Deployment and recovery was through a single hole in the steadily drifting ice cap. The vehicle was flown inverted for optimum use of its normally down-facing payload sensors, which included the GeoSwath 500 swath bathymetry sonar providing co-registered high-resolution swath bathymetry and sidescan sonar imagery, and a high-frame rate digital camera simultaneously providing a continuous photographic survey. Navigation was by an inertial navigation system aided by Doppler velocity log tracking the underside of the ice sheet, thereby referring both vehicle navigation and scientific data to the moving ice cap. The resulting data provided a uniquely detailed rendering of the underside of Arctic pressure ridges, which determine navigability of the future Arctic seaways as the ice cap becomes thinner as a result of global warming.

While the use of AUVs in polar ice is not a new technique, most of the previous operations have involved AUVs weighing several hundreds if not thousands of kilograms, which therefore require considerable support infrastructure to allow their deployment and recovery. Some examples of these vehicles are the groundbreaking UARS [1][2] and Autosub [3][4]. While there have been operations with smaller AUVs such as REMUS [5], the data obtained from smaller AUVs is often limited by the physical size of the vessel and the problems of integrating the sensors in such a small volume. The purpose of this paper is to discuss the operational techniques, successes and failures concerning the experimental deployment of a Gavia class AUV carrying an interferometric bathymetry system and inertial navigation system at two under ice locations during the winter of 2006/2007

Introduction to Gavia

The AUV used for this under-ice operation was a Gavia unit produced by Hafmynd. The AUV is of modular construction as shown in Figure 1. Different payload modules can be attached to the basic boat depending on the mission requirements. The modules are all 200mm in diameter (with the exception of the sensors and antennas which pierce the pressure hull) and the boat is typically between 2500 and 2700mm long, depending on the modules attached. The version used for the most recent under-ice operations is rated to 600m, although 2000m versions exist with identical dimensions.

The boat always consists of at least four basic modules: the propulsion module, which contains the propulsion and steering systems; the control module, which contains the main control computers, communications (Iridium, acoustic and WLAN) and basic navigation sensors; the battery module, which provides the power for all the boat systems; and the nose module, which contains the camera and collision avoidance sonar.

For most operations these are supplemented with the inertial navigation (INS) and Doppler velocity log (DVL) module which provides far more accurate navigation and positioning data than that available from the basic sensors in the control unit. For the under ice operations a GeoSwath module built by GeoAcoustics (UK) was added to provide high-quality 3D bathymetric data of the under ice surface. As configured for under ice operations the AUV weighs around 70kg in air and -0.5kg in sea water. While the AUV can run at up to 3m/s, surveying is usually conducted at 2m/s as a compromise between endurance, data densities and mission duration.

To allow the AUV to sail the planned missions and collect the required data at the desired locations, there are certain basic sensors and actuators required. Propulsion and steering is provided by the propulsion module. This contains both the main propulsion motor, and four servos which drive four independent hydrofoil control planes positioned behind the propeller and within the propeller shroud. The control of these effectors is provided by the main control computer via the internal LAN and microcontrollers within each module. The inputs to the controlling 'crew' are provided by various navigation sources and mission requirements. As mentioned previously, the control module provides basic attitude and depth data via a pressure sensor, a fluxgate compass and a three-axis inclinometer. Using these and propeller RPM or velocity vectors if a DVL is fitted, it is possible to calculate the position of the vessel's position by dead reckoning, normally working from an initial GPS fix.

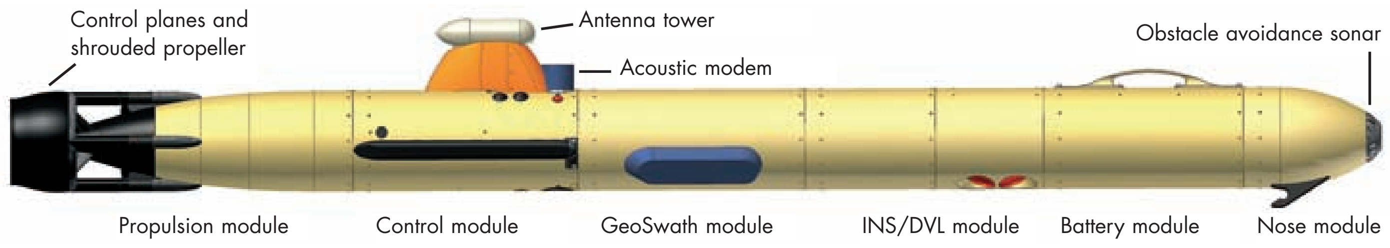

Figure 1. Gavia AUV showing modular construction and key features. The AUV is 2.7m long in this configuration

Figure 2. Views of the typical ice conditions at Pavilion (left) and APLIS07 (right). The ridges seen in the APLIS07 image are typically 1-1.5m high and are above ice keels that run to depths of 8-15m. The huts shown in the image are 2.5m high

However, for most operations the INS/DVL module is used to provide far higher quality navigational data using its own internal laser gyros, accelerometers and 3D velocity data from the DVL. The INS/DVL unit contains a Kearfott (USA) T-24 INS coupled to an RDI (USA) 1200kHz DVL. This module provides positioning data to within tens of centimetres and drift rates in the order of a metre per hour, so when available, this data is used in preference to the dead reckoning data.

When on the surface GPS fixes are fed into the INS to provide a geo-referenced position. Positioning can also be obtained from a TrackLink LBL positioning system, but this system proved problematic when used under ice, possibly due to multipath reflections.

The dive rate and depth control software primarily uses data from the pressure sensor for depth and the pitch, roll and yaw data provided by the inclinometers or the INS gyros to maintain the correct trajectory required by the mission plan. One final sensor in the nose provides some protection from the unknown by providing a forward-looking object avoidance sonar. This can detect an object up to 25m in front of the AUV so avoiding action can be taken, or should the object get too close the AUV can brake to avoid collision. In practice this was not used during the APLIS07 (2007 Applied Physics Laboratory Ice Station) operations as the complex ice keels and blocks under the floes caused false alarms and there was insufficient time to attempt to tune the system to this unusual environment.

For the under ice operations the main sensor is the GeoSwath bathymetry module, produced by GeoAcoustics. This is a special unit built to fit on a Gavia series AUV, but functionally is very similar to GeoAcoustics' conventional interferometric GeoSwath units used worldwide for shallow-water bathymetry. Operating at 500kHz, this provides a swath width up to 12x the vehicle's altitude; in practice

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the rough surface under the ice resulted in an average swath width of around 60-80m due to shadowing and attenuation. Raw data from the GeoSwath unit was stored on the internal storage until the mission end when it was copied off to be processed offline. The processing of the under ice data initially proved difficult owing to the unique geometry of the data, but modifications to the processing software eased this issue.

The on-board camera was also used to take medium resolution images of the overlying ice at 3.75 frames per second to provide a visual record of the ice surface being surveyed. The AUV used also carried a 900kHz/1800kHz sidescan sonar from Marine Sonic (USA) which was also tested under the ice but the data was not required for scientific uses.

Operational areas and conditions

Under ice operations were conducted at two locations. The initial system tests were performed at Pavilion Lake, British Columbia, Canada, (50°52'N, 121°44'W) from the 17-25 January 2007. These tests were performed at facilities provided by the University of British Columbia and as part of the university's limnology studies [6]. The Pavilion site was ideal for testing and experimentation with good communications, support equipment and dedicated staff. This allowed considerable development work to be done on site. The weather was benign during the operational period, so no shelter was necessary over the access hole – a tent was provided as a shelter next to the hole for the personnel. A period of warm weather towards the end of operations led to surface melting of the ice, making moving around difficult.

The main operation was conducted at the APLIS07 site between 4-13 April 2007 [7]. During this period APLIS07 was located 190 miles (306 kilometres) north of Prudhoe Bay, Alaska. The site was set up by the University of Washington Applied Physics Laboratory (APL-UW), USA, for naval operations and was released for US National Science Foundation (NSF) use at the beginning of April 2007. The site consisted of a small 'village' of plywood huts and tents constructed on a multi-year ice floe with an adjacent airstrip on a first year floe. Two sets of holes were melted with a 1m hot water drill to provide a 1m x 3m slot large enough to deploy the AUV horizontally. As the site was on floating ice floes the camp location was not fixed and drift rates of several kilometres per day were not uncommon.

At the APLIS07 site the air temperature was always below freezing, so a heated hut over the hole provided shelter for the equipment and personnel during operations. The oil fired heater proved very effective, but the heat loss through the ice and under the hut walls led to ice formation in the access hole, and ice formation on any wet equipment close to the floor, such as the spooled tether. To reduce this problem a ducted fan was used to redirect warm air from the hut ceiling towards the hole which helped reduce the icing rate. However, it was still necessary to ensure all equipment was kept high enough to prevent freezing, and that the AUV was warm enough to prevent ice formation on the sensors and control surfaces when deployed. At the beginning of each new day around 1cm of ice had to be removed from the hole, and during the day ice crystals had to be removed to maintain good visibility through the hole.

The initial test location at Pavilion Lake provided smooth clear ice around 40cm-50cm thick with no significant under ice features, as can be seen in Figure 2. The clarity of the ice meant that the AUV could be located by searching for its navigation lights should it fail to return to the access hole. The relatively thin, pure ice was also found to be less conductive than anticipated, and therefore it was possible to use the WLAN communications through the ice when the antenna tower was in contact with the lower surface of the ice, and the 457kHz avalanche transmitter attached to the AUV could be received reliably over a range of at least 30m.

In contrast, the ice conditions at APLIS07 consisted of floes ranging from 1.5m-2.9m thick and compression ridges extending to depths down to 15m. The upper surface of the ice was covered with 10cm-20cm of snow. This meant that location and recovery of the AUV in the event of a loss would be complicated and time consuming, even if the avalanche transceiver operated over a similar range to that seen in Pavilion. In light of the difficulties with reliably navigating to the access hole seen during tests at Pavilion, and the possible lost time should a recovery be necessary it was decided to run the AUV on a Kevlar tether until confidence in the navigation and return was high enough to merit its removal.

Prelaunch and launch

Once the AUV is powered up the INS module needs to be aligned so as to provide reliable navigation data. This process can normally be done in two ways, either a static or a moving baseline alignment. Both require an initial position fix, normally provided by the GPS receiver. The static alignment process does not need subsequent fixes, but the INS needs to be at a fixed location during the 20-minute alignment process. A moving alignment requires regular position updates as the alignment process proceeds, but does not need the AUV to be stationary.

At the Pavilion location both alignment processes could be used either on or off the ice, but the drift rates at APLIS07 limited the alignment process to moving base alignment. It was decided at APLIS07 to attempt to reference all runs to the location of the access holes, as this simplifies both data processing and mission planning. To do this the GPS position was 'fixed' after alignment by turning the GPS receiver off and sending regular fixes via the control software obtained from the hole prior to the first operation. This allowed the INS position to always be referenced to the access hole, whilst any rotation of the floe was compensated for by the heading information found during the alignment process and tracked by the INS.

A mission on the Gavia AUV comprises a set of lines or points with various properties. A line is composed of two points and a mission is built up by adding lines and points to define the mission path and sensor deployments. For any given point its location is defined as a three dimensional position (lat, long and depth). The AUV speed required is also defined, along with the sensors required and their settings for this mission section. This allows the control of the sensors on a line-by-line basis to allow fine control of data and power management. The mission is planned on the GUI and uploaded to the AUV prior to deployment.

For the under ice operations some additional mission parameters were added. To allow for releasing the AUV under the ice surface the mission start could be triggered by depth sensing. This allows the setting of arming and trigger depths so that the AUV can be lowered to below an arming depth, then when released it will float up, arming at the arming depth before triggering the mission at the trigger depth. Despite the inversion of the AUV the mission planning process was identical to that for a non-inverted mission as the AUV control software uses the vehicle attitude when calculating the required control plane motion, so an inversion of the AUV inverts the control actions.

In practice, as the AUV was attached to a tether for the APLIS07 missions the planned missions were usually composed of two lines, one running away from the hole followed by a near parallel return line. After some initial problems with line snagging the return line was set to a depth of 25m to try and avoid further problems. A typical mission track and depth profile are shown in Figure 3. Looped missions were also attempted with the AUV running out to the maximum allowable range

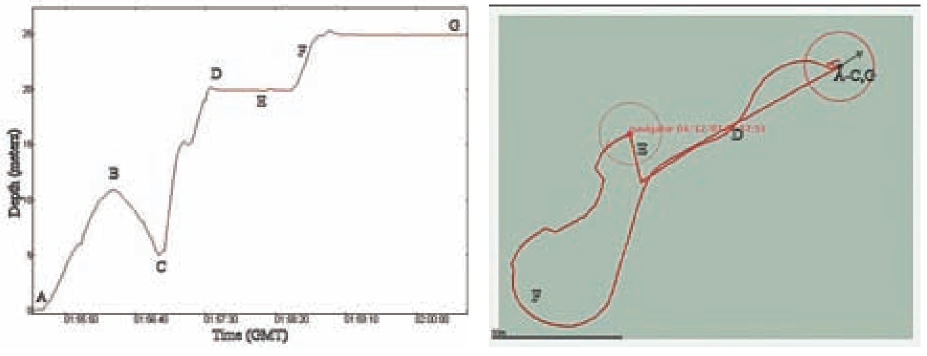

Figure 3. Dive depth profile and vehicle track during an INS/DVL alignment run. The letters are detailed in the main text. They refer to: A - deployment; B - release; C - mission start; D - outward line at 20m; E - DVL velocity accepted; F - turn and dive to 25m; and G - mission end

followed by a return to a similar range in the opposite heading from the hole, then a return to the hole, but this mission type proved to be particularly prone to problems with line handling, therefore most missions were out and back.

At both the Pavilion and APLIS07 sites the deployments were intended to be through holes approximately 3m x 1m, which allowed the AUV to be deployed horizontally. However, one of the holes at APLIS07 was only 2m long resulting in a diagonal deployment. Once the setup and configuration phase was completed the AUV was moved from its carrying frame to the hole and placed in the water. The AUV can be lifted and carried by two to four people. For the insertion into the hole it was suspended between two slings to allow easy handling.

Final system checks were performed once the AUV was in the hole. These tested the correct operation of the control and propulsion systems, the communication links and the mission payload sensors. Once these tests were completed the mission could be started if a depth start was planned and the release line and tether were attached. The AUV was then allowed to rotate to its inverted position. As the AUV was ballasted to float with 0.5kg uplift in seawater it floated on the surface until the release line was deployed or the mission was started. This stage is seen as point A in Figure 3.

During the testing at Pavilion two launch methods were tested, a surface start and a depth release. The surface start allowed the mission to be started with the propulsion module held out of the water and the antenna tower exposed. Once the mission start command was issued the propeller would spin and the AUV could be rotated to an inverted position then slid into the water with a pitch sufficient to clear the bottom edge of the ice in the hole. This had the advantage of ensuring that a false start was seen immediately, and therefore little time would be lost before the next attempt. However, this launch technique would cause the AUV to dive at a steeper angle than the trajectory calculated in the control software. The control software would attempt to return to the calculated dive trajectory, which would often lead to an overshoot and possible contact with the lower ice surface. The additional ice thickness at the APLIS07 site ruled out this launch technique, as the initial dive angle would have been excessive.

The second launch method was to lower the AUV well below the ice surface with a weighted line, and then use a depth triggered mission start. In this method a release line was attached to a 2kg clump weight which was sufficiently heavy to carry the AUV down to the desired depth. Above this weight a snap shackle was attached to a ring mounted below the centre of flotation of the AUV. From this shackle two lines ran to the surface, one to carry the weight of the AUV and release weight, the other to the release pin in the shackle. The AUV was lowered to the required depth using a measured length of line. Once the AUV had been lowered to below the arming depth it was released by pulling the release line, releasing the AUV (see point B in Figure 3). Once free the AUV would rise slowly towards the surface, first passing the arming depth and then starting the motors and beginning the mission at the trigger depth (see point C, Figure 3). This mission start method proved to be effective although there were a few start failures when the AUV was not lowered sufficiently to pass the arming depth.

Mission phase

During normal AUV operation with the INS/DVL module the velocity vectors' output from the DVL are input to the INS to correct for possible accelerometer offsets not fully set during the alignment process. With under ice operations working from moving ice floes, as found at APLIS07, these initial offsets found from the alignment process will match the movement of the floe in a georeferenced frame. However, once under the ice the velocity vectors are referenced to the floe itself and therefore will not match the offsets produced from the initial alignment process. To adjust the INS offsets so the positioning is floe-referenced, it was necessary to perform a dummy run lasting a few minutes before data collection was started. This time was needed for sufficient velocity data to be collected to satisfy the Kalman filter within the INS. Once these new offsets were in use in the INS, positioning and velocity data would be referenced to the ice floe and it was expected that the AUV would return to the planned mission end point.

If the DVL lost its lock on the lower surface of the ice during a mission, normally due to operating outside the maximum or minimum operating ranges of the DVL, the INS position accuracy would begin to degrade due to the drift rate of the INS. In practice this meant that the positioning quality provided by the INS/DVL unit would become too poor to use for safe navigation and swath integration after a few minutes without DVL data. When DVL data returned the INS would back-propagate the errors resulting in an apparent positional jump as the system calculated a new positional fix. This can be seen clearly at point E in Figure 3.

Normally the GeoSwath module data collection is controlled by the mission plan, so data is typically only collected on planned survey lines and not on turns or transits between lines. During the under ice runs it was decided to run the module manually to ensure maximum data collection on the short missions executed, and to allow the system operation to be checked prior to deployment. The data collected by the GeoSwath is stored on an internal hard disk for later downloading and processing, an example of a processed swath is shown in Figure 4. The camera system was also set to collect data continuously from deployment onwards to ensure maximum data. Each image obtained contains a comment field which details the vehicle position, attitude and configuration. A typical image collected on a return run to the hole is seen in Figure 5.

The obstacle avoidance sonar proved to be overly sensitive in the complex under ice conditions in APLIS07 so this data was not used for boat navigation under the ice. There were also concerns with the braking action of the AUV causing the tether to be drawn into the propeller. With the data obtained from the APLIS07 operations it is hoped to develop more suitable algorithms to handle this environment.

The tether used for the APLIS07

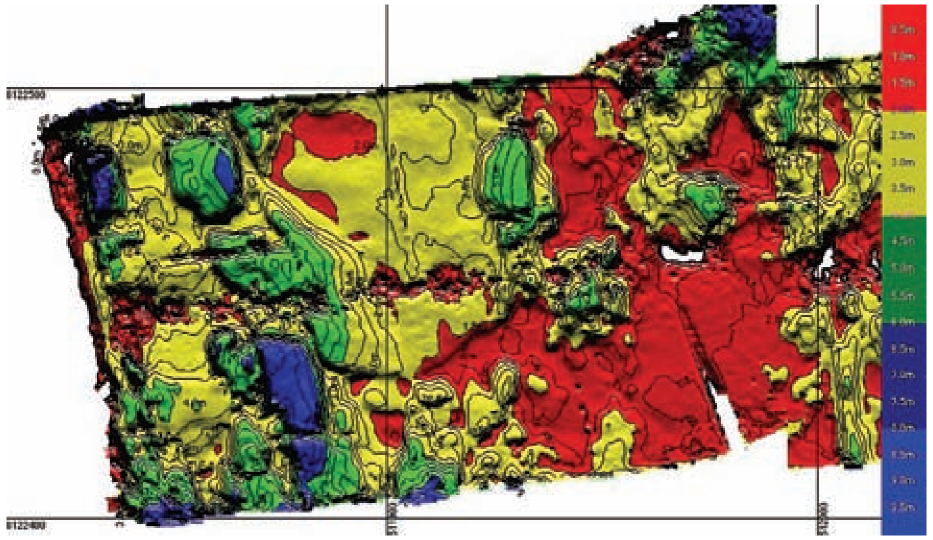

Figure 4. A section of a single swath from the GeoSwath module showing first year ice (red) between areas of multiyear ice (yellow) and ridging (green and blue). The grid lines are 100m apart and the contours are at 0.5m intervals

missions was composed of 400m of 2mm Kevlar line. This was chosen for its strength and its closeness to neutral buoyancy in seawater due to the trapping of small air bubbles when the line entered the water. The line was spooled such that it could run freely as the AUV ran, and gathered back in as it became slack on the return run. Despite this the AUV normally returned to the hole with many metres of line still in the water, partly due to the limited speed the line could be wound in, and so as not to disturb the mission path and risk snagging the line on projections. The line was attached as close as practical to the centre of mass of the AUV to minimise its effect on the planned mission. Unless the line was kept above freezing there were problems with ice formation on the line spool leading to difficulties in line payout. This was solved by keeping the line spool close to the hut roof.

Recovery and rescue

Missions both in Pavilion and APLIS07 were normally planned so that the mission end point was at the original access hole, to allow for recovery. The original intention was to trial a recovery net system, but various issues prevented the testing of this system at Pavilion and it was not required at APLIS07 with the tether system. As the AUV glides on for some distance ballistically after the propulsion stops, some tuning was needed to find the correct distance from the hole to allow for the AUV to come to a standstill at the hole. Currents under the ice further complicated this situation, particularly as this depended on the floe motion at that time. As a result of these effects, while the AUV did correctly return to the hole on several of its missions, it often came to rest under the ice some distance from the hole after floating up from its return leg depth.

For many of the missions it was necessary to pull the AUV back to the access hole to some extent. When the return point was very close to the hole, much of this was taking in slack in the tether, followed by gently pulling the AUV to the hole and rotating it to fit back through the slot. In the case of an aborted mission it was also necessary to pull the AUV back. During an early run at APLIS07 the AUV became stuck behind an obstacle under the ice when 350m from the access hole. An additional weight and 300m of line was attached which successfully pulled the AUV down and away from the obstruction and allowed recovery.

During the tests in Pavilion a SeaBotix (USA) LBV ROV was provided by Roper Resources of Victoria, British Columbia. This allowed the recovery of the AUV from the mission end points, and prompted the purchase of an AC-CESS (UK) ROV to be used at APLIS07 (however, due to delivery and shipping issues this did not arrive until the last day of operations). Divers were also operating at both locations and were willing to assist in the recovery of the AUV if required. The time required to prepare for this type of recovery meant that this option was not feasible as a standard operational procedure and it was held in reserve in case all other recovery methods failed. A Trackpoint LXT system was also generously loaned by Russ Light of APL-UW which provided a useful check on the AUV location, and would have proved invaluable in the event of losing contact with the AUV. Additionally the AUV was fitted with a 37kHz acoustic pinger and a modified avalanche transmitter on 457kHz to allow location from the surface.

Conclusions and some lessons learnt

During the initial planning for the APLIS07 operation it was hoped to operate untethered over an area limited only by the acoustic modem range (typically 1km in open water). In light of the tests and missions conducted at Pavilion, the uncertainties of the APLIS07 location and the limited time available for further changes and tests to the AUV, it was decided to operate with a tether until we were satisfied we could operate safely without. Despite improvements to the AUV operation and configuration both before and at APLIS07 it was never considered wise to run untethered. This was due to various reasons. Firstly the navigation quality was not completely reliable, due to both the differing reference frames of the ice and the georeferenced INS initial alignment, and the high drift rates seen when DVL velocities were not available. It was discovered after returning from the APLIS operation that the INS was damaged, and this damage may have been the cause of these high drift rates.

A second limitation on the operational safety was the feasibility of possible recovery in the case of the AUV becoming lost. This would involve three distinct stages: location; access; and recovery – all of which were potentially problematic. The location of the AUV should have proved possible assuming the search area was not excessive, as there were various independent acoustic and radio beacons attached for this purpose. However the time and manpower involved would have greatly reduced the available data collection time.

Access for divers or the ROV would have involved moving the 1m ice drilling equipment to the assumed location, and the drilling of one or two access holes (the divers would need a safety hole). Estimates for the time taken to do this were in the order of days, depending on the distance and terrain to be crossed and drilled. This would also have involved

Figure 5. A large ice block (about 18m x 6m), imaged from a depth of 25m by the on board camera

personnel involved in other science tasks. The recovery time would be partly dependent on the accuracy of the location procedure, the divers were limited to a single dive per day, and dive setup time was in the order of a day. ROV recovery would have proved much faster, but the ROV was not available for most of the operation.

Running tethered limited the range of missions to a maximum of 400m from the hole, but offered good data productivity. Considering the time spent solving other operational, processing and logistical issues at APLIS07 this seems to have been a good compromise, and the results produced so far [6] [7] seem to support this. Despite the limited range, very detailed coverage of areas of ice ridging were surveyed with unparalled accuracy and detail using a new tool offering access to hitherto virtually inaccessible areas.

Future plans

Work is ongoing on improvement to the under ice operation of the Gavia AUV, with future operations planned for winter 2007/2008 and spring 2008 in northern Canada. A vehicle homing system is being tested to allow the return to a recovery device, both at mission end and in the event of a mission abort. Further research is being done to try and simplify and improve the operation of the INS system at high latitudes and working with moving ice. It is hoped that LBL positioning will also prove to be more useful in providing additional data to the INS system. After the successes of these first under ice operations more time is being made available to test and develop solutions for these somewhat specialist applications.

Acknowledgments

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