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Project Cornerstone

A Landmark Use of High-Endurance AUVs

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DRDC Atlantic

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IMPORTANT INFORMATIVE STATEMENTS

Abstract

Enhanced high-endurance autonomous underwater vehicles (AUV) were developed and demonstrated as a solution to the problem of collecting bathymetric data under ice in the Arctic as part of the data collection for the Canadian submission to the United Nations Convention on the Law of the Sea (UNCLOS). Operations with the AUV were conducted from a freely drifting ice camp that the vehicle had to locate at the end of a three-day mission by using a new and highly successful acoustic homing system. A second acoustic localization system utilizing Benthos telesonar modems allowed the vehicle to determine its own location relative to the ice camp when at ranges less than roughly 4 km. This paper summarizes the development, deployment, and engineering results obtained to date. Bathymetric data collected will be released in the UNCLOS submission.

Résumé

Des véhicules sous-marins autonomes (AUV) améliorés et à haute endurance ont été mis au point et démontrés comme solution au problème de collecte de données bathymétriques sous la glace dans l’Arctique dans le cadre de la collecte de données en vue de la présentation du Canada à la Convention des Nations Unies sur le droit de la mer (UNCLOS). Les opérations avec l’AUV ont été menées à partir d’un camp de glace en dérive libre que le véhicule a dû localiser à la fin d’une mission de trois jours en utilisant un nouveau système de repérage acoustique très efficace. Un second système de localisation acoustique utilisant des modems télésonar de Benthos a permis au véhicule de déterminer sa propre position par rapport au camp de glace à une distance inférieure à environ 4 km. Le présent document résume les résultats obtenus à ce jour sur le plan du développement, du déploiement et de l’ingénierie. Les données bathymétriques recueillies seront publiées dans la présentation à l’UNCLOS.

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Project Cornerstone: A Landmark Use of High-Endurance AUVs

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Abstract

Enhanced high-endurance autonomous under-water vehicles (AUV) were developed and demonstrated as a solution to the problem of collecting bathymetric data under ice in the Arctic as part of the data collection for the Canadian submission to the United Nations Convention on the Law of the Sea (UNCLOS). Operations with the AUV were conducted from a freely drifting ice camp that the vehicle had to locate at the end of a three-day mission by using a new and highly successful acoustic homing system. A second acoustic localization system utilizing Benthos telesonar modems allowed the vehicle to determine its own location relative to the ice camp when at ranges less than roughly 4 km. This paper summarizes the development, deployment, and engineering results obtained to date. Bathymetric data collected will be released in the UNCLOS submission.

1. Introduction

This paper describes the efforts to employ a large high-endurance AUV to accurately map the deep Arctic Ocean bathymetry under ice. The data collected are in support of Canada's claim under the United Nations Convention on the Law of the Sea (UNCLOS).

The objective was to collect bathymetric data in areas that have been challenging locations for helicopters and ice breakers more commonly used in hydrographic surveys of the Arctic. Our first operations were conducted in the spring of 2010 from a freely drifting ice camp where the AUV returned after each mission for data transfer and battery recharging.

The random and unpredictable motion of the camp represented a particular difficulty for the autonomous vehicle and required the development of a new long-range acoustic homing system. A second time-of-flight acoustic system was developed to provide accurate localization of the vehicle at ranges shorter than about 4 km from the ice camp.

The entire project was carried out on a very short time line with a significant risk factor. Despite this situation, the vehicles were developed and successfully demonstrated. Unfortunately we were unable to run as many missions as originally planned in this first deployment due to limitations imposed by the weather and available time remaining on safe ice. The schedule was severely impacted with the result that only one of the two AUVs was actually deployed.

2. UNCLOS

The driving force behind the AUV project was the need to collect bathymetric information in ice covered regions of the Arctic. Bathymetry and other data are to be collected, maps generated, and a claim made to the United Nations in 2013.

Natural Resources Canada (NRCan) partnered with Defence Research and Development Canada (DRDC), and the Department of Fisheries and Oceans (DFO) to find a means of collecting the required bathymetric data in regions where the weather conditions limit the ability to use helicopters and where even ice breakers have had trouble with ice in compression.

Figure 1 is a map of Canada showing the existing 200 nm economic zone as a red line. The possible limit of the extended continental shelf provided by the UNCLOS is denoted by the white line. The particular map projection makes the northern extension appear relatively small in area; however, the extensions in the north and east are expected to have an area of approximately 1.5 million square kilometres.

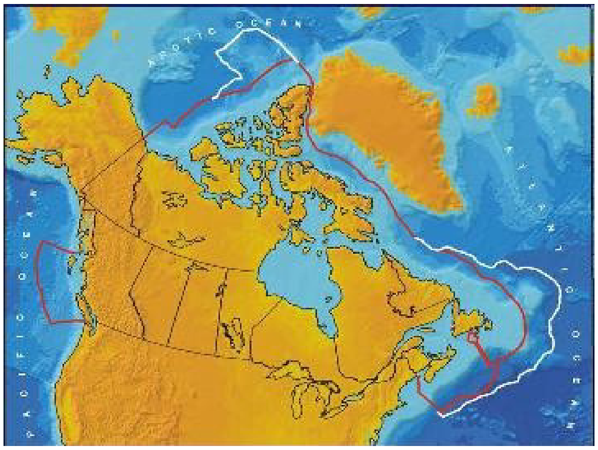

Figure 1. Map of Canada showing the 200-nm economic zone in red and the possible extension of the continental shelf in the east and north in white.

3. ISE Explorer AUVs

International Submarine Engineering (ISE) was selected to be the provider of two Explorer AUVs. The Explorer AUVs were chosen because they already possessed a number of desirable features and ISE has had extensive previous experience in the Arctic with the DRDC Theseus vehicle [1], which is still the largest AUV in the world and the previous holder of records of under-ice operations.

The two vehicles were serial numbers 5 & 6, which was also an important consideration as the four previous vehicles represent considerable experience and knowledge with this class of AUV. The vehicles were named in a contest created for northern schools. The names are Yamoria - the great traveller of the Dene people, and Qaujisati – from the Inuktitut language for one who searches.

The Explorer vehicles are modular, which allows them to be shipped to a work site in pieces that are small enough for transportation in small aircraft. They are also capable of diving to depths of 5000 m, which is required for operations in the Arctic Ocean.

The vehicles required four major additional features to meet the requirements of the proposed usage. These features are:

- Variable buoyancy system,
- Extended vehicle endurance,
- Underwater battery charging, and
- Advanced homing and localization system.

The variable buoyancy system (VBS) was developed by ISE and consists of a rigid spherical tank, pump system, and inflatable rubber bag. The VBS is at present limited to 4000 m due to the use of a valve that could not be cost effectively replaced prior to the first field deployment.

ISE provided the extended range by lengthening the vehicle with an additional module to allow more batteries to be placed within the pressure hull.

ISE also provided the underwater battery charging capability by equipping the vehicles with connectors able to mate underwater and the associated electronics to support the charging and high-speed Ethernet communications.

DRDC undertook the design of the acoustic homing system and localization system. The vehicles' acoustic receiving arrays are currently only certified to 3500 m due to some electronic component failures that were observed at 5000 m equivalent pressure in the present version. The array is currently the limiting depth feature in the vehicles. These acoustic systems are described in the next section of this paper.

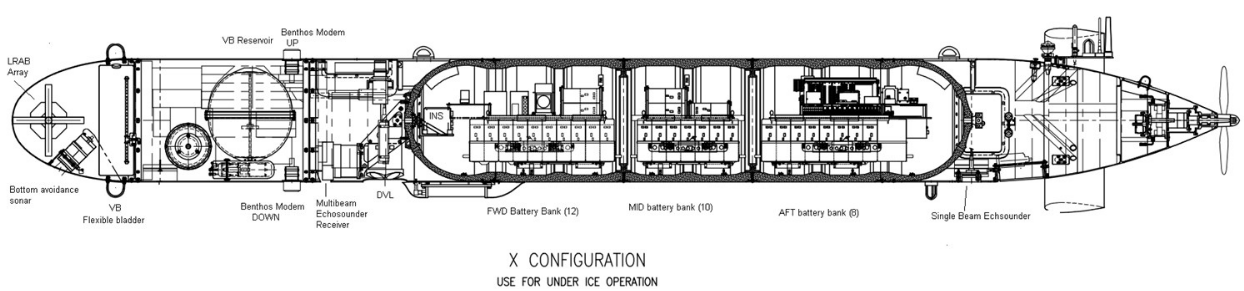

Figure 2. Side outline of the modified ISE Explorer vehicles.

Figure 2 shows the outline of the vehicles. The acoustic homing system is located at the point of the nose cone. The modem transducers are located just aft of the VBS tank.

4. The Acoustic Navigation Systems

Two problems had to be solved to reduce the risk to operations with the AUVs.

The first problem was that the vehicles would be operated from a self-contained ice camp that drifts erratically during the three-day AUV missions. It was determined that the ice camp could potentially drift as much as 20 km/day; therefore, the vehicles had to be able to autonomously locate the camp at a maximum distance of as much as 60 km.

The second problem was that inertial navigation systems are prone to drift when operating without a reference to a fixed object, such as the ocean bottom. Launching the vehicle in deep water provided a perfect opportunity for an unknown drift to occur during the descent to the bottom.

The first problem was solved by creating an acoustic homing system that has been shown to be capable of bringing the vehicle home from a distance of as much as 100 km in the deep ice-covered Arctic Ocean.

The second problem was solved by creating an acoustic localization system based on Benthos telesonar modems. This acoustic localization system, called Short-Range Localization (SRL), provided a way to determine the vehicle's actual position independent of the on-board inertial navigation system. In addition, the localization system potentially provides a way for the AUV to autonomously navigate to within a few metres of the recovery point, but this capability has not yet been demonstrated.

The acoustic navigation system components include:

- A high-power Multi-Mode Pipe Projector (MMPP) acoustic source[2], shown in Fig. 3,
- A digital 7-element acoustic receiving array based on Rapidly Deployable Systems (RDS) technology[3,4] called the Long-Range Acoustic Bearing (LRAB) array (Fig. 4). This array is mounted as far forward as possible in the AUV nose cone,
- A Benthos telesonar modem[5] in the vehicles with two transducers mounted on the top-side and bottom surfaces,
- A field of seven telesonar modems deployed at the centre and circumference of a nominal 1-km radius circle, and
- A small processor and array controller called the Acoustic Homing and Localization System (AHLS or 'Alice').

Figure 3. The Multi-Mode Pipe Projector used to emit the 189 dB//1μPa tone for the homing system.

The MMPP was lowered through a small hole from the ice surface to a depth of 100 m (although capable of operation to depths greater than 300 m). It was used to project a continuous-wave (CW) tone for three days at a time at its lowest resonance of 1367 Hz with a source level of 189 dB//1μPa @ 1 m.

Figure 4. Three LRAB arrays and the AHLS processors.

The LRAB was used to receive the CW tone. Data were collected for 15 seconds after which a spectral analysis was performed to detect the presence of the tone. If it was deemed to be present, the AHLS activated a phase gradient beamforming method, developed at DRDC, to estimate the horizontal and vertical arrival angles of the acoustic energy at the AUV. The horizontal angle is then used to steer the vehicle toward the acoustic source. The vertical angle and vehicle depth provide clues to allow the AUV processor to roughly estimate the range.

The SRL system makes use of ranges between modems to estimate the AUV position. The system works by first collecting ranges and position estimates from associated GPS receivers for each of the seven modems on the surface (1 at centre where camp is located and six on the circumference of the 1-km radius circle). All of the modems are allowed to move independently. This situation actually happens as the ice surface breaks. The surface constellation locations are optimized at intervals to provide the best current estimate of the surface modem locations. This data is periodically manually transmitted to the AUV using the telesonar modems.

When enabled in the pre-defined AUV mission plan, the AUV enters an SRL-mode under the control of the AHLS. The AHLS then sequentially polls each surface modem to determine the range to that modem. Range estimates are time-stamped and stored. Not all modems are reachable every time. Once the vehicle has collected three ranges to surface modems within a given time limit, the vehicle then determines its own depth from an on-board pressure sensor. The depth, the AUV navigation history, and three or more ranges are then used to solve for the position of the AUV relative to the camp and a chosen reference direction.

This position and time is reported to the operators in the regularly transmitted data telemetry packets. Theoretically, the AUV can use this information to navigate precisely to the recovery point; however, this mode has not been tested as of yet.

5. The Field Work

In the spring of 2010 a very large field effort was undertaken by NRCan, DFO, and DRDC. The Polar Continental Shelf Program (PCSP) base in Resolute, NU provided a centre for the field operations. A main field camp was set up on the shore-fast ice in Wilkins Strait on the south side of Borden Island. A second smaller field camp was established on the drifting pack ice approximately 300 km northwest of the main camp. The main camp is referred to as Camp Borden, while the remote camp is called Camp Cornerstone.

Camp Borden enabled the AUV operations as well as more conventional hydrographic data collection with helicopters along with a number of other experimental activities. The camp provided support for up to 50 people at a time. The vehicle was transported to Camp Borden in sections that were assembled in a large tent. The vehicle was tested while tethered at the main ice hole and on a number of increasingly complex and lengthy test missions.

Camp Cornerstone was essentially dedicated to AUV operations. Eleven people operated and maintained the camp that was free to drift on the 2.5-3.5-m thick ice. Camp Cornerstone remained intact throughout the trials period, but the ice around the camp did open up several times with the result that some of the modem nodes experienced significant movement.

6. Results

The weather during the field trial was very inhospitable and resulted in a significant number of delays. In fact, so much delay was experienced in the early part of the trial that only one of the two AUVs was transported to the main camp and assembled. The second AUV remained in storage at Resolute.

Because of the delays and the use of only one AUV there was time for only one transit of the AUV between the main and remote camps, one additional mission to the northwest of the remote camp, and the return transit to the main camp. The tracks of these missions are shown in Fig. 5.

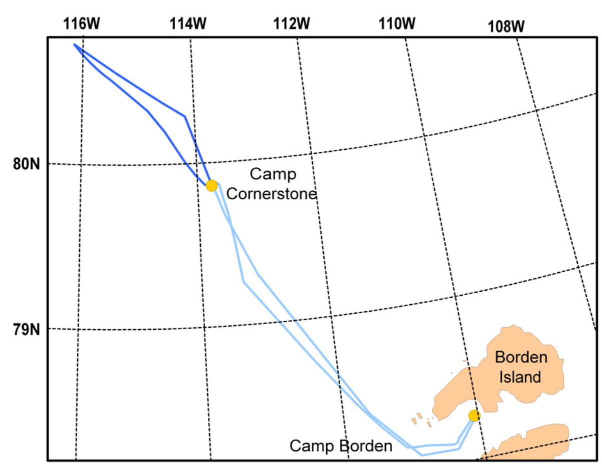

Figure 5. Map showing the AUV tracks for the journey to and from Camp Cornerstone (light blue) and the one mission to the northwest (dark blue).

The main sensor on the AUV was the single beam bathymetric sounder and this device worked perfectly throughout the trials. Multi-beam data were collected during the vehicle testing phase at Camp Borden. Figure 6 shows the raw data plotted in false colour obtained during a 7-km test run. Unfortunately, due to a faulty connector, the multi-beam sounder failed during the survey mission after collecting a limited amount of data. The test data at least confirms that the vehicle is able to collect high quality multi-beam information.

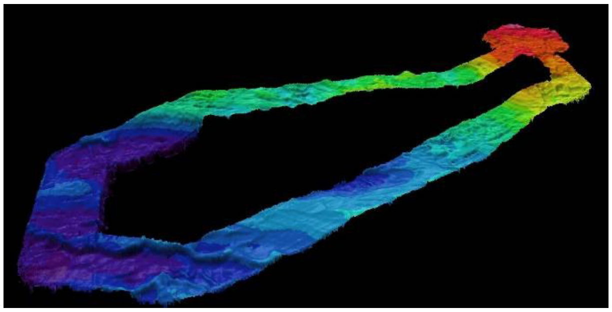

Figure 6. A 3D view of the multi-beam bathymetry data collected during a 7-km long test run in Wilkins Strait. The red colour near the launch and recovery point corresponds to a depth of approximately 110 m, while the purple at the lower-left corresponds to a depth of approximately 360 m.

The acoustic communications system allowed data telemetry packets to be sent on a nearly continuous basis from the vehicle to the operators during the start and end phases of a mission. Data packets contain vehicle state and position data that are displayed on the operator console.

Transmissions from the vehicle were received with high probability to horizontal ranges of over 4 km in both shallow and deep water ice-covered environments. Transmissions to the AUV were only received with a lower probability. It is suspected that the local noise field generated primarily by the AUV's planes prevented reliable two-way communications.

Maximum range for two-way communications appeared to be approximately 7 km, which is less than expected based on past experience with telesonar modems. Reliable two-way communications were generally possible only at relatively short ranges.

A serious issue with telemetry communications was observed in the deep water at near vertical angles. As the vehicle spiraled slowly to the bottom, good communications were held to a depth of about 600 m. After this point, communications from the vehicle were received well, but communications to the vehicle were received with decreasing probability. This was most likely again due to the noise of the vehicle. As the vehicle continued to the bottom, good 1-way communications were held throughout; however, as the vehicle neared an altitude of about 140 m from the bottom (~2000 m depth) there was a distinct change in the ability to send transmissions to the vehicle. It is hypothesized that the bottom-reflected messages resulted in inter-symbol interference that effectively blocked the ability to send commands to the vehicle. Tests are currently underway to determine if this was indeed the case. Future trials will have to seek a solution to this problem as it resulted in an inability to command the vehicle. The remote modems were used to command the vehicle, but not without similar difficulty.

The LRAB homing system worked perfectly throughout the testing and mission phases. The homing system was activated by the mission plan when the AUV reached a point that was 50 km from the mission end point. The homing system immediately estimated the camp's direction and guided the vehicle home. In fact, the homing system was able to hold the vehicle in a misshapen circular path of approximately 200 m diameter when the vehicle was 2 km directly below the MMPP beacon transducer.

Comparison of the vehicle's stored navigational information and the current GPS-derived position of the ice camp while the vehicle circled at depth below the camp indicates that the vehicle's navigation system had developed an accumulated error equivalent to a positional difference of approximately 1600 m. This error is a result of a slight misalignment between the Doppler velocity log and the inertial navigation system. Correction factors have been estimated by Pelavas et al.[6] that now allow for more accurate vehicle navigation.

Analysis of the recorded homing system data indicates that homing should be possible to ranges on the order of 100 km in the ice-covered Arctic Ocean. It was also noted that there are noise sources within the AUV itself that could be miss-identified as the current CW homing beacon signal if the actual beacon SNR was too low. To prevent this from happening a future development will introduce a more complex homing beacon signal.

The SRL system also worked well, but this system is not sufficiently well integrated with the AUV at present. It was used to estimate the AUV positions during the field trial, but data were often collected manually by an operator rather than autonomously by the AUV. In addition, SRL position updates are relatively infrequent because the vehicle does not receive transmissions from the remote modems very reliably due to the local noise and because the modems on which it is based are shared with the vehicle telemetry system. SRL, telemetry, and other operations are cyclically repeated.

The modem field at Camp Cornerstone is illustrated in Fig. 7. It was very interesting deploying this field of modems as the ice moved continuously, at first rigidly, and then later, as it broke apart, in several different directions all at once! Ice conditions were extremely rough and the deployment team travelled by snow mobile to a chosen modem deployment area. It sometimes took several hours to travel between the camp and the modem location during which the ice continued to move. Often positions had to be moved by several hundred metres due to the ice roughness and thickness, and the presence of open water or thin ice.

The modem deployment at Camp Borden was much simpler due to the stationary, land-locked, ice. The deployment pattern at this camp was much more regular with relatively smaller perturbations due to ice conditions or thickness.

The localization accuracy of the SRL technique was estimated during one of the 7-km long AUV test runs. The test run was long enough to take the vehicle more than 2 km beyond the circle of modems. Figure 8 shows the difference between the AUV inertial navigation position estimate and the SRL position estimate. A mean difference, shown by the red line, indicates a discrepancy of roughly 18 m between the two systems. This difference error is strongly dependent on the AUV location. Up until sample 300 the AUV is near the centre of the modem field. It is running the square figure-of-eight pattern prior to a

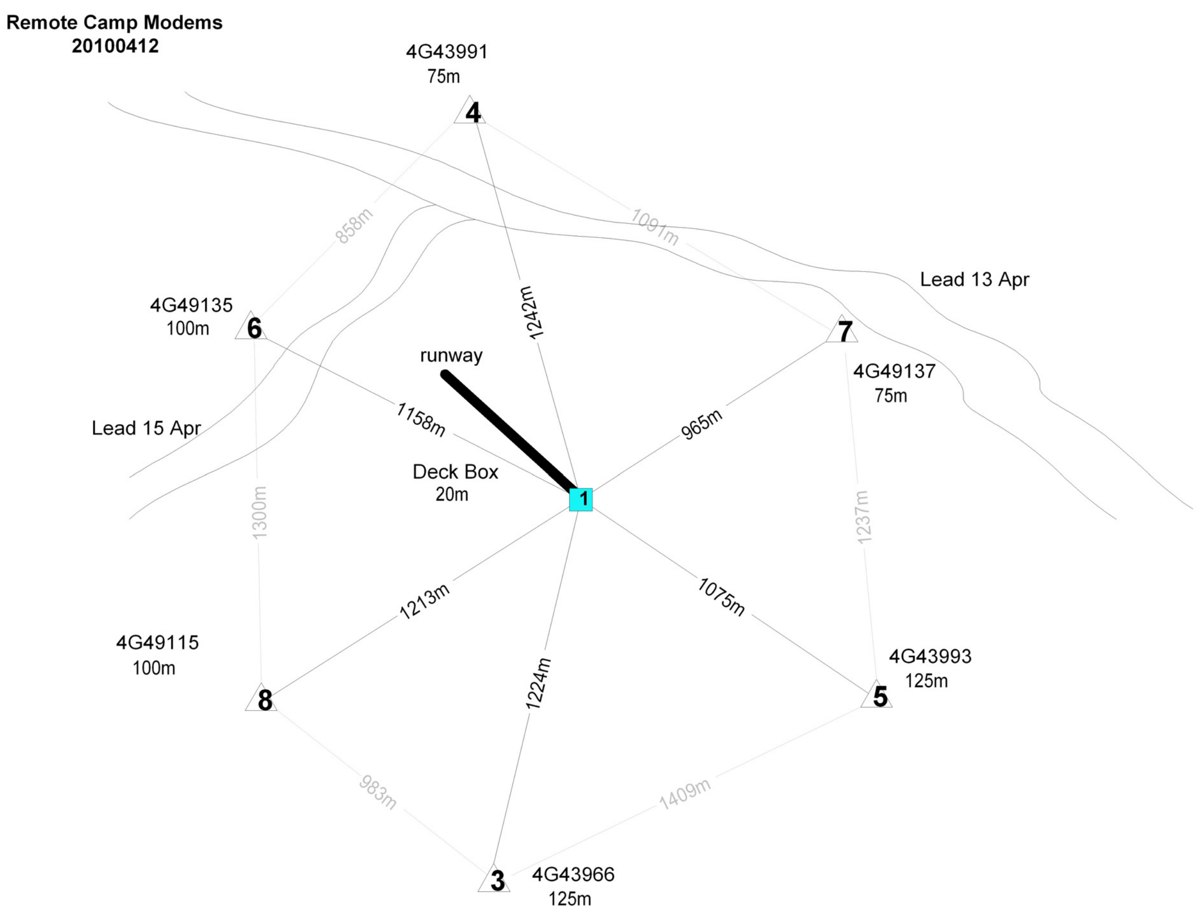

Figure 7. Modem layout at Camp Cornerstone before ice breakup. Modem ID numbers (4Gxxxx) are printed beside the bold-face modem addresses (1, 3, 4, 5, 6, 7, & 9) as are the depths at which the modems are suspended from the ice surface. This figure was accurate for 12 Apr 2010, but as noted on the figure two leads developed on the 13 & 15 April that will have changed inter-modem ranges.

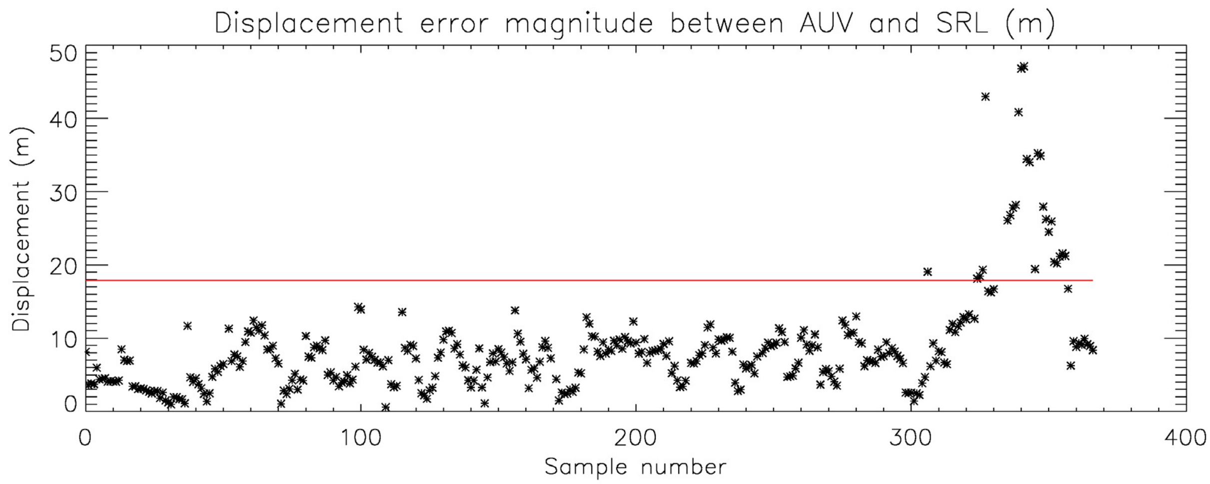

Figure 8. Difference between AUV inertial navigation system position and SRL position estimates during a test run at the main camp.

mission “go”. Difference errors are on the order of 7 m when the vehicle is operating in the figure-of-eight pattern near the centre of the modem field. The samples 300 to 370 represent the 7-km journey and it can be seen that the difference grows with range from the modem field centre. The maximum error (at a single point outlier) was 120 m. The average difference is just 22 m during the in- and out-bound AUV runs.

7. Conclusion

In the short 14-month time span available, two highly capable and complex vehicles were designed, constructed, and tested. In addition, new sub-systems were added to the vehicles, in particular the acoustic homing and localization systems, and a full Arctic deployment and data collection trial was carried out. The concept of operations from an ice camp was proven and valuable data were collected.

Unfortunately, weather conditions were extreme and we were not able to carry out the full planned mission with two AUVs. We will always be constrained by the weather, but our ability to adapt logistically, given our Arctic experience, can partially mitigate these problems in the future.

The acoustic homing system was a notable success. Refinements to this system are currently underway to provide a more definite homing signal signature to ensure that the vehicle locks on to the correct acoustic signal and also to provide a 1-way long-range command capability for the operators. In addition, a separate project has started to make the homing system available to nominally 6” diameter vehicles.

The SRL algorithm was shown to be highly accurate, but suffers from having to time share the modems with other activities, from minimal integration with the vehicle, and from modem signal reception problems due to local vehicle noise. In the current project we cannot add a separate modem system to provide a dedicated localization sub-system, but we can take some measures to increase the SRL integration and reduce vehicle noise through a feedback mechanism tuning of the AUV planes.

In the course of the field trial a number of new under-ice AUV records were set. The vehicle remained underwater in continuous operation for 10.5 days during which time it was recharged three times and covered almost 1000 km while reaching depths of up to 3300 m. The vehicle operated fully autonomously on missions of up to 3 days duration in what are essentially uncharted waters. The new homing system was repeatedly demonstrated at ranges of approximately 50 km. Put together these are very substantial achievements.

At the present time we are planning to deploy both vehicles from an ice breaker in summer 2011.

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(Security markings for the title, abstract and indexing annotation must be entered when the document is Classified or Designated)

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3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

Project Cornerstone : A Landmark Use of High-Endurance AUVs

4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)

Heard, G.J.; Pelavas, N.; Lucas, C.; Clark, D.; Fleming, R.; Pederson, R.; MacNeil, E. Hopkin, D.

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)	6b. NO. OF REFS (Total cited in document.)
October 2010	18	6

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Scientific Literature

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

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9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
11cu23	
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	**10b. OTHER DOCUMENT NO(s).** (Any other numbers which may be assigned this document either by the originator or by the sponsor.)
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AUVs; autonomous underwater vehicles; bathymetric data collection; high endurance; acoustic localization

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