Autonomous Underwater Vehicle Operations Beneath Coastal Sea Ice

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***Abstract*— Use of an autonomous underwater vehicle (AUV) to obtain environmental observations beneath coastal sea ice offshore of Barrow, Alaska is described. The work is motivated by the desire to obtain cross-shore hydrographic transects (temperature, salinity and velocity vs. depth) that would provide estimates of the transport of relatively dense, salty water from the Chukchi Sea to the Arctic Ocean in winter. Although person-portable AUVs are well suited to the task, it was recognized that achieving the science goals would require increasing the range of acoustic navigation and communication as well as developing a robust approach to through-ice deployment and recovery. These needs drove three modifications to the AUV: 1) Incorporation of a lower frequency (10 kHz) transponder and associated hardware for navigation and communication, 2) Addition of special-purpose sensors and hardware in a hull extension module, 3) Development of a homing algorithm utilizing Ultra-Short Base Line (USBL) acoustics. In March 2010, eight days of field work offshore of Barrow provided successful demonstration of the system. A total of 14 km of track lines beneath a coastal ice floe were obtained from four missions, each successfully terminated by net-capture recovery.**

***Index Terms*—Autonomous underwater vehicle, coastal sea ice, navigation, launch and recovery.**

I. Introduction

THE inflow of Pacific water from the Bering Strait is an important source of freshwater, carbon, and nutrients for the Arctic Ocean. On its way to the Arctic, this water traverses the shallow Chukchi Sea where its properties are modified, particularly by cooling, ice formation and brine rejection in winter [1]. Pacific water tends to follow three topographically-steered pathways through the Chukchi Sea [2]-[3]; the eastern most branch passes along the Alaskan coast and is concentrated between Barrow, AK and Barrow Canyon before entering the Arctic basin. Understanding the hydrographic properties and volume transport of the Pacific Water in this region is of great interest in the context of climate change and Arctic sea ice retreat.

The cross-shore length scales (10-20 km), water depths (10-120 m) and desired measurements (temperature, salinity and velocity vs. depth) in the study region (Fig. 1) are well suited to the observing capabilities of small (two-person portable), propeller driven autonomous underwater vehicles (AUVs).

Cross-shore hydrographic transects obtained offshore of Barrow with the Remote Environmental Measuring UnitS (REMUS) AUV in summer [4], [5] showed the utility of this approach, but it was recognized that obtaining similar transects in winter would require increasing the range of AUV acoustic navigation and communication, as well as developing a robust approach to through-ice deployment and recovery.

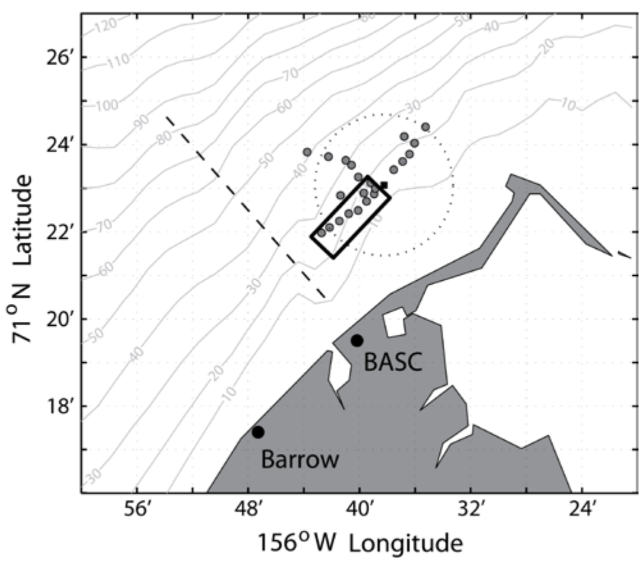

Fig. 1. Map of the study region showing the northwest coast of Alaska, the town of Barrow, the Barrow Arctic Science Consortium (BASC), and offshore bathymetry along the eastern flank of Barrow Canyon. Approximate locations of cross-shore transect occupied in the summer of 2005 (dashed line), acoustic survey points from the winter of 2008 (dots) and area of under-ice operations in the winter of 2010 (rectangle) are shown.

Coastal sea-ice conditions are complex and change rapidly [6], 7]. Shorefast ice floes are created in winter by attachment to grounded pressure ridges in shallow water, but are not stable throughout the season. Wind and currents can cause ice to separate from the coast and move significant distances along- or off- shore, leaving several miles of open water near the coast. Subsequent changes in wind and current conditions can result in compression events, where offshore ice moves onshore with sufficient force to break the floes and create multiple ridges with keels that may penetrate tens of meters below the surface. These dynamic ice conditions combined with shallow water in much of the region makes conventional

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ice-based observing approaches (icebreaker or plane-serviced ice camp) untenable. Seabed scouring from the movement of ice keels may lead to destruction of moorings in water depths less than about 30 m. Thus, observing the nearshore hydrography of the Alaskan coast in winter remains a challenge.

It has been recognized that AUVs are an important tool for addressing such challenges. Small AUVs were first used under-ice exploration in the 1970s and 1980s from camps in the Arctic pack ice [8], [9]. The use of larger AUVs in the Arctic was pioneered in the 1990s [10], while the use small vehicles from ice camps continued [11], The pace of development and use has increased significantly since, with a variety of vehicle types deployed within the pack ice and at the ice edge, in both Arctic and Antarctic [12]-[18].

Drawing on prior work using small AUVs for under-ice operations [9], [11], [17] as well as our experience with the REMUS AUV in open water, a modified REMUS vehicle capable of through-ice launch/recovery and autonomous under-ice navigation was developed and demonstrated in the field.

II. Hardware Configuration and Modification

A. The REMUS-100 AUV

A REMUS AUV [19], [20] was outfitted with a specific suite of sensors and hardware in preparation for under-ice observations (Fig. 2). The REMUS-100 (rated to 100 m depth) is relatively small (19.5 cm diameter by 1.8 meters long) and light (45 kilograms), allowing for economical transport to remote locations and simplifying field operations. A 1 kW-hr battery pack provides 8-10 hr of operation at the optimum speed of about 1.5 m/s. Attitude is controlled by yaw and pitch fins forward of the propeller. Air-side communications systems include a Global Positioning System (GPS) receiver, a WiFi local area network, and Iridium satellite telemetry. Although these systems are unusable during under-ice missions, WiFi allows pre-mission testing and configuration without a cabled connection to the vehicle and a GPS fix just prior to launch defines the mission start point.

The environmental sensors include a Neil Brown Ocean Systems conductivity-temperature-depth (CTD) sensor [21], a Teledyne/RDI dual (up- and down-looking) 1200 kHz Acoustic Doppler Current Profiler (ADCP), and a WetLabs Environmental Characterization Optics (ECO) sensor. The ADCP provides water velocity profiles to a range of about 15 m, depending on environmental conditions. When the AUV is within about 30 m of the bottom, the down-looking ADCP provides bottom-track velocity as an aid to navigation and also serves as an altimeter. The ECO provides optically-based estimates of Chlorophyll-a (from excitation/emission at 460/695 nm), colored dissolved organic matter (CDOM; from excitation/emission at 370/460 nm) and turbidity (from backscatter at 660 nm). A Marine Sonic Technology 900 kHz sidescan sonar system was integrated into the vehicle, but was not used in this study.

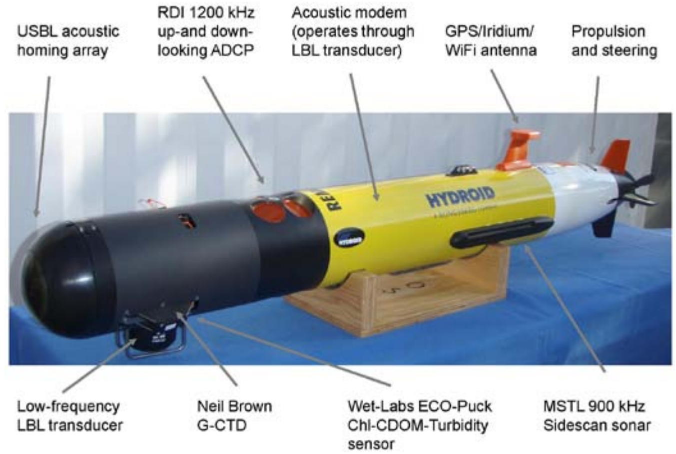

Fig. 2. The REMUS-100 AUV as delivered. The locations of principal systems and sensors are shown.

B. Hardware Modifications

The principal hardware modification to the standard vehicle was the addition of a 24 cm long, free-flooding hull module inserted between the forward hull section and the nose cap. The hull module housed devices for emergency vehicle location, ice avoidance, and sub-ice recovery (Fig. 3).

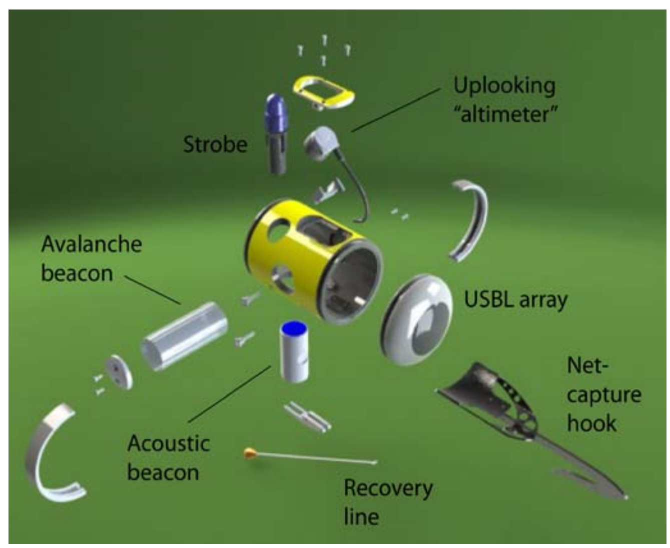

Fig. 3. Exploded design drawing of the AUV hull module and nose cap with Ultra-Short Base Line (USBL) acoustic array and net-capture hook.

Several location and recovery aids were incorporated into the hull module. A strobe light improves the likelihood of locating the vehicle visually at night. An avalanche beacon allows under-ice position to be determined from the surface at distances of up to about 100 m. Once located, the vehicle can be recovered though a hole cut in the ice. If the AUV cannot be accessed directly through the ice hole, an ROV can be used for recovery. The acoustic beacon can be used as a homing signal for a receiver on the ROV. A 45 cm long, weighted recovery line (vinyl coated wire rope) hangs below the hull module, serving as an attachment point for the ROV grabber.

A hook protrudes about 20 cm from the nose cap. The hook is used in conjunction with a cylindrical net and USBL transponder (Fig. 4) for under-ice vehicle capture and recovery. The net assembly consists of 3 mm diameter polyethylene fishing net attached to two 1.2 m diameter aluminum rings. The net is under tension during deployment due to the use of 8.2 Kg of flotation on the upper ring and 9 Kg of lead weight on the lower ring. When deployed, the net extends to 1.5 meters long and the webbing forms a series of 12 × 12 cm squares. The hook is designed to distort a square, extending it to nearly a line. Once the hook has penetrated, the tension on the webbing returns it to a square shape, capturing the vehicle in the net.

Fig. 4. Photo of the AUV capture net being prepared for deployment. Note the USBL homing beacon being suspended in the center of the net.

An Imagenex 852 narrow-beam echosounder was mounted in a bracket that allowed the beam to be positioned vertically or at a forward angle of up to 45^{o}. Tilted forward and integrated with the navigation system, the echosounder could be used for ice keel avoidance. For the missions described here, the echosounder was pointed vertically and used as an upside-down altimeter to record the distance from the vehicle to underside of the ice.

A propeller guard made out of a lightweight polycarbonate material was added to protect a temporary tether (used during testing) from getting cut by the propeller, and to protect the propeller from getting damaged by hitting the ice.

III. Acoustic Navigation and Communication

A. The Acoustic Environment

Arctic coastal waters offer unique acoustic propagation and noise field characteristics, particularly during ice-covered months in the winter. Weak stratification and cold near-surface water means that sound rays will refract towards the surface. However, in shallow coastal regions the water is not deep enough to allow the rays to fully refract, and instead they reflect from the bottom with a strength that depends on the carrier frequency and bottom type. Another aspect of working in coastal sea ice is that the ice tends to pile up, creating large keels which may impede sound propagation. Finally, shorefast ice (with the exception of compression events) is fairly stable, and thus there is little noise.

A one week reconnaissance mission was undertaken in the winter of 2008 to assess ice conditions and determine the feasibility of acoustic ranging beneath the ice. A base camp was established just offshore of the grounded ridges, from which a REMUS 25 kHz acoustic ranging system was used to interrogate beacons deployed through ice holes at various distances (Fig. 1). The acoustic survey lines (5-7 locations moving away from the camp) were accessed by snow machine using a handheld GPS receiver. Results indicated that acoustic ranging would be possible for distances of about 2.5 km along shore and up to 3.5 km across shore. While these results were encouraging, the ranges achieved fell short of those desired to achieve the scientific goals, and the quality of modem communication was not assessed.

Two aspects of the environment motivated the use of 10 kHz rather than the normal 25 kHz carrier for acoustic communications and navigation. First, the sound speed profile for the operations area, estimated from a CTD cast taken at the ice camp, showed total variation from top to bottom of only ~0.5 m/s, which means that sound will tend to travel in nearly a straight line over short distances. Thus, there is the potential for long-range direct paths and frequency-dependent absorption comes into play – the use of 10 vs. 25 kHz reduces that loss by approximately 2 dB per km. Second, with relatively straight ray paths the propagation from source to receiver is a function of interaction with the bottom of the ice, which can be quite rough, and the sea floor, which is fairly flat but may include gravel in addition to mud or sand. Lower frequencies may experience less loss during scattering from these rough surfaces, depending on the size of the features.

A key parameter influencing acoustic communication performance is the scatter that the signal is subjected to on the path from source to receiver. In Fig. 5, an impulse response obtained under coastal sea ice offshore of Barrow, AK is shown. The overall response duration of about 10 msec is seen to be comprised of two primary peaks, spanning about 4 msec each. The pattern is likely due to a combination of ice and bottom scatter, and while it appears as a significant amount of reverberation, the relatively short span of the two main arrivals means that acoustic communication is not precluded. Modem diagnostics obtained during 2010 field operations show that

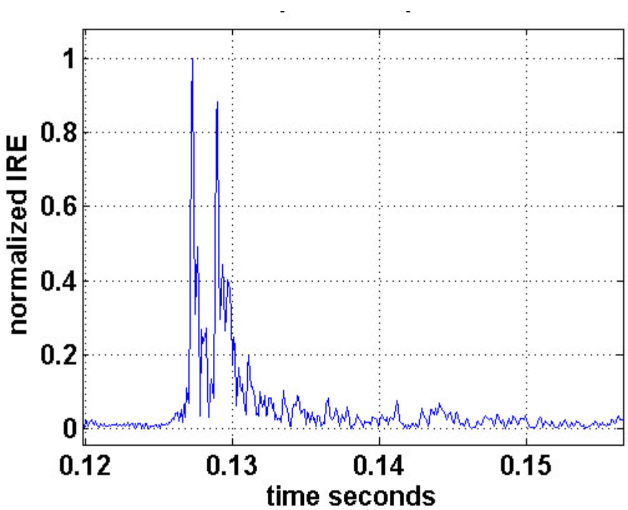

Fig. 5. Normalized 10 kHz acoustic impulse response function obtained from acoustic communications testing conducted during 2010 field operations.

communication was very reliable despite the scatter, presumably due to high SNR and modest spreading over short range.

B. Navigation and Communication Systems

The acoustic navigation and communication system on the AUV included a 10 kHz acoustic modem, a 10 kHz spread spectrum Long Base Line (LBL) navigation system, a 10 kHz transducer (shared by the LBL and modem), and a four element, 25 kHz Ultra Short Base Line (USBL) navigation system [22], [23]. The acoustic communications subsystem is interfaced to the vehicle controller, which sends out status and environmental information at regular intervals automatically, or may be queried by a modem base-station on a fixed schedule or on-demand by the operator. The vehicle status display is updated when a modem reception is received, showing position, depth, speed, battery voltage and other parameters used to monitor progress and the environment the vehicle is in.

While 10 kHz modem and LBL systems were used for increased range, the USBL system, used for homing and docking, remained at 25 kHz for increased accuracy. Using two different frequencies required modifications to the USBL transponder – the AUV interrogates the transponder at 10 kHz, but the USBL array expects a 25 kHz reply. The USBL transponder was modified to listen at 10 kHz and respond at 25 kHz. The USBL system computes a range and relative bearing estimate, and reports that to the vehicle controller.

REMUS normally broadcasts a 32 byte “health” message once per minute. A submerged transducer and hand held receiver can be used to listen to these messages, verifying that the vehicle is operating properly, is on course, and that the instruments are functioning. For under-ice missions, an acoustic modem was included with the receiver, allowing the operator to actively interrogate the vehicle, and providing additional data that can be evaluated in real time. Information about LBL and USBL fix age indicated whether the vehicle was navigating effectively or had lost contact with the transponders. Information about AUV range and heading to the ice hole made it possible to anticipate the vehicle approach to the net during docking trials. We were than able to see the vehicle approach visually and observe “near misses”.

REMUS continually estimates vehicle position during a mission. Dead reckoning algorithms incorporate compass data, propeller turns and water velocity estimates as well as bottom track data from the ADCP when available. Position estimates are updated and improved using other systems when available, including GPS (unavailable after launch for under-ice missions), LBL, and USBL.

In LBL navigation mode, the vehicle operates within acoustic range of two or more digital acoustic transponders with known, fixed positions. The LBL system provides simultaneous estimates of 1-way travel time. Travel times are converted to positions using triangulation and the transponder locations stored in the vehicle configuration file.

In USBL homing mode, the nose-cap array interrogates a single transponder as it approaches, allowing the range and bearing to the transponder to be determined from the received signal. Range and bearing are combined with the vehicle’s pitch, roll, and heading information to provide a position fix. USBL navigation is increasingly accurate as the distance between vehicle and transponder is reduced.

C. Docking Algorithm

A number of algorithms have been developed for docking REMUS to fixed and mobile platforms. When docking to a fixed platform mounted on the ocean floor, the AUV follows a pre-programmed glide path into a receiving cone at a known depth. The cone guides the vehicle into an inner cylinder where it establishes a hardwired power and data connection [23]. A mobile platform docking algorithm – e.g., for connection to a wire line under tow and suspended vertically in the water column – has also been developed. The mobile docking algorithm has the advantage of allowing the vehicle to approach from any direction, and is relatively insensitive to errors in depth. For these reasons, the mobile docking algorithm was chosen as the basis for under ice docking. For wire line docking, the vehicle is outfitted with a set of “whiskers” that are folded out of the way during the mission, but open during docking to increase the aperture, and make it easier to grab the line. The whisker/latch mechanism was replaced with a simple hook extending from the vehicle nose cap (Fig. 3). The hook captures the vehicle in a cylindrical net deployed from the recovery hole with a transponder in its center (Fig. 4). This approached increased error tolerance (since the net was significantly wider than a wire) and simplified the mechanics of the vehicle (by eliminating the articulated whiskers and latch), at a slight cost in hydrodynamic efficiency and some added risk that the hook would catch on an unintended object.

The docking algorithm uses USBL homing to determine the range based on the round-trip travel time and bearing to the “dock” (the net in this case) based on the relative phase difference across a four-element array in the nose cap. The USBL fixes provide relatively accurate ranges, but have relatively large angular errors. There are a number of potential sources for these errors. The manufacturing process results in static errors in the location of the hydrophones; resulting errors in bearing increase as the angle off-axis increases. The relative bearing from the USBL array is combined with the vehicle heading to produce the absolute bearing angle. Thus, the USBL angles are subject to magnetic compass errors. At longer ranges, acoustic multipath may have an impact on overall accuracy. Replies reflected form the seafloor and the ice mix with the direct path and corrupt the signal. Coded signals are mitigate this problem, but it can't be eliminated. At shorter ranges, the difference in path lengths make it easier to separate the two signals.

The algorithm will reject fixes with angles that are larger than a pre-set threshold or ranges outside of a dynamically adjusted range gate. This is necessary to avoid directing the vehicle off course as a result of occasional erroneous fixes. Since all fixes are logged, it is possible to review cases where bearing angles are rejected yet ranges show the vehicle approaching the beacon. The effect of angular errors decreases linearly as the distance to the transponder decreases. Thus, a variable rate filter is used on the USBL position fixes during the approach; as the vehicle gets closer, it will turn harder to stay on track to the transponder. This is not only because the USBL fixes are more reliable, but because faster response is required to minimize errors in the closing seconds of the approach.

The AUV continues towards the transponder between USBL fixes, which are obtained at a maximum rate of 0.33 Hz, the ping rate of the transponder. If the vehicle's estimated position is beyond the transponder, it attempts to determine whether it has successfully docked. A docked state is indicated by a range from the transponder that is not increasing combined with the inability of the vehicle to execute a turn. If a docked state is determined, the vehicle controller moves on to the next navigation objective. Generally the docking objective is the last one, so that the vehicle shuts down and the mission terminates. If not docked, the vehicle continues ahead until its computed location is a pre-programmed distance away from the transponder, at which point it turns and begins another approach. The distance away from the transponder, and the number of docking attempts, are programmable by the user.

IV. Field Trials

A. *Mendums Pond*

Preliminary tests of through-ice launch/recovery and under-ice navigation were conducted in Mendum's Pond, NH in February 2010. The freshwater Pond provided a benign environment (no ice ridges, minimal current) to test under-ice navigation and acoustics with little risk of losing the vehicle. Ice thickness was about 40 cm and water depths varied from 9 -13 m in the operations area. The first few missions at the pond focused on confirming vehicle function and determining the best launch method. It was found that lifting the tail out of the water, initiating the mission by spinning the propeller (one of several available mission start options) and using a fending pole to maintain a nose-down orientation of about 20^o as the tail was released provided controlled and consistent launches with the vehicle well clear of the ice upon its initial dive.

Initial tests at the pond also confirmed a suspected problem relating to vehicle recovery. If the vehicle completes its mission without successful net capture, or aborts unexpectedly, so that the (positively buoyant) vehicle is resting against the underside of the ice, it cannot not re-launch due to inability to pitch its tail up, gain momentum and dive as it would in open water. Recovery would require drilling a hole in the ice large enough to extract the vehicle. With this limitation in mind, we conducted tests at the lake using a tether – a Spectra® line tied to a lifting bail on the vehicle. The line is thin for its strength and slightly positive, minimizing interference with vehicle performance. In the event of an undesirable mission termination, the vehicle can be hauled back to the deployment hole by hand using the tether.

Five docking missions were conducted with the tether on the vehicle and the recovery net and transponder suspended at a depth of 4 m by means of a gantry. No LBL beacons were used; outbound navigation was by dead reckoning and the docking algorithm relied on USBL navigation. Bottom tracking was available throughout the missions. The outbound leg from the ice hole was 75 m long at a depth of 4 m and speed of 1.3 m/s, after which the vehicle turned back towards the net and initiated the docking objective at the same depth and speed.

All 5 attempts resulted in successful "docking" (net-capture) on the first approach. Results from 3 missions with similar characteristics are shown in Fig. 6. Note the relatively large excursions in heading and depth as the vehicle recovers from the turn and begins the approach (elapsed time = 100-130 s). The first good USBL fixes are obtained at distances of 85-95 m from the transponder. Depth then stabilizes near the 4 m target depth while heading adjustments of a few degrees are made in response to the USBL angle estimates (130-190 s). The beginning of rapid turns (190-200 s) indicate the vehicle is attempting to determine whether it is in a docked state. The USBL fix acceptance was 80-90% for these runs. The launch and recovery hardware, as well as the docking algorithm appeared to be working well. The next step was to move to the more challenging Arctic coastal sea ice environment.

B. *Arctic coastal sea ice*

In March 2010, field operations were conducted out of Barrow, AK, where Barrow Arctic Science Consortium (BASC) facilities were available for logistical support before and during the expedition. Prior to our arrival, a 2.8 km snowmobile trail was hand-cut out to a predetermined deployment site. The site was chosen based on our desire for a large ice floe connected to the shorefast ice, but with the potential for offshore missions (i.e. minimal ridging at the offshore edge of the floe). Snowmobiles pulling wooden sleds were used to access the operation sites on a daily basis. The first operations site (“Camp 1”, a 1 × 2 m hole, gantry, and tent) was established on a 300 m × 1500 m floe without significant offshore ridges. Conditions appeared ideal. However, within about an hour of the team departing from Camp 1 for the day, a significant compression event occurred, breaking up the floe and destroying the camp. We quickly learned what others [6], [7] have documented – the ice conditions not only change daily, but sometimes hourly and are hard to predict, making work from shorefast ice a logistically challenging and dangerous endeavor. From this point on, weather and ice conditions were reviewed (using a land-based radar, see [7]) each morning, no gear was left on the ice overnight, and the field party was prepared to pack up and leave the ice on short notice during daytime operations.

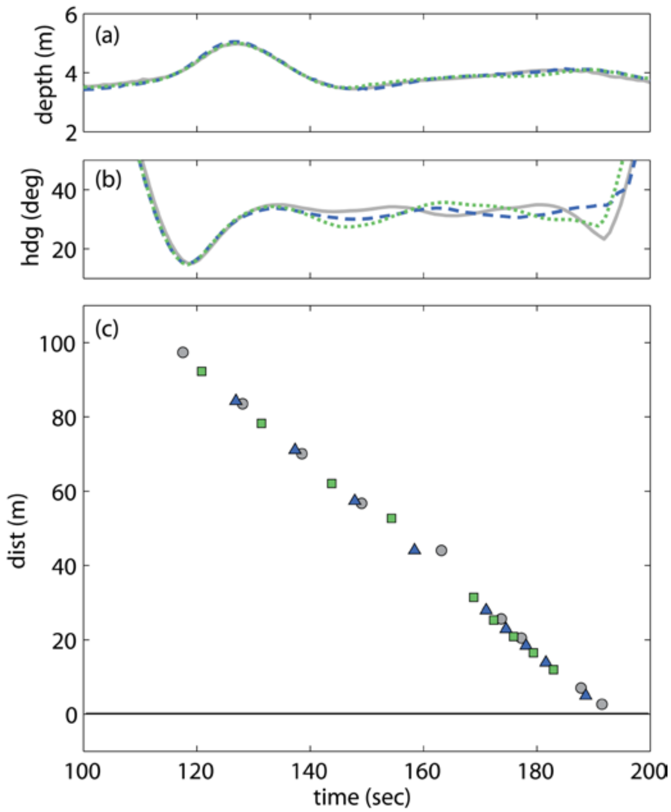

Fig. 6. Selected mission parameters for three docking trials at Mendums Pond. Vehicle depth (a), heading (b) and distance from the USBL transponder (C) are shown vs. elapsed time for the third (solid lines, circles), fourth (dashed lines, triangles) and fifth (dotted lines, squares) docking trial. Only fixes accepted by the docking algorithm are shown.

Camp 2 Operations

A second camp was established on the remains of the large floe identified for Camp 1, at the center of an open area of only about 50 × 70 m surrounded by ridges 1-2 m tall. During transit to the site, the vehicle was wrapped with a heat coil powered by a portable generator to keep the Lithium-ion batteries above 0°C. The team set up two tents, the first for the vehicle and communications gear which included acoustic tracking gear, a WiFi router for communicating to the vehicle and a laptop, and the second for a ancillary instrumentation and miscellaneous supplies. The ice thickness was about 60 cm. A 1 × 2 m hole was hand-cut for vehicle and net deployment. The water depth below the hole was about 15 m. The vehicle was ballasted, basic function checks were completed (Fig. 7), and several test missions were run (with the tether attached) to confirm proper functioning of the vehicle and associated navigation/communication systems.

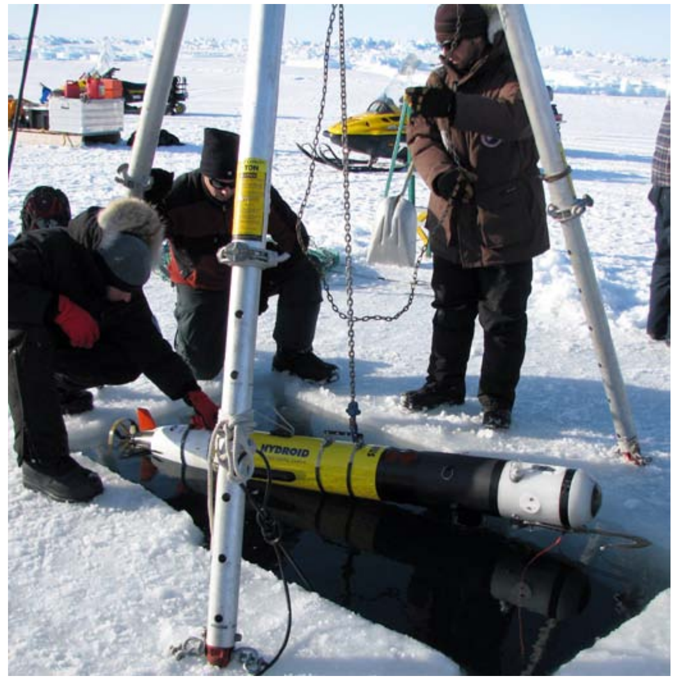

Fig. 7. Photo of AUV being prepared for deployment at Camp 2.

Upon completing the test missions, the USBL beacon and net were deployed in the center of the ice hole at a depth of 6 meters. Two docking trials were then conducted. No LBL beacons were used and the tether was on the vehicle. Bottom tracking was available throughout the missions. The first navigation objective was an outbound leg of 80 m distance at a depth of 8 m and speed of 1.3 m/s. Docking was the next navigation objective. The docking parameters were a depth of 6 m, speed of 1.5 m/s and a turnaround range of 50 m. The number of docking attempts was set to a large number (100) under the assumption that the mission would be ended either by successful docking or by manual abort.

Results of the two docking trials at Camp 2 are shown in Fig. 8. Neither mission resulted in successful docking; the first five approaches to the net for each mission are shown in the figure. The vehicle depth was typically within 0.5 m of the 6 m target depth, except during turns. USBL fixes were obtained at distances of 40-60 m from the transponder, but most were rejected by the docking algorithm. The USBL fix acceptance was only 13% and 29% for the two trials. The initial docking approaches were “close”, with minimum USBL ranges of 6 m and 14 m (Fig. 8c), but successive approaches show ranges further and further from the transponder.

Analysis shows that the rejected fixes with apparently valid ranges had estimated azimuth angles to the transponder that were larger than the algorithm threshold (+/- 20^{o}). The

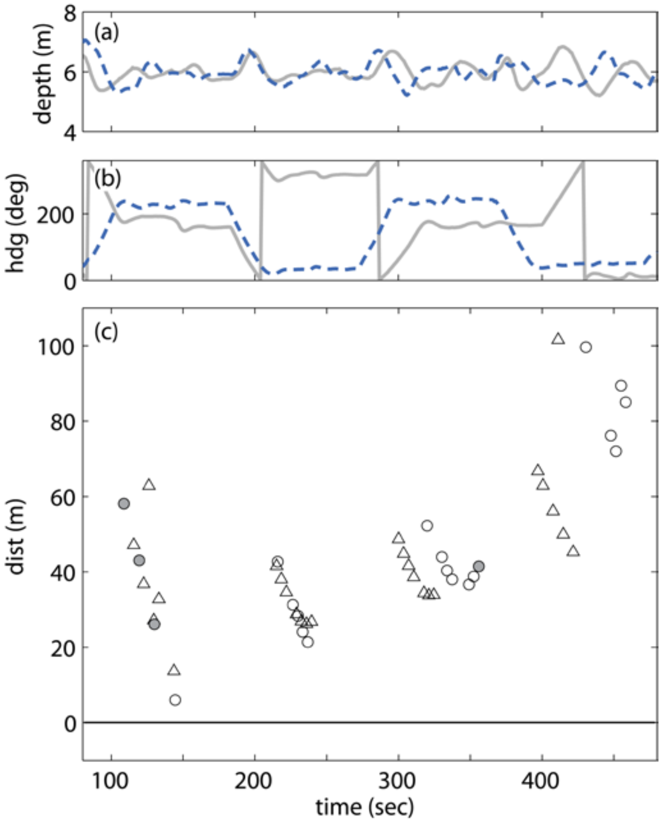

Fig. 8. Selected mission parameters for two docking trials at Camp 2, offshore of Barrow, AK. Vehicle depth (a), heading (b) and distance from the USBL transponder (c) are shown vs. elapsed time for mission 6 (solid lines, circles) and mission 7 (dashed lines, triangles). All fixes with valid ranges are shown. Fixes accepted by the docking algorithm have filled symbols, rejected fixes have open symbols.

presumed reason for this is as follows. Without a navigational reference, dead reckoning errors accumulate, particularly after turns. With each approach the vehicle's actual course to the transponder becomes further dissociated with its apparent (internally computed) course. USBL fixes indicating dramatic course corrections (e.g., 45^o-70^o during successive approaches of the Camp 2 trials) are rejected (although in some cases they may be accurate). Without any new fixes, the vehicle gets increasingly "lost" and each successive pass is worse.

Navigation accuracy at Camp 2 was not as good as expected (e.g., compared to Mendums Pond). The possible causes included compass error, strong currents, and drag from the tether. Data from subsequent runs using LBL navigation showed that that the compass, in fact, performed well (errors less than 1^o). Currents were relatively modest at 0.1-0.3 m/s. This left the tether as the suspected reason for poor navigation performance. Given the constraints of the small operational area for the vehicle to maneuver and the poor navigation performance, the reasons for low USBL acceptance rates were difficult to pin down. The possibilities considered included EM interference from the avalanche beacon, acoustic beacon, or strobe light, acoustic interference from the hook protruding from the vehicle's nose, poor sound propagation due to the proximity of ridges, and insufficient distance between the vehicle and the homing beacon on the inbound legs to give the vehicle time to establish a stable approach path.

The second docking trial at Camp 2 ended after 15 docking attempts. Each docking approach has an arbitrary "exit heading" determined by the last course correction before the beacon was passed. Similarly, an arbitrary "re-entry heading" is set by the details of the turn at the end of the outbound leg. Since both the exit and re-entry angle increments are small, there is a tendency to create a "bow tie" pattern from multiple missed docking attempts. As the number of attempts increases, there are enough different angles to fill in a "flower petal" pattern (Fig. 9).

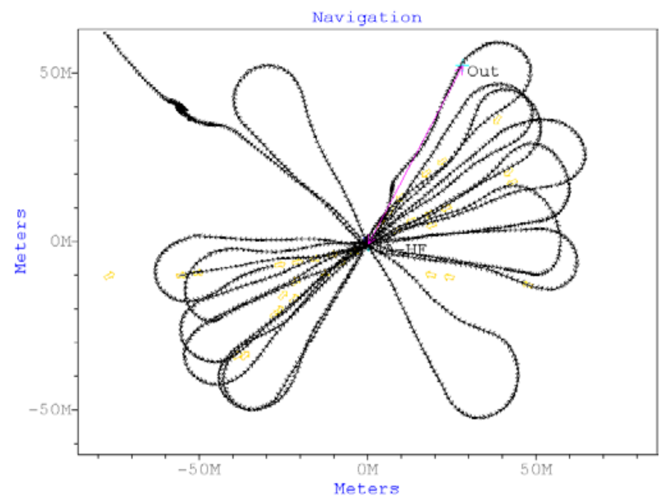

Fig. 9. Vehicle-computed navigation record for the second docking trial at Camp 2. The flower petal pattern is created by multiple approaches using the docking algorithm. The USBL transponder is at the center. Successful USBL fixes are shown as yellow arrows. Note that this is the "apparent" vehicle track, which indicates docking runs that passed very near the homing beacon (at the center of the pattern) on each attempt. In fact, the vehicle became increasingly "lost" with each pass.

Unfortunately, this mission was run with a cracked propeller shroud and ended when the tether was cut by the propeller blade, and the vehicle swam beyond its safe zone and got stuck in a "tunnel" within an ice ridge. The vehicle location was determined to within ~3 m using the avalanche beacon and a handheld receiver. Recovery of the vehicle from about 2.5 m deep under multiple layers of ridged ice was accomplished a day later. Recovery efforts started by drilling multiple 25 cm auger holes around the estimated vehicle position, using ice saws to cut out the ice between the holes, and then probing with an extensible pole attached to a camera with a live color video feed to a laptop in a tent to identify the vehicle. The ROV was then used to pull the vehicle out of a tunnel formed by multiple layers of ice. Just enough of the nose was accessible so that a loop at the end of a 3 m pole could grab the hook. Two people eventually wrestled the vehicle out of the hole. No damage was sustained except for a bent propeller, which was replaced.

An evaluation of Camp 2 operations concluded that the safe operating area was too small for additional tests. Snowmobiles and hand held GPS receivers were used to scout out a larger ice floe that would allow the vehicle more maneuvering room. Camp 3 was set up on this larger floe.

Camp 3 Operations

The third camp was accessed by hand-cutting a trail further northeast on the ice sheet. An un-ridged floe of about 200 × 500 m was identified. Two 10 kHz LBL transponders were deployed to improve the vehicle's navigation accuracy after experiencing poor results using only USBL. The LBL transponders were 1800 m apart with a baseline 300 m inshore of the camp. Successful ranging to the transponders was verified with the vehicle floating in the ice hole prior to deployment. Several missions were conducted at Camp 3 over two days.

The first day at Camp 3 included four tethered test missions followed by two untethered survey missions. The survey was a "mow the lawn" pattern centered on the ice floe, with three along-floe lines of 400 m and a line spacing of 30 m. All survey legs were run at a constant depth of 6 m. After completion of the survey, the vehicle was programmed for 6 docking attempts. The length of the inbound leg from the last survey waypoint to the net was 150 m. If the first docking cycle was unsuccessful, the vehicle was programmed to return to LBL navigation mode to re-establish its absolute position before initiating another docking cycle. The length of the inbound leg from the LBL navigation waypoint was 250 m. The docking parameters were a depth of 6 m, speed of 1.5 m/s and a turnaround range of 75 m.

Both survey missions were terminated by successful docking (net capture). The first survey (mission 12) included about 1800 m of track line along the survey grid followed by successfully docking on the second approach. Results for the docking portion of this mission are shown in Fig. 10. Note the stability of vehicle depth relative to previous, tethered missions. Depth decreases after an elapsed time of 1570 s as the vehicle and net are hauled out of the ice hole following successful docking. USBL fixes were obtained at a maximum range of 110 m during the initial approach and the overall fix acceptance was 75%.

The mission plan for the second survey was an exact repeat of the first survey. The vehicle missed the net on all six attempts of the first docking cycle, but then, on the outbound LBL navigation leg intended to re-establish the glide path, the vehicle accidently docked itself. The track line for this leg passed directly through the ice hole where the net was suspended, and the track-line following was sufficiently accurate to result in the vehicle hitting the net (USBL homing was not active). Although we considered this to be an accidental success, it highlighted the importance of LBL fixes for maintaining under ice navigation accuracy suitable for autonomous docking.

The second day at Camp 3 included two more "mow the lawn" survey missions. The third survey (mission 14) was identical to the first two, but with the acoustic beacon shut off to allow testing of modem performance without acoustic interference (see Sec. III.A). Results of the first docking cycle of this mission are shown in Fig. 10. The vehicle missed all six attempts in the first docking cycle. Note the increasing distance from the transponder and decreasing fraction of accepted. These results are reminiscent of the failed docking attempts at Camp 2 (Fig. 8). After the sixth failed docking attempt, the vehicle re-established its position in LBL navigation mode before initiating another docking cycle. The first try of the second docking cycle was successful. On the last approach, inbound from the LBL navigation leg, USBL fixes were obtained from maximum ranges of about 150 m during the first docking cycle and from over 240 m on the initial leg of the second docking cycle. The overall USBL fix acceptance for the seven docking attempts was 31%.

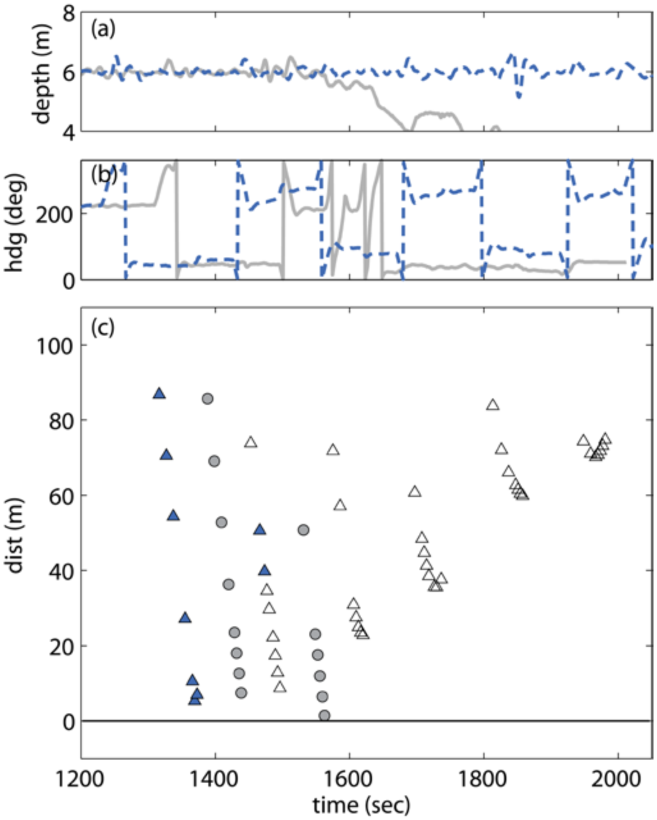

Fig. 10. Selected mission parameters for two survey missions at Camp 3. Vehicle depth (a), heading (b) and distance from the USBL transponder (c) are shown vs. elapsed time for mission 12 (solid lines, circles) and mission 14 (dashed lines, triangles). All fixes with valid ranges are shown. Fixes accepted by the docking algorithm have filled symbols, rejected fixes have open symbols.

For the fourth survey mission, two 400 m survey lines were added to more completely cover the ice floe area, and the vehicle was programmed to run in "triangle mode", cycling between 4 m below the ice and 2 m above the bottom at a rate of 10 m/min, rather than at constant depth. At the end of this survey, the vehicle docked successfully on its first attempt.

Examining fix acceptance for the four survey runs at Camp 3 (Table 1) shows that LBL acceptance was steady at 60-70%, while USBL acceptance varied from 30-40% associated with multiple unsuccessful docking attempts (surveys 2 and 3) to 70-75% when successful docking immediately followed an LBL leg (surveys 1 and 4). Perhaps the most important aspect is the high USBL acceptance on the initial approach of each docking cycle, which immediately followed LBL navigation. After the first approach, performance was similar to that at Camp 2. This indicates that the addition of LBL beacons was more important than removal of the tether to improved docking success.

TABLE I
NAVIGATION FIX SUCCESS RATES AT CAMP 3

Survey	LBL	USBL
1	69%	75%
2	60%	39%
3	66%	31%
4	60%	70%

V. DISCUSSION

In favorable conditions (bottom track available, weak currents), the USBL system works well, using successive fixes to make course adjustments during the approach and navigate the AUV to within ~1 m of the homing transponder without any other navigational aids. This capability was demonstrated for our modified vehicle by the under-ice docking trials at Mendum's Pond. However, Arctic trials indicated that USBL homing was not as robust in more challenging conditions.

The docking trials consisted of an outbound leg followed by a turn back towards the transponder. If the vehicle navigated perfectly and had no angular errors, it would be pointed directly towards the transponder (bearing=0) at the end of the turn. In fact, position offsets relative to the estimated track line and angular offsets (i.e. real or apparent azimuthal rotation of the vehicle relative to its estimated angle) contribute to non-zero bearing angles after the turn.

If the bearing angle is greater than the pre-programmed threshold (20^o in this case), the USBL fix will be rejected. Even if fixes are initially accepted, course adjustments may not be sufficient to avoid rejection of subsequent fixes if the bearing angles are near the threshold. Continued motion of the vehicle towards the beacon without course adjustment from a successful fix will increase the bearing angle, subsequent fixes will be rejected and the system will not recover (Fig. 11).

Dead reckoning speed errors are small when ADCP bottom track data are available, while fluxgate compass errors are estimated to be a few degrees. For an outbound leg of 80 m (as used at Camp 2) speed errors of 1% and heading errors of 3^o would contribute to position offsets of about 1 m and 4 m, respectively. The associated bearing angle offsets are a few degrees, increasing with increasing leg length.

The turn has a finite radius, but the navigation algorithm compensates for this by steering the vehicle towards the (pre-programmed) latitude/longitude of the transponder as the turn is completed. However, there is an initial angular overshoot at the end of a turn. This overshoot is exaggerated for the Arctic vehicle, which has a larger turning radius (~9 m, due to hull extension and hook) than an unmodified REMUS-100 (~5 m). Turn overshoot for the Arctic vehicle can be as large as 10^o-15^o after a 180^o degree turn. The overshoot is damped after about 30 s, but if the distance from vehicle to transponder is short, this delay may be sufficient to increase the bearing angle beyond the algorithm threshold (Fig. 11).

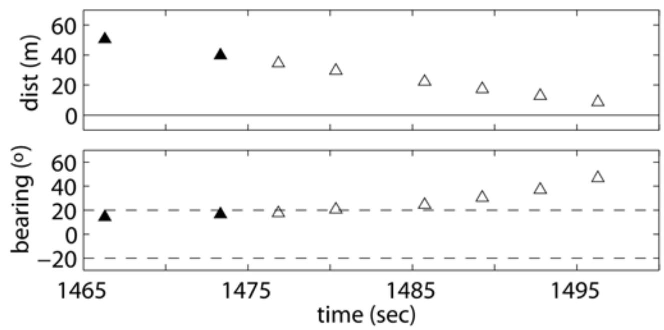

Fig. 11. Estimated distance (a) and bearing (b) to the USBL transponder are shown vs. elapsed time for a docking approach at Camp 3 (mission 14). All fixes with valid ranges are shown. Fixes accepted by the docking algorithm have filled symbols, rejected fixes have open symbols. The first two fixes are accepted, although bearing angles are very near the pre-programmed threshold (+/- 20^o, dashed lines). Subsequent bearing angles greater than the threshold are rejected, although the sequence of decreasing range and increasing bearing indicates that the vehicle is closing on the beacon.

Cross-track currents will have two effects on the turn. First, currents acting during the outbound leg will cause the vehicle to adopt a "crab angle" relative to the track line. Because the initial heading goal for turn completion is 180^o from the vehicle heading prior to the turn, the crab angle offsets the turn completion angle from the reciprocal of the outbound course. Depending on the direction of the current, this may add to the initial turn overshoot. Estimated crab angles for 0.1-0.3 m/s currents are a few degrees, increasing for stronger currents. Secondly, strong currents may make certain headings unstable, increasing the turn settling time or even making some heading goals unattainable.

In addition to position and angular errors due to navigation, there are the angular errors of the USBL fixes themselves (Sec. III.C). These are estimated to be only a few degrees in laboratory conditions, but have not been well characterized for specific vehicle configurations and field conditions (e.g. as a function of distance from the transponder).

With several sources of offset in the bearing angle to the homing beacon at the end of a turn that could accumulate to be larger than the 20^o threshold, it is clear that USBL docking with short approach legs in the presence of currents is challenging. Indeed, docking using only the USBL beacon proved difficult at Camp 2 where test missions were run within a restricted operating area (necessitating short approach legs) in the presence of modest currents. More than two successive docking attempts were increasingly futile – errors accumulated with each unsuccessful approach. The use of LBL navigation (which reduces accumulated position error) and longer approach legs (which reduces sensitivity to position error and turn overshoot) for the survey missions at Camp 3 improved docking performance.

Other strategies could be applied to improve performance in future operations. Strategies relating to USBL navigation include increasing the angular threshold for accepted fixes, using information from multiple fixes to adjust the threshold (Fig.11), and initiating an angular search mode if no fixes are obtained within a certain time after completion of the turn. Strategies utilizing LBL navigation include establishing the desired trajectory towards the beacon with successive waypoints prior to initiating USBL homing, enabling LBL navigation on the turnaround leg after an unsuccessful USBL docking attempt, and controlling the direction of successive approaches after a miss (e.g. 45^o orientation changes) to find a direction that minimizes cross-track currents. Other strategies to improve performance would involve hardware changes such as re-designing the hook to reduce the turning radius, increasing the ping rate of the USBL transponder, using an alternative to acoustic homing that improves data transfer rates [24] or utilizing an omnidirectional USBL array [25].

VI. Summary

The goal of obtaining hydrographic transects beneath coastal sea ice drove three principal modifications to the REMUS AUV: 1) Use of a lower frequency (10 kHz) transponder for LBL navigation and communication, 2) Addition of special-purpose sensors and hardware in a hull extension module, and 3) Development of a docking algorithm using a custom 10/25 kHz USBL transponder.

In March 2010, eight days of field work offshore of Barrow provided successful demonstration of the system. Complex and rapidly changing ice conditions dictated the timing and scope of operations. The use of an easily portable system was critical to achieving the necessary flexibility of operations. The AUV was launched by hand through a 1 × 2 m ice hole. A collapsible cylindrical net was suspended from the same hole using a gantry. A USBL homing beacon placed in the center of the net provided the signal for the docking algorithm. Physical docking was by means of a hook extending from the vehicle nose cap which captured the vehicle in the net. The vehicle and net were then recovered by hand.

In spite of successful tests in a frozen lake, docking beneath coastal sea ice proved difficult during trials using only the USBL transponder. Homing success appears to be most sensitive to the details of initiation and completion of the turn towards the transponder. Accumulated errors may result in offsets in the bearing angle that exceed the tolerance of the docking algorithm. The initial angular overshoot upon turn completion was determined to be the most significant contributor. Sensitivity to turn overshoot is highest for short docking approach legs, and the presence of currents is expected to increase the magnitude and duration of the effect. Dead reckoning speed and compass errors are minor contributors to angular offset. The use of a tether reduces vehicle depth stability during turns, but does not appear to have significant impacts on docking performance.

Utilizing two 10 kHz transponders for LBL navigation during survey missions and increasing the distance between vehicle and transponder for the docking approach improved homing performance and resulted in successful docking. A total of 14 km of track lines beneath a coastal ice floe were obtained from four survey missions using combined USBL and LBL navigation, each successfully terminated by net-capture recovery. These results demonstrate the ability to operate a REMUS AUV from shorefast coastal sea ice to measure the hydrography of Arctic shelf waters.

Attaining the original science goals depends on further evolution of the technical approach, as discussed above, and obtaining access to coastal sea ice under optimal conditions. The acoustic environment showed evidence of scattering, but was amenable to acoustic navigation and communication at 10 kHz. LBL navigation fixes were reliable at ranges of up to 1.25 km and modem communications were reliable at ranges up to 300 m. However, the sub-optimal ice conditions during the March of 2010 (a heavily ridged ice field following a compression event) precluded determination of the maximum range of the 10 kHz acoustics. Future experiments are needed to test performance with increased range. Other areas of interest include developing the capability for the vehicle to relaunch itself when floating up against the ice and evaluating EM interference from transmitters/receivers and the strobe flash that may affect ADCP, USBL and modem performance.

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