Under-ice Operations with a REMUS-100 AUV in the Arctic

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***Abstract*— Use of a REMUS-100 AUV to obtain hydrographic observations beneath coastal sea ice offshore of Barrow, Alaska is described. The work is motivated by the desire to obtain cross-shore hydrographic transects that would provide estimates of the transport of relatively dense, salty water from the Chukchi Sea to the Arctic Ocean in winter. The horizontal scales (~10 km), maximum water depths (~100 m) and desired measurements (temperature, salinity and velocity vs. depth) in the study region match the capabilities of a small AUV such as the REMUS-100. 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) transducer 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 an Ultra-Short Base Line (USBL) array in the AUV nose cap. 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 vehicles, navigation, launch and recovery, Arctic.**

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 transverses the shallow Chukchi Sea where its properties are modified, particularly by cooling, ice formation and brine rejection in winter [1],[2]. Pacific water tends to follow three topographically-steered pathways through the Chukchi Sea [3]-[5]; the eastern most branch passes along the Alaskan coast and is concentrated between Barrow, AK and the eastern flank of Barrow Canyon before entering the Arctic basin (Fig. 1). Understanding the hydrographic properties and volume transport of the Pacific inflow in this region is of great interest in the context of climate change and Arctic sea ice retreat.

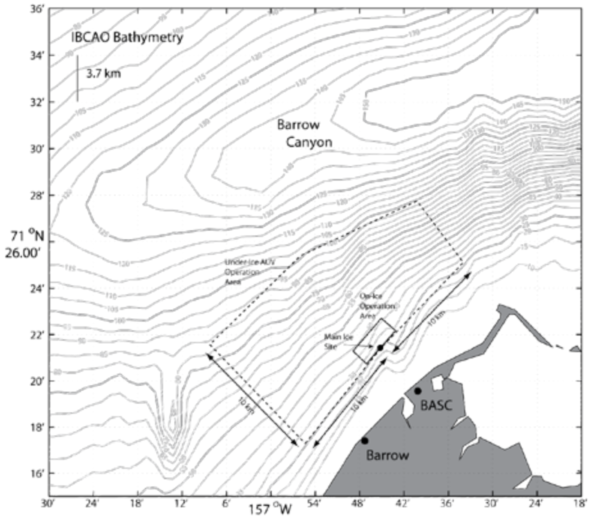

Fig. 1. Map of the study region showing the northwest coast of Alaska, offshore bathymetry along the eastern flank of Barrow Canyon, and the operation area occupied during March 2010 field work. Approximate locations of the town of Barrow, AK and the Barrow Arctic Science Consortium (BASC) are shown.

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 are well suited to the observing capabilities of small (two-person portable), propeller driven autonomous underwater vehicles (AUVs).

Cross-shore hydrographic transects obtained with the Remote Environmental Measuring UnitS (REMUS) AUV in summer [6] 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.

Coastal sea-ice conditions are complex and change rapidly [7], [8]. 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.

Drawing on prior work using small AUVs for under-ice operations [9]-[13] as well as our experience with the REMUS AUV in open water, a modified REMUS-100 capable of through-ice launch/recovery and autonomous under-ice navigation was developed and demonstrated in the field.

II. SENSORS AND HARDWARE

A REMUS AUV rated to 100 m depth [14], [15] was outfitted with a specific suite of sensors and hardware in preparation for under-ice observations (Fig. 2). The REMUS-100 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, the GPS receiver defines the launch point and the WiFi channel is used during pre-mission testing and configuration.

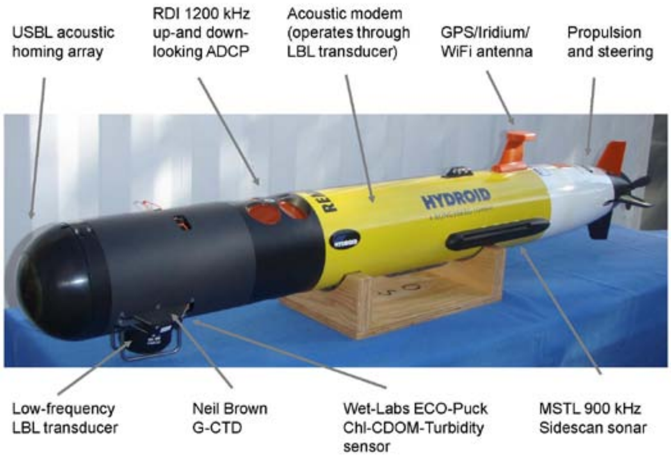

Fig. 2. The REMUS-100 AUV as delivered. The location of principal systems and sensors is shown.

The science sensors include a Neil Brown Ocean Systems conductivity-temperature-depth (CTD) sensor [16], a Teledyne/RDI dual (up- and down-looking) Acoustic Doppler Current Profiler (ADCP), and a WetLabs Environmental Characterization Optics (ECO) sensor. The 1200 kHz ADCP provides water velocity profiles to a range of about 15 m, depending on environmental conditions. The down-looking beams provide bottom-track velocity as an aid to navigation and serve 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 MTS 900 kHz sidescan sonar system was integrated into the vehicle, providing the capability for bottom imaging (or if inverted, under-ice imaging [12], [13]) but was not used in this study.

The acoustic system included a 10 kHz WHOI micro-modem, a 10 kHz spread spectrum Long Base Line (LBL) navigation system, and a four element, 25 kHz Ultra Short Base Line (USBL) navigation system [17]. The LBL system provides simultaneous estimates of 1-way travel time to two or more transponders. Travel times are converted to positions based on known transponder locations in the vehicle configuration file. 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.

Lower frequencies (10 kHz rather than the 25 kHz standard) were used for the modem and LBL system (see Sec III.A). 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 vehicle interrogated the transponder with its 10 kHz transducer (shared by the LBL and modem). The USBL transponder was modified to listen at 10 kHz and respond at 25 kHz, suitable for reception by the nose mounted array. The USBL system computes a range and relative bearing estimate, and reports that to the vehicle via an RS-232 interface.

The standard vehicle was augmented with 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).

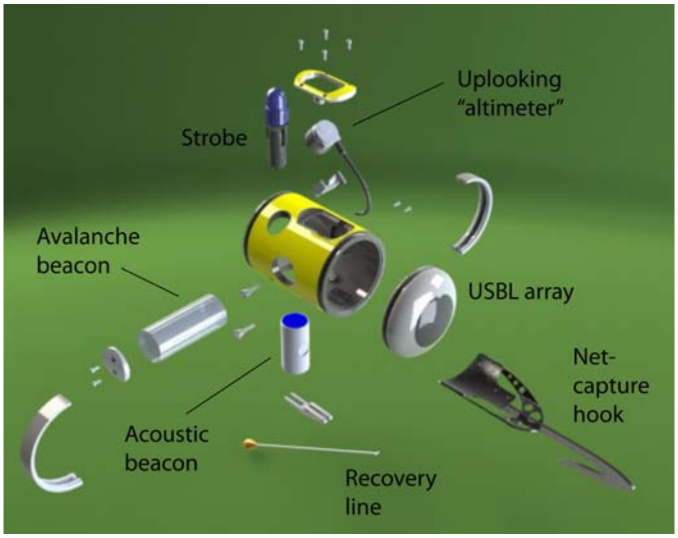

Fig. 3. Exploded design drawing of the hull extension module, the nose cap with USBL array, and the net-capture hook assembly.

A net-capture 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 forms a series of 12 x 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.

In the event of unsuccessful docking or vehicle failure, a number of alternative under ice location and recovery options were incorporated in the hull module. An avalanche beacon allows under-ice position to be determined from the surface at initial detection 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 Dive Tracker is an acoustic beacon that can be homed in on using 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 strobe light improves the likelihood of locating the vehicle visually at night.

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

An Imagenex 852 narrow-beam echosounder was mounted in a bracket that allowed the beam to be positioned vertically or at angles up to 45 degrees forward. 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. Tilted forward and integrated with the navigation system, the echosounder could be used for ice keel avoidance.

Additional mechanical hardware installed for vehicle protection was a prop guard made out of a lightweight polycarbonate material. The guard protects a temporary tether from getting cut by the prop during initial testing, protects the prop from getting damaged from hitting the ice.

III. ACOUSTIC NAVIGATION AND COMMUNICATION

A. *The Acoustic Environment*

Arctic coastal waters offer significantly different acoustic propagation and noise field characteristics than other parts of the ocean, particularly during ice-covered months in the winter. In mid-latitude oceans, surface water is typically warmer and thus the surface sound speed is faster, causing sound to turn away (refract) from the surface. In the Arctic, the surface water is colder so that sound rays will eventually bend back to the surface if the water is deep enough.

However, in coastal regions such as off Barrow, 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 near shore is that the ice tends to pile up, creating large keels which can completely block the sound. Finally shorefast ice (with the exception of compression events) is fairly stable, and thus there is little noise.

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, shows total variation from top to bottom is approximately one-half degree, 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.

The acoustic modem was used on all missions to monitor the progress and status of the vehicle. Because the missions were completed within ~300 m of the base camp, the maximum range of acoustic communications was not approached. Still, it is instructive to look at some of the parameters that affect performance. One key item is the scatter that the signal is subjected to on the path from source to receiver. In Fig. 5, an example impulse response is shown which exhibits two primary peaks spanning about 4 msec and an overall response duration of approximately 10 msec. 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.

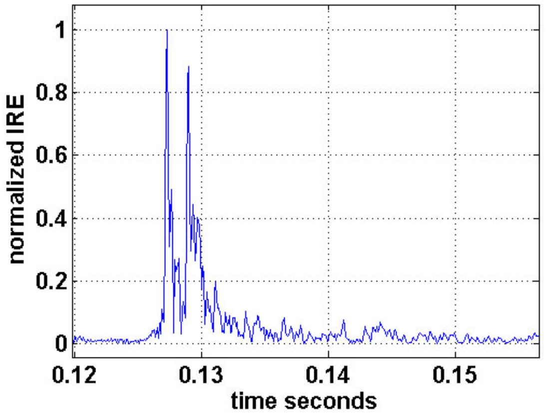

Fig. 5. Normalized impulse response function obtained from acoustic communications testing.

An example of acoustic communication results is shown in Fig. 6, where the power of the detected signal and the data quality are plotted versus time from mission start. The power varies by about 6 dB as the vehicle distance and orientation change throughout the mission and the quality factor stays high (because of the high SNR and the modest spreading). Nearly every packet that was transmitted was received. Thus, despite the scatter from the ice, short-range communications in this environment is quite reliable; future experiments are needed to test performance with increased range.

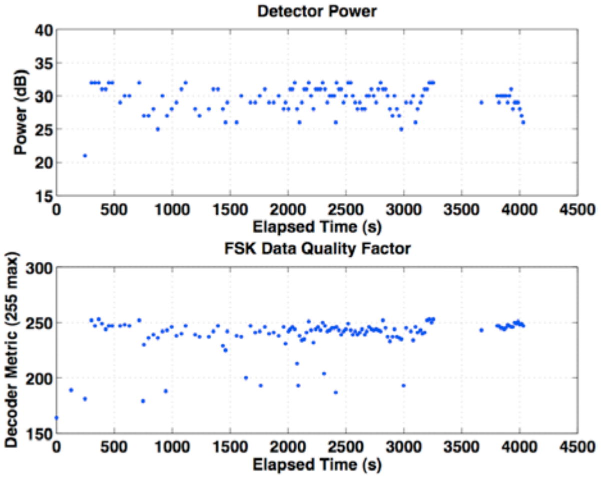

Fig. 6. Acoustic signal detection test showing signal power (upper) and quality (lower) vs. time during an under-ice mission.

B. AUV navigation and communication

Navigation modes

REMUS continually computes its best estimate of the current vehicle position during a mission. Its dead reckoning algorithms incorporate water velocity estimates and bottom track data from the ADCP, as well as information from the compass, and even the prop turns. The position estimates are updated and improved using other systems when available, including GPS, LBL, and USBL. Unfortunately, GPS does not function under water or under ice.

When using LBL the vehicle operates within acoustic range of two or more digital acoustic transponders. The location of each transponder is preprogrammed into the mission file – the vehicle determines its range to each transponder and computes its position by triangulation.

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 because most of the error/noise is angular.

Communication modes

REMUS normally broadcasts a 32 byte “health” message once per minute. This message allows the operators to verify that the vehicle is operating properly, is on course, and that the instruments are functioning. A simple hand held device (“the ranger”) can be used to listen to these messages. However, a more complicated system can also be used where the operator actively interrogates the vehicle, and additional data can be gathered and plotted on a map in real time.

LBL and USBL fix age received through the heath messages allowed us to know whether the vehicle was navigating effectively or if it had lost contact with the transponders. Given the ruggedness of our operations area and the potential need to mount a rescue effort, the most important real time data from the vehicle was range and heading to the ice hole. It was also possible to anticipate the vehicle approach to the ice hole in real time. We were able to then see the vehicle approach the net visually and observe “near misses”.

Docking algorithms

A number of algorithms have been developed for docking REMUS to fixed and mobile platforms. For fixed platforms mounted on the ocean floor, the vehicle follows a pre-programmed glide path into a receiving cone that guides the vehicle into an inner cylinder where it can make a hardwired power and data connection [17]. For mobile platforms, WHOI has developed procedures for docking to a line suspended vertically in the water column. This procedure uses a set of whiskers that are folded out of the way during the mission, but open during docking to increase the aperture, and thus make it easier to grab the line. There is a latch to firmly grasp the cable once it is captured. This procedure has the advantage of allowing the vehicle to approach from any direction, and is largely insensitive to errors in depth. For this reason, the “mobile docking” algorithm was chosen as the basis for under ice docking. The whisker/latch mechanism was replaced with a simple hook extending from the vehicle nose. The hook captures the vehicle in a cylindrical net deployed from the recovery hole with a transponder in its center (Fig. 4). This increased error tolerance (since the net was significantly wider than a cable) 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 some unintended object.

The docking algorithm used USBL homing to determine the range and bearing to the "dock" (the net in this case), and then the vehicle determined the appropriate course. If the vehicle missed the net, it would continue past it, then turn around and make another approach. In practice there proved to be a number of problems with this concept.

One of the problems was that if the vehicle repeatedly failed to get valid USBL fixes, it was effectively navigating by dead reckoning. This would typically result in additional navigational errors, and after several unsuccessful docking attempts, the vehicle could become "lost" (unable to determine its absolute position). Also, if the vehicle did not travel far enough from the net after a miss before turning around, it sometimes had a difficult time establishing a steady "glide path" towards the net.

An obvious improvement would be to have the vehicle also use LBL for navigation while docking. The vehicle also has navigation objective designed to "find" a lost transponder, which might prove useful in future experiments.

IV. DEPLOYMENTS

A. *Preparation and Testing*

Open water tests were done offshore of Woods Hole, MA in the September 2009 and January 2010. The performance of USBL, LBL, and modem systems were verified, and the appropriate diameter of the net capture system was determined by the average distance the vehicle missed the transponder. Current in Buzzard's Bay averaged 13 cm/sec and was presumed to be a minor factor in docking performance.

Preliminary tests of through-ice launch/recovery and under-ice navigation were conducted in Mendum's Pond, NH in February 2010. Mendum's Pond provided a benign environment (no ice ridges, minimal current) to test under-ice navigation and acoustics with little risk of losing the vehicle. All systems were tested including the ROV that would be used for recovery in the event the vehicle missed the net and was inaccessible through an ice hole.

We learned that a major drawback of the vehicle completing its mission without successful net capture, or aborting itself unexpectedly while under the ice, was that the vehicle could relaunch due to its inability to pitch its tail up, gain momentum and dive when not in open water. Under these circumstances, the only method of recovering the AUV is to drill a hole in the ice large enough to extract it. 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 in the vehicle's ability to drive forward and maintain depth. The results were encouraging with 100% (5/5) successful docking attempts in the net. We also were able to duplicate prior results [13], showing the ability to download data and manually drive the vehicle while under 25 cm of freshwater ice using WiFi. However, WiFi communication proved impossible through saltwater ice in the Arctic.

B. *Ice Access and Logistics*

In March 2010, field operations were conducted out of the Barrow, AK, where the Barrow Arctic Science Consortium (BASC) was available for logistical support before and during our 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 containing our gear were used to get to the operation sites on a daily basis. One bear guard per group and one weather and ice expert from BASC were hired to accompany the science team.

After a day unpacking and testing equipment, day two saw the establishment of an operations camp (a 1 x 2 m hand-cut hole, gantry, and tent) on a 300 m x 1500 m floe without significant offshore ridges. The conditions appeared ideal. However, within about an hour of Camp 1 being established, a significant compression event occurred, breaking up the floe and destroying the camp. The gantry, used for holding the capture net in place, was saved by our Inupiat guides. We quickly learned what others [7], [8] 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 we reviewed weather and ice conditions (using a land-based radar, see [8]) each morning, made only day trips leaving no gear on the ice, and were prepared to pack up and leave the ice on short notice.

C. *Camp 2*

On day three, a team was sent back out to establish Camp 2. A second 1 x 2 m hole was hand-cut for vehicle and net deployment. Ice thickness was about 20 cm. The water depth below the hole was about 15 m. This site was on the remains of the large floe identified for Camp 1, and consisted of an open area of only about 50 x 70 m surrounded by ridges 1-2 m tall (Fig. 7). The vehicle was ballasted, basic function checks were completed, and three test missions were run.

On day four, the gantry and tents were set up, and the complete science team and all of the gear was transported to Camp 2. The vehicle was wrapped with a heat coil powered by a Honda generator to keep the Lithium-ion batteries above 0°C. The team set up two tents, one for the vehicle and auxiliary tracking gear which included acoustic tracking gear, a WiFi router for communicating to the vehicle and a laptop, and the other for a CTD, personnel and miscellaneous supplies including food.

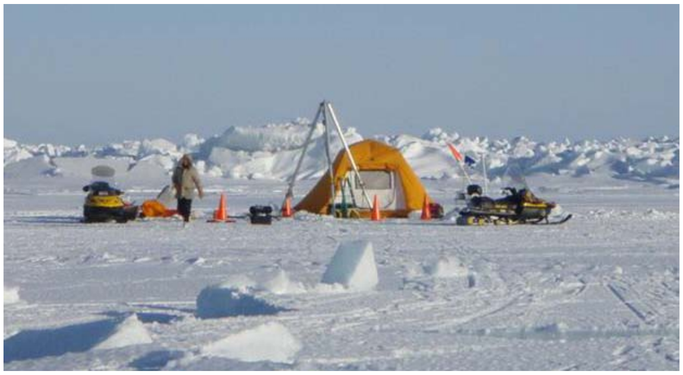

Fig. 7. Photo of Camp 2 showing operations tent, gantry and snowmobiles. Note the near proximity of ice ridges in the foreground and background.

REMUS was placed in the ice hole (Fig. 8) and pre-mission diagnostics were run using WiFi communications. Missions to test navigation, acoustic communication and compass performance were run using the tether. The vehicle was easily launched by lifting the tail out of the water and spinning the prop by hand to start the mission. The -20 degree pitch of the vehicle upon release was enough to dive the vehicle under the ice. The tether enabled us to pull the vehicle back to the ice hole for wireless data download and relaunching. All vehicle systems checked out OK during these missions, but the navigation performance was not as good as expected. Poor compass performance was suspected, but after examining vehicle data from subsequent runs, it was determined that the tether, coupled with high currents and no navigational beacons were the likely cause of poor vehicle navigation. The compass, in fact, performed well (see Sec. IV.D).

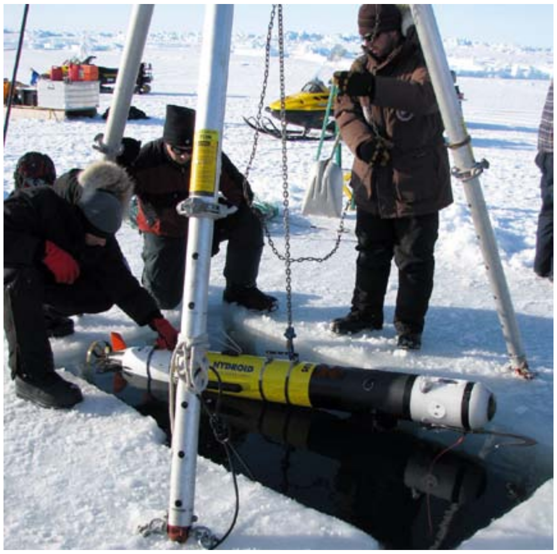

Fig. 8. Photo of AUV being prepared for deployment at Camp 2.

After two test missions, the USBL beacon and net were deployed in the center of the ice hole at a depth of 6 meters. The vehicle's initial leg was programmed to 80 meters at a depth of 8 meters and speed of 1.3 m/s. Docking was the next navigation objective. The docking parameters were a depth of 6 meters, speed of 1.5 m/s and a turnaround range of 50 m. The USBL array pings the transponder every three seconds on the inbound leg. If the vehicle misses the net it continues until the turnaround range is reached, turns, and approaches the beacon again using USBL homing. The number of repeats is preprogrammed in the mission configuration file.

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 a few missed docking attempts. As the number of attempts increases, there are enough different angles to fill in a "flower petal" pattern (Fig. 9). If the vehicle never hits the net, the mission will end and the vehicle will float up under the ice. With the tether attached, the vehicle is gently hauled back to the ice hole. Without a tether, the distance and location of the vehicle would determine whether we had to drill another hole or use the ROV through our existing launch hole for recovery.

The third mission, with the net and USBL beacon deployed but still using the tether, showed poor navigation performance and unsuccessful docking. Successful USBL ranging averaged only 14%. Given the constraints of the small operational area for the REMUS to swim in, the poor results were difficult to pin down. The possibilities considered included strong currents, EM interference from the avalanche beacon, strobe light, or Dive Tracker, 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 glide path.

The fourth and final mission of day four was run with a cracked prop shroud and, in an attempt to diagnose docking performance, a large number of pre-programmed docking attempts. After 15 missed docking attempts (Fig. 9), the tether was cut by the prop and the vehicle swam beyond its safe zone and got stuck in a "tunnel" within an ice ridge. The vehicle was pinpointed to a range of ~3 m using a handheld avalanche beacon receiver. Augers were used to drill 5 cm holes to get an understanding of the ice thickness. A custom-made melter was retrieved from shore in an attempt to melt a hole large enough to retrieve the vehicle, but the combination of minor damage from the bumpy sled ride and the frigid temperature of -35 °C prevented it from working. We were unable to send or receive any commands to and from the vehicle and given the time of night, decided to leave the vehicle under the ice and return on day five with a variety of tools for location and recovery.

Final recovery of REMUS from about 2.5 m deep under multiple layers of ice was accomplished on day five 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 broken prop guard and bent prop.

An evaluation of Camp 2 operations concluded that the safe operating area was too small for additional tests. We decided to use day six to scout out a larger ice floe that would allow the vehicle more space for acquiring USBL fixes using turnaround legs of 75 meters instead of 50 meters.

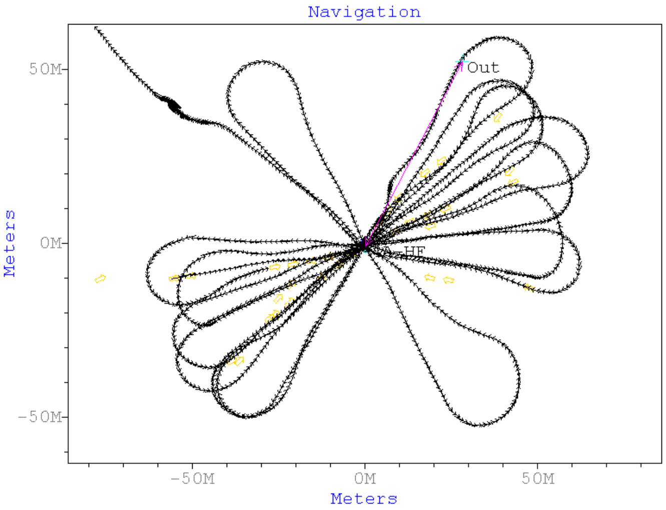

Fig. 9. Navigation record for the final mission at Camp 2. The flower petal pattern is created by multiple passes using the docking algorithm. Successful USBL locations are shown as yellow arrows.

D. *Camp 3*

Camp 3 was accessed by hand-cutting a trail further northeast on the ice sheet. An un-ridged floe of about 200 x 500 m was identified. We also deployed two 10 kHz LBL transponders to help aid the vehicle's navigation after experiencing poor results with using solely USBL. The transponders were 1800 m apart and 300 m inshore of the baseline. Successful ranging to the transponders was verified with the vehicle floating in the ice hole prior to deployment.

Day seven included four tethered test missions followed by two untethered survey missions terminated by successful docking (net capture). The survey mission 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 before heading out on an LBL navigation leg to re-establish the "glide path" for subsequent docking attempts.

The first survey mission included about 1800 m of track line along the survey grid followed by successfully docking on the second try. The vehicle hit the center of the net with the hook and remained stuck in the net until we manually pulled the vehicle up by hauling the net and releasing the hook. The vehicle's prop was still spinning and we found that it was still in mission mode because it had remaining objectives in its mission file. In order to stop the prop we had to manually apply the magnetic "off" switch or send an acoustic abort command.

The mission plan for the second survey was an exact repeat of the first survey. The vehicle missed the net on the first six tries, 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 showed that LBL fixes are a key component to obtaining under ice navigation accuracy suitable for autonomous docking.

On day eight, two more "mow the lawn" survey missions were run at Camp 3. The first mission plan was identical to those of the previous surveys, but with the Dive Tracker shut off to allow testing of modem performance without acoustic interference (see Sec. III.A). At the termination of this survey, the vehicle missed all six attempts in the first docking cycle. After re-establishing the glide path following an LBL navigation leg, it caught the net on the first try of the second docking cycle.

For the second survey mission, two 400 m 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.

The docking lesson from the survey runs was that if the vehicle did not dock successfully on the first few attempts, repeated approaches were increasingly futile – a LBL navigation leg was essential for the vehicle to re-establish the track line for a docking approach.

Analysis of mission files from the survey runs showed that, based on the LBL nav fixes, the True North compass was less then 1 degree off from its local declination of 18.79^o east positive. This was significantly better than expected, and eliminated compass error as being a significant factor in the relatively poor USBL performance experienced in previous missions.

The USBL fix success rate increased dramatically (from 14% in early runs) during the survey missions where LBL beacons were included (Table 1). This was particularly evident when successful docking immediately followed an LBL leg (surveys 1 and 4), where USBL fix success was 70-75%.

TABLE I
NAVIGATION FIX SUCCESS RATES

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

Percentage of "accepted" fixes for LBL and USBL navigation legs during four survey missions conducted at Camp 3.

V. SUMMARY

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

In March 2010, eight days of field work offshore of Barrow provided successful demonstration of the system. The AUV was launched through a 1 x 2 m ice hole without special equipment. A collapsible cylindrical net in conjunction with a hook extending from the vehicle nose cap was used for mechanical recovery. A USBL homing beacon placed in the center of the net provided the signal for a custom homing algorithm. Complex and rapidly changing ice conditions dictated the timing and scope of operations. Net capture proved difficult during short test missions using only the USBL beacon. The addition of two 10 kHz LBL transducers (and removal of a tether used during initial tests) greatly improved navigation performance and resulted in successful homing to the capture net. A total of 14 km of track lines beneath a coastal ice floe were obtained from four survey missions, each successfully terminated by net-capture recovery. This work demonstrates 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 and obtaining access to coastal sea ice under optimal conditions. Future developments relating to the docking algorithm include allowing LBL navigation on the outbound legs after unsuccessful docking attempts, using longer outbound legs to give the vehicle more time to find the transponder after the turn, increasing the length of outbound legs dynamically based on the relative success of USBL fixes on the previous inbound leg, determining the nature of off-axis responses that are rejected by the algorithm, and determining the utility of the ‘Find’ objective as a means of re-establishing the range and bearing to the dock after multiple unsuccessful attempts. Areas of interest other than the docking algorithm include developing the capability for the vehicle to relaunch itself when floating up against the ice and further evaluation of EM interference from transmitters/receivers and strobe flash that may affect ADCP, USBL and modem performance.

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