Long Range Acoustic Communications and Navigation in the Arctic

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Abstract— **A long-range acoustic navigation system with built-in acoustic communications capability has been developed for use by underwater gliders, drifters and vehicles under Arctic ice where surfacing to acquire GPS position may be risky or impossible. The system consists of multiple buoys placed on the ice with transducers suspended 100 m below, each of which is programmed to transmit in a specific time slot at regular intervals. The system operates at 900 Hz, and has programmable bandwidth, from 25 to 100 Hz. The communications data rate for the system is several bits per second, sufficient to transmit the GPS location of the buoys and several bytes of data to vehicles under the ice. The system was deployed in March of 2014 and operated through the fall of 2014, testing the performance of both the navigation and communications capabilities of the system in conjunction with Seagliders deployed by the University of Washington. Ranges of greater than 400 km were achieved with range accuracy of 40 m RMS for the case where the speed of sound is known. The long range and excellent accuracy were the result of ducted sound propagation in the Beaufort Sea.**

I. Introduction

Unmanned systems, whether powered, gliding or drifting, represent the best platforms for extensive sampling of the ocean in areas that are ice-covered. However, navigation, telemetry and control of these platforms are all difficult because the ice makes it hazardous for them to surface for a GPS fix and to receive commands via satellite. While inertial navigation and Doppler velocity logs continue to improve the navigation capabilities of underwater vehicles, for water column operations these methods are not presently practical, and thus, acoustics is presently the only practical long-range method for positioning and maintaining control of under-ice platforms.

There are multiple range scales for acoustic positioning under Arctic ice, which are summarized in [1] along with methods for joint use of low frequency sources for both long-range navigation and acoustic tomography. Frequencies between 250 and 1500 Hz have been regularly used for Arctic medium-scale tomography experiments and offer a combination of moderate cost for sources and ranges in excess of 100 km (Arctic) and 500 km (Antarctic).

Navigation of gliders using fixed sources has been performed in Davis Strait by researchers at the Applied Physics Laboratory at the University of Washington. The group uses fixed sources moored to the ocean bottom, which transmit on regular intervals [2]. The locations of the sources are known, and the location of the gliders is estimated by converting the measured travel times from two or more sources to ranges and calculating the position. This method works very well for operations that are conducted in fixed areas, but it is not feasible to place bottom sources over very large areas of the Arctic, motivating development of ice-based navigation sources that are co-located with above-ice instrumentation. However, ice-based sources must also transmit their location along with the ranging signal, increasing the complexity and power of such systems.

In anticipation of future under-ice operations by autonomous vehicles, the Woods Hole Oceanographic Institution began working on developing methods and establishing the performance of acoustic communications for the Arctic in 2007. The work described here builds on that published in [3], which reported on two earlier experiments, one north of Alaska, the other north of Svalbard. In both the maximum ranges that were achieved were less than 100 km and limited by prevailing propagation conditions and source/receiver placement.

The present development effort whose results are reported here was undertaken for the US Office of Naval Research Marginal Ice Zone Departmental Research Initiative (MIZ-DRI). The goal of that program is to simultaneously sample above, within, and below the ice from winter through summer, and to do so using sensors that are co-located. Thus data collected by gliders or profiling floats in the water column beneath the ice needs to be from the same area as sensors measuring sunlight, temperature, wind, waves and other parameters above. This need for co-located data drove the decision to place the navigation beacons on the ice, and the need to provide real-time navigation for the gliders drove the requirement for the beacons to transmit their locations.

The paper is organized as follows: The approach and description of the hardware is provided first, followed by a summary of the buoy-to-buoy range and time-of-arrival statistics. A discussion of the acoustic propagation conditions based on transmission loss modeling is included to help explain the excellent performance of the system followed by conclusions and future plans.

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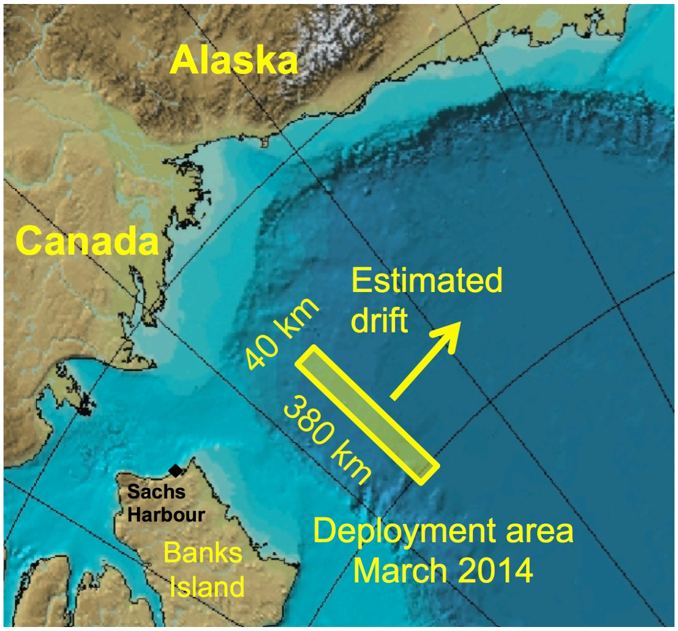

Figure 1. Location of the equipment deployments in March 2014. The navigation systems and sensors were deployed by plane from Sachs Harbour on Banks Island, Canada.

II. Experiment and System Overview

The study area for the MIZ-DRI is the Beaufort Sea and Canada Basin spanning the Arctic Ocean from Banks Island in Canada to the Chukchi Sea (Figure 1). The deployment of the sensor array, including the navigation sources, was done along a north-south line spanning approximately 400 km. Sensors were grouped in clusters that transitioned from solid winter ice through the melt phase in late summer, and then into open water in fall of 2014. Details are included in the science plan for the effort [4], with many publications forthcoming based on data collected during the 2014 experiment.

The navigation system itself consists of an array of sources suspended from the surface with the electronics enclosed in a buoy that sits on the ice. The buoys are equipped with GPS receiver, Iridium terminal, acoustic modem, amplifier and battery. Each source operates on a fixed schedule, broadcasting six times per day with each transmission synchronized precisely to GPS time. The transmissions consist of a navigation signal, data with the location of the source at the transit time, and an optional command. Receivers on navigation clients, for example a Seaglider, are turned on for a 30 minute window when the sources are active.

While the buoys operate on a fixed schedule, they check for incoming commands via Iridium every time they turn on to perform a transmission. Thus it is possible to change the schedule or disable transmissions in response to changes in season or location, something that is not possible with fixed sources located on the seafloor. The programmability of the system was utilized to perform a number of different tests during the experiment and after the main part of the test was over. These tests included different data rates and bandwidths, allowing exploration of link efficiency and travel time estimation accuracy.

A. Source Buoy Design and Construction

The surface buoy design is new but based on several generations of Ice Tethered Profilers (ITP) that have been used for many years to collect water column data in the Arctic using a cable-crawling sensor package [5]. The buoy consists of a shaped foam collar with aluminum pressure housing with a radome on top to protect the GPS and Iridium antennas (Figure 2) plus a urethane-filled hose with spiral conductors for the through-ice transition where a cable would be vulnerable.

The buoy is designed to float after melting out of the ice floe that it is installed on, so that it will continue to provide navigation information in the MIZ, and it is constructed for easy recovery when drifting. The source is mounted into a cage suspended 100 m below the buoy, and requires a ten-inch diameter hole be drilled in the ice. A 30 kg weight provides a compromise between deployment ease and keeping the cable as vertical as possible when the ice is moving. The deployment of the source directly below holds the buoy upright after it is positioned over the hole in the ice.

Figure 2. Navigation buoy after deployment from Sachs Harbour.

B. Navigation and Communications Signal

The carrier frequency for the signal was chosen to be 900 Hz, and the bandwidth (and thus the symbol rate) was 25 Hz. While bandwidths from 10 to 100 Hz (and higher) are possible with the processing system, the optimal band for maximum power efficiency is 25-50 Hz. A number of experiments were done with 50 Hz and performance with respect to bandwidth and range will be included in future papers. While the data rate is also programmable, very conservative low-rate coding was employed and the resulting data rate was approximately 1 bit per second. The source level is approximately 183 dB re micro-Pascal which requires 50 W electrical. The acoustic source is a commercial flexural disk design that is nearly omnidirectional.

The beacon transmission includes a frequency-modulated (FM) sweep, followed by phase-modulated data with the source location and optionally several bytes of commands or information for the glider resulting in a total of 5 bytes to 9 bytes of data. The time of arrival based on the FM sweep and the source position encoded in the data are provided to the glider after the reception is complete. The glider then uses the source schedule to identify what minute the buoy transmitted and computes the one-way travel time. While the transmissions occur every four hours, the interval is programmable and can be changed if necessary depending on requirements and mission length. To avoid interference between the signals from different buoys they transmit in four-minute slots, which allows for approximately 240 km of channel-clearing time because the signal lasts approximately one minute. The position of the source is encoded in 40 bits, providing 22 m resolution in latitude and 10 m resolution in longitude at 75 deg N.

C. *Vehicle Hardware and Installation*

A low-frequency version of the WHOI Micro-Modem [6] is also used on the client systems, though without the amplifier and source. The reeiver hardware consists of a small circuit board that is in the dry space of the vehicle, and an external hydrophone (Figure 3). The vehicle controller turns on power to the receiver using the fixed *a-priori* transmission schedule, and the receiver remains active for the 30-minute period when all of the sources are active, each of which transmits in a 4-minute window. The time base on the gliders and floats systems is a SeaScan clock (drift of less than 1 msec/day), and the modem receiver is synchronized to the clock each time it is powered on. The modem provides the exact time of arrival, and the vehicle processor computes the one-way time-of-flight based on the known transmit time, then converts that to range based on measured or estimated average sound-speed. In the case of the gliders they can use measurements made with their on-board CTD. Finally, the on the Seagliders position is calculated using multiple range estimates from the different receivers and possibly combined with dead-reckoning [7].

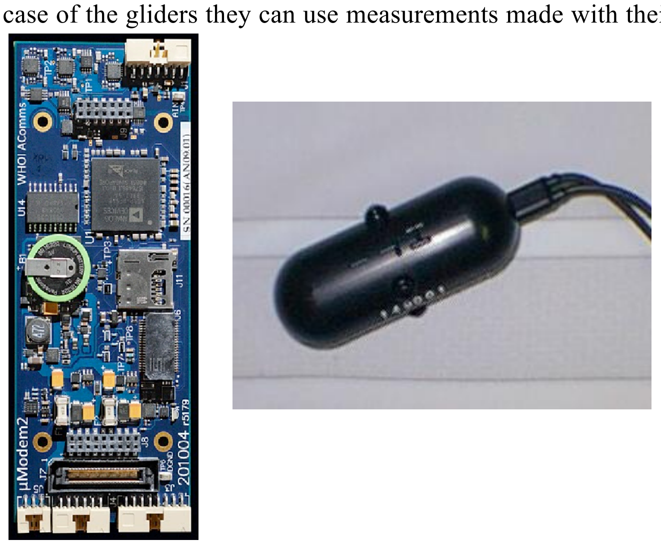

Figure 3 Navigation client equipment installed on the Seagliders and profiling floats. Left: Micro-Modem electronics board. Right: High-Tech Inc. hydrophone.

III. RESULTS

The on-ice instruments, nine acoustic beacons and ten profiling floats were deployed by small plane from Banks Island in Canada in March of 2014 in the area shown in Figure 1. The APL-UW Seagliders were deployed from Deadhorse, Alaska in July in open water and recovered in September, also in open water. From July through September the Seagliders transited north to the ice edge and then into the MIZ. They used a combination of the acoustic ranging system described here and GPS fixes acquired during occasional surfacings to navigate during time they were under ice. Initial results from the Seaglider operations and details about the Kalman filter used to integrate GPS, dead-reckoning and the acoustic-derived ranges are provided in [7]. Due to an unknown flaw in the configuration or programming of the profiling floats none of them reported data or were recovered, and thus they are not discussed further here.

A. *Receiver Performance*

The receivers on each of the buoys are enabled during the entire period when they transmit, and thus it was possible to monitor the performance of the system as soon as the network was deployed in late March, 2014 and continuing through the fall to the point where the buoys began to fail or drift into the Chukchi where the acoustic propagation changed. The original plan for beacons was based on maximum ranges of approximately 100 km, but after deployment it quickly became clear that the system was operating at several times that range. Reasons for that will be discussed in a later section.

The performance of the system in terms of navigation error was calculated by comparing the GPS-derived range with the measured acoustic travel time. To make an estimate of the best-case error the sound-speed is estimated such that the mean of the range error is near zero. This represents the case where sound-speed is perfectly known, providing a lower bound. The range error histogram for one buoy pair over several weeks at ranges that varied between 200 and 250 km is shown in Figure 4. The standard deviation is 40 m for this data set, and results were similar for most of the rest of the acoustic array.

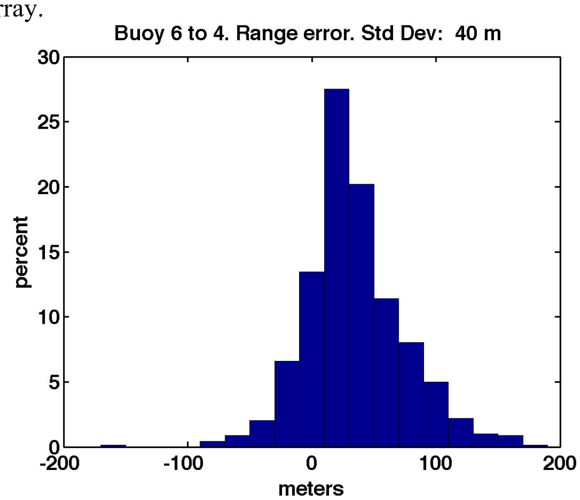

Figure 4 Range error for absolute ranges between 200 and 250 km for a specific buoy pair.

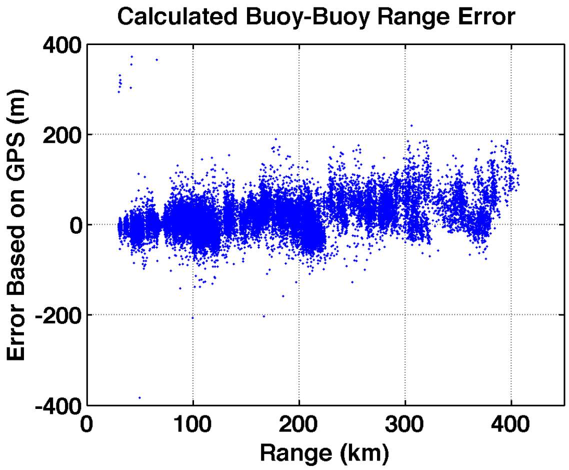

Figure 5 Error versus range for all of the buoy pairs from start through July. The residual slope is due to a slight difference between the estimated and real sound speed for all of the pairs.

The entire record of range errors from the field of buoys is shown in Figure 5. While the range error does increase as the distance between buoys grows, it is remarkably similar between 100 and 400 km. It is assumed that this low error is because there is very little time-spread in the propagation of the signal from source to receiver as will be described below.

IV. ACOUSTIC PROPAGATION

The WHOI ice-tethered profilers that were deployed as part of the instrument array transmit CTD information after each profile. The temperature profile from one of the casts right after deployment is shown in Figure 6.

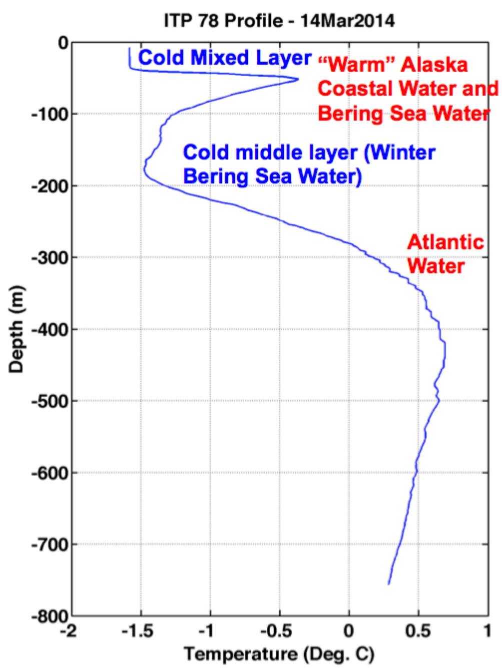

Figure 6 ITP profile showing the temperature with respect to depth and annotations with the assumed source of the different water masses.

The profile shows a distinct layer of cold winter water from the Bering Sea between 100 and 200 meters that is trapped below the 50 m deep winter mixed layer, and above the warm Atlantic water whose maximum temperature is at 400 m depth. The sound speed corresponding to the ITP temperature profile is shown in Figure 7, and it shows that the differential between the cold upper layer and the warm water below creates a sound-speed maxima which is responsible containment of the acoustic energy in the cold middle layer.

The upper layer of the duct prevents the signal from interacting with the ice, where it would scatter, and the combination of the warm Atlantic water and the pressure effect on sound speed combine to refract the signal back toward the surface without bottom interaction. The sound is thus trapped and consequently propagates for hundreds of kilometers as demonstrated in the transmission loss plot in Figure 8.

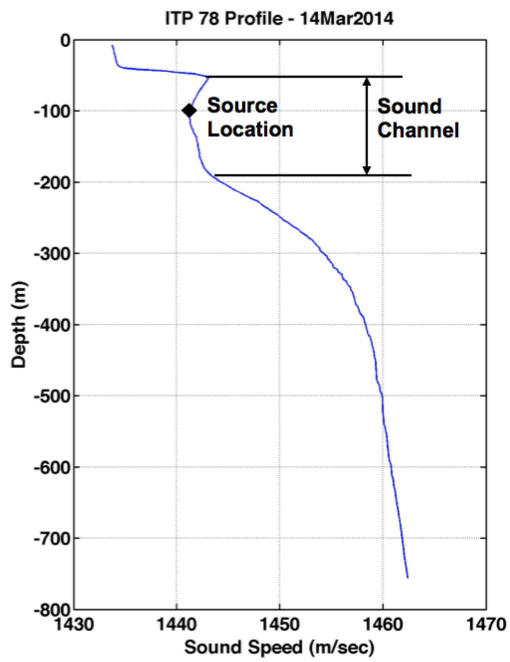

Figure 7 Sound speed corresponding to the CTD profile from the ITP in March 2014.

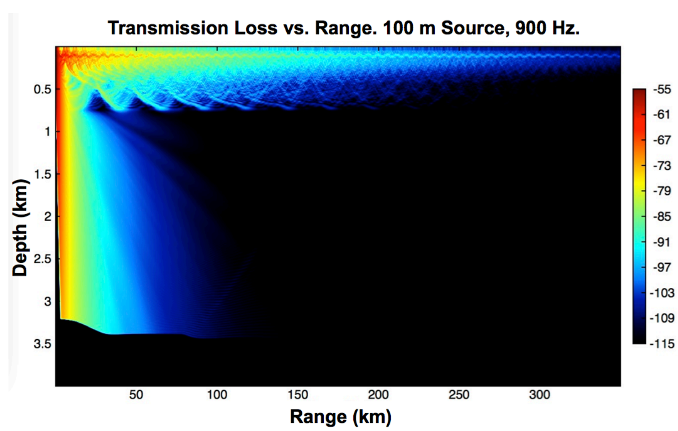

Figure 8 Transmission loss with respect to range corresponding to the sound speed profile from the ice-tethered profiler from March 2014. Courtesy K. Heany, OASIS.

V. Conclusions

An underwater acoustic communications and navigation system for use in the Arctic by autonomous vehicles and floats was designed, built and demonstrated for a major marginal ice zone field program. The system includes digital data telemetry, solving the problem that results when sources are moving with the pack ice, and it also provides for short commands to be sent to the underwater vehicles. Despite the required brevity of the commands there is sufficient bandwidth to include destination addressing and information such as new waypoints or headings for the vehicles.

While in the eastern Arctic north of Svalbard the range of the 900 Hz system is approximately 100 km, in the western Arctic north of Alaska the intrusion of warm summer water above cold winter water creates a layer that refracts sound away from the surface. The result is acoustic ranges in excess of 400 km with very low dispersion and thus very low RMS error in travel time. Exploitation of the favorable propagation conditions will enable future robotic exploration of ice-covered areas of the western Arctic Ocean.

Acknowledgments

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