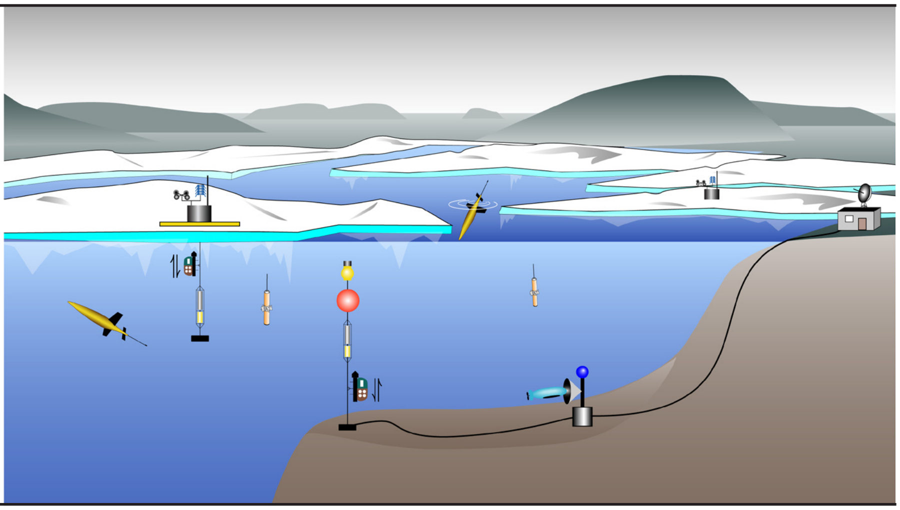

Acoustic Navigation and Communications for High-latitude Ocean Research

A Report from an International Workshop Sponsored by the National Science Foundation Office of Polar Programs

27 February – 1 March 2006
Applied Physics Laboratory
University of Washington
Seattle, WA, U.S.A.

The ANCHOR Workshop report was prepared by the Applied Physics Laboratory, University of Washington, Seattle, and distributed in July 2008 under National Science Foundation Office of Polar Programs grant ACR-0511163.

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Executive summary

Motivated by potentially large advances in Arctic Ocean observing offered by emerging autonomous sampling platforms, the National Science Foundation Office of Polar Programs sponsored a workshop to explore Arctic acoustic navigation and communications. Autonomous platforms require geolocation and telemetry. In ice-free environments, the Global Positioning System (GPS) and Iridium Satellite Communications System provide these services. Together, these two critical enabling technologies fostered a revolution in lower-latitude ocean observing that includes the ARGO float program, the global drifter array and numerous glider operations. In the Arctic, ice cover blocks surface access, severely limiting the utility of GPS and Iridium across much of the basin. The ANCHOR workshop thus focused on defining an acoustic system capable of providing geolocation and telemetry to platforms working for extended periods beneath the Arctic ice. Workshop participants recognized that a carefully coordinated, multi-national, consensus approach to the design and implementation of acoustic infrastructure will be required to overcome the logistical and financial challenges of employing these technologies and addressing significant questions in Arctic Ocean science. An immediate goal was to coordinate ongoing, early efforts to address acoustic navigation and communications issues. Overall workshop goals included defining drivers, summarizing the state of knowledge, developing system specifications, and recommending research and development paths.

Science mission requirements, platform needs and marine mammal concerns shaped system performance specifications. Examples include large-scale Arctic circulation measurements which demand basin-scale geolocation and raid-response autonomous investigations of slumping events that might require more precise navigation and limited telemetry. The ANCHOR platform suite includes floats, gliding and propeller-driven autonomous undersea vehicles (AUVs), ice-based observatories and moorings. Each platform possesses unique capabilities and constraints

that shape the nature of the navigation and communications infrastructure. For example, long-range, extended endurance platforms (e.g. floats and gliders) drive basin-scale geolocation while their limited payload and energy reservoirs cannot readily accommodate outgoing long-range communications. After considering the full suite of requirements, ANCHOR workgroups outlined a three-tiered system to provide basin-, regional- and local-scale navigation, low-bandwidth one-way (source-to-platform) basin- and regional-scale communication and high-bandwidth, short-range two-way telemetry.

At the basin scale, a relatively small number of bottom moored, large, low-frequency (20–100 Hz) sound sources could ensonify the entire Arctic, broadcasting navigation, tomography and low-rate data signals. The low-frequency system would thus provide GPS-style navigation across the entire Arctic, measure Arctic Ocean integrated heat content and, perhaps, low-mode vertical structure and provide a limited number of mooring sites that could be exploited to conduct other measurements. Mid-frequency (250–1000 Hz) sources attached to moored, ice tethered, and drifting platforms provide supplementary navigation signals and a homing mechanism for mobile platforms to reach data upload sites. Existing acoustic modem technologies offer the functionality required for high-bandwidth data transfer. A common protocol will provide interoperability between different elements of the system. Autonomous platforms operating beneath the ice relay their data via high-frequency acoustic modem to ice-based platforms, which can then forward the data via Iridium phone. Alternatively, mobile autonomous platforms can seek ice-free waters that allow them to utilize their own satellite communications.

ANCHOR participants identified several near- and medium-term development priorities. Marine mammal issues were discussed during the workshop, with participants agreeing that these concerns warrant early analysis to inform system design, minimize impact and seek ways to exploit the resulting system for animal monitoring. Effort should be directed at design studies and experiments focused on optimizing low-frequency source type and frequency. Likewise, an appropriate regional-scale frequency must be chosen that, together with new signal processing techniques, provides improved navigation ranges compared to existing RAFOS systems. Efficient methods for encoding position in the navigation signals must also be researched. At high-frequency, a collaborative group needs to specify a capable, open communications protocol that can be implemented alongside each vendor's proprietary system. A regional-scale pilot program focused on a scientifically important region (perhaps the Beaufort Gyre) would provide a test of both the low-frequency navigation system and autonomous platform behaviors while demonstrating the scientific advances enabled by these new platforms. The regional pilot would also serve as a testbed for refining technologies in preparation for larger-scale deployment.

Of necessity, ANCHOR system components will be developed and deployed by diverse groups, beginning with limited-scope efforts associated with the NSF Arctic Observing System and EU DAMOCLES program. As these and other projects progress, efforts must focus on promoting technical exchange, coordinating development and deployment efforts and maintaining community consensus as the technical specifications evolve. The ANCHOR group anticipates a continued role coordinating development efforts and fostering exchange and cooperation between the various teams.

1 Introduction

Recent reports on autonomous and Lagrangian platforms and Arctic observing [6, 15, 5] identify under-ice navigation and telemetry technologies as one of the critical factors limiting the scope of high-latitude measurement efforts. Recent advances in autonomous platforms (profiling floats, drifters, long-range gliders and propeller-driven vehicles) promise to revolutionize ocean observing, providing unprecedented spatial and temporal resolution for both short-duration process studies and multi-year efforts designed to quantify long-timescale environmental changes. This new generation of platforms facilitates access to logistically difficult regions where weather and remoteness challenge conventional techniques. These platforms could provide persistent, high-resolution, basin-wide sampling in ice-covered regions and operate near the critical ice-water interface. Currently, however, navigation and telemetry for these platforms relies on satellite positioning (GPS) and communications (Iridium, ARGOS, ORBCOMM) that are poorly suited for high-latitude applications where partial or complete ice cover restricts access to the sea surface. A similar backbone infrastructure offering basin-wide geolocation and telemetry in ice-covered regions would allow the research community to employ autonomous platforms to address previously intractable problems in Arctic oceanography.

Motivated by the dramatic advances in temporal and spatial reach promised by autonomous sampling and by the need to coordinate nascent efforts to develop navigation and communication system components for near-term observational efforts, an international group of acousticians, autonomous platform developers, high-latitude oceanographers and marine mammal researchers gathered in Seattle, U.S.A. from 27 February–1 March 2006 for the workshop Acoustic Navigation and Communication for High-latitude Ocean Research (ANCHOR). Ongoing efforts to employ autonomous systems for sampling beneath ice and the ambitious European Union DAMOCLES (`http://www.damocles-eu.org`) project, which includes acoustic navigation and communication development, require an overarching system specification to guide the engineering of interoperable systems. A carefully coordinated, multi-national, consensus approach to the design and implementation of acoustic infrastructure will be required to overcome logistical and financial challenges and address significant questions in Arctic Ocean science. Toward this end the workshop goals were (1) to define science and platform drivers, (2) to summarize the current state of knowledge concerning Arctic acoustics, navigation and communications, (3) to begin development of an overarching system specification to guide community-wide engineering efforts, (4) to identify elements that require additional research, (5) to recommend near-term research and development activities and (6) to establish an active community and steering group to guide long-term engineering efforts and ensure interoperability between elements developed by disparate teams.

Platform requirements and the needs of key science missions defined performance specifications. The ANCHOR platform suite included floats, gliding and propeller-driven AUVs, ice-tethered platforms and moorings. Potential science missions included broad-scale circulation studies, bathymetric mapping, hydrate and cold seep characterization, ice thickness studies, investigations of the warm Atlantic layer and quantification of freshwater exchange with lower latitude basins across critical exchanges and gateways points. From these drivers several key technical requirements for both navigation and communication were identified.

Large-scale circulation studies and trans-Arctic sections demand basin-wide navigation at kilometer or better accuracy. Gliders rely on access to one or more fixes per day to accurately navigate, while propeller-driven AUVs currently carry inertial navigation systems that require only occasional reference positions. Although floats do not steer actively, frequent positioning allows them to resolve high-frequency motions such as inertial oscillations and tides. Other missions, such as bathymetric mapping and small-scale process studies, require navigation accuracies of meters, with frequent positioning, over regions spanning O(100 km).

Mobile (ice suspended) acoustic sources must be capable of transmitting their position as part of the navigation signal. It is desirable for all long-range sources, both bottom moored and ice drifting, to be able to send additional telemetry to provide command information to autonomous platforms. A very few bytes could add significant mission flexibility. Although technological constraints (e.g., transducer size) prevent outgoing long-range communication from autonomous platforms, short-range O(1 km) telemetry at rates of O(1 kbps) would allow efficient data transfer between autonomous systems, moorings and ice tethered platforms. With standardized acoustic systems, any platform in the system could serve as a node in a store-and-forward network, increasing reliability and data recovery rates.

ANCHOR workgroups outlined a three-tiered system to provide basin-, regional- and local-scale navigation, low-bandwidth one-way (source-to-platform) basin- and regional-scale communication and high-bandwidth, short-range two-way telemetry. Details of the proposed system are discussed in more detail in section 4.

The Seattle workshop represents the start of long-term efforts to establish an Arctic Ocean navigation and communication infrastructure and, ultimately, to exploit autonomous technologies to achieve large advances in Arctic oceanography. Knowledge gaps and development steps identified during the workshop, along with the near-term needs of the European Union DAMOCLES program, point to several near-term efforts. Marine mammal issues, discussed during the workshop, warrant early analysis to inform system design, minimize impact and seek ways to exploit the resulting system for animal monitoring. Additional investigation is required to identify the highest frequency source capable of providing a trans-basin navigation signal. Although previous results indicate that 50 Hz signals will span the basin, higher-frequency sources would be less costly, more reliable and logistically simpler, motivating an effort to optimize source frequency choice. A timely effort might exploit IPY activities to conduct an efficient low-frequency propagation experiment. Likewise, an appropriate regional-scale frequency must be chosen that, together with new signal processing techniques, provides improved navigation ranges compared to existing RAFOS systems. Efficient methods for encoding position in the navigation signals must also be researched.

Of necessity, system components will be developed and deployed by diverse groups, beginning with NSF-supported efforts toward a pilot regional system and the large DAMOCLES observing system. As these and other projects progress, efforts must focus on promoting technical exchange, coordinating development and deployment efforts and maintaining community consensus as the technical specification evolves. An international ANCHOR steering group will guide these activities, using mailing lists (anchor@apl.washington.edu), a web site (`http://anchor.apl.washington.edu`), special sessions at upcoming meetings and publications to coordinate activities and promote interaction. ANCHOR products, such as the meeting report, technical documents and the evolving system specification, will be offered to the community through the web site.

2 Science missions

Basin-scale geopositioning and communications would open the Arctic Ocean to a range of new observing technologies, such as floats and autonomous undersea vehicles that could provide persistent, year-round measurements in remote locations and access to critical areas such as marginal ice zones and the region near the ice-ocean interface. Inexpensive, reliable geolocation (GPS) and satellite communications (Iridium) facilitated the recent advances in autonomous platforms that are transforming ocean observing in ice-free oceans. ANCHOR participants view the analogous enabling technologies of acoustic navigation and communications as keys to driving new advances in critical areas of Arctic Ocean research and for supporting the long-term operational observing called for in recent Arctic Observing Network plans. To illustrate these connections, workshop participants outlined examples of several research areas that stand to benefit from access to these new technologies.

2.1 Ice thickness

In the last 20 years submarine measurements of sea ice draft have shown a 40% reduction in average sea ice thickness while satellite remote sensing has shown a 14% reduction in sea ice extent over the same period. Current forecasts indicate that if these trends continue the Arctic Ocean could be ice-free before the end of this century. Global climate models exhibit significant sensitivity to sea ice thickness distribution, which impacts surface albedo feedback through its role in governing sea ice extent and concentration. Thickness, extent and concentration together define the sea ice volume. Quantifying their annual and interannual variability and understanding the processes that govern these fluctuations are important steps toward evaluating and constraining models for short- and long-term prediction. Although satellite remote sensing can provide measurements of sea ice extent and concentration, in situ measurements of ice draft produce more accurate thickness estimates than those inferred from remotely sensed sea ice freeboard. However, sea ice thickness varies over a broad range of temporal and spatial scales, presenting severe challenges to in situ measurement programs. Ice motion should be collected with thickness measurements to allow separation of dynamical and thermodynamical processes. Modern approaches include point measurements from moored upward-looking sonars (ULS), occasional sections collected from transiting submarines and time series collected at drifting ice-based observatories. Though these approaches provide excellent data, none offers the broad spatial distribution, long endurance and persistence required to deliver a robust quantification of annual and interannual ice thickness variability.

Robust quantification of sea ice thickness distribution and temporal variability (at seasonal to decadal timescales) requires a basin-scale network capable of sustained sampling across many years. Ice-based observatories provide measurements in regions of perennial ice cover, but survivability in regions of unreliable or seasonal ice makes this approach impractical in many locations. The ARGO Program, designed to provide long-term, operational measurements spanning the lower-latitude oceans, offers a model for how low-cost drifting platforms could be employed to collect sustained, basin-wide Arctic ice draft measurements. Drifting instruments, such as the ULS Float developed under the DAMOCLES program, could complement ice-based draft measurements, providing spatially distributed ice thickness measurements with a system that is cost effective to sustain over decades of sampling. Although ULS floats currently exist, the utility of measurements collected by these drifting platforms, and thus their application toward the creation of a sustained Arctic observing system, depends on access to basin-scale geopositioning.

Additionally, the low-frequency signals themselves might provide basin-scale ice thickness data. The received amplitude or propagation loss of the low-frequency acoustic signal will depend upon the Arctic ice roughness, which is correlated directly with its thickness. Long- term reduction in the received amplitude implies greater roughness and hence thickening of the sea ice and a long-term increase of amplitude implies thinning of the ice cover. The seasonal variation of sea ice thickness was observed with low-frequency acoustics by this technique in 1998–1999 [4]. While ice extent can be observed by satellite, ice thickness has required either upward looking sonar from submarines, ice camp measurements or aircraft ice landings. The low-frequency network acoustic measurement will provide a rapid synoptic picture. While the precision of the method is still being investigated, long-term trends in propagation loss combined with sea ice extent from satellites would indicate corresponding changes in the Arctic sea ice mass, a critical input for global climate models. Assimilation of both low-frequency travel times and propagation loss trends into coupled Arctic ice and circulation models would provide powerful integrative constraints.

2.2 Arctic Ocean circulation, heat and freshwater balances

The episodic disappearance of sea ice in the western Arctic in the summer of 2007 lends urgency and importance to investigations of the Arctic Ocean heat and salt balance control mechanisms. Changes in Arctic Ocean stratification, heat and freshwater storage result from shifts in the relative contributions of inflowing Atlantic (Fram Strait and Barents Sea opening) and Pacific (Bering Strait) waters, discharges through Fram Strait and the Canadian Arctic Archipelago, atmospheric fluxes and terrestrial runoff. Changes in both storage and fluxes must be documented to understand the Arctic Ocean's response to and impact upon climate change. Given the large-scale interannual variation in the polar atmospheric circulation, we expect these pathways and exchange mechanisms to vary on these longer time scales. As the permanent ice cover transitions into seasonal ice, the pycnocline will be more exposed to surface forcing, possibly exposing the surface layers to the heat contained in the Atlantic and Pacific waters. Thus, under warming conditions, these water masses and their distribution within the Arctic will only increase in importance.

2.2.1 Storage

Changes in Arctic Ocean water masses over multi-year time scales must be documented to determine the influence of the global ocean changes on the Arctic. The waters of the Arctic Ocean have been warming since the mid 1990s, with average maximum temperatures rising by more than 1°C. For example, temperature anomalies of more than +1°C have been observed in the Nansen Basin in the 1990s, which has displaced the cold halocline from the Amundsen Basin to the Makarov Basin. Because multi-year, broadly distributed measurements are difficult and costly to collect, data scarcity hinders attempts to characterize basin-scale changes.

A combination of drifting, ice-based observatories and ARGO-style floats could provide cost-effective, basin-wide coverage to gauge changes in water mass structure and integrated storage, while autonomous gliders could occupy strategic cross-basin surveys and critical sections across narrow boundary currents and frontal zones. When supported by a basin-scale geopositioning network and a smaller number of moored measurements, this system of complementary platforms could provide

Arctic-wide sampling of watermass changes over periods of years to decades.

Acoustic thermometry is a technique to measure basin-integrated heat content that exploits the capabilities of the low-frequency navigation array. Sound speed in water is related directly to water temperature, and to a much lesser extent, salinity. By measuring the change in the travel time of a sound pulse between a source and a receiver we can determine the change in the average temperature along the path. This was demonstrated in the Arctic in 1994 [11] and 1998–1999 [12]. Conventional oceanographic sections to obtain ocean temperature require a submarine, ice-breaker or a campaign of aircraft landings on the sea ice. Furthermore these measurements are generally limited to the spring through fall seasons in the Arctic as operations in the total darkness of the Arctic winter are extremely hazardous. The proposed low-frequency network would be able to “take the temperature” of the entire Arctic Ocean in less than one hour and repeat the measurement weekly on a year-round basis. The acoustic signal takes approximately 30 minutes to cross the entire Arctic compared to a submarine transit of approximately one week.

2.2.2 Circulation, Atlantic and Pacific inflows

The pathways of the Atlantic water along the boundaries of the Eurasian and Canadian Basins have been inferred from distributions of temperature and salinity and limited tracer and direct velocity measurements. There is strong evidence for a bifurcation in the pathway at the Lomonosov Ridge, but schematics of circulation also suggest bifurcations into the interior at other topographic features, such as the Mendelevev Ridge, which are not as well documented. The inflow of Pacific water through the Bering Strait has been observed to flow along the Alaskan coast to Barrow Canyon and also through Herald Canyon and then eastward where it combines with the coastal pathway. The eventual pathway for this water as it flows eastward is poorly understood. It is clear that there is a strong circulation of Atlantic and Pacific waters along the margins of the basins and sluggish flow in the interior, dominated by strong eddies. The connections between the coastal currents and basin interiors are likely dominated by instability processes, which are also probably the source of the eddies observed in the interior.

Given the episodic disappearance of sea ice in the western Arctic in the summer of 2007, the mechanisms that remove the heat and salt from the Atlantic layer water are becoming increasingly important. To address these issues it is critical to document and understand the velocities within and pathways of the Atlantic water in both the Eurasian and Canadian basins so that we can estimate where and how this heat and salt are advected into regions of the Arctic. The relative roles of boundary mixing along the periphery and vertical fluxes within the basins have strong implications for the removal of sea ice and/or its annual cycle as well as strong contributions to the advective–diffusive balance that determines the temperature and salt distributions in the Arctic. For example, the vertical flux of heat across the pycnocline in the basin interior is due to double-diffusive processes. Based on limited observations from ice-tethered profilers, these layers have extremely high lateral to horizontal aspect ratios of order 10^7 or higher. This implies that we need to implement a large scale monitoring program within the basins and higher resolution sampling near the continental slopes.

Limited access to ice-covered regions and platform persistence again constrain data availability and, thus, our understanding of Arctic Ocean circulation and the fates of the major inflows. The suite of floats, ice-based observatories and gliders envisioned for quantifying changes in basin-scale heat and freshwater storage could be augmented with platforms targeting specific currents, frontal zones and coastal boundary layers .

2.2.3 Exchanges at critical Arctic gateways

Freshwater and heat exchange between the Arctic and subarctic Atlantic and Pacific provide critical mechanisms through which Arctic variability and global climate interact. Atlantic waters flowing northward through the eastern Fram Strait maintain a warm, high-salinity subsurface layer that can be traced across much of the Arctic. Although a buoyant near-surface layer typically insulates the sea ice from exposure to the warm Atlantic inflow, changes in barrier layer thickness and/or diapycnal mixing rates could increase exposure to this reservoir of heat, accelerating ice loss. At Bering Strait, the Pacific gateway, inflowing Pacific waters supply heat to melt back sea ice during summer, but typically act to stabilize the upper ocean in winter. Bering Strait inflow also represents the largest oceanic nutrient flux into the Arctic upper ocean. Arctic freshwater discharges through Davis and Fram straits into deep water formation regions west (Labrador Sea) and east (Greenland/Irminger seas) of Greenland. Fresh Arctic waters contribute a buoyant surface layer that acts as a barrier inhibiting convective overturning and deepwater formation. Arctic discharge strength determines layer thickness and modulates dense water production, which impacts Atlantic Meridional Overturning Circulation (MOC) strength and thus the oceanic pole-to-equator heat exchange that acts to warm northern latitudes. Global climate models predict the MOC to be highly sensitive to variability in northern freshwater flux [7], suggesting a delicate competition between freshwater supply and heat loss to the cold, high-latitude atmosphere. Recent assessments of decadal-scale variability in North Atlantic freshwater content [2, 3] reveal systematic freshening in the receiving basins west and east of Greenland, while Zweng and Munchow [16] use archived data to identify freshening along the western side of Baffin Bay, extending southward through Davis Strait and into the Labrador Sea. These studies implicate enhanced Arctic outflow as the dominant contributor to growing freshwater inventories in these important MOC control regions, though estimated freshening falls below the levels required for MOC shutdown in modeling studies [14]. Further south, attempts to quantify temporal changes in MOC strength at 25°N suggest a 30% slowdown between 1957 and 1994 [1] – larger than predicted for the estimated freshening but in the correct sense. Although models and observations indicate that Arctic freshwater outflow can impact climate by modulating MOC strength, only a weak quantitative understanding of the Arctic outflows exists [10, 9].

Efforts directed at understanding gateway exchanges must resolve dynamically wide straits (strait widths much larger than the internal deformation radii, thus admitting small-scale eddies and recirculations), sample the critical area just beneath the ice–ocean interface, collect profiles over shallow, sometimes broad, ice-covered shelves and maintain operations in regions of seasonal ice cover. A complementary system of autonomous gliders and moored platforms can overcome these challenges, with autonomous gliders contributing the necessary spatial resolution, sampling near the ice–ocean interface and providing year-round access and persistence. Gliding platforms will require under-ice geolocation, which could be provided by the low-frequency, basin scale array, augmented by additional navigation elements mounted on the strait moorings when dictated by location and geometry.

2.3 Arctic Basin geology and geophysics

The recent release of the newest International Bathymetric Chart of the Arctic Ocean (IBCAO) digital terrain model [8] concludes with an important, and sometimes overlooked, observation: "Even if the new IBCAO is far superior compared to its predecessors, it is not flawless: it retains certain errors such as track line artifacts, terracing from the use of contours, and in areas where there are no available soundings, it relies on contours from maps with sometimes no source information…" Much of the Arctic Basin, especially in perennially ice-covered regions, has never been mapped by modern sounding techniques. This lack of data limits geological and geophysical investigations of large- and small-scale topographic features in the Arctic Basin. Because of the strong control topography exerts on Arctic Ocean circulation, it also impacts oceanographic research. Sonars mounted on the hulls of icebreakers will likely expand bathymetric maps as waning ice cover permits more incursions into unexplored regions, but even in an ice-free Arctic, surface ships will acquire data with lower resolution than platforms that can operate within the water column. Given that many geoscientific investigations need map data with resolutions on the order of meter- or even sub-meter scales, accurate navigation of these submerged systems is imperative.

Geological and geophysical issues that still require investigation in the Arctic Basin span broad spatial and temporal ranges. Formation of some major physiographic features (e.g., the Amerasia Basin and the Alpha Ridge) remains controversial. Resolving these questions requires mapping over thousands of square kilometers at resolutions on the order of tens to hundreds of meters in regions that are still inaccessible to icebreakers and even nuclear-powered submarines. Detection of methane hydrates and seeps in regions such as the North Slope of Alaska and Chukchi Borderland will cover much smaller areas at higher resolutions. Events such as teleseismically detected earthquakes along Gakkel Ridge or mass wasting slumps along continental margins can best be explored by rapid response of autonomous vehicles, yet they require precise navigation and accurate maps of potential topographic obstacles to be successful. The best measurements of sediment fluxes through canyons and other gateways need to include repeated surveys of sediment pathways, especially in response to significant events such as storm surges. Ultimately, analysis of the environmental change that is occurring in the Arctic must examine the Arctic Ocean as a system with a perspective that extends from the ocean floor to the atmosphere. Recent, successful deployments of AUVs in the Arctic show that the underwater portion of this perspective is coming into clearer focus, but it will require an infrastructure that allows all of the measurements to be co-registered in space and time.

3 Mobile platform considerations

3.1 Floats

The first attempt to implement an autonomous float program in the Arctic started in 1989–1990 when 80 Hz SOFAR floats and ice-tethered listening stations were deployed in the Arctic as part of CEAREX. These floats were isobaric floats that stayed at fixed depth and transmitted an acoustic signal to track their position. This experiment basically did not work, probably due to electronic failures during float deployment and also the limited output of the acoustic transducers. Gascard also deployed higher frequency (260 Hz) floats in the vicinity of Fram Strait during this time period and had some floats operating under ice, but with limited ranges. Gascard did obtain interesting trajectories within the Greenland Sea, but not many under the ice.

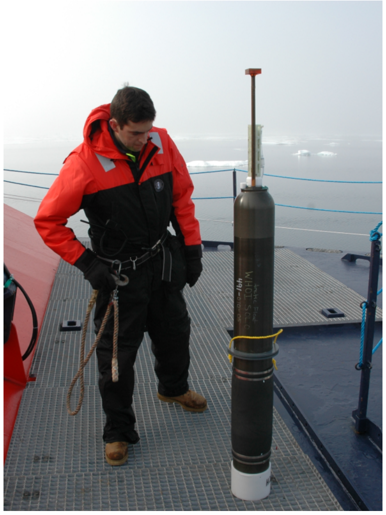

Fig. 1: Polar profiling float on deck before deployment.

More recently, polar profiling floats (PPF) (Fig. 1) similar to those used for the Argo float program have been deployed in the Arctic. These floats drift at an intermediate depth, for example at 300 m in the Atlantic Layer, and then descend to a deeper depth, typically 1000 m, and then make a profile to the surface. Once these floats penetrate through into air, they obtain a GPS fix and offload their position and profile data through the Iridium satellite system. In addition to the profile data, the distance between surfacing can be used to determine a drift displacement or drift velocity. While the temperate latitude versions of these floats obtain position as soon as they reach the sea surface, the polar profiling float has an algorithm that attempts to find leads or open water by checking for a connection with the Iridium communications system and if a link is not established, the float sinks to 50 m, waits 30 minutes, and then tries again. For each dive, it repeats this procedure roughly 100 times and then starts the next dive if a link was not established. Under optimal conditions, the float often finds open water and under thick ice conditions with few leads, the float obtains infrequent positions, but sends back all the profiles. The PPF has been equipped with RAFOS float technology to listen for ice or bottom moored sound sources so that it can obtain its position acoustically even when it cannot find open water.

Prototypes of the PPF float were deployed in the Arctic in the late summer of 2005 and were able to find open water, even in the high Arctic. Software errors caused these floats to fail prematurely. Improved versions of these floats deployed off Antarctica in the Bellingshausen Sea have both found open water in ice covered regions and also worked for over one year so far. Eight PPF floats will be deployed around the margin of the western Arctic in August–September 2008.

While the present floats only make profiles of temperature, salinity and dissolved oxygen, other sensors can be added, as is the case for those that are part of the Argo array. Additional sensors that either have been or can be added easily include optical backscatter, fluorescence, chlorophyll and nitrate. We expect other sensors developed under the auspice of the ALPS program to be added to polar floats.

As part of the DAMOCLES experiment, Gascard has deployed isobaric floats that are equipped with an upward looking sonar (ULS), a 1560 Hz transceiver, a 780 Hz receiver, and an acoustic modem. These are coupled with ice platforms that contain 780 Hz acoustic transducers that serve as location beacons for the floats and 1560 Hz transceivers and acoustic modems for communications. The 1560 Hz system is used for limited command and data telemetry. If the system determines that the floats are within close range of the ice platforms the ULS data is off-loaded using the acoustic modem. Obviously, this system has quite limited range. It will be used with an array of order 100 km scale.

Thus, at present there are floats that can operate on basin scales, but will not always have positions when they profile and there are floats that are being deployed in a limited spatial domain that use acoustic signals for positioning, but the latter floats have not yet been proven to work routinely. These floats can be equipped with acoustic receivers and other sensors that are being developed for floats and gliders under the ALPS initiative.

The next step in the development of the PPF, in conjunction with the proposed basin scale acoustic array, would be to equip the floats with a receiver and computational capability to process navigation signals. This would allow localization without access to open water and also permit floats to serve as tomographic receivers. It is envisioned that this next generation float would retain satellite communication capabilities that would operate only in summertime or in the present mode, sending back position, tomographic arrival times and profile information whenever the float finds open water.

3.2 Autonomous underwater vehicles

3.2.1 Gliders

Fig. 2: Seaglider on deck before deployment.

The current generation of operational autonomous gliders (e.g., Webb Research Corporation's Slocum, UW's Seaglider, UCSD's Spray) are small, buoyancy driven underwater vehicles capable of profiling from the surface of the ocean to as deep as 1000 m (Fig. 2). They differ from profiling floats in their ability to project a portion of their vertical buoyancy force into horizontal thrust and control their heading, thus allowing them to navigate between waypoints along a specified survey route. In open ocean operations they rely on GPS for positioning and Iridium satellite communications for data telemetry and command and control. Satellite based positioning and communications must be replaced by an acoustic infrastructure in arctic applications of these vehicles.

Recent NSF-OPP supported efforts have successfully adapted the UW Seaglider for extended (many months to one year) operation in ice-covered oceans. This ice-capable glider navigates using real-time trilateration from a multi-element 780 Hz RAFOS (mid-frequency) array but relies on Iridium satellite communications (and thus access to open water) for telemetry. Extended operation without human intervention also required significant augmentations to glider autonomy. These changes allow gliders to make their own mission-critical decisions, such as when to attempt to surface and how to respond to unexpected situations such as growing indications of hardware failure or extended loss of acoustic navigation signals. These gliders were developed to support sampling in seasonally ice-covered Davis Strait, and executed their first successful excursion under the ice in winter 2006.

Gliders operate by attempting to follow straight line tracks between user specified waypoints. At each surfacing in open water, the glider gets a GPS fix and calculates a bearing to the next waypoint. Using the difference between dead reckoned distance through the water (based on vehicle attitude and vertical speed) and distance over ground (from GPS fixes over successive dives) gliders can compute an estimate of depth averaged current. This current estimate is used together with the waypoint bearing to calculate the heading solution for the next dive. A typical glider operating in 1000 m water depth might travel 5 km over ground per six-hour dive. With GPS positioning errors of just a few meters and an accurate calculation of distance through the water, gliders can navigate reasonably efficiently along a designated survey track.

In the acoustic system proposed herein, the principal navigation source for gliders will be low-frequency basin-scale sources. With basin wide coverage a glider will always be in range of the two or three sources necessary to compute a navigation solution. Required frequency (fixes per day) and accuracy of these solutions is application dependent. For example, using existing RAFOS style signaling and processing it is possible to achieve 1–2 km positioning accuracy (Fig. 3). This represents 20–40% error in the calculated dive distance over ground for a 5 km dive. This accuracy is not sufficient for calculation of per dive depth averaged current.

At one fix per every one or two dives (3–4 fixes per day), 1–2 km accuracy is sufficient to keep a glider moving towards a target, albeit with reduced efficiency. In this scenario, a glider can re-point frequently enough that the lack of current information is not prohibitive. Defining navigation efficiency as the distance made

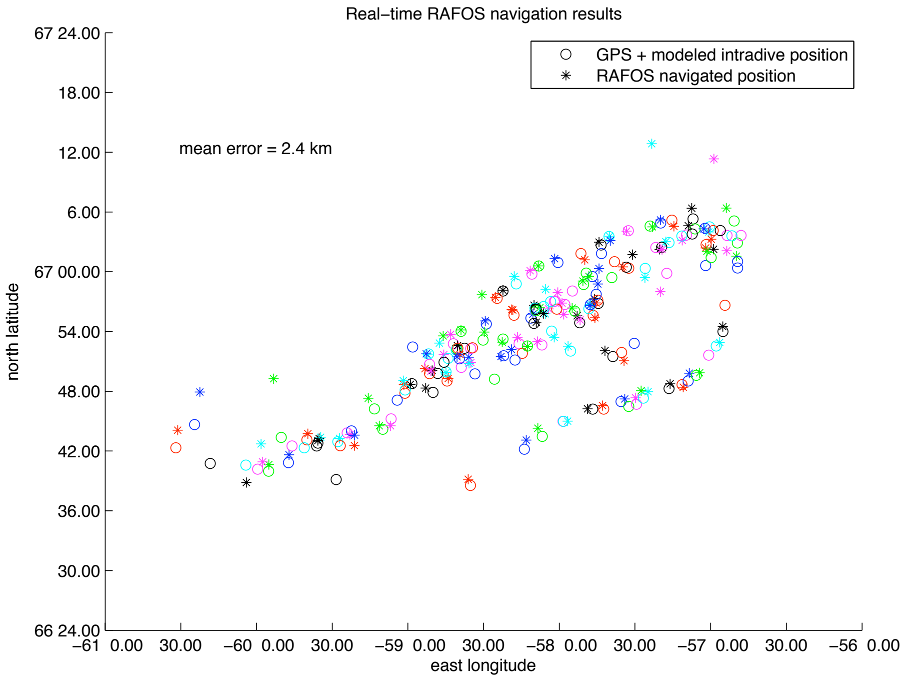

Fig. 3: Real-time RAFOS based navigation solutions compared to GPS plus dead-reckoned intradive position for a glider operating in a network of 780 Hz RAFOS sources. Coloring is intended to distinguish between fixes only.

towards a target divided by the distance over ground traveled, efficiency is reduced with less frequent position updates. Without sufficient position information a glider might spend several dives pointing away from a target before information becomes available to make an appropriate correction. A further advantage to more frequent updates is that filtering and averaging could be employed across multiple dives to resolve steady, larger scale current features. This would facilitate solution techniques like those employed for open water navigation with current estimation.

The frequency of fixes could be reduced somewhat with higher accuracy. Position accuracies O(100 m) would likely permit per fix depth averaged current calculations that would be usable for computing course corrections. With better steering information the glider can travel efficiently without the need for a position update.

It is desirable to have navigation source transmissions clustered together in time. With vehicles moving approximately 1 km per hour, navigation solutions based on ranges with O(1 km) error become more difficult when the ranges are spread out in time. For the low-frequency system, however, clustering can be difficult as allowances must be made for the signal from one source to clear the entire basin before the next transmits. For a four to six source system that could mean two to three hours for a complete cycle of transmissions. Ranges used in a navigation solution for a moving vehicle can be spread in time, but the vehicle motion over the time window becomes one more unknown that introduces further uncertainties in the computed solution.

Navigation from intermediate frequency sources has similar requirements to the low-frequency system. Depending on spatial and temporal distribution of platforms with intermediate frequency sources attached, gliders could rely on these sources in combination with low-frequency sources for navigation solutions. In process study type experiments over regional scales of a few hundred kilometers, an array of intermediate frequency sources can serve as the only navigation system. As discussed in section 4.2 it is important that mobile sources (such as those suspended from ice based observatories) include position telemetry as part of the navigation signal. This is required of course for a navigation solution, but would also provide the glider with a potential destination in data shuttle applications.

Within the high-frequency data telemetry system, gliders operate as mobile, navigable nodes in the larger network. When operating under ice for long periods they could use the network to offload their own data or receive new programming. As data shuttles, gliders function as part of the network infrastructure, serving as delivery trucks to carry data from fixed assets with no surface expression to (likely) mobile assets with satellite telemetry capability, such as ice based observatories.

Data telemetry bandwidth requirements for gliders are highly application dependent. Assuming compression to one byte per channel per sample, a 5 m resolution data set for a 1000 m profile of CTD, oxygen and three optical channels could

Fig. 4: (a) Gavia person portable AUV and (b) Autosub long-range AUV hanging from its shipboard overboarding system.

be stored in 1400 bytes. At four dives per day one month of profile data could be offloaded to another network node in less than 10 minutes at commercially available 2400 bps acoustic modem speeds.

For a data shuttle servicing an ADCP equipped mooring, the bandwidth requirements could be considerably higher. With annual or semi-annual servicing the data payload from a single ADCP could be several megabytes. The glider would need to station keep near the mooring for several hours to affect a transfer and then spend a similar amount of time and a considerable amount of energy transmitting this data to another node for satellite transmission. Effective sampling, averaging, and compression strategies will be critical throughout all elements of the network to make best use of available resources. Assuming 0.05 J/byte to transfer data acoustically, every 10 MB of data transferred represent 3% of the 15 MJ total available battery energy (for all systems) carried on typical gliders.

3.2.2 Powered AUVs

While different glider models are similar in operational characteristics, the range of powered or propeller driven AUVs is quite broad. They range from small, person-portable vehicles (Fig. 4a) designed for missions of a few hours/kilometers to large vehicles requiring dedicated shipboard handling systems capable of operating for days (Fig. 4b).

In many visions of long-term observational networks, powered AUVs achieve extended endurance by operating with the support of docking stations. In the

Arctic network, AUV docks could be deployed on fixed source moorings or ice based platforms. Vehicles would home to the docks using a combination of the same long-range and short-range navigation systems described for floats and gliders. Precise navigation for homing into the dock would likely come from a specialized very short-range system. When operating as part of the network these docked vehicles could be used for event driven or adaptive sampling, receiving command and control telemetry either via satellite (when docked to an ice based platform) or via low-frequency acoustic system (when docked to an uncabled subsurface fixed platform). In the latter case they would store their data between service intervals or could receive periodic visits from data shuttling gliders.

Propeller driven AUVs capable of transiting more than a few hundred kilometers are relatively rare. Some visions of Arctic observing include these vehicles and even more capable, still-to-be-developed basin scale vehicles for missions such as bathymetric mapping. These missions will drive the accuracy requirements of the acoustic navigation systems. For transiting from point to point over long distances, the same level of accuracy as needed for gliders would be acceptable. Geo-registering sonar data will require significantly higher levels of accuracy.

3.3 Ice based observatories

Ice based observatories (IBO) could support two functions of an Arctic acoustic navigation and communications network for instruments and vehicles operating beneath the sea ice. First, IBOs could provide short- or medium-range navigation capabilities by carrying intermediate frequency acoustic sources broadcasting signals encoded with position that could be used by other platforms to triangulate their position. Second, the IBOs could provide mailbox service to shore labs for other under-ice systems via high-frequency modems. Either by homing in on, or by opportunity, under-ice systems sufficiently near to IBOs could transfer data to the IBOs, which would then be telemetered via Iridium or other satellite systems in near-real time, and receive messages (such as mission changes) via the same link.

Either of these functions could be readily implemented with current technology, or by reasonable reengineering of current technology.

IBOs that could support the necessary navigation and communication devices require a surface expression to house the navigation device and electronics needed to support the satellite communications, and a cable extending through the ice to communicate with the subsurface apparatus. That cable will need to be at least several tens of meters long to extend through the upper mixed layer and sharp thermoclines that characterize the near-surface Arctic waters that suppress or inhibit acoustic communications with subsurface vehicles (which would typically be operating at greater depths). Information to and from the subsurface acoustic sources and modems could be transferred to the surface using dedicated conductors within the cable or inductively along the wire strength member of the cable.

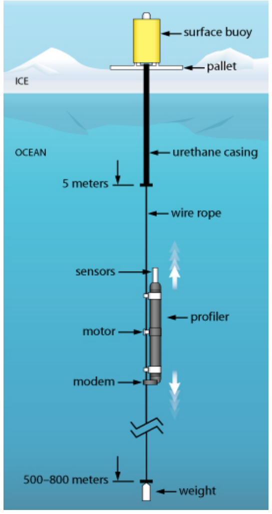

Fig. 5: WHOI Ice-tethered Profiler components.

Presently, several IBO systems exist that are capable of being adapted to the above requirements, including the JAMSTEC/Metocean Polar Ocean Profiling System (POPS) and WHOI Ice-Tethered Profiler (ITP) buoys (Fig. 5). In addition, an Acoustic Ice-Tethered Platform (AITP) is under development specifically to provide intermediate frequency navigation source and data transfer as part of the European Union's DAMOCLES program. In the cases of the POPS and ITP, several characteristics of the systems must be considered for adaptation as navigation and communications mailboxes. For instance, on each system a CTD instrument profiles between 10 and at least 800 m, which precludes the attachment of acoustic devices between these depths. Most likely, the acoustic devices (with self-contained power sources) would need to be installed below the maximum profiling depth (>= 800 m). In addition, the subsurface elements of the POPS and ITP moorings are designed to fit through a 10" hole in the ice (for ease of deployment). Making the acoustic devices similarly sized would greatly facilitate their deployment. Furthermore, it should be understood that IBO systems are designed to be expendable instruments with lifetime heavily dependent on ice conditions, so it is not advisable to attach expensive, non-expendable devices to these platforms.

The amount of additional data from underwater devices that could be relayed by IBOs was estimated based on the presently available specifications for the ITP technology. Using the present powering technology (lithium battery packs), several hundred megabytes of information could be relayed from subsurface platforms to shore during the expected three-year lifetime of an ITP at the relatively inexpensive rate of about $100 per megabyte (based on current Iridium and battery costs).

4 System overview

ANCHOR workgroups outlined a three-tiered system to provide basin-, regional- and local-scale navigation, low-bandwidth one-way (source-to-platform) basin- and regional-scale communication and high-bandwidth, short-range two-way telemetry. The components of the system would span acoustic frequencies from 10 Hz to 100 kHz (Figure 6).

Previous investigations of low-frequency acoustic propagation loss beneath Arctic ice indicate that 50 Hz sources would provide the necessary trans-basin range, with the possibility that source frequencies up to 100 Hz might also suffice. Logistical constraints favor the smallest, most energy-efficient (e.g., higher-frequency) sources capable of fulfilling system requirements, while propagation losses associated with surface ducting, reflection off the ice bottom and high ambient noise levels favor low-frequency sources. The trans-basin range offered by these sources allows a small (< 10) number of carefully chosen sites to provide navigation for platforms operating anywhere in the Arctic basin, eliminating the need for multiple project-specific systems and opening the basin to exploration using autonomous platforms. Basin-scale sources might also provide tomographic signals for Arctic Ocean ther-

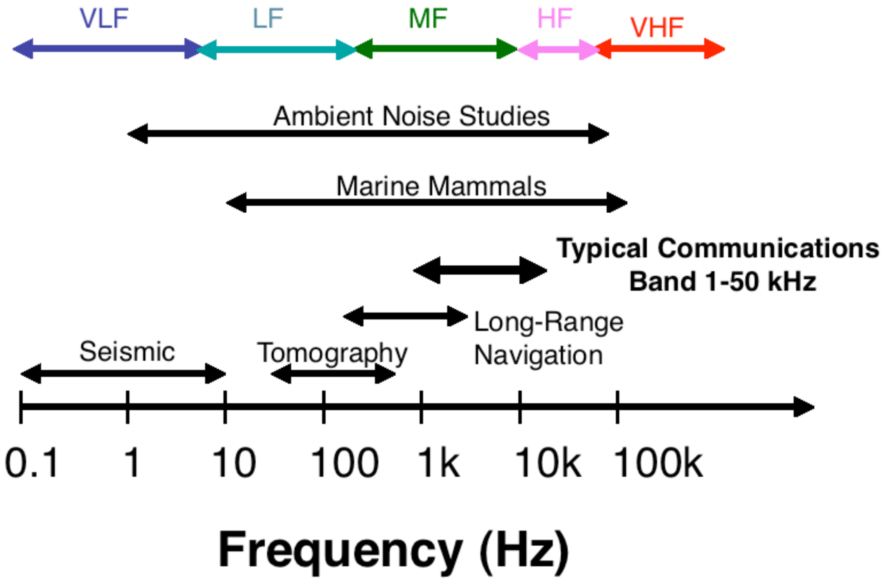

Fig. 6: Standard definitions of acoustic frequency bands.

mometry, monitoring integrated heat content at weekly to decadal timescales.

Nested within this, sources based on a proposed enhancement of O(1 kHz) RAFOS technology would provide O(1 m) accuracy, regional-scale (hundreds of kilometers) navigation and low-bandwidth, one-way source-to-platform communication. Tasked to support focused studies and mapping efforts, these sources would be relatively inexpensive and sized small enough to facilitate a wide range of deployment options (e.g., moorings, ice-tethered platforms, transport aboard small, ice-capable aircraft).

Existing acoustic modem technologies offer the functionality required for high-bandwidth data transfer and short-range homing navigation. A common protocol, implemented in tandem with vendor-specific functionality, will provide interoperability between all systems while allowing enhanced capabilities for elements employing proprietary technologies. The network design must consider that autonomous platforms typically operate on extremely tight energy budgets that exclude large, power intensive solutions. In particular, large volume data transfers may come at significant cost to overall mission endurance.

All three components are critical pieces of a basin scale network for an ice covered Arctic. For development and prototyping, however, workshop participants did see value in rapid development and implementation of the lower cost and logistically simpler mid- and high-frequency technologies. These components could be developed and tested in low-risk regional experiments that would not require significant infrastructure or international coordination. These prototype implementations could proceed in parallel with the more deliberative community building effort required for the basin scale low-frequency system. In the discussions about implementation strategies, workshop participants did not consider the implications on network design of significantly reduced sea ice.

4.1 Basin scale low frequency

The proposed system for long-range navigation, tomography, and communications consists of up to seven source moorings positioned around the periphery of the Arctic Basin and one to three moorings in the interior. Such a system can cover the entire basin (Fig. 7). The sources should be capable of transmitting signals at trans-basin ranges of up to ~3000 km. The network nodes should operate as transceivers, capable of sending and receiving. This will permit long-range two-way communications with the source and reciprocal tomography. Two-way communications are needed to command the source to adjust transmission schedules, and allow for possible marine mammal mitigation, if required after Environmental Assessment (EA) analysis. Where practical, low-frequency source moorings should be cabled to shore. This would remove batteries as an endurance limiter and would provide a mechanism to broadcast real-time system status and ephemeris information.

Co-located with each source a vertical hydrophone array should span enough of the water column to include the Atlantic Intermediate Water in the 100–800 m depth range to measure the acoustic modes that propagate in this layer for tomography and thermometry. These arrays will support tomography signal reception

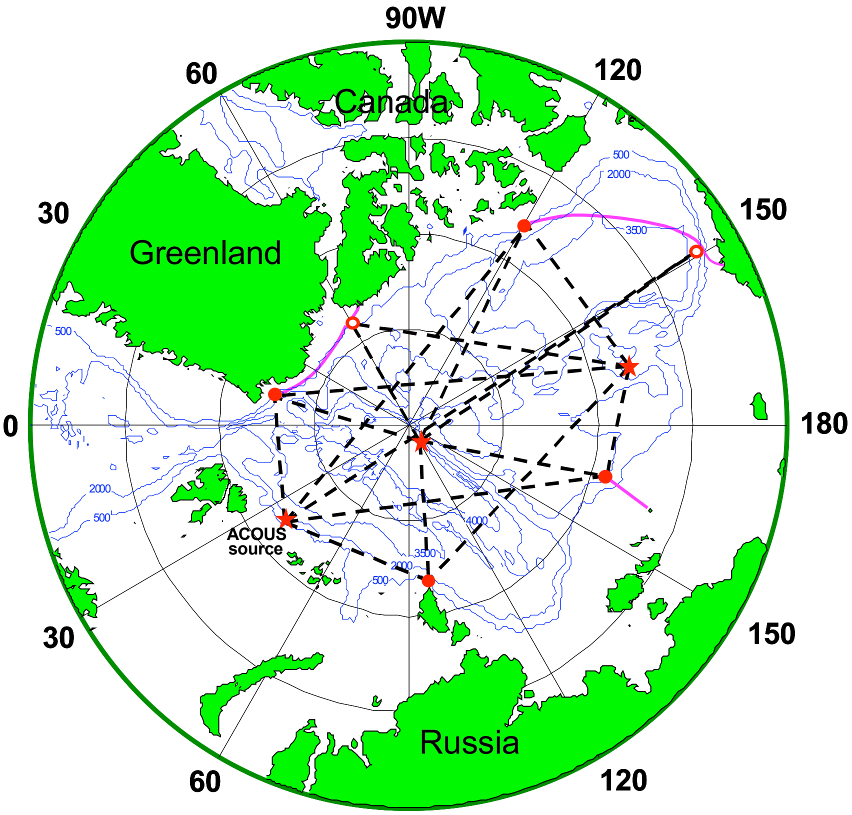

Fig. 7: Notional acoustic network for basin-wide navigation, tomography and communication

and provide gain for two-way communications. For source and array moorings in the deeper parts of the Arctic Ocean, an USBL navigation system will be required to monitor the tilt and shape of source moorings, which is necessary for correction of absolute travel time measurements for horizontal motion of transceivers.

The optimum transmission frequency for the basin-wide network should be determined through numerical modeling and experimental examination. The highest frequency within the practical band is preferable, because it would require smaller sources, which are also more reliable and cheaper. Based on preliminary propagation loss estimates and coherent pulse compression gain of 20 dB, 50 Hz should be sufficient to reach the maximum ranges (Fig. 8). Higher frequencies might be possible, but better estimates of coherent processing gain at the higher frequencies

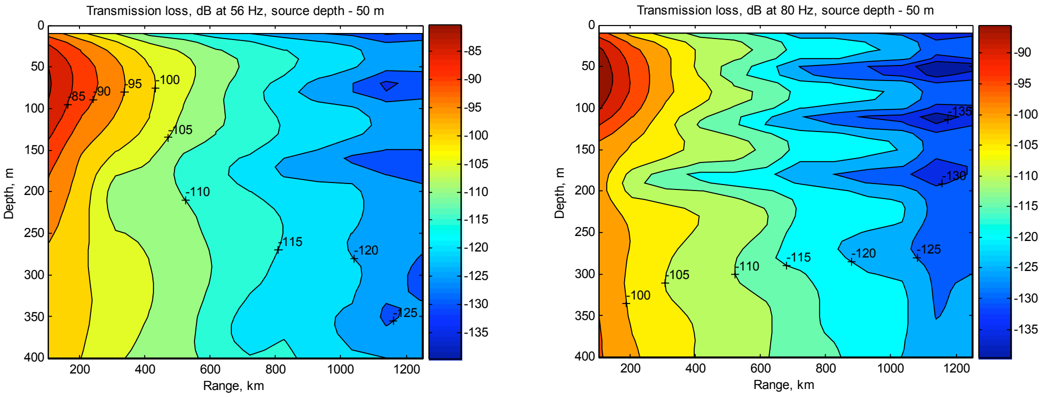

Fig. 8: Modeled propagation loss at 56 Hz (left panel) and 80 Hz (right panel) for a source at 50 m.

are needed along with propagation loss measurements in the Arctic.

The transmitted waveform will support navigation and tomography requirements and can be encoded using standard communications schemes to provide a messaging capability. A frequency sweep signal also seems possible if a resonant source operating at $\sim$ 80 Hz can be built that can achieve cross-arctic transmissions. Adaptive channel equalization techniques should be much less computationally intensive in the stable Arctic acoustic channel.

When it comes to low-frequency sources and coherent transbasin propagation and processing there is some significant experience with low-frequency coherent transmissions in the Arctic Ocean from the Trans-arctic Acoustic Propagation (TAP) experiment [11] conducted in 1994, and the Arctic Climate Observations using Underwater Sound (ACOUS) Experiment conducted from October 1998 to December 1999 [13]. The sources used were at 20 Hz and were electromagnetic and therefore quite large, heavy, and complex. The ACOUS source, which was moored and sent autonomously a 20 minute M-sequence signal every four days during the 14-month period, weighed 5000 kg and was deployed from an icebreaker. The technology has made significant advances since then and a careful investigation of the current state of the art is needed. One design that is very promising is the resonant tube source designed and built by Webb Research. This source would be much less complicated and hence potentially more reliable than the electromechanical designs and has a high efficiency of approximately 70%. A 2 Hz bandwidth continuous waveform signal can be swept across a bandwidth of 20–40 Hz. This chirp signal can support the navigation, tomography and communications requirements. The disadvantage is that the size of the resonant tube required is half the wavelength of the center frequency. At 5 Hz this would require a 15 m long tube (at 80 Hz, this would be 10 m). While this complicates deployment, this concern needs to be traded off against the liabilities of other designs, such as reliability, efficiency and cost. These issues may or may not outweigh the challenges posed by the large size of the resonant tube approach.

To determine the highest frequency that can satisfy the requirements for this system it is recommended that an Arctic experiment conduct propagation loss measurements and transmission of prospective waveforms using prototype sources. These measurements should be made at various source depths and ranges from an ice tethered vertical array. This might best be accomplished by deploying an ice tethered array from an ice camp and employing an ice breaker to deploy a source at various ranges and depths, testing frequencies from 40–100 Hz. There are several sources that could be used for this purpose. The best solution would be to use a single source that could transmit all the desired frequencies, such as the Engineering Acoustics Inc. 5–100 Hz source or the new Institute of Applied Physics (IAP) source designed by Boris Bogolyubov.

4.2 Regional scale intermediate frequency

Platforms carrying intermediate frequency (250–1500 Hz) components serve both as navigation beacons, to supplement and enhance the coverage provided by low-frequency sources, and as bridges between the underwater acoustic and satellite telemetry networks. In the latter application the mid-frequency acoustic source serves as a homing beacon to bring mobile data collecting platforms within range of the high-frequency acoustic telemetry system. Generally these platforms would be ice tethered or ice based observatories with access to the air–sea interface for satellite telemetry.

Much like the low-frequency navigation sources, mid-frequency sources mounted on these ice-tethered platforms would broadcast signals on a fixed schedule. The transitory nature of these platforms requires that some information be coded with the navigation signal. At a minimum each broadcast must contain the instantaneous position of the transmitting platform. More useful would be ephemeris for larger portions of the network, such as broadcast schedules and positions of other elements. A low-bandwidth channel could also be used to relay basic command and control messages to under-ice assets. Data carrying capacity at these frequencies needs further investigation.

Considerations for under-ice platforms are largely the same as for the low-frequency system. The receive hydrophone could be shared. It is also possible that some under-ice platforms could carry mid-frequency source projectors. For larger AUVs and floats such a projector could serve as a locator beacon when operated in SOFAR mode, in which multiple receive stations are used to calculate the position of a transmitter. If development of data telemetry at these frequencies supports bandwidths of a few tens of bits per second, then limited data upload from these platforms is also possible.

Key considerations in specifying this part of the system include transducer size (lower frequency means larger transducer), range (lower frequency means longer range), bandwidth (broader band means higher bandwidth) and ease of logistics (higher frequency means smaller transducers). Currently, 780 Hz narrowband RAFOS sources are available with transducers that are 60 cm long and 22 cm in diameter, weigh 75 kg when batteried for 4000 transmissions and could cost as little as US$10,000 in quantity. They could be deployed via small aircraft through an augured ice hole. Currently available 260 Hz RAFOS sources have transducer dimensions of 36 cm diameter by 1.8 m long, weigh 360 kg (again with batteries for 4000 transmissions) and would likely have to be deployed by icebreaker.

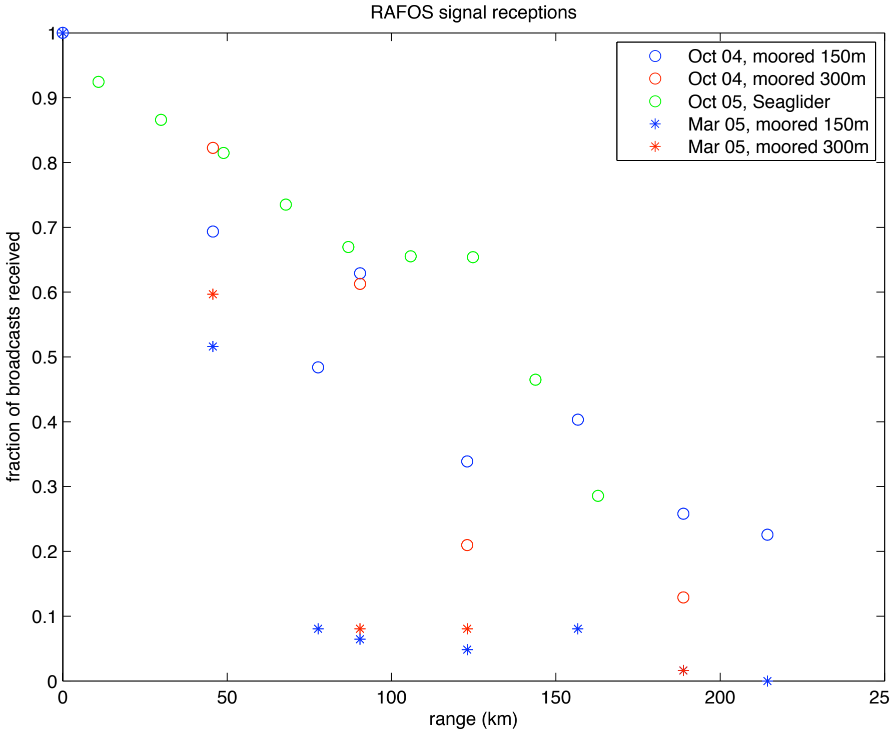

Fig. 9: Percentage of 780 Hz RAFOS transmissions received at moored receivers in ice free (October) and ice covered (March) periods.

Signaling range at these frequencies in ice covered environments is another area that needs further investigation. Compared to open ocean conditions, RAFOS signaling ranges are significantly reduced under ice. In recent experiments in Davis Strait, signal reception at ranges greater than 50 km dropped dramatically under ice (Fig. 9). Some participants reported that 260 Hz RAFOS ranges under ice were not significantly better. Others reported success with under-ice RAFOS in the Weddell Sea to ranges of 500 km. Possible reasons for this discrepancy are not well understood, though ice roughness spectra likely plays an important role. Workshop participants supported the development of more sophisticated signal processing techniques that might improve under-ice performance of these systems through additional processing gain and appropriate handling of multipath.

4.3 Short range high frequency

High-frequency acoustic communication is the most commercially mature of the technologies proposed for integration into the system. Numerous existing commercial offerings meet the basic requirements of the short-range telemetry function envisioned as part of this layered system. Based on existing capabilities, workshop participants agreed that as a minimum goal the components in the high-frequency system should be capable of 1 kbps net throughput at 5 km range operating at 10 kHz.

Meeting these requirements under ice will require additional testing and perhaps additional development. More challenging than this technical effort will be the work required to ensure interoperability. Given the number of countries and funding sources, a successful basin scale system requires that components from multiple vendors must be interoperable. To achieve interoperability, the user community can exert some influence with modem vendors by specifying clear requirements and then working with multiple vendors to exchange information and work toward a common specification that meets those requirements. The common protocol needs to be open and transparent, so that a wide range of users and vendors can design components to operate within the network. A solution that promises to endure for some time will make adoption by multiple vendors more likely.

Modem hardware and programming interfaces need to be provided as pluggable modules that ease integration onto a variety of platforms. Network protocols, store-and-forward functions, buffering, etc. should be included in the modem so that to the degree possible core platform functions are not impacted by modem integration. Easing integration issues makes uptake by platform operators more likely and hence increases the density and functionality of the network.

5 Environmental impacts

ANCHOR activities must integrate efforts to analyze, understand and, where necessary, mitigate impacts of sound on marine mammals during system design and implementation. Marine mammals rely on sound production and hearing for tasks that directly impact their reproductive fitness. Several whale (bowhead, beluga and narwhal) and seal (ringed, bearded, harp, hooded, ribbon and spotted) species as well as walrus and polar bears are of great importance to human communities culturally and as a food source. Given that Arctic environmental change already threatens both marine mammal and human populations, ANCHOR systems must be designed to minimize the introduction of additional stress.

As part of the initial design phase, ANCHOR participants will work with marine mammal specialists to synthesize the results of previous Arctic and lower-latitude acoustics studies, marine mammal population and migration data and human subsistence activity data to asses the potential for adverse impacts (Fig. 10). The frequencies envisioned for basin-scale (10–100 Hz) and mid-range (100–1000 Hz) navigation systems lie within the vocalization range of several cetacean species (Fig. 11).

ANCHOR investigators will thus need to work with administrators and scientists at the National Oceanographic and Atmospheric Administration and the Fish and Wildlife Service to assess source broadcast amplitudes, depths, duty cycle and proximity to marine mammal populations and migration routes for potential impacts.

The ANCHOR consortium will strive to design systems that meet the criteria for an Environmental Assessment “Finding of No Significant Impact” (`http://www.nmfs.noaa.gov/pr/permits`). Mitigation strategies might include careful choice of sound source frequency, amplitude, depth and location, operating with limited duty cycles and scheduled, temporary deactivation of specific elements to accommodate seasonal migration patterns or other transient animal concentra-

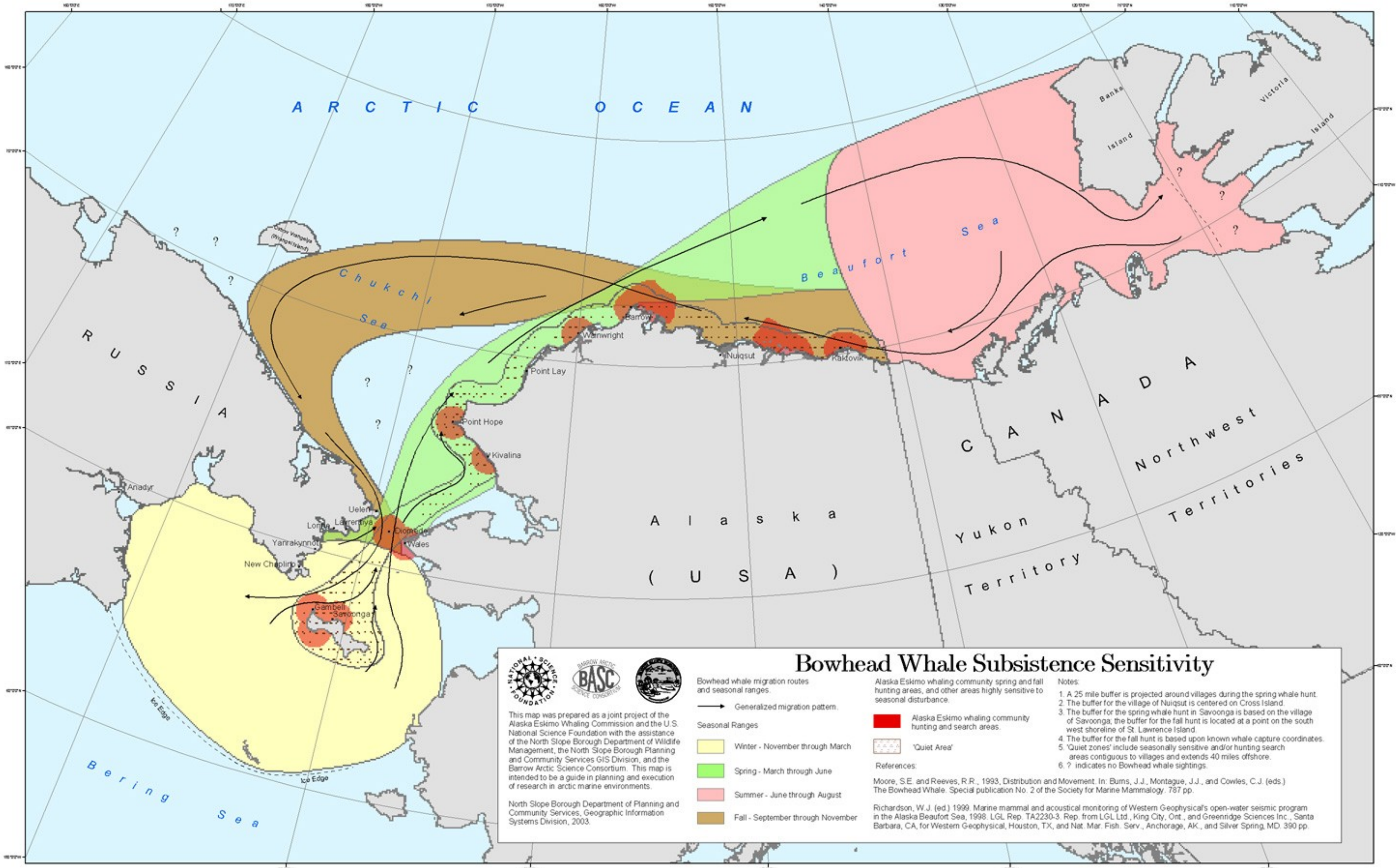

Fig. 10: Example map of bowhead whale distribution and consideration of human subsistence activities. Colors denote bowhead range in winter (yellow), spring (green), summer (pink) and fall (brown). Red areas denote Alaska Eskimo whaling community hunting and search areas.

tions. Should efforts to establish long-range acoustic communications (low bandwidth) succeed, individual sources could be temporarily switched off in response to marine mammal “events.”

The ANCHOR array will also carry hydrophones to track and count marine mammals and support a quantification of the Arctic acoustic noise budget. This will provide additional data for impact assessment, perhaps leading to system refinements to further reduce impacts. The ANCHOR consortium also recognizes the possibility that the system will require Letters of Authorization (LOA) and Incidental Harassment Authorizations. While this process would be far more involved, the approach of bringing marine mammal concerns forward at the start of the design process should serve to minimize the system’s impacts regardless of which regulatory path the effort eventually follows.

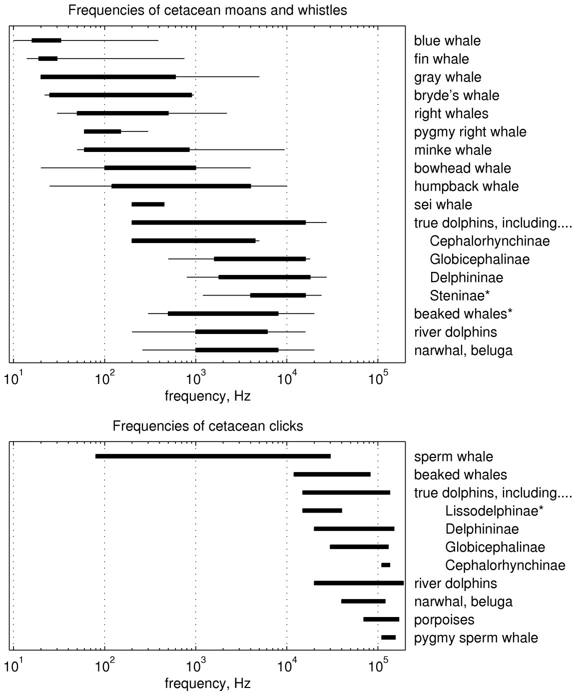

Fig. 11: Cetacean vocal frequency ranges.

6 International cooperation

The ANCHOR system will require international collaboration to achieve pan-Arctic coverage and to support the broad array of Arctic science the system is designed to enable. Early development efforts, such as those in the Davis (U.S .National Science Foundation Arctic Observing Network) and Fram (European Union DAMOCLES Program) straits focused on limited regions and were thus implemented by small numbers of partner nations. These projects fostered active exchanges of scientific and technological expertise, and underscored the value of open standards and coordinated development.

As the building blocks created by the various regional efforts grow toward achieving the pan-Arctic coverage envisioned by ANCHOR participants, international coordination and cooperation will play an increasingly important role. The ANCHOR consortium aims to provide a framework for coordinating design and implementation efforts. An international steering group will foster technical exchange, broker and maintain community consensus on system standards and coordinate development activities and system deployments. Acoustic geometries will dictate mooring locations situated within the Exclusive Economic Zones (EEZs) of several countries that border the Arctic Ocean. Additionally, the source moorings require regular service and science efforts will likely span multiple EEZs. International cooperation will be needed to spread the burden of maintaining the system and to secure the necessary permissions for working within host country EEZs.

The nested system for acoustic navigation and communications would open the Arctic to new, long-endurance autonomous platforms that could play large roles in future Arctic Observing Networks. ANCHOR system development, implementation and governance will thus be coordinated with the organizations, such as SEARCH and ISAC, that have been tasked to guide arctic observing network development.

7 Recommendations

The ANCHOR workshop produced recommendations to guide the next steps toward developing a pan-Arctic navigation and communications network. At low frequencies, the group placed high priority on conducting design studies and experiments focused on optimizing acoustic source type and frequency. Range, cost, size, reliability, marine mammal impacts, logistics/handling, energy efficiency, and signal carrying capacity/bandwidth must be appropriately balanced when considering design choices. Additional data will be needed to guide these decisions. This, combined with the need to test autonomous platform behavior under low-frequency navigation suggests a regional-scale, low-frequency pilot, designed to provide geolocation signals across a significantly larger area than the current efforts (Davis and Fram straits). Designing the pilot around a specific regional-scale science problem would provide appropriate constraints and offer the potential for both system development and novel science. A carefully designed regional testbed could serve both purposes, speeding ANCHOR development by providing an efficient avenue for testing and refining new ideas.

At mid-frequency, an emerging system that employs gliders for year-round sampling in the seasonally ice-covered Davis Strait has demonstrated under-ice navigation using standard RAFOS sweep signals. The next stage of development toward Arctic network applications should proceed along two paths. Existing source technologies should be modified to employ new signal types and processing aimed at enhancing range and achieving the ability to transmit data over long ranges (source to mobile platforms, for command and control). Existing RAFOS technologies should also be deployed in an array of fixed nodes for a regional-scale experiment designed to test and refine interactions between fixed and mobile platforms. This experiment could be embedded within the low-frequency regional pilot, and might also serve as a testbed for new mid-frequency technologies.

The highest priority task for the high-frequency system is coordinated specification of a capable, open protocol that can be implemented by multiple vendors. This coordination is probably best facilitated through a combination of market driven, serendipitous development and formal processes. The market will respond if early developers and users of commercial acoustic modem technologies insist that their vendors ensure interoperability between the various modem designs. This could be achieved through a collaborative process, perhaps guided by a small, technically focused group. This group could guide vendors toward an open standard, perhaps implemented alongside their proprietary technologies, that could provide the interoperability required by a truly pan-Arctic system.

An international ANCHOR steering group will guide these activities, using mailing lists (anchor@apl.washington.edu), a web site (`http://anchor.apl.washington.edu`), special sessions at upcoming meetings and publications to coordinate activities and promote interaction. ANCHOR products, such as the meeting report, technical documents and evolving system specifications, will be offered to the community through the web site.

8 Afterword

The ANCHOR workshop took place prior to the unprecedented 2007 sea ice minimum. Although workshop participants did not consider scenarios that involved seasonally ice-free conditions across much of the Arctic, the 2007 minimum suggests that the implications of such a fundamental change should be considered in conjunction with workshop recommendations. More recent workshops (e.g., the Autonomous and Lagrangian Platforms Workshop held as part of the 2008 NSF Arctic Observing Network meeting) have explored the potential impacts of reduced ice cover. Dramatically reduced summer–autumn sea ice extent would increase the likelihood that mobile platforms (e.g., gliders and floats) could reliably locate open water, thus improving the utility of satellite-based communications for data offload. Reliable access to open water, even if only for a short period each year, would allow long-endurance platforms to transmit their data via satellite and thus mitigate the need for medium-frequency data-relay sites. Implementation of the basin-scale, low-frequency array alone might then be sufficient to open the Arctic to a wide range of long-endurance autonomous platforms.

Greatly reduced summertime sea ice extent would impose new operational constraints while also easing some aspects of system implementation. Drifting, ice-based observatories and navigation/communications beacons might experience shortened lifetimes due to premature melt-out, with melt-back patterns inhibiting drifting access to some regions. New "amphibious" designs capable of surviving melt-out and refreeezing might overcome these difficulties, while the ice-free areas could be accessed with the more conventional drifter technologies employed in the lower-latitude oceans. The retreating ice cover might also provide seasonal open-ocean access to some Arctic regions that currently experience perennial ice cover. This would ease the burden of servicing bottom-moored elements (such as the low-frequency sources) and provide access to a broader range of potential sites.

If sea ice extent shifts to a regime that includes regular summertime minima similar to those observed in 2007, the priorities for near- and mid-term ANCHOR activities might shift. Development efforts could emphasize low-frequency navigation and interactions with autonomous platforms, as mid-frequency geolocation and high-frequency acoustic communications might play a reduced role in a seasonally ice-free environment. The regional-scale low-frequency pilot program (described above in section 7), would take on additional importance as it might truly represent a test of the complete system.

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Acoustic Navigation and Communications for High-latitude Ocean Research (ANCHOR) Workshop

Call for Participation

27 February – 1 March 2006, University of Washington, Seattle, U.S.A.
http://iop.apl.washington.edu/projects/anchor/index.html

Summary

Recent community reports on autonomous and Lagrangian platforms and Arctic observing identify the development of under-ice navigation and telemetry technologies as one of the critical factors limiting the scope of high-latitude measurement efforts. An NSF-sponsored workshop will address these needs, bringing together international participants from the fields of acoustic navigation and telemetry, arctic oceanography, acoustical oceanography and autonomous platforms. Workshop participants will begin the coordinated definition of an acoustic navigation and telemetry system capable of supporting a diverse range of Arctic observational activities. Efforts will focus on comprehensive system design, including specifications for components comprised of mature technologies and identification of areas requiring additional development.

Background

Geographic remoteness, severe operating conditions and issues associated with ice cover have hindered high-latitude measurement efforts and thus limited our understanding of polar and subpolar regions. Recent advances in autonomous platforms (profiling floats, drifters, long-range gliders and propeller-driven vehicles) promise to revolutionize ocean observing, providing unprecedented spatial and temporal resolution for both short-duration process studies and multi-year efforts designed to quantify long-timescale environmental changes. This new generation of platforms facilitates access to logistically difficult regions where weather and remoteness challenge conventional techniques, making them attractive for polar applications. These platforms could provide basin-wide sampling in ice-covered regions, operate near the ice-water interface and, when combined with moorings and ice-tethered platforms, provide a multi-node store-and-forward network to maximize data return from the entire suite of vehicles. Autonomous platforms could provide efficient, extended-endurance measurements at the temporal and spatial scales needed to address many SEARCH ocean and ice science goals.

Reports from recent community workshops (Instrumentation for Arctic Ocean Exploration, 2002; Ice-Based Observatories, 2004; Autonomous and Lagrangian Platforms and Sensors- ALPS, 2003) identify under-ice navigation and telemetry as important enabling technologies whose development would allow high latitude research to benefit from new platform technologies that are becoming operational in ice-free waters. Navigation and telemetry for the current generation of platforms relies on absolute positioning (GPS) and global communications (Iridium, ARGOS, ORBCOMM) provided by orbital systems that are poorly suited for many high-latitude applications where partial or complete ice cover restricts access to the sea surface. The ALPS workshop report noted that acoustic systems for both under-ice navigation and telemetry are technologically feasible, but will require significant infrastructure to provide basin wide coverage. The Arctic Instrumentation Workshop report lists under-ice navigation as an ‘over-arching technical challenge that presently limits most types of Arctic research’.

The Ice-Based Observatories Report provides one vision of how acoustic systems could be embedded in an integrated Arctic observing system to support navigation and telemetry under ice. Two specific system objectives are : 1) provide reliable, several times per day, basin-wide navigation signals and 2) provide a network for data telemetry that offers a high probability of connection for navigable vehicles and some reasonable probability of encounter for drifting platforms. Participants in the Ice-Based Observatories workshop defined a system composed of three elements, each based on particular acoustic frequencies and protocols.

1. At the basin scale, a relatively small number of bottom moored, large, low-frequency (20 - 50 Hz) sound sources could be used to ensonify the entire basin, broadcasting navigation signals on fixed, several times-per-day schedules.
2. At the next level, observatory elements, primarily ice based observatories (IBO), with a surface expression (providing GPS and satellite telemetry) would carry mid-frequency (200 - 1000 Hz) sound sources that broadcast scheduled signals coded with position. With their position determined by a combination of these signals and those from the low frequency system, mobile platforms could use the coded position information to home to the IBO. Floats, with no ability to home, could still make use of this system for positioning redundancy.
3. Finally, IBOs and mobile platforms would carry high frequency (10 - 30 kHz) acoustic modems for short range homing and data transfer.

Workshop goals

Workshop participants will focus on the design and technical specifications for basin- to small-scale Arctic (under-ice) navigation and telemetry systems, potentially comprised of both mature and developmental technologies. Smaller-scale systems are already under development, but do not involve the full suite of elements required to achieve the vision outlined above. Significantly, the recently-funded European Union DAMOCLES project involves an extensive Arctic observing program that will require navigation and telemetry for autonomous platforms operating beneath the ice. DAMOCLES acknowledges that developing, deploying and operating a basin-scale system will require effort and support from the researchers and funding agencies of multiple nations, and thus anticipates a collaborative effort. Projects undertaken as part of the approaching International Polar Year may also involve navigation and telemetry elements. The workshop will establish ongoing coordination of the diverse efforts to maximize interoperability of the resulting systems.

Although motivated by outstanding Arctic science issues, the workshop agenda will concentrate on technical objectives. The primary objective is to produce a specification from which research teams could begin implementing components of the Arctic navigation and telemetry system. Among the specific questions to be addressed in achieving this objective are:

- Is the three tier model described above the right approach? Can the functionality of the low and intermediate frequency systems be combined? Do we need significant telemetry capability at intermediate frequencies? Should timing signals be included in the telemetry?
- What knowledge gaps must be addressed to inform the final choice of protocols and frequencies? How does propagation range change as a function of frequency? How does ice cover modulate acoustic telemetry? How does the severity of ice-induced modulation vary with frequency?

- What specific technologies (e.g. hardware, encoding and signal processing techniques) will be used in the system? What protocols might be used for intermediate frequency position encoding? How much bandwidth can we expect from inexpensive, readily available sources? Is there an emerging standard for high frequency telemetry? What should transmission and interrogation schedules be?

Additional tasks include coordination with efforts to define acoustics contributions to lower latitude ocean observatory efforts and discussion of marine mammal impacts and permitting issues.

Organization and logistics

The Arctic Navigation and Telemetry Workshop will be held in Seattle from 27 February to 1 March 2006. Additional information will be posted on the website and distriuted by email over the coming months. As a starting point for discussion the workshop will be initially organized around the three-tiered acoustical system described above. This suggests working groups focused on:

- Low frequency navigation.
- Intermediate frequency navigation and homing with limited telemetry.
- High frequency, short range telemetry.
- Platforms (floats, gliders and actively driven AUVs).
- Marine mammal monitoring and protection.
- Synergistic acoustical oceanography applications.

Participants knowledgeable in acoustic navigation, acoustical oceanography, marine mammal acoustics, acoustic telemetry, high-latitude oceanography, and float, glider, and AUV developers and operators are particularly encouraged to attend. Participants actively working on technology development in a relevant subject area may be asked to give a brief presentation about the state-of-the-art in that area.

The workshop will produce a report that features a detailed technical specification for the navigation and telemetry system. Selected issues may be targeted for additional study. We will also use the workshop to develop communication and decision making procedures for the Arctic navigation and telemetry community. This will facilitate coordinated responses to proposed specification changes and strengthen the long-term cohesiveness of the resulting system. Successful implementation of a large-scale Arctic navigation and telemetry system will rest largely on continued communication between the diverse research groups.

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Acoustic Navigation and Communication for High-latitude Ocean Research (ANCHOR) Workshop

Applied Physics Laboratory, University of Washington,
Seattle, WA, 27 February – 1 March 2006

preliminary agenda

Monday, 27 February

0800 – 0830	registration, coffee, poster setup
0830 – 0900	welcome, logistics information, lightning round introductions
0900 – 1030	background presentations
	Lee Freitag: state-of-the-art in acoustic communications
	Tom Rossby: current state and future developments in long range navigation
	Alexander Gavrilov: low frequency propagation in the Arctic
	Sue Moore: marine mammal issues
1030 – 1050	coffee
1050 – 1200	drivers and requirements presentations
	DAMOCLES overview
	initial requirements
1200 – 1300	lunch
1300 – 1600	multi-disciplinary working groups doing parallel system development
1600 – 1730	refreshments and poster viewing

Tuesday, 28 February

0800 – 0830	coffee
0830 – 1000	working group summaries
1000 – 1020	break
1020 – 1200	whole group discussion toward a single design vision
1200 – 1300	lunch
1300 – 1500	disciplinary working groups addressing specific design requirements
1500 – 1520	break
1520 – 1630	working groups continued
1630 – 1730	working group summaries

Wednesday, 1 March

0800 – 0830	coffee
0830 – 0900	context
	Bruce Howe: synergies with global scale efforts
0900 – 1200	whole group discussion
	recommendations to funding agencies
	workshop report assignments
	future directions for ANCHOR group
1300 – 1500	steering committee wrap-up