THE FRAM STRAIT ACOUSTIC SYSTEM FOR TOMOGRAPHY, NAVIGATION AND PASSIVE LISTENING

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Abstract:

For the first time, a multipurpose acoustic system has been deployed in a Marginal Ice Zone (MIZ) to serve acoustic tomography, navigation of gliders, tracking of floats and passive acoustics. A triangle of acoustic transceivers and a vertical receiver array in the centre were deployed in Fram Strait during summer 2010 and will be recovered in 2012. The system provides acoustic travel time measurements along six sections for direct assimilation into ocean models and for tomographic inversions. Gliders, equipped with acoustic receivers and software for acoustic navigation, will use the acoustic signals to perform under ice surveys during summer/autumn 2011. Furthermore, ambient noise measurements from five vertical arrays will be used to detect and study the sounds from marine mammals and sea ice dynamics. The system will be used to observe ocean temperature and currents, and points towards the future development of acoustic multipurpose systems for the Arctic Ocean.

Keywords: *Arctic, Fram Strait, acoustic tomography, ambient noise, glider navigation*

1. INTRODUCTION

The Fram Strait is a key location to study the impact of the Arctic Ocean on global climate change. The Fram Strait, with a sill depth of 2600 m and a width of nearly 400 km, is the only deep connection where exchanges of intermediate and deep waters take place between the North Atlantic and the Arctic Ocean. On the eastern side of the Strait, the northbound West Spitsbergen Current transports Atlantic water into the Arctic Ocean, whereas on the western side the southbound East Greenland Current transports sea ice and polar water from the Arctic Ocean to the Nordic Seas and the Atlantic Ocean.

Since 1997 an array of 16–18 oceanographic moorings has been maintained in the northern Fram Strait at 78°50'N, covering the Strait between the east Greenland shelf and the shelf slope west of Svalbard. It is logistically and economically demanding to maintain the moored array, which also suffers from limitations in spatial resolution and in real time capability [1]. Our goal is to improve the accuracy of the heat, mass and freshwater transport estimates through the Fram Strait using an innovative and cost efficient four-dimensional data and model system combining acoustic travel time measurements and ocean data from gliders and moorings with high resolution ice-ocean modelling through data assimilation. A partial implementation of the ocean-acoustic system components was initiated within EU DAMOCLES (2005–2010) [2].

Under the EU ACOBAR (2008–2012) project the separate moored arrays have evolved and merged into the multidisciplinary integrated Fram Strait Observatory. The system consists of oceanographic moorings, acoustic tomography transceivers and a long vertical receiving array, passive listening systems, RAFOS sound sources, gliders and floats (see http://acobar.nersc.no).

This paper focuses on describing the technical details of the Fram Strait acoustic system, the ongoing and planned exploitation of the system, and the role of such multipurpose acoustic systems in the future Arctic Ocean Observing System.

2. THE FRAM STRAIT ACOUSTIC SYSTEM

2.1. The Fram Strait acoustic experiments

The first steps towards an integrated data and model system in the Fram Strait, combining high-resolution ice-ocean models (3.5 km horizontal resolution) and ocean acoustic tomography, were taken under the DAMOCLES EU/FP6 project (2005–2010, http://www.damocles-eu.org/). A single-track acoustic thermometry experiment was carried out in the Fram Strait during 2008–2009. Broadband acoustic signals (190–290 Hz) were transmitted every three hours for a year, and the signals were received 130.010 km away on a 700-m-long vertical array with eight hydrophones spaced 96 m apart.

The single-track acoustic experiment was followed by implementation of a multipurpose acoustic network in the Fram Strait for tomography, ambient noise, and glider navigation (http://acobar.nersc.no, [2], [3]). The network was deployed in August/September 2010 from R/V Håkon Mosby and the Norwegian Coast Guard ship K/V Svalbard. Three tomographic transceivers (A, B, C) and one central receiver (D) are configured as shown in Fig. 1. Two of the tomography moorings, B and C, are positioned in the MIZ and frequently covered with ice. Those two moorings will be recovered after two years during summer 2012. The source near Svalbard (A) and the receiver mooring (D) will be recovered and redeployed after replacing batteries during September 2011. Two 260-Hz RAFOS sources are also integrated into the acoustic network (Fig. 1). The RAFOS sources will also be recovered in 2011 for replacement of batteries.

During the experiment, the tomography sources transmit 60-s-long linear frequency modulated (LFM) signals sweeping from about 200 Hz to 300 Hz. The LFM signals are transmitted every three hours in a cycle involving each of the three sources, every other day. The tomographic signals from the different sources are separated in time by seven minutes and are also distinguished by slightly different start and end frequencies for each source. The "triangle experiment" configuration provides two-way acoustic travel times along the three sides of the triangle and one-way transmissions between each of the transceivers and the vertical receiving array in the center.

In addition, the tomography sources are programmed to transmit standard narrowband RAFOS signals for glider navigation, sweeping linearly from 259.375 Hz to 260.898 Hz in 80 s. RAFOS signals are transmitted by the three tomography sources and the two RAFOS sources every day during fall 2010 and fall through winter 2011–2012 to accommodate glider operations. The RAFOS signals are transmitted in cycles involving each acoustic source separated by 30 minutes every six hours.

All sources were confirmed to be working at the end of the K/V Svalbard deployment cruise in 2010. Source signals (both RAFOS and tomography) were received on several sonobuoys during a mission on 4 October with P3 aircraft from the Norwegian Air Force. RAFOS signals were also heard around 1000 km away by the acoustic floats in Lofoten Basin (H. Søyland, 2010).

2.2. Acoustic receivers.

The experiment schedules for the tomographic transceivers and vertical receiving array are controlled by the *Simple Tomographic Acoustic Receiver* (STAR) technology, which was developed at Scripps Institution of Oceanography. The standard STAR technology provides a precise clock, using a two-oscillator system (MCXO plus Rubidium). This time keeping system provides a precision/stability better than 3 ms over a year. Furthermore, the STAR system together with four acoustic transponders surrounding each mooring location provide a long-baseline acoustic navigation system to measure the position of the control unit with an accuracy of about 1 m. The four transponders are deployed 1–2 km away from the anchor position of each mooring, with the distance depending on the height of the navigation transducer on the mooring above the sea floor. A standard STAR comes in a pressure case containing the electronics and lithium batteries.

The standard STAR electronics supports four hydrophones, each with a separate cable; the length of each cable cannot exceed 300 m. In the vertical arrays integrated with the sources, the hydrophones are spaced by 9 m (1.5 wavelengths at 250 Hz) to be able to measure both arrival time and arrival angle through array processing. In the standalone receiver mooring in the center of the triangle, a 686-m long, 8-element vertical receiver array is formed using two STARs, with the hydrophones for each STAR 96 m apart. The upper STAR instrument is at 300 m, and the first hydrophone is positioned 7 m below the STAR navigation transducer. The hydrophones are at 307 m, 403 m, 499 m, 595 m, 691 m, 787 m, 883 m, and 979 m.

More recently, a flexible Distributed Vertical Line Array (DVLA) receiver has been developed at Scripps Institution of Oceanography (Worcester et al., 2009). The DVLA is constructed of subarrays, each of which can be up to 1000 m long and include up to 99 hydrophone/logger systems freely distributed along the mooring wire. An inductive modem is used to send commands and synchronization signals from a central controller to the individual hydrophone/logger systems over the mooring wire. This development provides a new capability to map the arrival time structure as a function of depth, to use spatial filtering to separate the acoustic field into normal modes, and to implement advanced beam forming techniques.

2.3. Acoustic sources

The organ pipe sources used in ACOBAR/DAMOCLES are commercially available from Teledyne Webb Research Corporation, USA [4]. The sources produce broadband frequency modulated (FM) signals, sweeping over approximately 200–300 Hz. The source level and duration of the transmissions are easily adjustable. The source can also be programmed to produce CW signals at selected frequencies or standard RAFOS signals. On axis, the maximum source level is close to 190 dB re 1 μPa at 1 m. To obtain accurate clock and positioning of the source in the water column, the sound source is integrated with STAR electronics in as single pressure housing. The sound source is generally rated down to 2000 m, but can be rated to deeper depths on request.

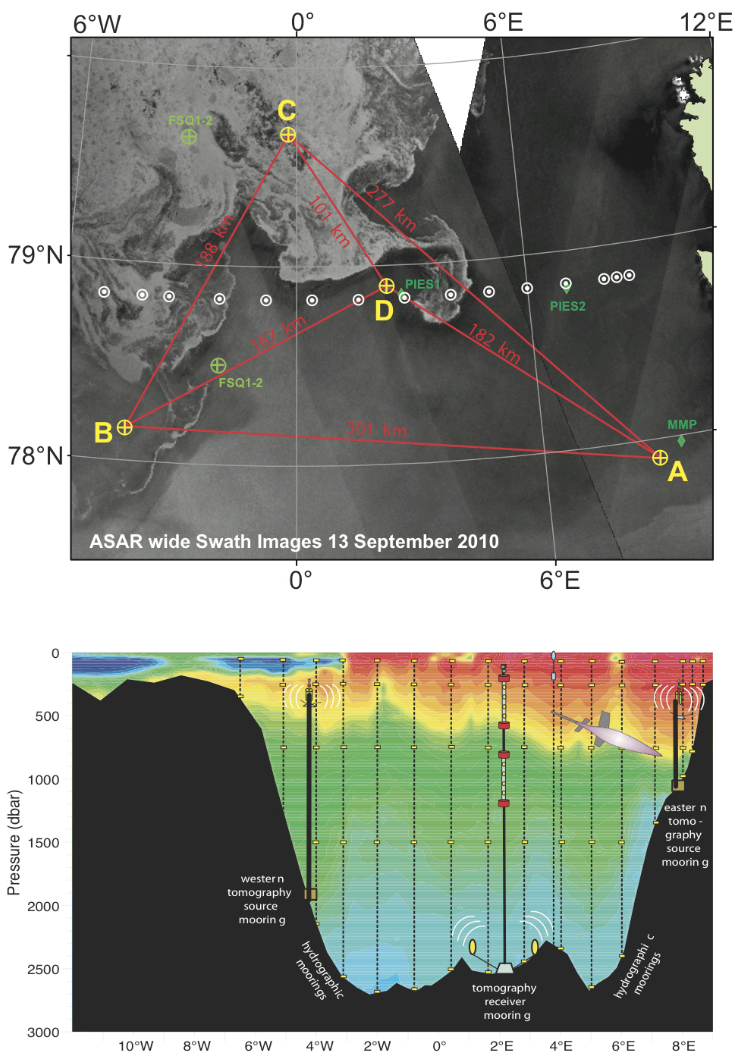

Fig. 1: The upper panel shows an ASAR image. The grey/white areas correspond to sea ice, while the darker areas are open water. The image shows a very dynamic MIZ, and in particular a vortex pair under development.
Superimposed on the ASAR image we have mapped the transceiver moorings (labelled A, B, C), receiver mooring (D), two RAFOS sources (labelled FSQ1-2), and oceanographic moorings (white dots). An oceanographic profiler (MMP) is located near transceiver mooring A.

The lower panel shows moorings overlaid on the temperature distribution in Fram Strait. Red colouring indicates warm Atlantic water and blue depicts cold Arctic waters.

2.4. Passive acoustic system

The 700-m-long vertical hydrophone array in the middle of the triangle (D) and the 250-Hz vertical arrays attached to each of the three acoustic sweeper sources (A, B, C) provide not only acoustic travel time measurements, but also ambient noise data sampled at 1000 Hz. Each of the transceivers records 2*100 s every three hours every day, and the receiver array records 3*100 s every three hours every day. These data will provide spatial coverage of ambient noise in the Fram Strait MIZ through different environmental conditions at daily and seasonal time scales.

An autonomous acoustic recording system developed by NAXYS AS is integrated into the northernmost mooring (C) at a depth of 350 m. The system is designed to monitor acoustic emissions in the low- to medium-frequency range, spanning from ~1 Hz to 6250 Hz. This system has a 2-m-long, four-channel vertical hydrophone array and is programmed to record for five minutes every hour for two years.

3. EXPLOITATION OF THE FRAM STRAIT OCEAN ACOUSTIC SYSTEM

There is a significant lack of ocean data from the Arctic regions. Acoustic thermometry/tomography systems are particularly well suited for observing the interior of the Arctic Ocean environment. This has been demonstrated through previous successful experiments, in particular the Greenland Sea Experiment in 1988–1989 [5], the 6-year-long Labrador Sea experiment [6], the Transarctic Acoustic Propagation (TAP) Experiment [7], and the 14-month-long ACOUS experiment [8].

3.1. Acoustic monitoring

The Fram Strait single-track acoustic experiment was successfully carried out during 2008–2009 in the Fram Strait under the DAMOCLES project [2]. Data from each of the hydrophones has been collected, quality checked, and pre-processed [9], which involves detection of arrivals and correction for mooring motion and clock drift. After pre-processing, the data has been used for inversion [10] and ocean model validation [9].

The ultimate use of acoustic travel time measurements or acoustically derived parameters is to integrate them with ocean circulation models through data assimilation techniques. Acoustic travel times are currently being used for testing of assimilation into ocean models under the ongoing ACOBAR project using the EnKF formulation (http://acobar.nersc.no; [2]). Assimilation of acoustic travel times from six tracks into the TOPAZ system (http://topaz.nersc.no) is the goal of ACOBAR.

3.2. Acoustic underwater "GPS" system.

Gliders and floats have become popular and important platforms for oceanographic data collection. Gliders are remotely steered by an operator via satellite communication and have operated for up to nine months in temperate waters, while floats drift passively with the current for 2–4 years. Profiling Argo floats and gliders provide their position and data when they surface. However, in ice-covered areas gliders and profiling floats cannot rise to the surface to use satellite-based navigation (GPS) and data telemetry via IRIDIUM and ARGOS. For the Arctic, it is therefore necessary to develop acoustic navigation and telemetry systems for gliders similar to the tracking system of RAFOS floats [11].

Narrowband acoustic signals (RAFOS) have been used for several decades for tracking of non-profiling RAFOS floats, with travel time residuals of up to 2–3 s, causing inaccuracies of the order of kilometres in the localization. Under-ice navigation capability has been developed by APL-UW for the Seaglider. The first under-ice operation of a glider using 780-Hz narrowband RAFOS sources was done in the Davis Strait in 2008 [12]. Using this experience, the first trials of acoustically navigated gliders in Fram Strait are planned for summer 2011, exploiting the multipurpose acoustic network installed in the Fram Strait.

Multipurpose acoustic networks provide 100-Hz bandwidth signals for tomography, which can also be used for improved long-range acoustic navigation [13]. The position accuracy of floats and gliders can be improved from the order of kilometres using RAFOS signals to the order of 100 meters using broadband acoustic tomography signals.

3.3. Passive acoustic systems.

There is no permanent operational systems for passive acoustics in the Arctic basin, but several scientific systems have been deployed for limited time periods, in particular during the 1980s and 1990s. The seasonal variation and impact of tidal currents on ambient noise in the Barents Sea was studied in a 1-year-long experiment (1992–1993) by NDRE and NERSC [14]. More recently, in 2008, two passive recording systems were deployed in Fram Strait in order to monitor marine mammals and anthropogenic sound (personal communication, S. Moore, 2009).

Data from the Fram Strait acoustic system will provide benchmark information over a period of two years on ambient noise levels in the region, including noise generated by sea ice, seismic and other anthropogenic sounds, and the vocalizations of marine mammals in this remote area. One purpose is to analyze the ambient noise generated by dynamic processes in the ice, with particular focus on the period of waves in ice [15] and seasonal changes in sea ice dynamics.

4. ACOUSTIC MULTIPURPOSE SYSTEMS IN THE ARCTIC

An acoustic network can measure acoustic travel times to derive heat content and mean circulation on regional or basin scales in minutes or hours, respectively, and provide information about ice dynamics, earthquakes, and marine mammals through passive listening. Furthermore, the same network of acoustic sources forms an underwater "GPS" system providing the navigation and timing needed by gliders and floats under the ice in the Arctic. Gliders and floats provide oceanographic fields at a high resolution in space, complementing the high temporal resolution, horizontally-averaged acoustic measurements. In this way, acoustic infrastructure and measurements can contribute to fill the significant gap in ocean observations in the Arctic, including the marginal ice zones. It is therefore cost effective to develop and implement an acoustic multipurpose system in the Arctic [16].

A major challenge is to provide a real time capability for observing systems in the Arctic. In the interior Arctic, drifting local acoustic networks (<100 km) consisting of ice-tethered platforms (Lagrangian) with surface units can provide data in real time. In areas with drifting and dynamic sea ice processes, as in the Marginal Ice Zones, the best solution is underwater moorings, floats, and underwater vehicles. However, underwater moorings, of any kind, in the Arctic have a major problem in achieving real time capability, as they cannot be attached to surface units placed on a drifting ice floe. Acoustic communication can be used for small amounts of data, but the changing environmental conditions in the MIZ put severe limits on the transfer capabilities.

The best solution would be to have a cabled system, integrated with mobile autonomous systems capable of navigating and communicating under ice. A cabled acoustic network consisting of a modest number of moorings in the Arctic would be a robust and manageable observing system. This would provide basin-wide measurements in real time and year round. Providing continuous data availability in fixed critical locations, the cabled network could observe episodic events such as eddies or the passage/influx of warm or cool water masses *when they happen* to permit researchers to deploy/redeploy/direct other assets such gliders, unmanned systems, ice-tethered or moored platforms to monitor, track, analyze and study the event. It is not a technological problem to integrate acoustic sources and receivers into a cabled network. The issue is more one of economics.

5. RECOMMENDATION

Implementation of cabled systems in the Arctic can only be developed through international collaboration. To proceed towards an operational acoustic network in the interior Arctic, co-ordinated actions involving multiple disciplines are required. The international ANCHOR (Acoustic Navigation and Communication for High-Latitude Ocean) group of experts was established to coordinate interoperable acoustic infrastructure in the high Arctic [11]. European efforts to establish an acoustic network infrastructure covering the Arctic have to be coordinated with Russian, Canadian and U.S. initiatives and interest. Actions to establish an international network are in progress both on European and U.S. side. The Svalbard Integrated Observing System can offer opportunities to develop a system in the European sector of the Arctic.

An environmental assessment report has been developed for the ACOBAR project (see http://acobar.nersc.no for a summary). A final environmental assessment will also include the interior Arctic.

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