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Ice-Tethered Acoustic Buoys for Real-Time Acoustic Monitoring, Navigation, and Communication through the Beaufort Lens

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Ice-Tethered Acoustic Buoys (ITABs) are developed in the NRL Acoustic Division to be used as a real-time acoustic monitoring system for environmental characterization, acoustic navigation, and acoustic communication. During April 2021, five ITABs were deployed in the Beaufort Sea to conduct an under-ice acoustic propagation experiment in the 900-1000 Hz frequency band. Reciprocal transmission data were collected until September 2021, covering different ice-concentration periods. Ambient noise measurements were also accomplished in the Arctic using a passive ITAB, deployed during the Navy's ICEX 2022 expedition. Both active and passive experiments showed that ITABs can be used for long-range, under-ice, real-time acoustic monitoring, navigation, and communication as well as real-time ambient noise measurements in the Western Arctic.

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EXECUTIVE SUMMARY

Ice-Tethered Acoustic Buoys (ITABs) are developed in the NRL Acoustic Division to be used as a real-time acoustic monitoring system for environmental characterization, acoustic navigation, and acoustic communication. During April 2021, five ITABs were deployed in the Beaufort Sea to conduct an under-ice acoustic propagation experiment in the 900-1000 Hz frequency band. Reciprocal transmission data sets were collected until September 2021, covering different ice-concentration periods. Ambient noise measurements were also accomplished in the Arctic using a passive ITAB, deployed during the Navy's ICEX 2022 expedition. Both active and passive experiments show that ITABs can be used for long-range, under-ice, real-time acoustic monitoring, navigation, and communication as well as real-time ambient noise measurements in the Western Arctic.

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ICE-TETHERED ACOUSTIC BUOYS FOR REAL-TIME ACOUSTIC MONITORING, NAVIGATION, AND COMMUNICATION TROUGH THE BEAUFORT LENS

1. INTRODUCTION

The Arctic oceanic environment is undergoing dramatic changes due to recent trends in the global climate, including major fluctuations in the ice cover and the disappearance of older, thicker, multiyear ice. With the reduction of the sea ice-cover, increase in maritime activities and demand for increased naval presence are expected. Under-ice environmental information is essential for the Navy's future operations and therefore, recent changes in ocean stratification in the Western Arctic would have great impact on sonar performance, long-range acoustic communication and under-ice navigation. Decrease in loss mechanisms and favorable undersea acoustic propagation conditions provide an opportunity for long-range undersea environmental monitoring in the Arctic.

The concept of real-time acoustic monitoring in the Arctic was envisioned and realized by developing active and passive Ice-Tethered Acoustic Buoys (ITABs) to deploy in the Western Arctic during 2021 and 2022. This memorandum reports the main results from these two experiments and summarizes the ongoing work on the temporal and spatial coherency of acoustic signals transmitted through a secondary sound channel at a depth of 150 m (Beaufort Lens) in the Western Arctic.

2. HARDWARE

2.1 Active ITAB

The active ITAB was designed to perform reciprocal transmissions in the Beaufort Lens [1]. Each ITAB has one Geospectrum flexural disk transducer (900-1000 Hz) and eight HighTech HTI-96-MIN hydrophones. One hydrophone was placed at 30 m to receive signals in the near-surface duct and seven hydrophones were placed at 130-145 m depth in a secondary duct, called the Beaufort lens (see Fig. 1a). Source and receivers are connected to an on-ice topside unit with 150 m of cable (see Fig. 1b). The topside unit includes a National Instrument 16-bit A/D converter, a CPU (Raspberry Pi), an Iridium Modem, a GPS, and battery packs. After deployment, each ITAB transmits 60 s long LFM signals every six hours with 5-minute time lags between each node. In addition, each ITAB records 5 minutes of data, performs matched-filtering, and finds the strongest arrival to capture the signals from the other ITABs, transmitted every six hours. Then, the 5-second segment of captured signals are transferred to the Naval Research Laboratory in real time by an Iridium modem. Some of the experimental parameters such as transmission/reception intervals, source levels, captured signal duration, etc. can also be changed in real-time by two-way satellite communication.

2.2 Passive ITAB

Passive ITAB was designed to collect third-octave ambient noise levels between 10 Hz and 2000 Hz. The system can collect real-time ambient noise data at 0-150 m water depths covering both the surface duct and the Beaufort Lens. The system has the capability of eight simultaneous recordings with 18-bit resolution

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and 200 kHz sampling rate per channel. Figure 1c shows a four-channel configuration of a passive ITAB that was deployed during the Navy's ICEX 2022 expedition in the Beaufort Sea. The topside unit of the passive ITAB includes a Measurement Computing 18-bit A/D converter, a CPU (Raspberry Pi), an Iridium Modem, a GPS, and battery packs. After deployment, 5-minute blocks of 25-minute data are collected every 4 hours, and third-octave spectra are calculated and averaged for each 5-minute block. Then third-octave spectral values for each 5-minute block are transferred to the Naval Research Laboratory by an Iridium modem.

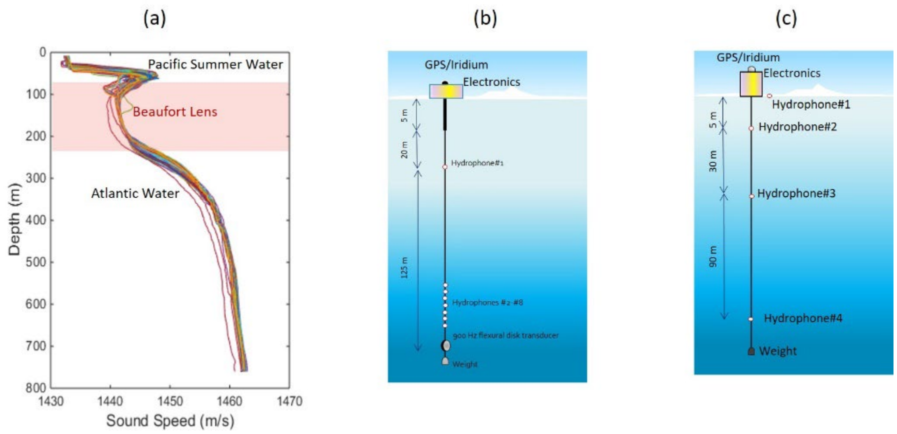

Figure 1. a) Measured sound-speed profiles showing the surface duct and Beaufort Lens in the Western Arctic, b) components of active ITAB, and c) components of passive ITAB.

3. EXPERIMENTS

3.1 2021 Active ITAB Experiment

The active ITAB experiment started during early April 2021 by deploying five active ITABs in the Beaufort Sea in a pentagon configuration, covering ranges from 60 km to 150 km (see Fig 1).

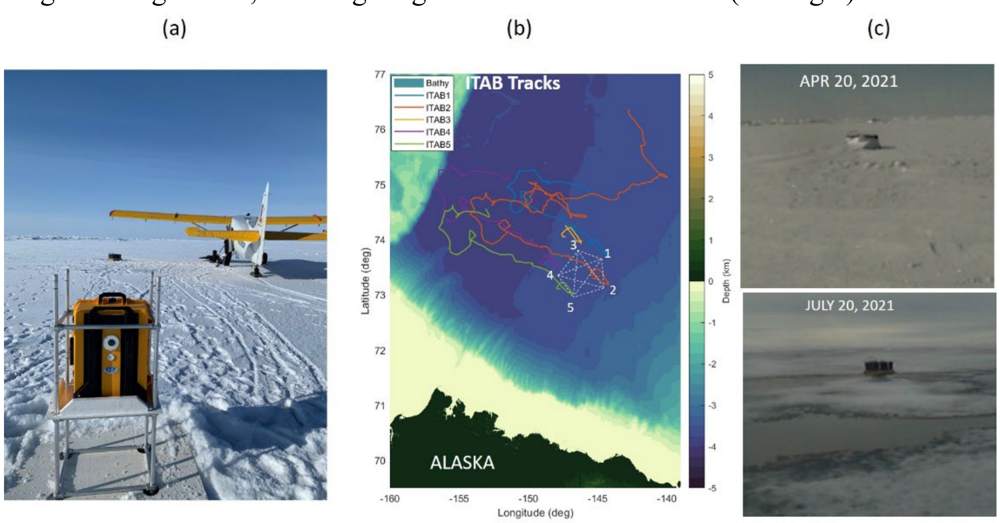

Figure 2. a) Deployment of an active ITAB in the Beaufort Sea, b) ITAB tracks during the experiment, and c) two picture showing the state of the ITAB and ice conditions at different times.

A single-engine Turbine Otter with skis was used to deploy each ITAB at a pre-determined position. Figure 1a shows the deployment of an ITAB with a Pacific Gyre camera in the foreground, transmitting two pictures per day through an Iridium modem. The pictures are used to monitor the state of the ITAB as well as the condition of the ice. Figure 1b shows the track of each ITAB during the experiment and Figure 1c shows the condition of the ice on April 20, 2021 and June 20, 2021. Typical reciprocal transmission data between ITAB5 and ITAB4 are shown in Fig. 3. Four pings per day are depicted while the distance between the ITAB4 and ITAB5 is increasing in time. Pings are aligned using the strongest Beaufort-Lens arrival that are time stamped using the PPS signals from the GPS. The accuracy of the time stamp is 0.25 ms since the PPS signals are digitized at 4000 Hz sampling rate. Earlier deep arrivals are also shown in Fig.3. Arrival time differences between the deep arrival and Beaufort Lens arrival increase as the ITABs drift apart. Distances between three ITABs are shown in Fig. 4 for the same period. Comparison between Fig. 3 and Fig. 4 indicates a similarity between the distance travel-time difference between deep arrival and Beaufort Lens arrival. This would indicate a potential passive source ranging capability in the Beaufort Lens [2].

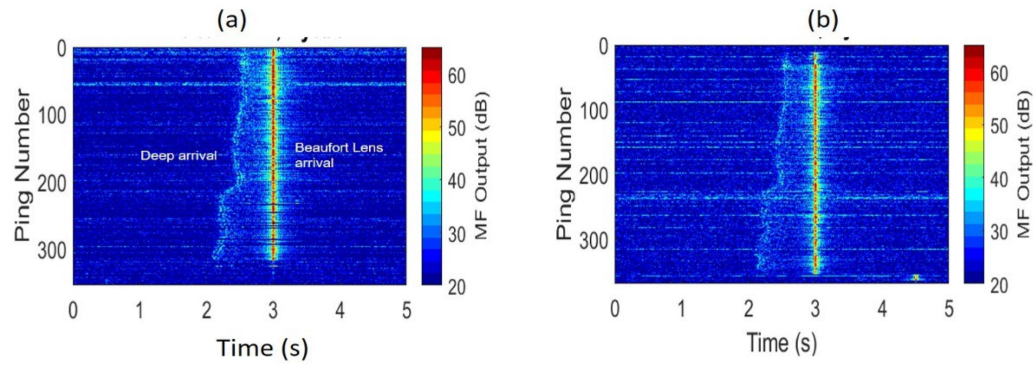

Figure 3. Reciprocal transmissions; a) transmitted from ITAB5 and received on ITAB4 hydrophone#6 in the Beaufort Lens, b) transmitted from ITAB4 and received on ITAB5 hydrophone#6 in the Beaufort Lens.

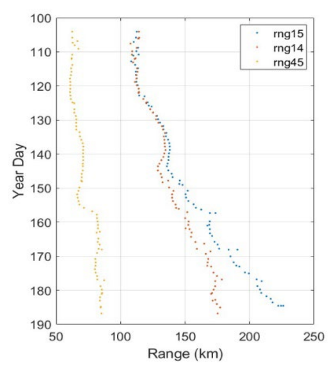

Figure 4. Ranges calculated from GPS data on ITAB1, ITAB4, and ITAB5. The ranges between ITAB4 and ITAB5 resembles the travel-time differences between deep and Beaufort-Lens arrivals (see Fig. 3).

Figure 5 shows the navigation performance of ITAB1 by using acoustic signals received from ITAB3,

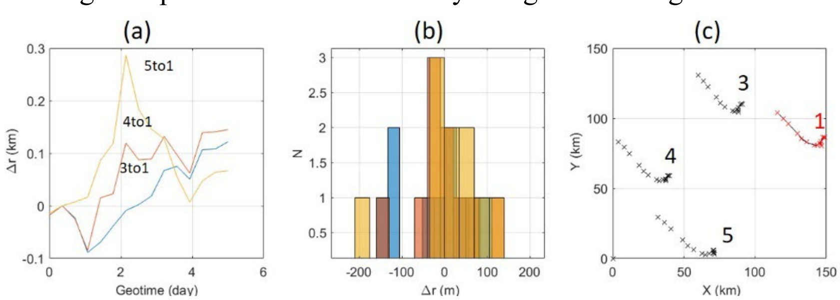

Figure 5. Navigation performance of ITAB1 by using acoustic signals received from ITAB3, ITAB4, and ITAB5. a) range differences calculated from GPS data and acoustic travel-time data assuming an average sound speed of 1450 m/s, b) histogram of the range differences, and c) navigation performance of ITAB1 using calculated ranges from acoustic travel-time data.

ITAB4, and ITAB5. Figure 5a shows the range errors calculated as the range differences between GPS data and acoustic travel-time data assuming an average sound speed of 1450 m/s in the Beaufort Lens. Figure 5b shows the histogram of the range errors. Figure 5c shows the navigation performance of ITAB1 in XY domain using the Moore-Penrose pseudoinverse. The agreement between the GPS data (blue line) and positions estimated from the acoustic travel-time data (red x marks) indicates robust navigation capability using the acoustic signals transmitted through the Beaufort Lens. Figure 6 shows Channel Impulse Response (CIR) functions and Q-functions [3] (autocorrelation functions) measured at various ranges between ITAB4 and ITAB5 using the full 100 Hz bandwidth and 1 Hz filtered bandwidth. The CIR with 1 Hz bandwidth still shows a 10 dB SNR at 112.86 km range and minor multipath interference. This would imply that acoustic communications with rates of 1 bit/s or higher would be possible through the Beaufort Lens at very long ranges (>100 km). Multipath interference can be further reduced by using data from the 7-hydrophone Vertical Line Array (VLA) with a 2.4 m spacing. The Q-functions depicted in Fig. 7 shows further reduction of multipath interference with Single-Input Multiple-Output (SIMO) configuration for both 100 Hz and 1 Hz bandwidths.

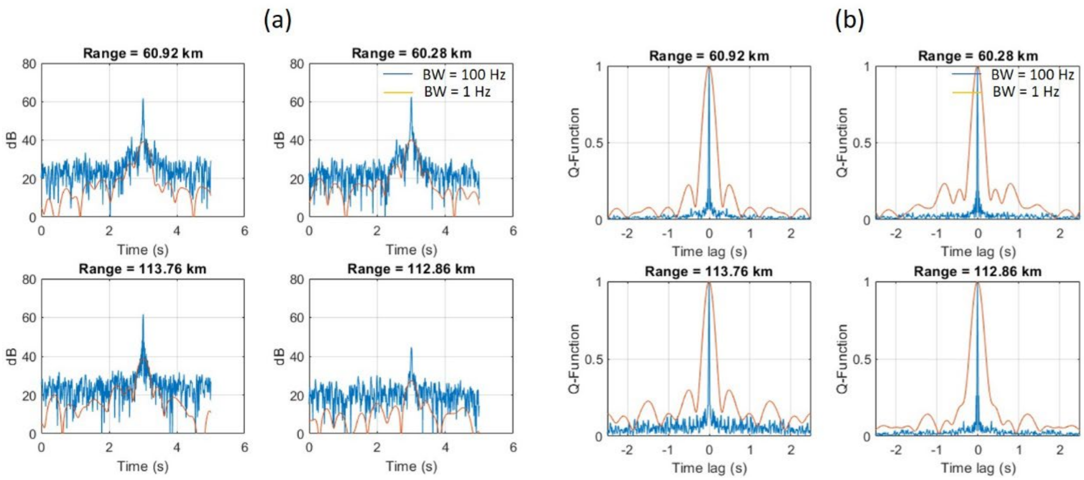

Figure 6. Channel Impulse Response Functions (a) and Q-functions (b) measured at various ranges between ITAB4 and ITAB5 using the full 100 Hz bandwidth and 1 Hz filtered bandwidth.

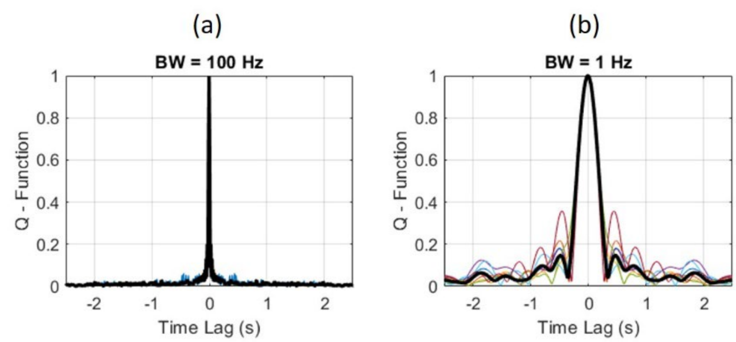

Figure 7. Q-functions for the ITAB4 VLA (black) and each ITAB4 hydrophone measured at a) 100 Hz bandwidth, and b) 1 Hz bandwidth.

3.2 2022 Passive ITAB Experiment

A passive ITAB was deployed in April 2022 during the Navy's ICEX 2022 expedition. The ambient noise data sets were collected and processed every 4 hours for 25 minutes. Third-octave ambient noise levels were calculated for 5-minute blocks and transferred to the NRL in real time. Figure 8 shows the third-octave ambient noise levels measured on April 19, 2022 at 125 m, 35 m, and 5 m depths (Figs. 8a, 8b, and

8c). A fourth hydrophone was inserted ~12 inches below the ice surface and coupled to the ice with the surrounding water that was frozen later. Percentiles are also plotted at 1%, 5%, 50%, 95%, and 99% levels. An increase of the noise levels at 95% and 99% levels are due to the transient events caused by pressure ridging.

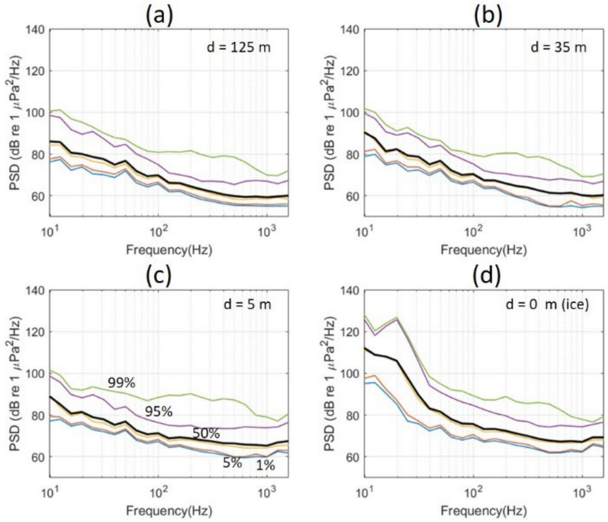

Figure 8. Third-octave ambient noise levels measured on April 19, 2022 at a) 125 m, b) 35 m, c) 5 m water depths, and d) 0.2 m below the ice surface. Mean level (black line) and percentiles are plotted at 1%, 5%, 50%, 95%, and 99% levels.

4. UNDER-ICE ACOUSTIC PROPAGATION MODELING

To study the under-ice broadband signal transmission, a comprehensive acoustic propagation model has been developed. The model uses the rough-surface Parabolic Equation model [4] and treats the elastic ice as a fluid with complex density [5]. This treatment provides a similar reflection coefficient to that of an elastic medium including shear waves. It provides a robust propagation model with less CPU requirements so that the broadband calculations at high frequencies would be possible in the deep Arctic. Figure 9 shows Continuous-Frequency (950 Hz CW) and broadband (900 Hz to 1000 Hz) simulations in the Beaufort Sea.

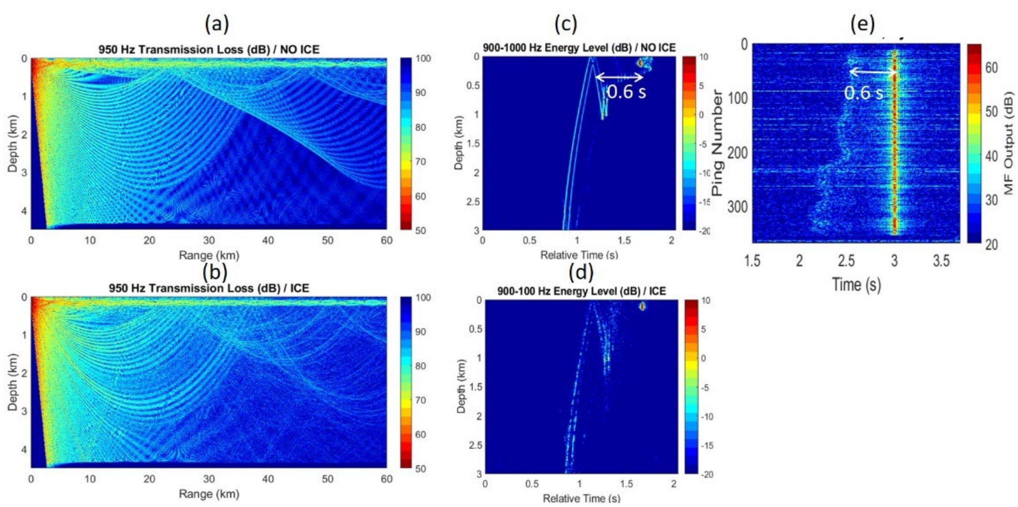

Figure 9. CW (a,b) and broadband simulation results (c,d) and comparison with the measurement (e). Open-ocean (a,c) and under-ice (b,d) propagations are depicted for comparison

Figures 9a and 9b compare the Transmission Loss between no-ice and ice cases at 950 Hz. Similarly, Figs. 9c and 9d compare the broadband energy levels of a 900-1000 Hz pulse, received at a range of 60 km. Both CW and broadband simulations show the scattering effects of a rough ice layer at the surface. In Fig, 9d, loss of structured arrival is evident due to the scattering from rough ice. The scattering effects cause additional energy loss in the ice-interacting arrivals, leaving a strong Beaufort-Lens arrival at 1.75 s relative time. Note that there is a ~0.6 arrival-time difference between the bottom arrival and direct Beaufort-Lens arrival for both simulated and measured signals (see Figs. 9d and 9e). A stochastic ice model was also developed to mimic the observed under-ice topography. Figure 10 shows the use of existing data set from the CANAPE 2016 experiment and how it is used to generate random realizations of under-ice topography that was input to the Complex-Density PE model. Seasonal variations of the ice topography can be measured by an airborne LiDAR survey or an Upward Looking Sonar (ULS). Figures 10a and 10b show the above-ice topography from CANAPE16 LiDAR surveys during March 2017. In Fig. 10b, the buoyancy relationship is used to estimate the under-ice topography. Figure 10c shows the PDFs calculated from ULS ice-draft data from October 2016 to March 2017, capturing the seasonal variation from open water to well-developed ice keels. Figure 10d shows one realization using the statistical parameters obtained from LiDAR estimations or ULS measurements of under-ice topography. Namely, mean ice draft, normalized skewness, characteristic length, rms height, and fractal dimension are estimated from the data. Then, a random realization with a Gaussian PDF [6] is transformed to a realization with Gamma distribution, as described in Goff [7].

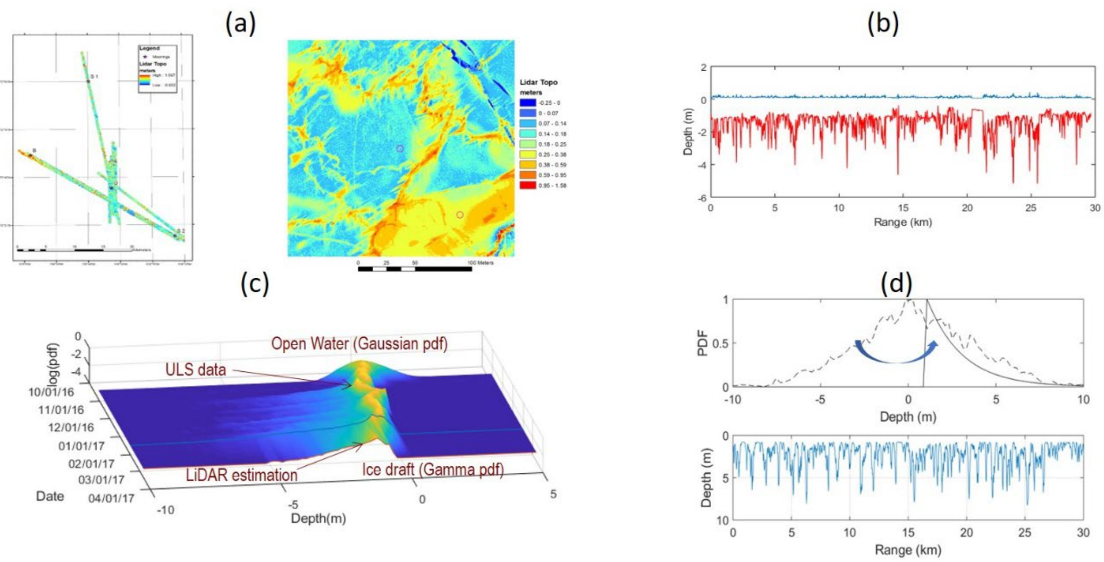

Figure 10. a) Above-ice topography measured during the CANAPE16 airborne LiDAR survey, b) estimated under-ice topography using LiDAR data, c) ice-draft PDFs from the CANAPE16 upward looking sonar data, and d) a random realization using measured ice-draft statistical parameters.

5. TEMPORAL AND SPATIAL COHERENCE

Temporal and Spatial coherence of the reciprocal transmissions between ITAB4 and ITAB5 are also studied to quantify the signal variations in time and space. Both temporal and spatial coherences within the Beaufort Lens are expected to be high, realizing the existence of strong single pulse arrivals (see Fig 3). Figures 11a and 11b show the temporal coherence of the 900-1000 Hz LFM signals at each receiver of ITAB5 and ITAB4, respectively. Temporal coherence remains to be higher than 0.8 for the entire 40-day period except for the Hydrophone#8 that is in the near-surface channel (30 m depth). Similar results were observed for the entire data set except for some periods with very low SNR. Figures 11c and 11d show the spatial coherence of 900-1000 Hz LFM signals received at ITAB5 and ITAB4, respectively. The spatial coherences are calculated in reference to the deepest hydrophone (Hydrophone#1 at ~ 145 m depth). Spacing between the first seven hydrophone is 2.4 m ,providing a 14.4 m aperture in the Beaufort Lens. Spatial coherence for Hydrophone#8 is at ~0.4 levels since it is in the near-surface channel, being exposed to the ice-interacting propagation conditions. A thorough analysis of both temporal and spatial coherences is planned to be published in a refereed journal.

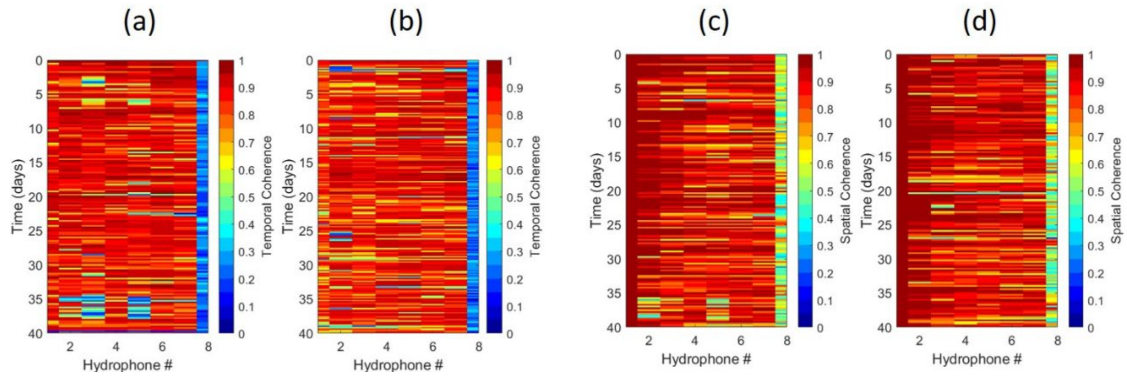

Figure 11. Temporal (a,b) and spatial (c,d) coherence measured on ITAB5 (a,c) and ITAB4 (b,d) using ITAB4 and ITAB5 signals, respectively.

6. SUMMARY

The concept of real-time acoustic monitoring in the Arctic was demonstrated by deploying active and passive Ice-Tethered Acoustic Buoys (ITABs) in the Western Arctic during 2021 and 2022, respectively. The ITABs were designed and developed in the NRL Acoustics Division to be deployed in the Arctic. During 2021, five active ITABs were deployed in the Beaufort Sea in a pentagon configuration, covering acoustic transmission ranges from 60 km to 300 km. A strong single pulse arrival through a secondary surface duct at 150 m depth (Beaufort Lens) was observed on each ITAB. This provided excellent acoustic navigation and communication performance. Both active and passive experiments showed that ITABs can be used for under-ice acoustic navigation and communication as well as real-time ambient noise measurements. Due to the existence of a strong single pulse arrival, high levels of temporal and spatial coherence (>0.8) were also observed in the Beaufort Lens throughout the experiment. Tomographic sensing of the environment was limited due to the small number of rays received in the Beaufort Lens. An independent study from the ONR CANAPE16 tomographic data has shown that deep arrivals are very stable in the Arctic and travel-time variations are at one order of magnitude less when compared to those in open oceans at mid-latitudes [8]. These small variations would imply that the acoustic monitoring technologies, developed under this project, can be applied to robust acoustic navigation and communication as well as passive ranging in the Western Arctic.

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