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EXPLORATION OF NONTRADITIONAL UNDERSEA DETECTION IN A CHANGING ARCTIC OCEAN

by

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March 2022

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EXPLORATION OF NONTRADITIONAL UNDERSEA DETECTION IN A CHANGING ARCTIC OCEAN

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ABSTRACT

During Navy Ice Exercises (ICEX) in 2018 and 2020, the NPS team collected acoustic data using a dual-headed 38-kHz and 70-kHz echo sounder and a custom-designed ice-coupled acoustic recorder (or cryophone). The echo sounder was used to determine if signals from hydrodynamically disrupted thermohaline staircases could be identified in the water and if present, to observe their reformation. The cryophone collected passive sonar data through the ice generated by a submerged mobile training target up to 10 nautical miles away. Analysis of the signals from ICEX and models generated in Bellhop and Navy Standard Parabolic Equation provided insight that the cryophone shows promise as a useful tool. More work will be required in order to start using the cryophone in the field as intended. The echosounder results are covered in a supplemental document. Both of these concepts offer new possibilities for underwater acoustic data collection in the Arctic, and if development continues, could potentially provide inexpensive acoustic monitoring in this rapidly changing environment.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASW	Anti-Submarine Warfare
dB	Decibel
CTD	Conductivity, Temperature, and Depth
DBDB-V	Digital Bathymetric Data Base Variable Resolution
DI	Directivity Index
DT	Detection Threshold
EMATT	Expendable Mobile ASW Training Target
FFT	Fast Fourier Transform
ICEX	Ice Exercise
NL	Noise Level
NSPE	Navy Standard Parabolic Equation
PE	Parabolic Equation
PSW	Pacific Summer Water
PWW	Pacific Winter Water
RD	Receiver Depth
RL	Reverberation Level
SD	Source Depth
SL	Source Level
SSP	Sound Speed Profile
TL	Transmission Loss
TS	Target Strength

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I. INTRODUCTION

A. ARCTIC OCEAN

The Arctic Ocean, the smallest ocean in the world, is approximately 9.5 million square kilometers. It represents about 2.6 percent of the oceanic surface (Rey 1982) and is predominately landlocked, with the exception of the Bering Strait and the Greenland, Iceland, and United Kingdom (GIUK) Gap. Most of the fluid transport occurs through the Fram Strait with a less substantial amount from the Bering Strait. The extremely cold temperatures and relatively fresh water of the Arctic make it a large contributor to global oceanic circulation.

In the past, the Arctic has been almost untouchable due to the extremely cold temperatures and limits in technology. There is practically no land, only large, shifting sheets of ice that sheer, break, and crack unexpectedly. The only way to traverse the Arctic was by dog sled or on foot, both of which were extremely dangerous and often resulted in the death of the expeditionary crews. However, the Cold War brought new technology and drove innovation. The first air landing at the North Pole was accomplished in 1948, and the first nuclear submarine, the USS Nautilus, sailed under the North Pole in 1958 (McCannon 2012) opening new possibilities to explore this foreign region.

Due to rising ocean temperatures, there has been noticeably less sea ice in the Arctic Ocean (Gilday 2021). With less ice in the warmer months of the year, travel through the Arctic has become more accessible. Incorporating shipping routes through the clear waters of the Arctic could save China 3700 km for shipments to Europe or 3800 km for shipments to the U.S. East Coast. China is also investing in natural resource exploitation and fishing in the region. It is unclear what China’s strategic angle is in the Arctic, but the increased presence will only further disrupt this changing ecosystem (Lajeunesse and Choi 2021).

B. MOTIVATION

The Arctic is changing, and so is the way the world is looking at it. As polar ice continues to melt, and the Arctic becomes more blue, economic and military exploitation will become easier. While only a small percentage of international trade currently occurs through the Arctic Ocean, over the next few decades, key strategic choke points, like the Bering Strait and the Fram Strait, are expected to be taken advantage of that could radically change international commerce. Russia is investing in and developing security on its northern boarders, and China is chasing after the expansion of its economic opportunities in all ways possible. The U.S. will retain its enhanced presence to continue research, protect its boarders, and develop technology to maintain its national security.

Traditional understanding of the sound speed profile (SSP) in the Arctic is significantly different than the actual profile seen today. Without an accurate SSP, the already difficult job of underwater navigation and acoustic avoidance becomes harder. If the models used are expecting sound at the surface of the water to travel differently than they are, object avoidance and target location become increasingly challenging.

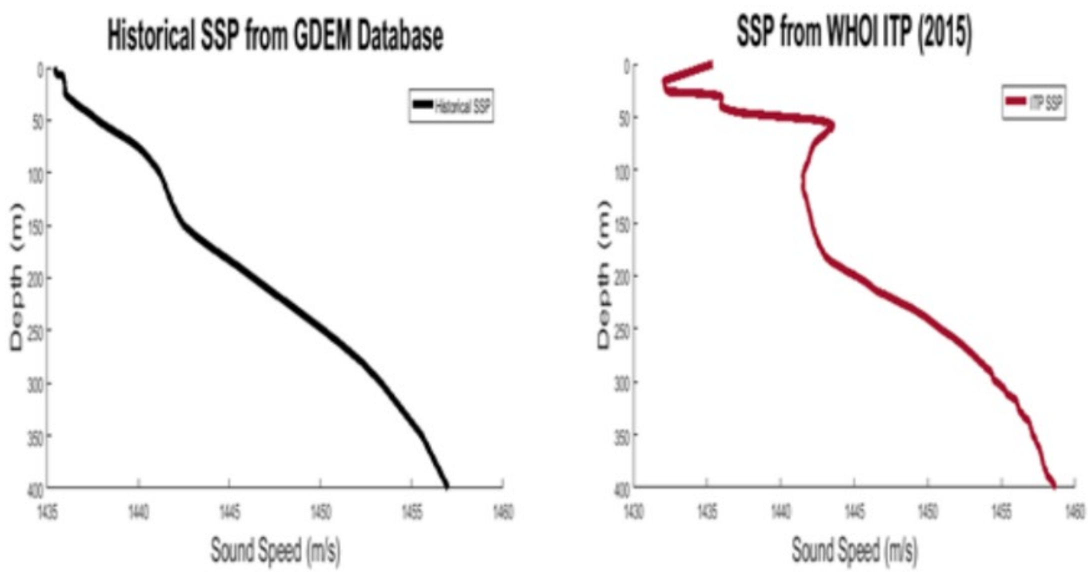

Figure 1. Historical versus Realistic SSP for the Arctic. Source: Nelson (2016).

Further investigation and research on exploiting the SSP is increasingly important as the U.S. increases its Arctic presence (Gilday 2021). The long endurance and ability to operate in harsh environments make submarines a key platform to operate in this region, and understanding the nuances of the water column is crucial for successful operations.

Many naval operations occur in the first 200 m of the ocean, and with the historic SSP, the acoustic models were not always correct. With the dawn of the Chinese submarine force both rapidly expanding and becoming more willing to venture outside of their local waters (Lajeunesse and Choi 2021), the U.S. will need to continue to develop new ideas and technologies to maintain its edge.

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II. BACKGROUND/THEORY

A. BEAUFORT SEA

The Beaufort Sea is a marginal sea located north of the Northwest Territories and Alaska. It is known for its harsh climate and one of the sources of Arctic Sea Ice. In the past, the sea was covered in ice for much of the year, but now that the Arctic is warming, areas are becoming less covered in the warmer months.

The Beaufort Sea is characterized by a narrow shelf and a rapid drop off to an approximately 3500 m basin. The surface layer, known as the Beaufort Gyre, rotates in an anticyclonic (clockwise) motion. The intermediate layer and deep layer rotate in cyclonic (counterclockwise) manner. Surrounding the Beaufort Gyre along the coast of northern Alaska, the surface layer rotates in a cyclonic direction, known as the Alaskan Coastal Current. This cyclonic current originates from the Bering Strait and carries water from the Northern Pacific to the Northern Atlantic.

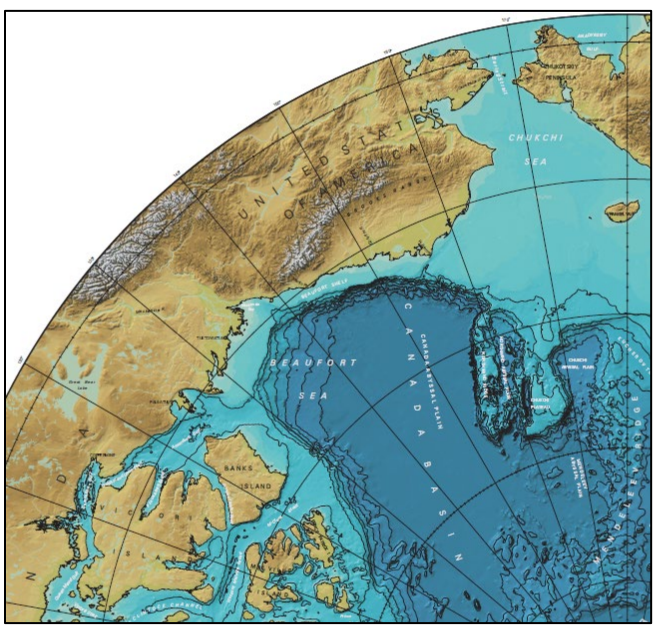

Figure 2. Beaufort Sea. Adapted from General Bathymetric Chart of the Oceans (2012).

The shallows of the Beaufort Sea are composed of several different distinct layers of water. At the top, the mixed layer sits on top of the Pacific Summer Water (PSW) with a local temperature maximum. Under the SPW is the Pacific Winter Water (PWW). Beneath that is the warmer, more saline Atlantic water, and at the bottom is the Deep Arctic Water.

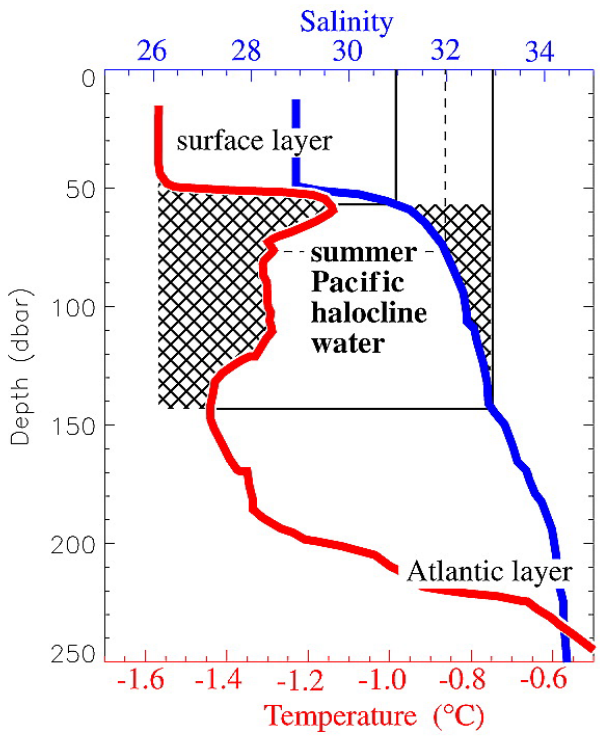

Figure 3. Shallow Water Beaufort Sea. Source: Steele et al. (2004).

The warm PSW present in the shallows of the Beaufort Sea creates a local sound speed maximum followed by a decrease in temperature as the denser PWW decreases the sound speed again. The local max coupled with the sudden decrease in sound speed is a phenomenon called the Beaufort Lens. It typically occurs around 100-200 m in the Beaufort Sea and acts as an additional sound channel (Goodwin 2021). Undersea vehicles often operate within this depth range, so the lens influences the way they position themselves for research or tactical operations.

B. ACOUSTICS

Sound in water acts as longitudinal pressure waves. These waves are affected by several different parameters in the water like pressure (depth), salinity, and temperature.

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016z$$

This simplified equation (Jensen 1994) describes the speed of sound in a water column, which drives how sound waves propagates underwater. One tool to predict if a received signal is strong enough to overcome the competing background noise or other interfering conditions are the sonar equations. The sonar equation expands how sound travels in water and arranges it in terms of the equipment used, the medium, and the target. All units in the sonar equations are in decibels (dB) (Urick, 1983).

1. Passive Sonar Equation

The passive sonar equation is used when the only emission of sound originates from the target. The signal then travels one way from the target of interest to the receiving equipment.

$$SL - TL = NL - DI + DT$$

The left side of the equation is composed of projector source level (SL) and transmission loss (TL). If the target is known, the SL may be known. If the target is not known, like an enemy submarine, SL can only be approximated, and investigation would be required. Ambient noise level (NL) is the measure of the accumulated background noise present in the water. Self-noise level (NL) is a known quantity, or it can be determined by testing. Receiving Directivity Index (DI) is an equipment parameter, so it is also known, and the last parameter is Detection Threshold (DT). Detection threshold deals with the probability that a detection is made. If the signal-to-noise ratio (SNR) is greater than the DT:

$$SL - TL + TS - (NL - DL) = DT$$

a target will give a positive return. If the SNR is less than the DT, there will not be a positive return (Urick 1983).

2. Active Sonar Equation

The active sonar equation is used when a transducer produces a sound, and it reverberates off the target after traveling through the water.

$$SL - 2TL + TS = NL - DI + DT$$

The most notable difference between the active sonar and the passive sonar equation is the TL is multiplied by two because the signal travels twice the distance, from the transducer to the target and back to the transducer. Target strength (TS) is the measure of how much energy is reflected towards the receiver after it hits the target. It is affected by the aspect of the intended target relative to the transducer and the material composition of the target. If the background is reverberation instead of noise, the active sonar equation changes:

$$SL - 2TL + TS = RL + DT_R$$

RL is reverberation level, and the detection threshold is a different value than the noise limited background (Urick 1983).

3. Transmission Loss

The ocean is a very complex medium for sound to travel in. There is an upper and lower boundary layer as well as internal structures that affect sound. Transmission loss describes the weakening of sound between one meter from the receiver and at a distant location. Transmission loss accounts for multiple effects combined into one term. There are two types of transmission loss: spreading and attenuation. Spreading is broken up into two more categories: spherical and cylindrical spreading. A source can be assumed to be a point source and that sound radiates in all directions equally. Since the energy propagates equally in all directions, and acoustic energy is a function of range.:

$$P = 4\pi r_1^2 I_1 = 4\pi r_2^2 I_2$$

I_1 and I_2 are intensities of the acoustic sound and if r_1 is located one meter away from the source:

$$TL = 10\log\frac{I_1}{I_2} = 10\log r_2^{\ 2} = 20\log r_2$$

Cylindrical spreading occurs when the source is in a medium with two parallel planer upper and lower boundaries. A similar concept is used to arrive at the TL equation, except the shape is assumed to be cylindrical:

$$P = 2\pi r_1 H I_1 = 4\pi r_2 H I_2$$

If the same assumption about range is used again:

$$TL = 10\log\frac{I_1}{I_2} = 10\log r_2$$

Cylindrical TL is just reduced by a factor of two from spherical spreading. Cylindrical spreading applies when sound is trapped in a channel since both the upper and lower sound speed maximums act like parallel boundaries (Urick 1983).

Attenuation is comprised of absorption, scattering, and leakage. Absorption represents the energy loss of a signal in water due to the conversion of acoustic energy into heat energy, but it is too difficult to empirically distinguish between absorption and scattering in the ocean environment, so attenuation is accounted for in one parameter (Jensen 1994). A simplified equation to calculate attenuation is:

$$\alpha = \frac{0.1 f^2}{1+f^2} + \frac{40 f^2}{4100+f^2} + 2.75x10^{-4} f^2 + 0.003$$

The attenuation coefficient α has units of dB/km and frequency is in Hz. (Urick 1983). Higher frequency signals get attenuated faster than lower frequency signals.

Transmission loss, because it depends on multiple parameters, can be difficult to calculate and it changes as oceanic conditions change in the water column. It is not a constant, but rather it is a variable that moves with the medium. Calculating TL by hand would be challenging and time consuming, so computer aided modeling allows for much more rapid TL computation.

4. Cutoff Frequency

In the Arctic, there is often a shallow water channel created by the local temperature maximum created from the PSW. If the PSW is not present, the SSP will look very similar to the historical profile. This shallow channel traps high frequency signals, but it does not trap low frequency signals. This acoustic phenomenon is called the low frequency cutoff. The longer wavelengths of low frequency signals no longer fit into the shallow channels. An approximate equation for calculating cutoff frequency is:

$$\lambda_{\max} = 4.7x10^{-3} H^{3/2}$$

with height, H, and wavelength, $\lambda_{\max}$ in feet (Urick 1983). Calculating an example:

Table 1. Cutoff Frequency Example

H	164	ft
$\lambda_{\max}$	9.871056	ft
c	4921	ft/s
f	498.5282	Hz

A normal upper layer in the Beaufort Sea is approximately 50 m, and if converted to feet, is about 164 ft. If the sound speed is assumed to be 1500 m/s, it will equal 4921 ft/s. If those two assumptions are made, the cutoff frequency for the upper layer in the region ICEX-20 took place would be approximately 500 Hz. The equation provided by Urick does not account for Arctic ice present at the surface of the water.

5. Doppler Shift

The received frequency shift of an object emitting sound traveling relative to a receiver is known as Doppler shift. If the receiver is motionless, then a source traveling away from the receiver will have a lower frequency, and the reciprocal is true if the source is traveling towards the receiver. The relation can be represented by:

$$\Delta f = \frac{2v}{c} f$$

where v is the relative velocity between the source and the receiver, c is the sound speed, and f is the emitted frequency of the source (Urick 1983). An example calculation:

Table 2. Doppler Shift Calculation Example

v	-2.572	m/s
c	1500	m/s
f	1000	Hz
Δf	-3.42933	Hz

provide that the shift in frequency for an object emitting a 1000 Hz tone at 5kts would be approximately 3.4 Hz lower than the emitted sound.

When an object is moving, the only time a received signal is the same frequency as the emitted signal is when the source's direction of motion and bearing to the receiver are perpendicular, otherwise there is some frequency shift.

$$f_r = \frac{f_s(c + v\cos\theta)}{(c - v\cos\theta)}$$

In this equation (Medwin and Clay 1998), f_r is received frequency, f_s is the frequency of the source, and θ is the angle of the receiver relative to the velocity of the source. If θ equals $\pi/2$, the received frequency will be equal to the signal frequency. Sources are treated as omni-directional, so just because the direct path signal is higher if the source is traveling towards the receiver, or lower if it is traveling away, there are other rays that could reach the receiver. With an ice layer, there is a hard surface that could bounce different Doppler frequencies to the receiver, so the receiver will see a wide band of frequencies. If the object is traveling away, the band will be anywhere from just under the signal frequency all the way to the lowest frequency due to the Doppler shift. As the source travels farther away, the bounced rays will become closer to the lowest Doppler frequency until a point where the signal is only the lowest frequency.

C. MODELING

The paths that sound travels underwater are related to the water column's SSP and Snell's Law:

$$\frac{\cos\theta_1}{c_1} = \frac{\cos\theta_2}{c_2} = const.$$

Theta is the angle of the ray with respect to the horizontal, c is the local sound speed, and their relation to each other is held constant in water. Because a signal follows Snell's Law, sound will bend towards areas of lower sound speed and tend to get trapped. Using computer aided models, underwater sound paths can be rapidly generated. Common features that are needed for these models are the sound speed in the water with respect to depth, bathymetry information, and source and receiver depth.

The two modeling programs that were utilized for this report were Bellhop and Navy Standard Parabolic Equation (NSPE). While they both model acoustic paths in underwater settings, they use different approaches to accomplish their goal. Bellhop is a ray trace model, whereas NSPE is a parabolic equation model.

Ray models have been used since the early 1960's and are still widely used in operational settings because their faster generation speed is favored over finer accuracy at higher frequencies. Operators in the fleet care more about decent resolution with high continuity of use, knowing the fine details at the cost of lag time is not a luxury they can afford. One anomaly that occurs in ray trace models are shadow zones where no rays pass. These regions with no rays appear to have pressure zones of exactly zero, which is not realistic. Another physical issue is the presence of caustics. These spots are where rays cross and their predicted intensity rises to infinity, another physical impossibility (Jensen et al. 1994).

Parabolic equation models were developed later, but once the Fast Fourier Transform (FFT) numerical solution was developed in the 1970's, Parabolic Equation (PE) methods for underwater acoustics became much more readily available. This method focused on solving the PE wave equation with the FFT numerical solution. Ray based models may be easier to visualize and are less computationally intensive, but PE models produce more realistic results and handle wave to wave interactions more accurately. The drawback is PE models become computationally expensive at higher frequencies. For academic purposes, PE models are more useful since time and computing power are less of a concern than achieving the most realistic result.

D. THERMOHALINE STAIRCASES

Thermohaline staircases are strongly stratified temperature-salinity profiles that occur in the upper ocean in a few regions in the world. Their presence was discovered in the late 1960's and have been a fascination by oceanographers since. The oceanography community quickly devised and accepted an explanation for salt finger staircases, but the origin of diffusive staircases is still under debate. One reason for the lack of understanding of diffusive staircases is their difficulty to reach in the world. Diffusive staircases tend to occur in high latitude locations, which are difficult to access and research. The oceanographic community did not begin researching their origin until the late. While there are a number of theories at this point, not one theory consistently explains how diffusive staircases are created (Radko 2013).

Although the origin of the diffusive staircases is under investigation, theoretical testing can still be conducted on this phenomenon. One study explored how long it took for these staircases to reform after being hydrodynamically disrupted. Theoretical modeling suggests it takes anywhere between a few hours to the time scale of a day for reformation (Davis 2018). However, there is a lack of empirical data that validates these findings.

Thermohaline staircases were present at ICEX-18 (Collins 2019), and so it is likely they would be present at future ICEX's. The staircases in Figure 4 started around 140 m and went at least until the bottom range of the echosounder at 200 m. The horizontal lines in shallower than 140 m were not part of the staircases, but rather isolated areas of stratification in the water column.

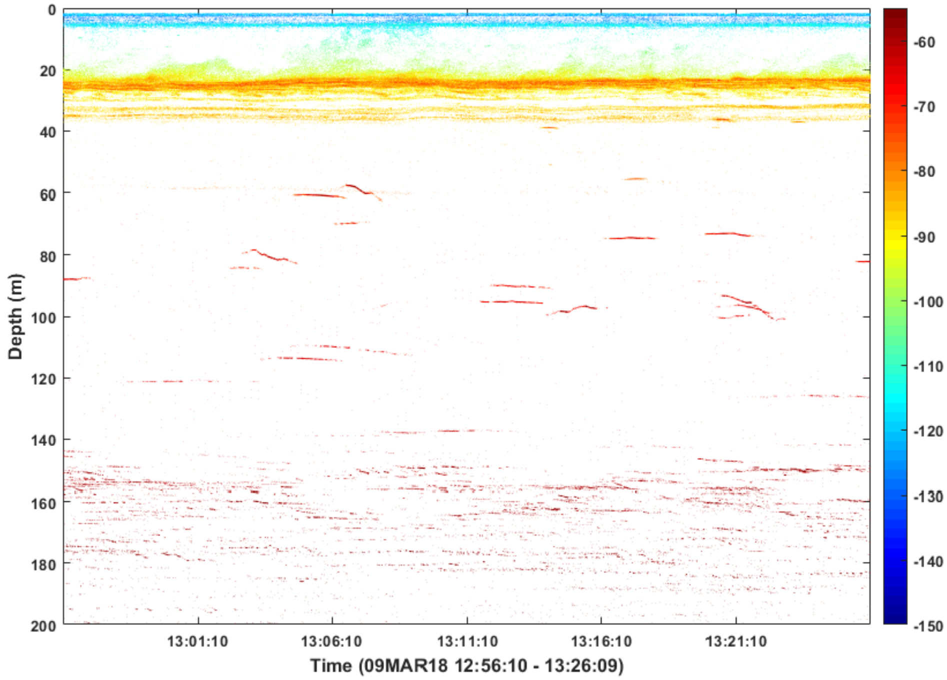

Figure 4. Thermohaline Staircases Present at ICEX-18. Source: Collins (2019).

III. EXPERIMENTAL DESIGN

A. ICEX-2020

The U.S. Navy, as well as joint forces, allies, and partner agencies, held Ice Exercise 2020 (ICEX-20), as a continued effort to develop understanding of the Arctic polar region. During the exercise, USS-Toledo and USS-Connecticut assisted in research and practice of Arctic antisubmarine warfare tactics.

Camp Seadragon, the name of the ice camp for ICEX-20, was located on multi-year ice in the Beaufort Sea off the coast of northern Alaska in early March. The NPS team was composed of two faculty members and one student. They arrived at Camp Seadragon on March 1st and worked until March 6th. The team focused on collecting conductivity, temperature, and depth (CTD) data, testing their cryophone, and using an echosounder to measure hydrodynamic disturbances of thermohaline staircases.

There were many challenges for the researchers in this environment. For instance, the isolated location of the camp led to logistical challenges. ICEX is conducted on multi-year ice in the Beaufort Gyre. Every piece of equipment must be flown to a camp via a single or double propeller plane, so there is a space and weight limitation. The plan for completing experiments must be well thought out and streamlined because there is little room for errors like equipment malfunctions. Another challenge was the harsh environment. The extreme cold prevented researchers from overexerting themselves and equipment failures were common. Equipment and personnel redundancy had to be chosen very carefully, and operations required the ability to adapt when issues arose.

B. EQUIPMENT

1. CTD

The NPS team used an RBR Concerto CTD to collect SSP data. The device was equipped with a wireless end cap to allow the team to retrieve the CTD data after each run without having to open the cast and wire download the data. This was advantageous for operation, especially in harsh environments like the Arctic.

2. Cryophone

The cryophone was a custom design from the NPS team. It contained three single-channel accelerometers, three single-channel signal conditioners, and a Zoom H4N four-channel digital recorder. All of these were housed in an airtight clear cylindrical container with an energy source to power the unit. This was a prototype design to prove that this device could be constructed simply and inexpensively to record acoustic data.

3. Echosounder

The team used the DT-X Extreme Autonomous Portable Scientific Echosounder. The echosounder was capable of operating with split beam or single beam transducers and included data collection and analysis software. Attached to the echosounder were two single beam digital transducers, one 38 kHz and one 70 kHz, that were lowered two meters into the water column to be below the ice. The transducers were oriented downward facing the water, and the interpreting hardware remained dry above the ice. There was a Panasonic Toughbook wirelessly connected to the echosounder running the Biosonics software so the researchers could see the data real time and record data.

4. EMATT

The team used the MK-39 Expendable Mobil Antisubmarine Warfare Training Target (EMATT) as a mobile acoustic source. The device could operate in a wide range of depths and have programmable tracks and tones. The expected source level of signals emitted were approximately 140-150 dB re 1 μPa at 1 m.

C. EXPERIMENTS

To accurately measure sound speed in the water and for analyzing the data collected, the NPS team collected CTD data multiple times throughout their time during ICEX-20. A hole was dug through the five feet of ice using a battery powered, handheld auger and the CTD was lowered into the water using a small electric winch. A tent was set up over top of the site to shelter the working researchers from the extremely cold conditions that reached -40^{o}C at times. The CTD was lowered and raised multiple times over the duration of ICEX to ensure there were useable results.

The cryophone was tested by digging out a 10 cm deep hole into the ice, placing the receiver in the hole, and refreezing the device into the hole. The device needed to be completely coupled with the ice while allowing the researchers to retrieve data, refresh batteries if needed, and recover the device when the experiment was completed. After the cryophone was successfully frozen into the ice, the EMATT, which was pre-programmed to transmit two series of tones at 1 kHz and 2.9 kHz, was placed into the water. The EMATT autonomously drove its course of 290 degrees for two hours at five knots and then it turned around drove a reciprocal course of 110 degrees at five knots for six hours. The cryophone recorded the EMATT signal for approximately three hours after it was deployed. After the EMATT completed its run, the researchers collected the data from the cryophone from the ice. Given the recording time was limited to just a few hours by the battery pack, a better power source would help improve data collection in future work. Rethinking the power source would be crucial for implementation of this device as development progressed.

The purpose of the cryophone experiment was to test how acoustic propagation of underwater sound could be recorded on a device imbedded at the surface of Arctic ice floes. Of interest is whether the ice hindered or helped the sound propagation and understanding how underwater sound propagated to a receiver at the ice surface. There was an in-water collection device, but it was lost during experimentation. A device in the water could be used to directly compare the cryophone's data against recorded data that does not have to pass through the ice to see if there is a range improvement or quality improvement.

The second experiment that was conducted by the NPS team was the echosounder experiment. That experiment did not occur as it was hoped to due to uncooperative ice flow conditions. During previous ICEXs, the multi-year ice had more significant westward motion, but in 2020, the camp did not move nearly as much as expected during the time NPS conducted its experiments. The original plan was to have an underwater vehicle pass near the ice camp in a lawnmower pattern while crossing through the thermohaline staircase structure commonly present in the Beaufort Sea. The echosounder would observe the staircases as the ice camp passed over the site. Since the ice was not moving, the vehicle passed under the echosounder multiple times instead. The intention was to have the echosounder collecting data prior to the vehicle’s appearance to observe the presence of the staircases, and then see them disrupted after the vehicle passed by. The researchers wanted to see if the reformation of the staircases as predicted through modeling, according to Davis (2018), could be tracked.

IV. DATA ANALYSIS

A. SOUND SPEED PROFILE

The SSP in Figure 5 was derived from the CTD data collected in ICEX-20. The data was selected by choosing the deepest, most continuous signal for the largest SSP.

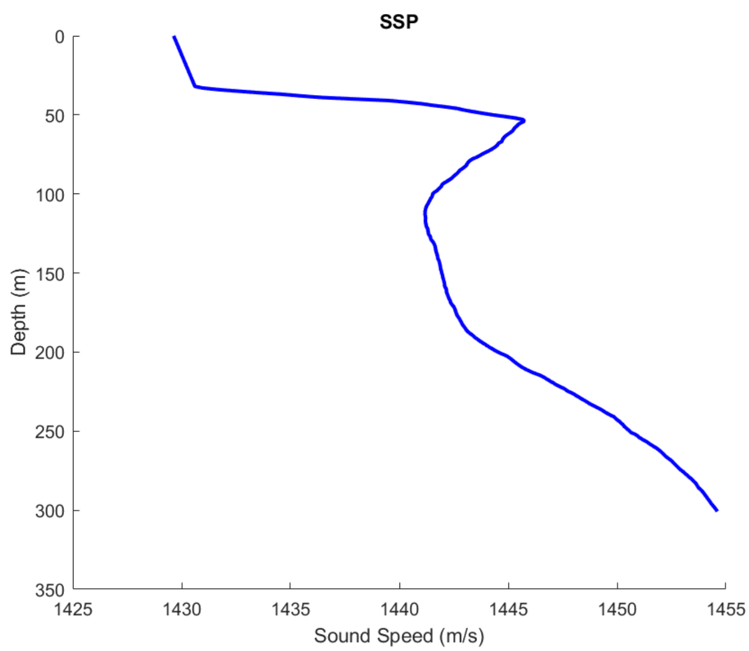

Figure 5. Sound Speed Profile from CTD Data in ICEX-20

After the 2020 data was used, the SSP for the remainder of the water column to the full water depth was completed by using climatology information from the Navy's Generalized Digital Environmental Model (GDEM). The SSP from Figure 6 was the SSP that was used for the model runs without the ice layer.

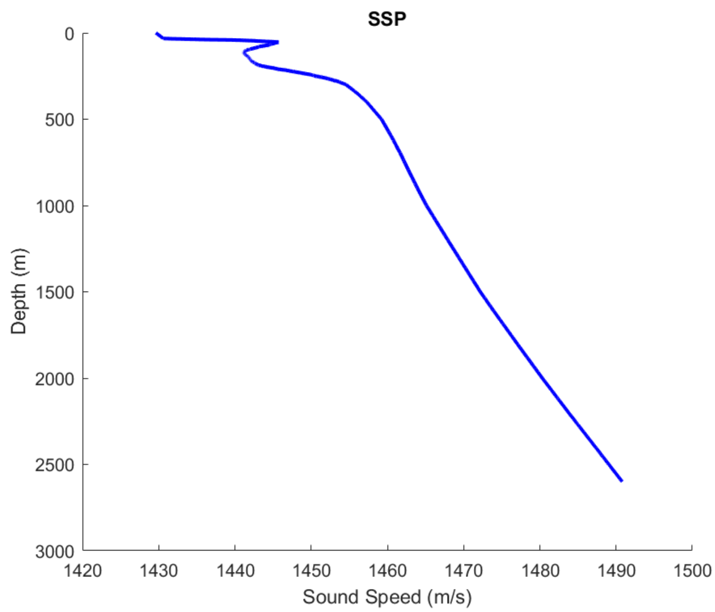

Figure 6. Sound Speed Profile with Historic Data

B. MODELING FOR CRYOPHONE

The purpose of the modeling was to create variables to see how both Bellhop and NSPE treated sound propagation with an ice layer at the ocean's surface. Bellhop is a ray based underwater acoustic model and NSPE is a parabolic equation based acoustic model. A few variables were chosen to flex the modeling: source depth, frequency of the signal, and ice thickness. The signal frequency and the source depth were input variables in both programs, so their implementation was simple, but the ice layer had to be generated by hand. Sound speed in ice is linearly related to temperature. As temperature goes down, sound speed goes up (Vogt et al. 2008).

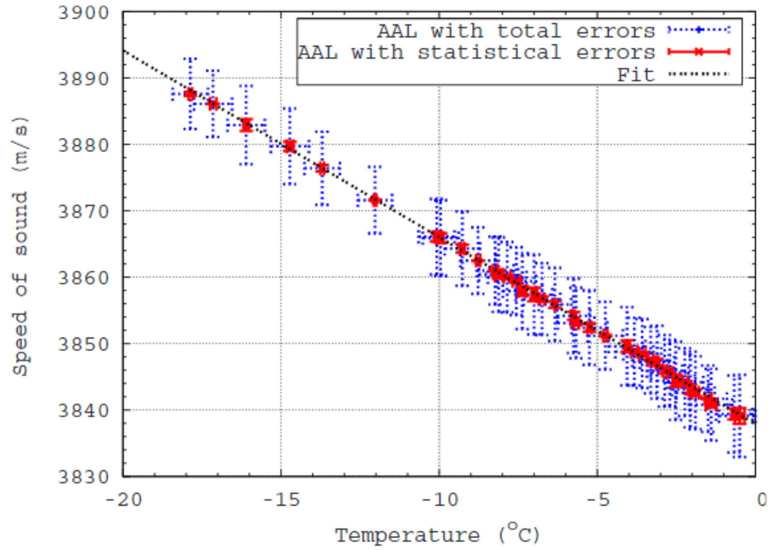

Figure 7. Sound Speed in Bubble Free Ice Adapted from Vogt, Laihem and Wiebusch (2008).

Bubble free ice is not realistic for the Arctic because the water would contain air, but the data from Vogt, Laihem, and Wiebusch (2008) provides a decent estimate of how sound would travel in ice. The data is a good linear fit for the low temperatures tested in this report, but the Arctic sees much lower temperatures than the range of temperatures in Figure 7. The data was linearly extrapolated out to -40° C. Since ice thickness was the variable tested, the ice temperature was assumed to linearly increase from -40° C at upper boundary that touched the air to 0° C at the lower boundary that was in contact with the water.

Table 3. Sound Speed Compared to Depth of Ice

Temp (C)	Sound Speed (m/s)	Depth (m)	Depth (m)	Depth (m)
-40	3908	0	0	0
-30	3894	0.2	0.4	0.8
-20	3880	0.4	0.8	1.6
-10	3866	0.6	1.2	2.4
-5	3852	0.8	1.6	3.2
0	3838	1.0	2.0	4.0

Since there are bubbles and imperfections in the ice located in the Arctic, the sound speed may be lower, but without actual numbers, it would just be a best guess what the profile would look like. These models were supposed to represent an estimate of how the sound is traveling in the Arctic, not a fine-tuned mathematical representation of the scenario. The approximation that the ice was bubble free was adequate for this situation as a tool to be used in model comparisons. The ice layer for the model used was a constant, smooth ice layer that was assumed to be bubble free and constant thickness. The ice model did not incorporate any roughness that would be present in the underside of the ice in the environment. The roughness would increase the amount of scattering so it would increase the overall TL, especially near the surface. The roughness was not included to minimize the complexity of the model. It was assumed that the temperature of the air was -40^{o} C at the surface and 0^{o} C at the ice/water interface and the sound speed was linearly decreasing from 3908 m/s at the top to 3838 m/s at the bottom.

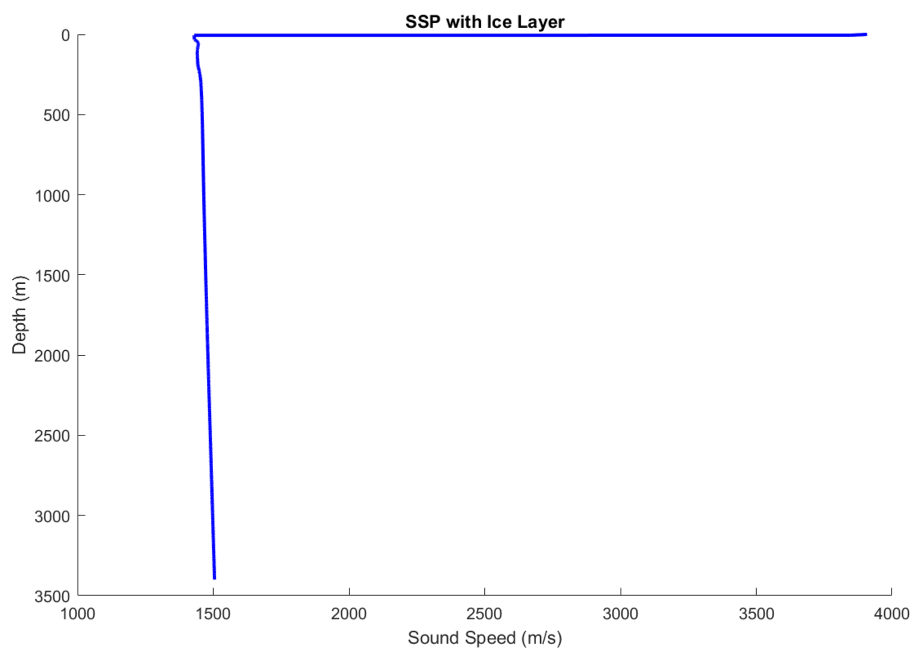

Figure 8. SSP of Beaufort Sea with Ice Layer

To create a more accurate model, bathymetry was needed in the region the experiment took place. The bathymetry used in all the model runs was extracted from the Navy's variable resolution Digital Bathymetry Database (DBDB-V).

It was noticed that the bathymetry formed a sawtooth shape, which did not match the expected bathymetry of the region. This was likely caused by interpolation of the database producing unrealistic features that could result in misleading propagation effects in the model output.

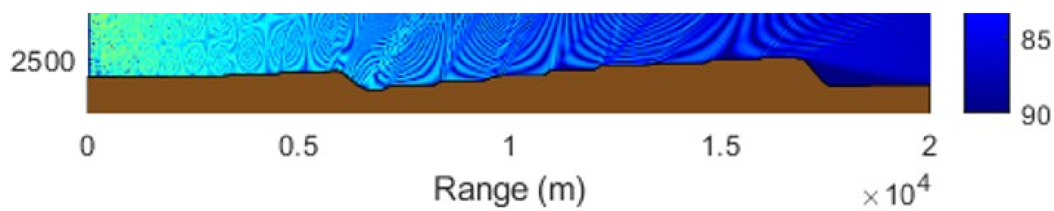

Figure 9. Incorrect Bathymetry

The Canadian Basin is relatively flat once it reaches depth, so abrupt changes in depth over the span of the 20 km used was unlikely. An assumption was made that the bathymetry was closer to a linear grade and points were changed to reflect that.

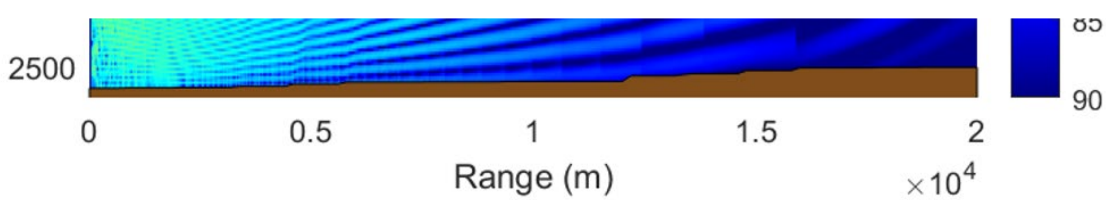

Figure 10. Adjusted Bathymetry

Multiple frequencies were chosen to analyze in both Bellhop and NSPE. The EMATT emitted two signals, 1 kHz and 2.9 kHz, so both of those frequencies were chosen. A third frequency, 50 Hz, was chosen as well because it is a common signal found in the maritime world, plus it provided a low frequency signal to include in the modeling. Two different depths were analyzed in the modeling. The EMATT operated at 25 m, so that was chosen, plus it was in the surface duct. A second depth, 125 m, which was located within the Beaufort Lens was chosen to observe how sound reached the surface ice from within that channel.

C. CRYOPHONE DATA

The recorded cryophone data was imported into a program called Audacity. The raw data (a .wav file) was transformed into a spectrogram so both the 1kH and the 2.9 kHz EMATT signals could be examined. The largest window size (32768 – Most Narrowband) available in the program was used because it presented the cleanest picture. The dB gain was also altered to 40-90 dB to best see the recorded signal.

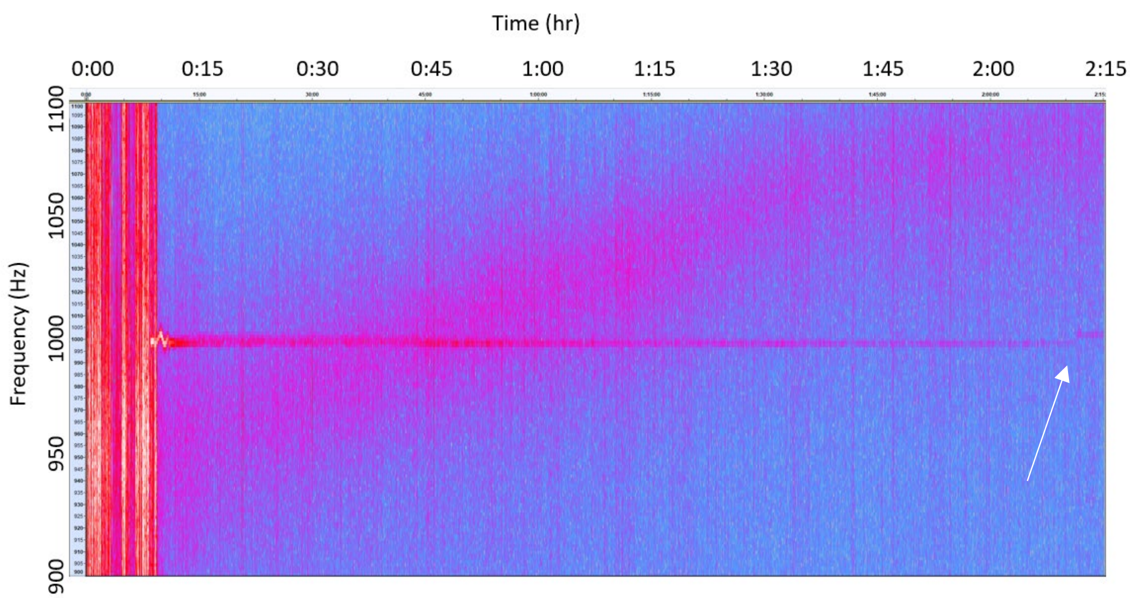

Figure 11. 1 kHz Cryophone Data for First EMATT Leg with arrow pointing to upshift in frequency

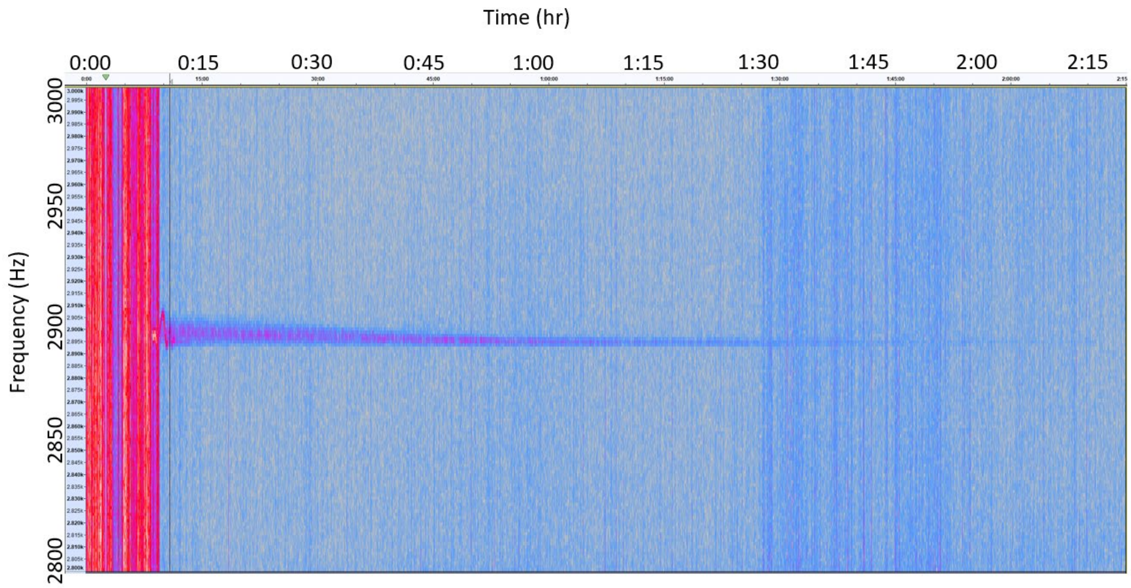

Figure 12. 2.9 kHz Cryophone Data for First EMATT Leg

The signal in Figure 11 was slightly below 1 kHz due to the Doppler shift lowering the received frequency as the EMATT moved away from the receiver, and the second leg experienced a higher received frequency for the same but opposite reason. At the far-right side of the 1 kHz signal, at about two hours, there was a sudden upshift in frequency when the EMATT turned around. The turnaround was not visible in the 2.9 kHz signal because there was too much attenuation for the sound to reach the cryophone.

Both signals experienced a wider frequency band while the EMATT was closer to the launch site due to multipath propagation and scattering off the surface ice. The energy reflecting off the ice was leaving the source at higher angles relative to the motion of the EMATT and therefore experienced less Doppler shift. As the EMATT's distance from the starting location increased, the ice reflected rays were more horizontal and in line with the EMATT travel. Therefore, they experienced a larger downshift in frequency similar to the more horizontal direct path until the only signal received were rays that experienced the maximum Doppler shift. The large broadband swath present in Figure 12 was not part of the experiment, but rather ambient noise from the camp.

D. TL PLOTS

Transmission loss plots were generated in both Bellhop and NSPE. To compare the models were working correctly, the ice layer was not initially included in the SSP. The source depth was 25 m to simulate the depth of the EMATT during ICEX-20 and the control frequency for the modeling was 1 kHz because the EMATT had a 1 kHz signal during the experiment.

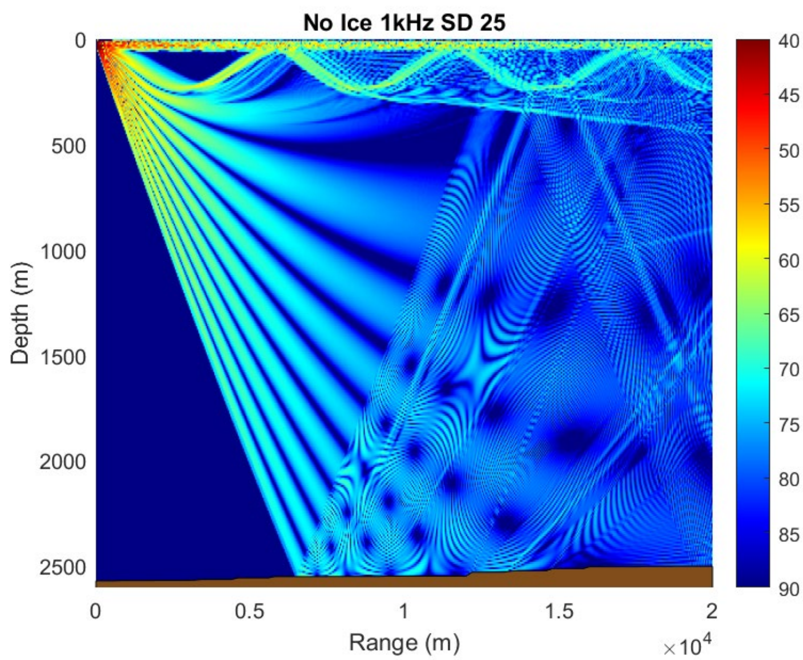

Figure 13. 1kHz Signal at 25 m Source Depth with No Ice in Bellhop

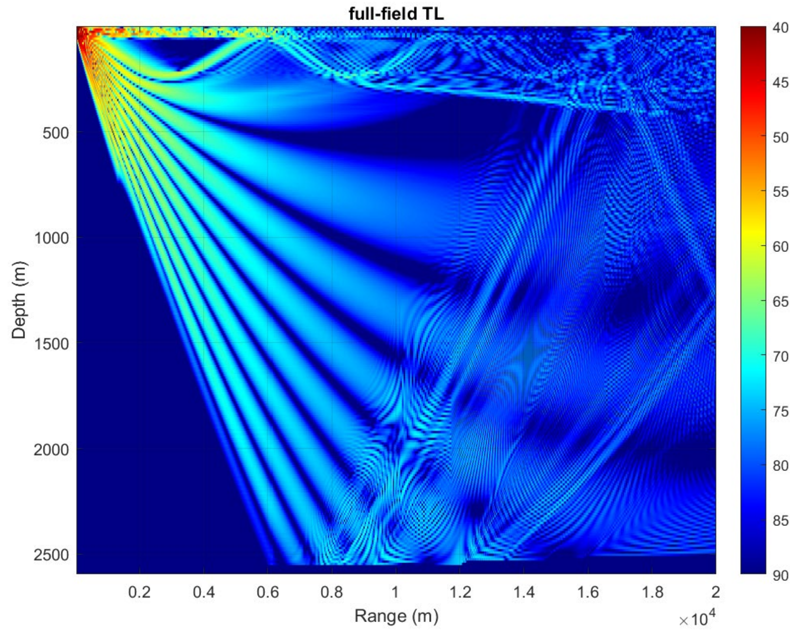

Figure 14. 1 kHz Signal at 25 m Source Depth with No Ice in NSPE

The Bellhop and NSPE runs with no ice were not exact replicas of each other, but they shared many of the same characteristics. Both runs showed significant ducting that persisted the whole length of the plots as well as propagation present around 200 m that represented the Beaufort Lens. There was also a major bottom bounce signature that reached the surface around 16 km in both plots. The major difference between the two figures was the signal continued to propagate indefinitely in the surface duct and the Beaufort Lens in the Bellhop plot, but it weakened as range increased for the NSPE plot. This was because Bellhop, a model based on ray theory, did not treat leakage the same way as NSPE, a model based on wave theory. In NSPE, some of the sound energy trapped in the surface duct leaked out and dispersed within the water column, but in Bellhop, it did not experience the same leakage because it is a ray-based model, so it continued to propagate indefinitely.

When an ice layer was added to the top of the SSP for both programs, the results for Bellhop and NSPE diverged. The NSPE model did not have a large change in appearance. There was more leakage from the surface duct, but most of the features remained the same.

In Bellhop, the shallow surface duct began to form but it stopped at about two-kilometers and the first upward refraction within the Beaufort Lens was present similar to the run with no ice, but after around seven-kilometers, there was high transmission loss. This phenomenon occurred in all the runs in Bellhop with the ice layer, so Bellhop was systematically treating the surface of the water column this way. Another major shortcoming from Bellhop was chaotic rays propagating almost vertically downward. several ray path models were generated to see if the vertical rays could be seen, but they were never duplicated. Similar to the propagation stopping when it came in contact with the surface, the vertical rays occurred in every run that included the ice layer, so it was clear that the ice layer was the cause of the issues in Bellhop. Ray based models assume small sound speed gradients, but with the ice layer added, the gradient was very large as seen in Figure 8. The high gradient may have caused mathematical instabilities in the model resulting in chaotic rays.

Transmission loss line plots were also generated to compare the transmission loss for the cryophone and the transmission loss for a receiver in the water column. The goal of the model is to investigate whether the cryophone is a useful tool in the Arctic.

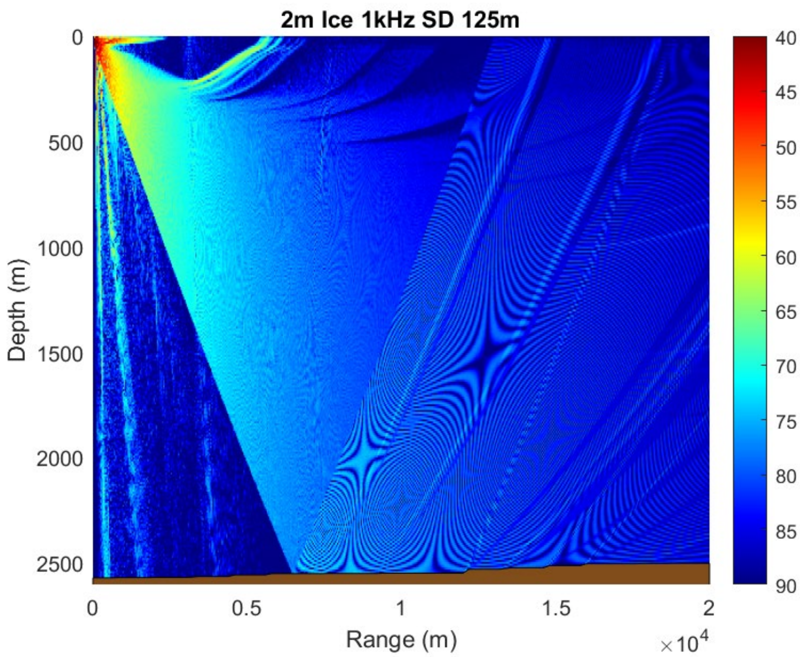

Figure 15. 1 kHz Signal at 25 m Source Depth with 2 m Ice Layer in Bellhop

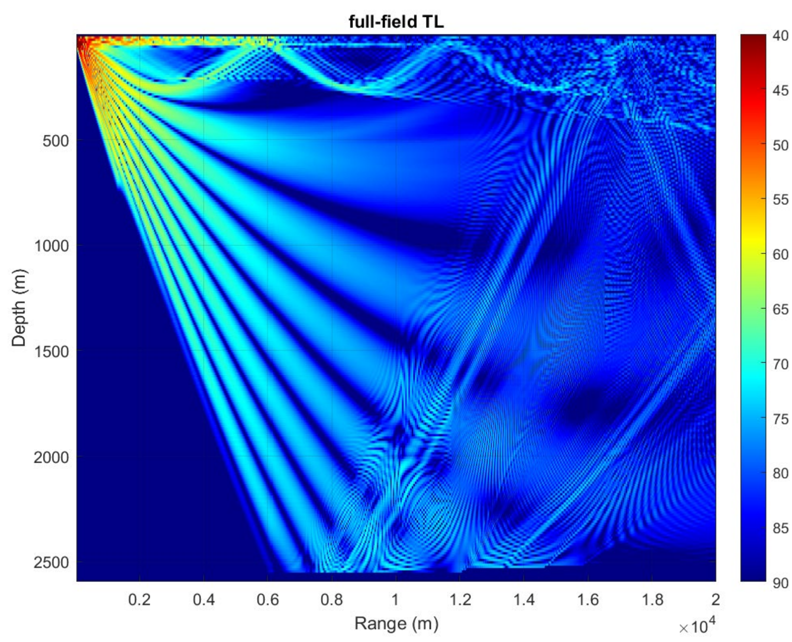

Figure 16. 1 kHz Signal at 25 m Source Depth with 2 m Ice Layer in NSPE

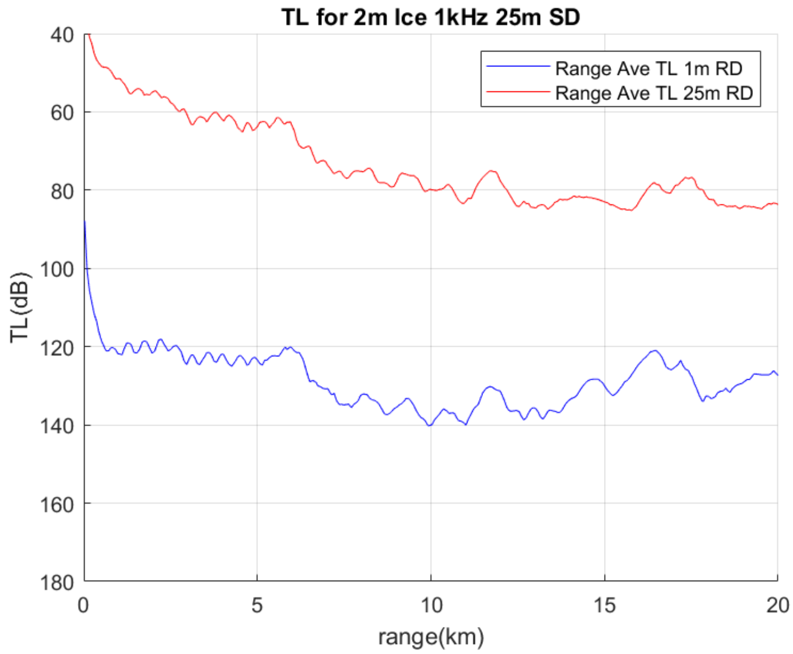

Figure 17. 1 kHz Signal at 25 m Source Depth with 2 m Ice Layer in NSPE Numerical TL

1. Source Depth

Source depth was also considered as a variable for the model. All the previous examples presented were at 25 m, but 125 m was also considered to predict how the model would handle an object within the Beaufort Lens. Bellhop and NSPE were run with no ice, and then the two-meter ice layer was added, but since the Bellhop model did not operate well with the added ice layer, only the NSPE examples were closely examined.

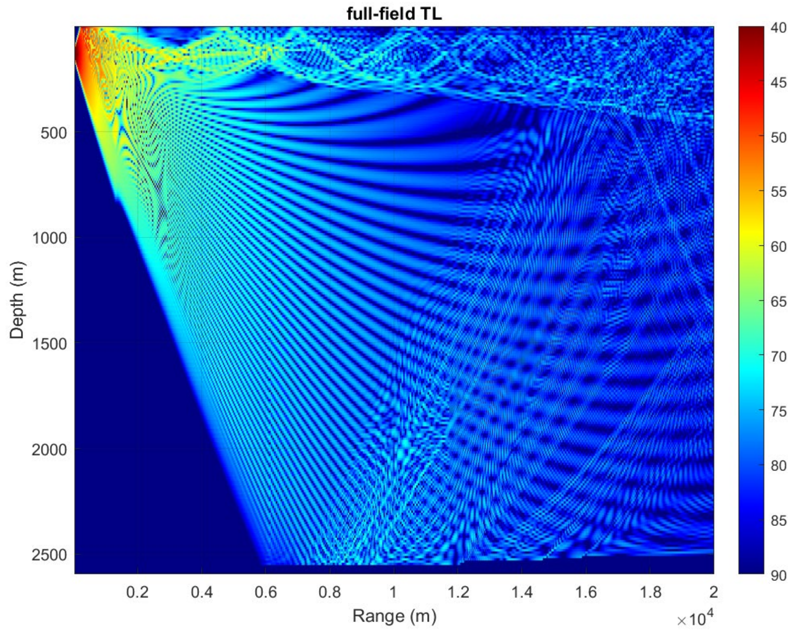

Figure 18. 1 kHz Signal at 125 m Source Depth with No Ice Layer in NSPE

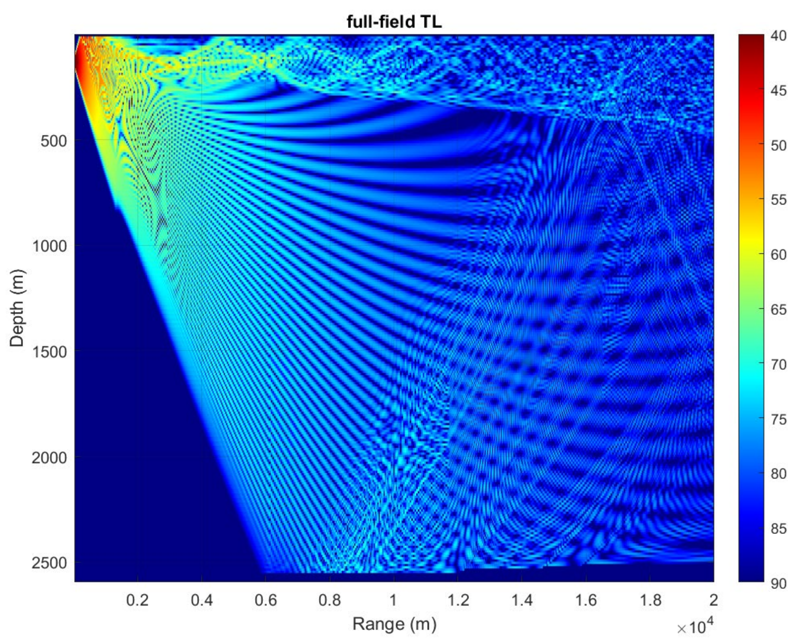

Figure 19. 1 kHz Signal at 125 m Source Depth with 2 m Ice Layer in NSPE

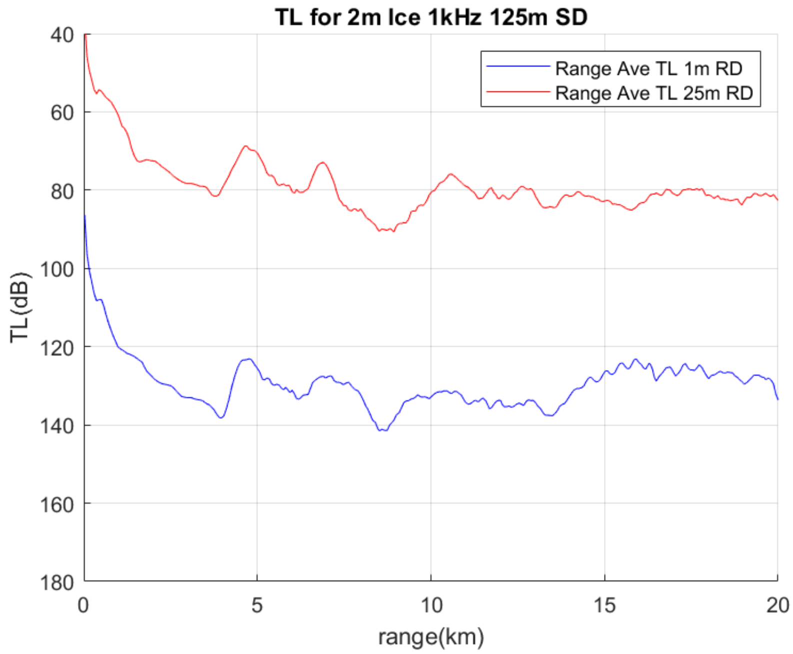

Figure 20. 1 kHz Signal at 125 m Source Depth with 2 m Ice Layer in NSPE Numerical TL

2. Frequency

Since the EMATT had two different frequency tones, both were included in the modeling. The second frequency that was tested in the model was 2.9 kHz. Higher frequency tones experience more attenuation in water, so it was important to see how they would interact with ice. It was expected that the TL was greater for the higher frequency since the cryophone data showed a loss of signal at the end of the initial EMATT leg for the 2.9 kHz tone, while it still held the lower frequency signal at the turn around point.

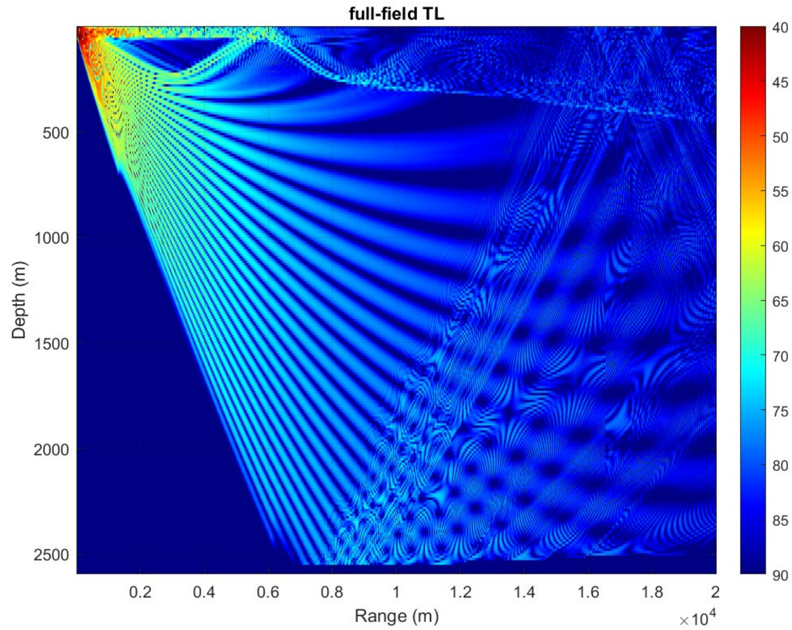

Figure 21. 2.9 kHz Signal at 25 m Source Depth with No Ice in NSPE

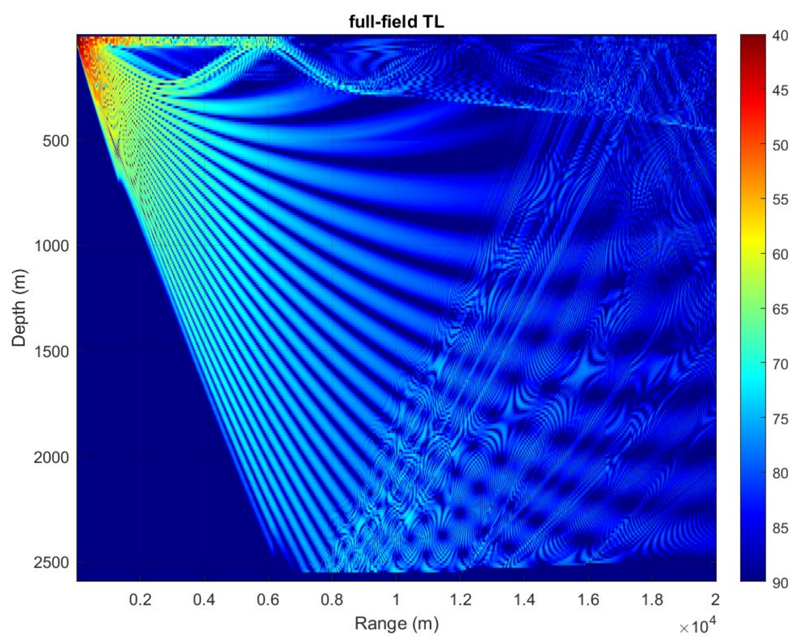

Figure 22. 2.9 kHz Signal at 25 m Source Depth with 2 m Ice Layer in NSPE

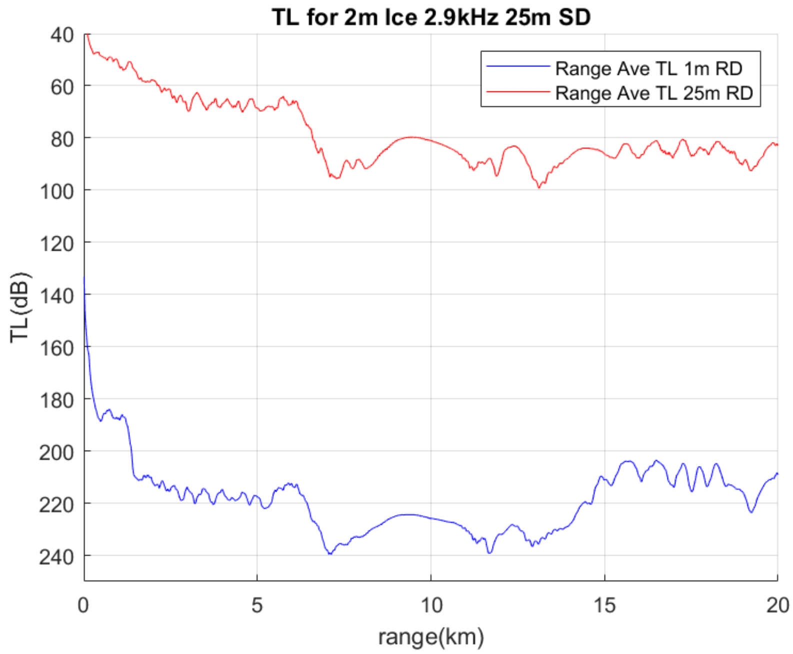

Figure 23. 2.9 kHz Signal at 25 m Source Depth with 2 m Ice Layer in NSPE Numerical TL

3. Ice Thickness

Ice thickness was also examined as a variable. The same linear profile for sound speed was used for each different ice thickness and only the height of the ice layer was altered. The three thicknesses included were one-meter, two-meters, and four-meters. The two-meter case was displayed in previous figures, so the one-meter and four-meter ice were included in this section. Knowing how ice thickness affected the cryophone's ability to detect underwater signals would help further research and testing of the device.

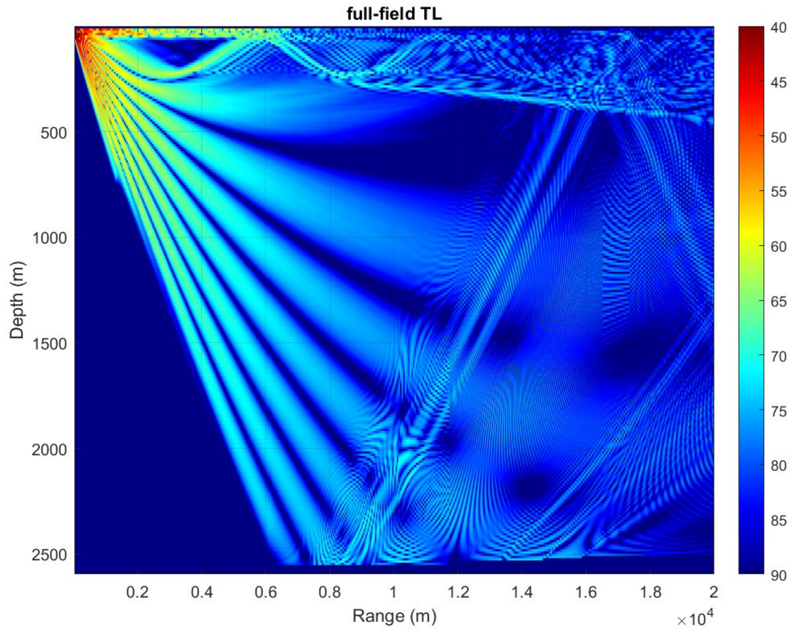

Figure 24. 1 kHz Signal at 25 m Source Depth with 4 m Ice Layer in NSPE

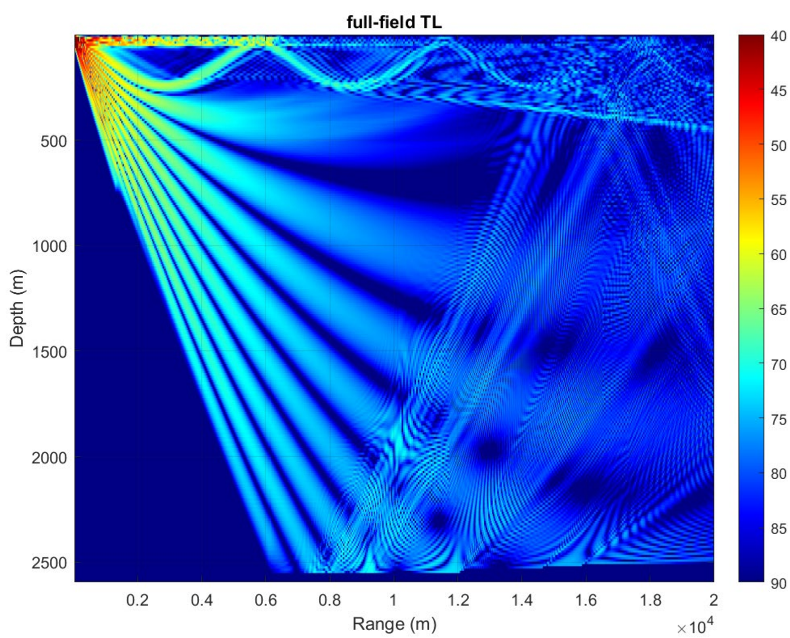

Figure 25. 1 kHz Signal at 25 m Source Depth with 1 m Ice Layer in NSPE

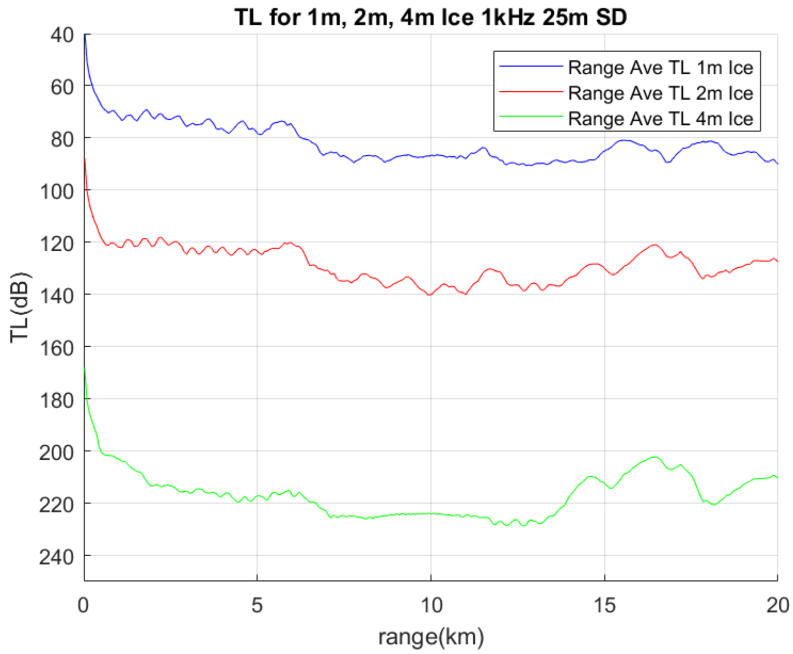

Figure 26. TL Comparison for 1 m, 2 m, and 4 m Ice Thickness for a 1kHz Signal

Since the results from the different ice thicknesses produced relatively linear TL graphs, testing to see if the linearity was caused by the amount of ice the sound had to travel through would help determine future implementation of the device. To further examine ice thickness and how it affected the cryophone's performance in the model, the cryophone was placed at different depths within four meters of ice at intervals of one meter. The first location was at one meter depth, then two meters, and finally at three meters.

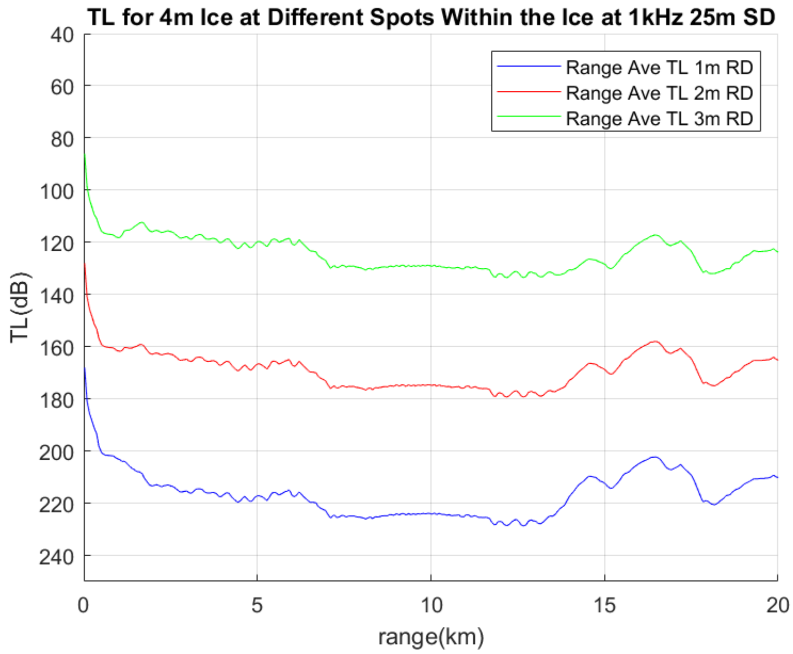

Figure 27. Receivers at Different Depths in 4 m Ice

4. Cutoff Frequency

The Bellhop examples did not show any indications of cutoff frequency in their runs, but the NSPE model did. The frequency was examined at 50 Hz and increased by 50 Hz until the sound no longer appeared to be trapped in the upper layer.

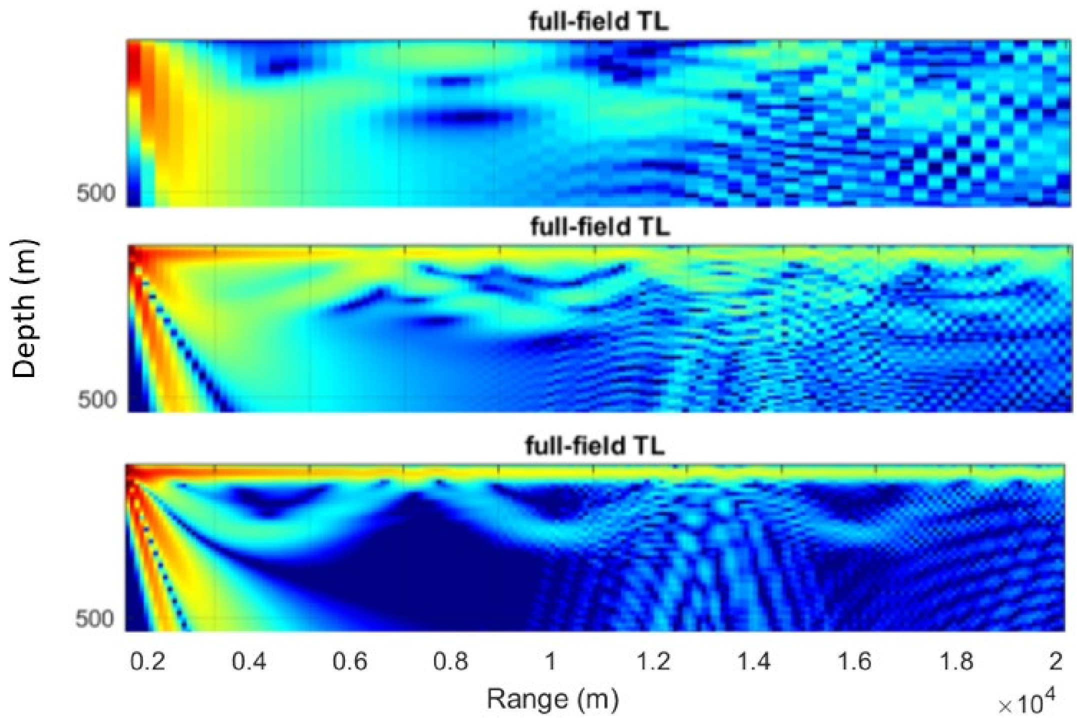

Figure 28. No Ice first 500 m for 50 Hz, 100 Hz, and 150 Hz

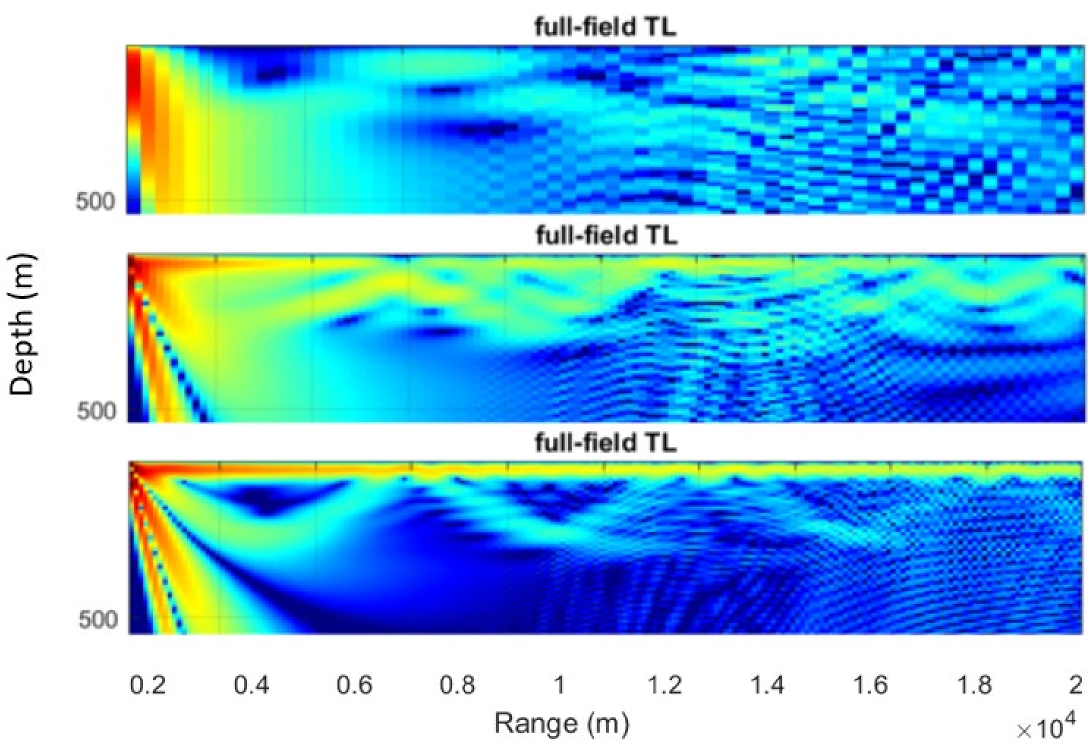

Figure 29. 2 m Ice first 500 m for 50 Hz, 100 Hz, and 150 Hz

V. DISCUSSION

A. RESULTS

1. Program

With no ice layer added, both NSPE and Bellhop perform about the same. They both included the shallow surface duct and the upward refracting characteristics caused from sound traveling upward from the Beaufort Lens. The deep-water sections were very similar, and both included a noticeable bottom bounce feature that reached the surface at approximately 15 km. As soon the ice layer was added to both the programs, Bellhop showed non-realistic results.

The first issue with Bellhop was the surface duct. With the ice layer present, the surface duct suddenly stopped at approximately two kilometers. The duct showed low TL near the source, but it transitioned to medium and then high TL and rapidly merged with the first shadow zone. Secondly, the sound energy in the Beaufort Lens was completely attenuated when it came in contact with the surface around six kilometers. The sound, when it met the surface ice layer, stopped propagating instead of being refracted or reflected off the ice. The lack of interference patterns in the deeper water that were present in the run with no ice were absent because the downward refracting sound that should have been present, disappeared. The removal of the sound when it met the high sound speed of the ice could further be examined by looking at Snell's Law. If a speed of 1500 m/s was assumed for water and 3800 m/s was assumed for ice, Snell's Law looks like:

$$\frac{\cos(\theta_1)}{1500} = \frac{\cos(\theta_2)}{3800}$$

the result, θ_2, is an imaginary number until θ_1 is about 67 degrees. If 3800 m/s becomes 340 m/s, the approximate sound speed for air, the number becomes a real number for all angles. Since the incidence angle was greater than the critical angle and the sound speed of the ice was greater than the sound speed of the water, the waves no longer propagated vertically, but only horizontally. They also decayed exponentially along the y-axis in the model. (Kinsler et al. 2000)

With all of these reasons combined, Bellhop does not create a realistic model for an ice layer scenario. NSPE did not exhibit any of the characteristics that Bellhop falls short with, so it seemed to be a more reliable modeling program for the Beaufort Sea.

The observed TL for the cryophone was presented in Figure 17. The comparison was between a receiver placed at 25 m, in the surface duct, and a receiver placed at one meter, in the ice. The intention was to see how well the cryophone handled sound traveling through the high sound speed medium that originated in the water. There was a noticeable increase in TL for the receiver in the ice. The increase in TL was expected due to the increased reflection, and refraction, but the goal was to observe if it was still possible to receive signals.

2. Source Depth

Source depth did not change the TL plots appreciably between the run with no ice and the run with the ice layer. This was because the sound energy was getting trapped in the Beaufort Lens, so the ice layer was not having much of an effect on the propagation path. This was one area that was a shortcoming of this model design. The ice layer was a flat static ice layer, which is not what occurs in nature. There are ice keels that reach down into the water column at random intervals and depths, inducing scattering and further TL. A more sophisticated ice layer may be needed in order to determine the effect it would have if a source was located in the Beaufort Lens or deeper.

3. Frequency

The most notable changes when frequency was altered occurred within the first 500 m of the water column. Predominantly, the deeper water TL did not have significant changes with changes in signal frequency. Both the surface duct and the shallow water experienced changes when frequency was altered. The sound that escaped the surface channel and became trapped in the Beaufort Lens became more defined in both the 1kHz and the 2.9 kHz, but it was more defined in the 1 kHz run. A notable difference for the 2.9 kHz run was the abrupt stop in the surface duct at approximately 6 km, at approximately the same location as where the first upward refraction from the Beaufort Lens reached the surface duct. The surface duct continued for another 2-3 km in the 2.9 kHz no ice scenario, but not when there was an ice layer.

The shortened surface duct was caused by sound that was leaking out of the surface duct and into the Beaufort Lens. Since the sound speed of the ice was so much greater than the sound speed of the water, the energy was getting refracted at a higher angle in the ice and reentering the surface duct at an angle such than it escaped into deeper water. It was likely that some of the sound that was leaking out of the surface duct was contributing to the extra sound that was propagating in the Beaufort Lens, which was why the signal was seen to be stronger with the ice present.

To tie what was seen in the model to what the team recorded in ICEX-20, the EMATT was operating at 25 m, which was the same depth as the source for the model. The 2.9 kHz signal in Figure 13 can be seen all the way to the turnaround point, which was approximately ten nautical miles (18.5km). If the sound was only propagating in the surface duct, it would not have been seen at such a far distance. Another point to consider, this model does not account for sheer losses in the ice. If sheer was incorporated, the surface duct would have been even shorter since that would have been an extra source of loss. The signal seen in the recorded data had to have reached the cryophone some other way.

4. Ice Thickness

In NSPE, altering the ice thickness changed the propagation in the Beaufort Lens. Thinner ice (one-meter) and thicker ice (four-meter) increased the TL in the channel produced by the Beaufort Lens. The one-meter ice run had less TL than the four-meter case in the Beaufort Lens. The downward leakage escaping at eight-kilometer is less in the two-meter case, which is why the TL is less in the duct.

When the numerical TL was examined, there was a linear relationship between the TL and the depth of the ice present when viewed from the one meter cryophone's perspective. There was approximately a 50 dB increase in TL for every meter increased in ice thickness. The increase in TL may have been caused by increased refraction as sound traveled through the ice. Since the ice's sound speed was so high relative to the water's sound speed, more rays could refract back into the water and experience more attenuation.

Since there appeared to be a linear relationship between the TL for different thicknesses of ice, the model was run again with the same thickness of ice and the receiver was placed at different locations within the ice, Figure 27. Again, there was a linear relationship between the amount of ice the sound had to travel through to get to the receiver and the amount of TL observed. The 50 dB loss per meter was seen again when the receiver depth was changed within the ice column.

5. Cutoff Frequency

The previously calculated cutoff frequency using a 25 m mixed layer was 500 Hz, but Figures 27 and 28 did not appear to be trapped past 150 Hz. That would imply that, according to this model, Urick’s equation, which was designed for more traditional SSP’s, did not adequately fit the SSP in the Beaufort Sea.

6. Echosounder

Results from the echosounder can be found in the supplemental section.

B. CONCLUSION

The cryophone is a fascinating new piece of technology that needs to be explored more in the field. The modeling done, and the data collected at ICEX-20 has shown that this tool can be used as a passive detection device in the Arctic even if it is not as good as an in-water hydrophone. The key piece that makes this technology so promising is its ease of deployment. It is difficult to operate in the Arctic and deploying hydrophones would be very hard to do from the air or water. While water-borne receivers will have less TL, dropping a network of cryophones from the air could provide a use as a passive detection tool.

Higher frequency signals are not as viable for this technology as mid or lower frequencies. Thinner ice would be preferable as a deployment location over thicker ice because there is a significant loss of sound as it travels through ice.

C. OPERATIONAL SIGNIFICANCE

The Arctic is an ever-changing theater and with continuous development comes new technology. The cryophone could be set up into an above water network of passive detection devices. The intention would be to deploy these from aircraft with built in heating units to fuse itself into the ice and then take advantage of solar and wind power to communicate collected signals. This technology is far from ready to be used in a militaristic scenario against live adversaries, but it should be further investigated as a tool.

D. FUTURE WORK

This technology is still in a proof-of-concept stage. Taking what has been learned about this tool and creating a product that could be used by future researchers or the government will still take more work. Unfortunately, the opportunity to test new ideas in the field are limited to expensive expeditions like ICEX, so it is important to incorporate time for scientific research into events like that. Testing how to best deploy this technology and have it successfully operated in ice is a future step that would be very important to ensure this technology could be used. Continuing to refine the model for in ice deployment would help determine how to best deploy the cryophone. Testing the cryophone with a hydrophone in nearby water is crucial for determining if the cryophone can provide useable results.

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VI. SUPPLEMENTAL: ECHOSOUNDER RESULTS

The Supplemental identified here has a SECRET classification and a restricted distribution statement, which further limits access. Please email inquiries to **rresources@nps.edu**.

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