Title

Localization and propagation of seismic shots in the deep-water Beaufort Sea

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Capstone Advisory Committee Final Capstone Project Signature Form

Localization and propagation of seismic shots in the deep-water Beaufort Sea

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Spring 2012
MAS Marine Biodiversity and Conservation
Capstone Project

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Abstract

Sound propagation models were developed for modally dispersed seismic shots to determine range to a seismic source from two High-frequency Acoustic Recording Packages (HARPs) deployed on the continental slope break north-northwest of Point Barrow, Alaska in the fall of 2007. Range estimates were compared to known locations of the Canadian Coast Guard Ship (CCGS) *Louis S. St-Laurent* (*LSSL*) conducting a geophysical seismic survey in the deep-water Beaufort Sea. We report transmission loss and received level estimates at the HARPs as a proxy for sound levels that would be experienced by bowhead whales (*Balaena mysticetus*) near the study site. Received levels at the HARPs ranged from 109.5 dB to 135.0 dB rms re 1 μPa, with an average received sound level of 112.8 dB rms. The furthest modeled seismic shots were at a distance of 751 km. These received level measurements coincide with levels that have shown to elicit behavioral responses in bowhead whales, and raise concerns about how seismic activities may potentially impact marine mammals across large spatial scales and international maritime boundaries.

Although guidelines have been established to reduce such impacts, current mitigation measures show considerable variation between countries and do not take into account the transboundary nature of sound in the ocean. To provide an international framework for the regulation of seismic surveys in the Arctic, a better understanding of how sound propagates in a changing Arctic environment, in addition to how the cumulative impacts of multiple seismic activities may influence ambient noise levels across large spatial scales is needed. A collaborative approach to management, mitigation, and research is essential to provide effective protection for marine mammals as a result of increased international and multi-industry interest in the Arctic and its natural resources.

I. Introduction

Combinations of climate change and industrial development may severely impact the Arctic ecosystem. Rapid loss of sea ice is providing new access for anthropogenic activities, causing concern about future increases of ambient noise in the ocean and the potential impacts to marine mammals. In the Arctic, much of the concern focuses on seismic surveys for geophysical research and oil and gas exploration and the potential impacts to bowhead whales (*Balaena mysticetus*) and other marine life. The high-intensity, low-frequency sounds produced during seismic surveys can propagate over hundreds or even thousands of kilometers, potentially affecting animals across large spatial scales. Although guidelines have been established to reduce such impacts, current mitigation measures show considerable variation between countries and do not take into account the transboundary nature of sound in the ocean. Since sound is not restricted by national boundaries it cannot be regulated by domestic policy alone, and the potential impacts to marine mammals must be addressed internationally. To provide an international framework for the regulation of seismic surveys in the Arctic, a better understanding of sound propagation is needed as climate change continues to alter the acoustic environment.

During the fall 2007, the Canadian Coast Guard Ship (CCGS) *Louis S. St-Laurent* (*LSSL*) conducted a geophysical seismic survey in the deep-water Beaufort Sea to collect data for Canadian extended continental shelf claims under Article 76 of the United Nations Convention on the Law of the Sea (UNCLOS) (Jackson, 2007). Seismic shots generated by the *LSSL* were detected on two High-frequency Acoustic Recording Packages (HARPs) deployed on the continental slope break north-northwest of Point Barrow, Alaska. We report localization estimates for seismic shots generated by the *LSSL* using sound propagation modeling to provide a better understanding of how sound attenuates and propagates during a year with record low sea ice concentrations in the Arctic (Stroeve et al., 2007). In addition, we provide estimated received sound pressure levels experienced by bowhead whales near the HARPs during their fall migration from the Beaufort to the Chukchi Sea.

II. Background

Geophysical Seismic Exploration and Sound Propagation in the Arctic

The opportunity to explore for and extract hydrocarbon reserves in the Arctic has prompted many countries to seek an extension of their territorial claims over natural resources under UNCLOS. While providing a comprehensive legal framework for nearly all ocean uses, UNCLOS also establishes a nation's sovereign rights, or Exclusive Economic Zone (EEZ). A nation's EEZ extends to 200 nm (370 km) offshore or to the continental shelf,[1] and includes jurisdiction over all mineral and biological resources in the water column and on and below the seafloor (UNCLOS, 1982). However, Article 76 of UNCLOS establishes criteria to determine areas beyond a nation's EEZ that could be defined as "extended continental shelf (UNCLOS, 1982)." As a result, countries with territorial claims in the Arctic have been conducting seismic surveys to acquire the necessary geophysical data to determine the outer limits of their extended continental shelf.

Seismic surveys involve the use of airgun arrays, which are used in seismic reflection profiling to obtain images of the Earth's crust. An airgun array consists of up to 12-48 individual airguns that release a specified volume of high pressure air, creating a high intensity sound pressure wave that penetrates the seafloor and reflects back to the surveying ship towing acoustic

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[1] Under UNCLOS, "continental shelf" refers to a legally defined region of the seafloor rather than a morphological shallow-water area adjacent to continents (UNCLOS, 1982).

receivers (Dragoset, 1984; 2000). Seismic shots are generated every 10-20 seconds and seismic surveys can last for days at a time (Caldwell and Dragoset, 2000; Dragoset, 2000; Greene and Moore, 1995) with source levels as high as 260 dB rms re 1 μPa @ 1 m output pressure (Turner et al., 2006) and peak frequencies in the band from 5-300 Hz (Hildebrand, 2009). Sounds from airgun arrays also ensonify the water column, creating increased noise levels across ocean basins. Nieukirk et al. (2004) found that seismic exploration along the continental margins of Canada, South America, and West Africa were a significant component of low-frequency noise recorded by hydrophones over 3,000 km away in the North Atlantic. In the Arctic, Thode et al. (2010) showed that airgun pulses generated in the deep-waters of the Beaufort Sea have been detected between 400 km and 1300 km from the seismic source.

The cold surface temperatures of the Arctic yield sound speed profiles with a minimum at or near the surface and increase with depth (Marsh and Mellen, 1963), allowing sound to propagate with minimal bottom interaction and reduced transmission loss (Thode et al., 2010). Sea ice also plays a role in limiting sound propagation (Diachok, 1980), ultimately influencing how seismic surveys contribute to ambient noise levels in the ocean. Roth et al. (2012) showed that average noise levels in the Alaskan Arctic in September are 5-20 dB higher than during seasons with sea ice coverage. Additionally, seismic surveys conducted during this open-water period raised average noise levels by 2-8 dB on the continental slope of the Chukchi Sea. During open-water conditions, sounds from seismic surveys will propagate further, thus potentially influencing bowhead whales and impacting subsistence hunts across larger spatial scales.

Impacts of Seismic Exploration on Bowhead Whales and Subsistence Hunts

Bowhead whales are an endangered marine mammal species with a circumpolar distribution in seasonally ice-covered waters of the Arctic. The western-Arctic stock of bowhead whales is the best studied of five extant populations (Burns, 1993; Moore and Reeves, 1993). During their fall migration (Figure 1), bowhead whales migrate west through the Beaufort Sea to the Chukchi Sea, passing through regions currently exposed to the high intensity, low frequency sounds produced by seismic surveys for geophysical research and oil and gas exploration (Moore and Reeves, 1993).

The sounds produced by seismic airgun arrays overlap in frequency with calls of bowhead whales (Richardson et al., 1995), and may affect the whale's ability to detect, interpret, and respond to biologically relevant sounds (MMC, 2007). Bowhead whales produce tonal frequency-modulated calls that have been detected 10 km or more away with received levels as high as 189 dB (Cummings and Holliday, 1985; Ko et al., 1986; Clark et al., 1996). Most calls range in frequency from 50-400 Hz, although their repertoire includes a variety of calls up to 4 kHz (Cummings and Holliday, 1985; Würsig and Clark, 1993), and models suggest their hearing ranges from 5-20 Hz to 20-30 kHz (Weilgart et al., 2007). Although not well documented, bowhead whale calls may function to maintain social cohesion in groups during migration, feeding, and other vital life functions (Würsig et al., 1983; Ljungblad et al., 1986; Würsig and Clark, 1993).

The behavioral responses of bowhead whales to the sounds produced by seismic airgun arrays are complex and are also poorly understood (Richardson et al., 1995). When exposed to playback sounds and in the presence of seismic exploration, bowhead whales have displayed subtle changes in surfacing and breathing patterns (Richardson et al., 1995), the reduction or cessation of vocalizations (Richardson et al., 1986; Greene et al., 1999; Blackwell et al., 2009; Wartzok et al., 1989), and avoidance of the survey region (Miller et al., 1999; Richardson et al., 1999). While bowhead whales have shown strong avoidance behavior at or below received levels ranging from 160-170 dB (Miller et al., 1999; Richardson et al., 1999), responses have also been reported at moderate received levels around 114 dB (Hildebrand, 2005). Bowhead whales have also shown variable responses to seismic surveys depending on their current behavioral state, suggesting that individuals may be more tolerant of noise while they are feeding than when they are migrating (Miller et al., 1999). Bowhead whales migrating west across the Beaufort Sea in the fall showed avoidance occurring out to distances of 20-30 km from the seismic source with received sound levels ranging from 107-135 dB (Miller et al., 1999; Richardson et al., 1999), demonstrating that even relatively low levels of seismic activity could potentially disturb bowhead whales.

The disturbance and potential displacement of bowhead whales by sounds produced from seismic exploration is a major concern related to the subsistence use of the Beaufort and Chukchi Seas. Bowhead whale hunting is the foundation of the socio-cultural system of many native communities on the North Slope of Alaska, providing a unique and powerful basis for sharing and community cooperation (Stoker, 1983; MMS, 2007). This culturally significant species is a major food resource for communities and is central to many traditional feasts, as well as the focus of *Nalukataq*, which celebrates the bowhead whale harvest (MMS, 2007). Subsistence hunts take place in both the spring and fall; however, unpredictable sea ice conditions are causing many to join the fall pursuit of bowhead whales on their migration west through regions currently exposed to seismic surveys (AEWC, 2008). The sounds produced by seismic airgun arrays have been shown to disturb migrating bowhead whales, causing them to alter their migration route and avoid the survey region (Miller et al., 1999; Richardson et al., 1999). As a result, the harvest of bowhead whales could be more difficult and dangerous, forcing crews to travel greater distances, therefore creating a safety hazard and limiting the chances of successfully striking and landing a whale (MMS, 2007).

Mitigation Measures: Safety Zones

Mitigation measures have been established by many countries to minimize behavioral disturbance and potential auditory and physical injury to marine mammals during seismic surveys. Within any given set of guidelines, safety zones (or exclusion zones) are key mitigation tools designed to reduce such impacts (Compton et al., 2008). A safety zone is usually defined as the radius around a seismic source within which real-time mitigation measures are implemented if a marine mammal is detected (HESS, 1999). This zone is based on the assumption that lower received sound levels will not injure the animal or impair their hearing abilities (NMFS, 2007). Sound pressure levels of 160 dB rms and 180 dB rms are commonly quoted for the inducement of behavioral responses and auditory/physical injury in cetaceans, respectively (Castellote, 2007). Depending on the size of the airgun array, as well as site-specific factors including the depth, bottom substrate, and sound speed profile, a 180 dB rms safety zone may vary from 200 m to over 1 km from the seismic source (Pierson et al., 1998).

Defining the safety zone around an airgun array is a fundamental component of mitigating potential adverse impacts to marine mammals; however, guidelines currently in use worldwide show considerable variation. For example, some countries establish a generic safety zone that applies regardless of the size of the airgun array or site-specific variables (Compton et al., 2008). For effective mitigation, more research is needed to determine how sound propagates and influences ambient noise levels in a changing Arctic ecosystem, while taking into account the environmental, biological, and contextual factors that may affect how marine mammals perceive and respond to sound, in addition to the effects of long-term sound exposure (Ellison et al., 2011).

III. Methods

Acoustic Recording and Analysis

Two High-frequency Acoustic Recording Packages (HARPs) located 48.9 km apart were used to make long-term recordings of underwater sounds during 2007 (Figure 2). The HARP at Site B (72°27.626 N, 157°23.932 W) was deployed to a depth of 235 m at the edge of the continental slope 125 km north-northwest of Point Barrow, Alaska. The HARP at Site C (72°47.908 N, 158°23.880 W) was deployed to a depth of 328 m at the edge of the continental slope 170 km north-northwest of Point Barrow, Alaska. Site B and Site C are located between the Beaufort and Chukchi Seas, allowing for the recording of both shallow water sound propagation from the eastern Chukchi Sea and deep ocean acoustics from the western Beaufort Sea. Wiggins and Hildebrand (2007) describe the HARP, including design of the seafloor package, data acquisition system, and hydrophone (Figure 3).

For 2007 deployments, the HARPs recorded data on a 50% duty cycle, with 7 minutes of continuous recording on a 14 minute interval. Data were recorded at a 32 kHz sample rate using a 16-bit data logging system. Raw data from these instruments were processed into XWAV format analysis files based on the WAV format, but with additional meta-data included in the file header (Wiggins and Hildebrand, 2007). Analysis of XWAVs was accomplished by using spectrograms and acoustic playback of the recordings. A Matlab-based program called *Triton* (Wiggins and Hildebrand, 2007) was used to view spectrograms of XWAV files, to playback recorded sounds, and to log call detections. Hydrophone calibrations were conducted to allow the raw data to be converted into sound pressure expressed as dB re: μPa.

Identification and Analysis of Seismic Shots

Seismic surveys were recorded by HARPs at Site B and Site C between September 16 and October 7, 2007. A maximum of twenty consecutive seismic shots were analyzed per bout every 3 hours 44 minutes to provide a sufficient sample size, show any appreciable changes in the seismic shots, and to account for the 7 minute duty cycle of the recorder. Shots were classified into descriptive categories based on their shape and size in a spectrographic display (Figure 4). In addition, start and end times for each shot were logged, as well as prominent features, for example maximum frequency and mean duration of the shot. Masking, attenuation, and other factors made it difficult to log all shots. If a bout could not be logged every 3 hours 44 minutes, another bout was selected before or after to fill in gaps between logged bouts.

Localization of Seismic Activity Using Sound Propagation Modeling

Knowledge of sound propagation in the Arctic is critical to determine how seismic surveys influence ambient noise levels with increasing distance from the seismic source. Determining range, however, depends on the characteristics of the seismic shot and the acoustic environment. Noise from anthropogenic activities such as shipping, or from natural sources such as storms, may reduce the range at which the shot is detected. In addition, sound propagation in the Arctic Ocean is highly influenced by complex environmental factors including sea ice concentrations and the water temperature profile (Wiggins et al., 2004)

The temperature-density gradient in the deep-water Arctic creates a near-surface waveguide that minimizes the effects of bottom topography on sound propagation (Yang, 1984), contributing to long-range propagation with reduced transmission loss (Thode et al., 2010). Similar to a shallow-water waveguide, the constructive and destructive interference of the seismic shot creates multiple mode arrivals and dispersion of the signal, where different frequencies travel at different velocities. The variation of velocity with frequency allows range estimates between the seismic source and receiver to be made for shots that sweep through a band of frequencies (Wiggins et al., 2004). For this study, a dispersion ranging method described by Yang (1984) in combination with a sound propagation model for modally dispersed seismic shots was used to determine the range from the HARPs to a seismic source.

A sound propagation model for dispersed shots was developed to estimate the range between the seismic source and the HARPs using the code-set Acoustic Toolbox developed by Michael Porter (http://oalib.hlsresearch.com/). Sound speed values and depths from all CTD data contained in the World Ocean Database (19,795 casts) at the National Oceanographic Data Center for latitudes greater than 65° N (Roth and Schmidt, 2010) were used for the model. Two models were developed based on this data: Model 1 is the mean sound speed value and Model 2 is the lower limit of the sound speed profile represented by the histogram in Figure 5.

To determine the range to the seismic source, the slope of the time-frequency curve for the second mode was compared to modeled modes for dispersed shots at varying ranges. Figure 6 shows modes from Model 2 overlaid on a dispersed seismic shot approximately 500 km from the HARPs. In this study, the second mode was selected because the first mode was often not visible above the low frequency ambient noise. A frequency range from 25-30 Hz was used to calculate the time difference between frequencies on the curve as they arrived at the HARPs. This frequency range was the most consistent across bouts; frequencies below 25 Hz were often difficult to log due to the limited excitability of the mode at lower frequencies, while those above

30 Hz were poor fits for the model. The poor fit is presumably the result of our assumption that the sound speed profile is laterally homogenous; however, this is not the case due to the variability seen in the modes in the surface layer of the water.

The time-frequency difference from Site B and Site C were compared to the model to estimate a range to the seismic source. Ranges for other seismic shot categories (multi-banded, corset, short, U, L, J, and other) could not be calculated because sound propagation models have only been developed for dispersed shots. Bearings were also calculated for each bout using a time-distance of arrival (TDOA) estimate. A Microsoft Excel add-in was then used to calculate the position of each bout with a bearing and range estimate from the midpoint between Site B and Site C.

Range predictions from the models were compared to observed ranges for modally dispersed shots generated by the *LSSL* conducting a geophysical seismic survey in the deep-water Beaufort Sea. The 2007 field report and track line data from the seismic watch log were obtained from the Geological Survey of Canada for comparison. The positions of the *LSSL* were logged every half hour, on average, allowing recorded seismic shots to be compared to positions within 15 minutes from when they were fired. Track line data from the *LSSL* and positions using the model and TDOA estimates were then plotted using ArcGIS for spatial comparison.

Received Levels and Transmission Loss

The development of a sound propagation model would not only provide range estimates to the seismic source, but could also be used to estimate the received sound pressure levels experienced by bowhead whales as the seismic shot travels through the waveguide away from the source. Received levels of sound at Site B and Site C were calculated for dispersed shots by taking the start and end times of logged seismic shots and filtering for the frequency band of the shot (10 – 1000 Hz) to avoid edge effects associated with a smaller filter. Peak-to-peak (pk-pk) values were then calculated for each shot and converted to dB. Received levels were plotted against the log of the range and transmission loss was determined by the slope of a linear fit to the data.

IV. Results & Analysis

Descriptive Analysis of Seismic Shots

In September and early October, ambient noise levels were elevated due to the presence of seismic surveys in the Arctic (Figure 7). Seismic activity was detected spanning 511 hourly windows; only 79 hourly windows had no detectable airguns (Roth et al., 2012). Additionally, seismic shots varied in intensity, presumably owing to the distance to the seismic source.

Table 1 provides a descriptive statistical analysis of each category based on the features of each shot that were logged. The dispersed shots were the most abundant and comprised 50% of all logged shots, while the multi-banded shots had the highest recorded frequencies with a mean of 308.6 Hz. The J shots were the most difficult to log because they do not have distinct start and end times like many of the other types of shots observed. The category other is only made up of 1 logged bout, and was given its own category because it did not distinctly fit into one of the other 7 categories.

Localization of LSSL Geophysical Seismic Activity

Track line data from the seismic watch log for the *LSSL* in the deep-water Beaufort Sea are shown in Figure 8. Track lines 1 and 2 were completed before the HARPs began recording on September 16, and seismic data were only recorded for track lines 3 through 8 until the completion of the survey on October 7. Figure 9 shows positions of *LSSL* seismic activity used for comparison against the sound propagation models. These positions were chosen because the second mode was not affected by masking, attenuation, and other factors that made other bouts difficult to log.

Comparison between positions in the *LSSL* seismic watch log and positions calculated with range estimates from Model 2 are shown in Figure 10, with a close up of Lines 3 and 5 in Figure 11 and a close up of Lines 4, 6, 7, and 8 in Figure 12.

Table 2 shows a comparison between ranges from the midpoint (between Site B and Site C) to positions in the *LSSL* seismic watch log and estimates from Model 2. Ranges differed from 0.6 km to 147.6 km. In addition, the difference between positions was calculated when Model 2 range estimates were combined with bearings, and differed from 1.4 km to 153.7 km. All but four survey bouts were within 34 km of the positions recorded in the *LSSL* seismic watch log.

On October 1, ranges differed from 77.1 km to 147.6 km, and on October 7, one range differed by 66.4 km. Since the model assumes a sound speed profile that is laterally homogenous, a combination of models may be more appropriate to estimate range across a large ocean basin such as the Beaufort Sea. Range estimates for these survey bouts were recalculated using Model 1and are shown in Figure 13. Table 3 shows a comparison between ranges from the midpoint to positions in the *LSSL* seismic watch log and estimates from Model 1. Ranges differed from 4.1 km to 60.1 km. In addition, the difference between positions was calculated when Model 1 range estimates were combined with bearings, and differed from 4.7 km to 72.4 km.

While Model 1 closed the gap between the estimated ranges and positions in the *LSSL* seismic watch log for some surveys, one survey on October 1 and on October 7 were still off by 60.1 km and 46.1 km, respectively. In some cases, the difference between the positions exceeded the difference between the ranges, which may be a factor of how the features of the seismic shots were logged for the bouts.

Received Levels and Transmission Loss

For several hours at a time, airgun shots were produced at 10-20 s intervals, and the quality of signal that was received depended upon the distance between the source and the HARPs. As expected, the sound levels associated with the *LSSL* seismic survey decreased with increasing range to the HARPs (Figure 14). Using a linear fit, transmission loss was 14.627*log(10)(range), intermediate between cylindrical and spherical spreading, as expected for propagation in this region.

Received sound levels recorded by the HARPs during the study period for logged bouts ranged from 118.5 dB pk-pk to 144.0 dB pk-pk at distances from 296 km to751 km. The furthest logged survey for this study was approximately 751 km from the HARPs with an average received sound level of 121.8 dB pk-pk.

V. Discussion

Under ice-free conditions in the Arctic, sounds from seismic activities have been detected hundreds to thousands of kilometers away from the source (Nieukirk et al., 2004; Thode et al., 2010). In this study, the sounds produced by the *LSSL*'s seismic activity were recorded approximately 751 km away in the deep-water Beaufort Sea by HARPs located on the continental slope break north-northwest of Point Barrow, Alaska. Although the survey was conducted beyond the maritime boundaries of the United States, seismic activity raised ambient noise around the study site in national waters to levels that have been shown to disturb bowhead whales (Miller et al., 1999; Richardson et al., 1999).

Bowhead whales have a known presence at the study site and their calls have been recorded by the HARP at Site B (Baldwin et al., 2012)(Figure 15). With previous research detecting bowhead whale calls up to 10 km or more away from a source (Cummings and Holliday, 1985; Ko et al., 1986; Clark et al., 1996), bowhead whales recorded by the HARPs would be exposed to similar received levels from seismic surveys as the recording instrument.

In this study, received levels recorded at the HARPs for dispersed shots ranged from 118.5 dB pk-pk to 144.0 dB pk-pk. Pk-Pk sound pressure is the algebraic difference between the maximum positive and maximum negative instantaneous peak pressure, while the rms is the average of the squared pressure over time (Southall et al., 2007). For comparison to the rms measurements used for safety zone mitigation, pk-pk values are approximately 9 dB higher than rms values; therefore, received levels at the HARPs ranged from 109.5 dB rms to 135.0 dB rms. At a range of approximately 751 km, the furthest analyzed seismic bout had an average received sound level of 112.8 dB rms (121.8 dB pk-pk). These received level measurements coincide with levels that have shown to elicit behavioral responses in bowhead whales, and raise concerns about how seismic activities can potentially impact marine mammals across international maritime boundaries.

To estimate received levels potentially experienced by bowhead whales in the region, a source level of 228 dB rms at 1 m (5.1 bar-m, 0-pk) was calculated for the airgun array based on the information provided in the 2007 *LSSL* field report (Jackson, 2008; John Shimeld, pers. com.). Using the furthest analyzed seismic bout as a reference point, received levels were calculated for ranges from 1-750 km based on the transmission loss of the signal as it propagates to the HARPs (Figure 16). Table 4 shows a comparison between rms and pk-pk received levels at 1 km, 10 km, 100, km, 250 km, 350 km, 500 km, and 750 km from the seismic source.

Received levels recorded by the HARPs were 1-4 dB lower than the received levels calculated using an estimated source level of 228 dB rms. This difference may be due to the downward directing properties of the airgun array, which would reduce the amount of energy that propagates horizontally toward the recording instruments. In addition, the 2007 *LSSL* field report and seismic watch log document heavy ice during this portion of the survey, which would also contribute to the lower received levels recorded by the HARPs.

In the Arctic, the United States National Marine Fisheries Service (NMFS) has required a 120 dB rms monitoring zone in the Beaufort and Chukchi Seas (NMFS, 2007) after bowhead whales had shown behavioral responses to received levels ranging from 107-135 dB (Miller et al., 1999; Richardson et al., 1999). Based on the calculated received levels, this monitoring zone would extend out to 350 km from the seismic source; however, these mitigation measures only apply if the seismic activity occurs in U.S. waters or by U.S. citizens on the high seas. Thus, due to the transboundary nature of sound in the ocean, the potential impacts of seismic activity must be addressed internationally.

Currently, there are no bilateral treaties or agreements that specifically address the potential impacts of anthropogenic sound on marine mammals or how to mitigate such impacts at an international level (Jasny et al., 2005). A better understanding of how sound propagates in a changing Arctic environment, in addition to how the cumulative impacts of multiple seismic activities may influence ambient noise levels across large spatial scales is needed. The international character of the Arctic demands a collaborative approach to management, mitigation, and research to provide effective protection for marine mammals as noise levels in the ocean continue to rise.

VI. Conclusion

These findings illustrate how modeling sound propagation in the Arctic Ocean can lead to a better understanding of how seismic activities influence ambient noise levels, and potentially bowhead whales, across large spatial scales. The transboundary nature of sound in the ocean has the potential to affect marine mammals across international maritime boundaries, which proves difficult when establishing mitigation measures to prevent potential short- and long-term hearing loss and behavioral disturbance to bowhead whales.

The potential impacts of seismic exploration on bowhead whales is a function of the amount of sound introduced into the ocean, as well as response to a combination of short- and long-term exposure (MMC, 2007). In September and early October, noise levels near the study site were elevated due to the presence of seismic surveys. Although sound propagation models were only used to estimate range to one survey, others were recorded by the HARPs during the study period. While a single seismic survey may have minor impacts, overall impacts may be collectively significant when considered together with other industrial activities on a regional scale. This is important to consider since there are international and multi-industry interests in the Arctic's natural resources, including exploration and drilling for hydrocarbon reserves by the oil and gas industry, which will ultimately contribute to higher levels of ambient noise in the marine environment.

Moore et al. (2012) propose creating an acoustic-habitat map comprising all sound sources as a means to address their cumulative effects on marine mammals over a range of temporal and spatial scales. In combination with modeling the acoustic environment, this approach could provide a framework for assessing how marine mammals may be affected within a region by anthropogenic activities occurring at much greater distances. This approach, however, requires a collaborative international interest in protecting the Arctic ecosystem. Additional research is also needed to determine what levels of sound cause behavioral disturbance and potential auditory and physical injury in marine mammals while taking into account the environmental, biological, and contextual factors that may affect how marine mammals perceive and respond to sound, in addition to the effects of long-term sound exposure (Ellison et al., 2011). In the meantime, precautionary measures must be incorporated to protect marine mammals while uncertainties are being resolved.

Long-term acoustic monitoring in the Arctic is a useful tool to track changes in ocean noise, in addition to providing an effective way to monitor and collect data on marine mammal distribution as changes in sea ice and other environmental conditions cause shifts in the ecology of the Arctic. A better understanding of the acoustic environment is essential in determining the effects of anthropogenic sound on marine mammals, especially since sound propagates differently as a result of complex environmental variables. Acoustic baseline measurements are needed in the Arctic for further analysis to observe and compare shifts in ambient noise due to the decline in sea ice and the increase of industrial activities. In addition, anthropogenic and non-anthropogenic source data should be collected to develop a global model of sound in the ocean to be made available to agencies to make informed policy decisions based on the best available science.

Without some effort to monitor, reduce, or limit the levels of anthropogenic sound in the ocean, it is likely to increase and continue to degrade the acoustic environment in the ocean. Before poorly understood damage occurs, anthropogenic sound must be managed to protect marine mammals and the ecosystem. Reducing anthropogenic levels of sound is one precautionary measure. Another approach could be to provide incentives for agencies and stakeholders to develop an adaptive research program directed toward the conservation of marine mammals without having to impede on human activities in the ocean (Weilgart, 2007). In sum, increasing our knowledge in the face of uncertainty has the potential to lead to regulations that are less burdensome and disruptive for industry, while providing effective protection for bowhead whales in the Arctic.

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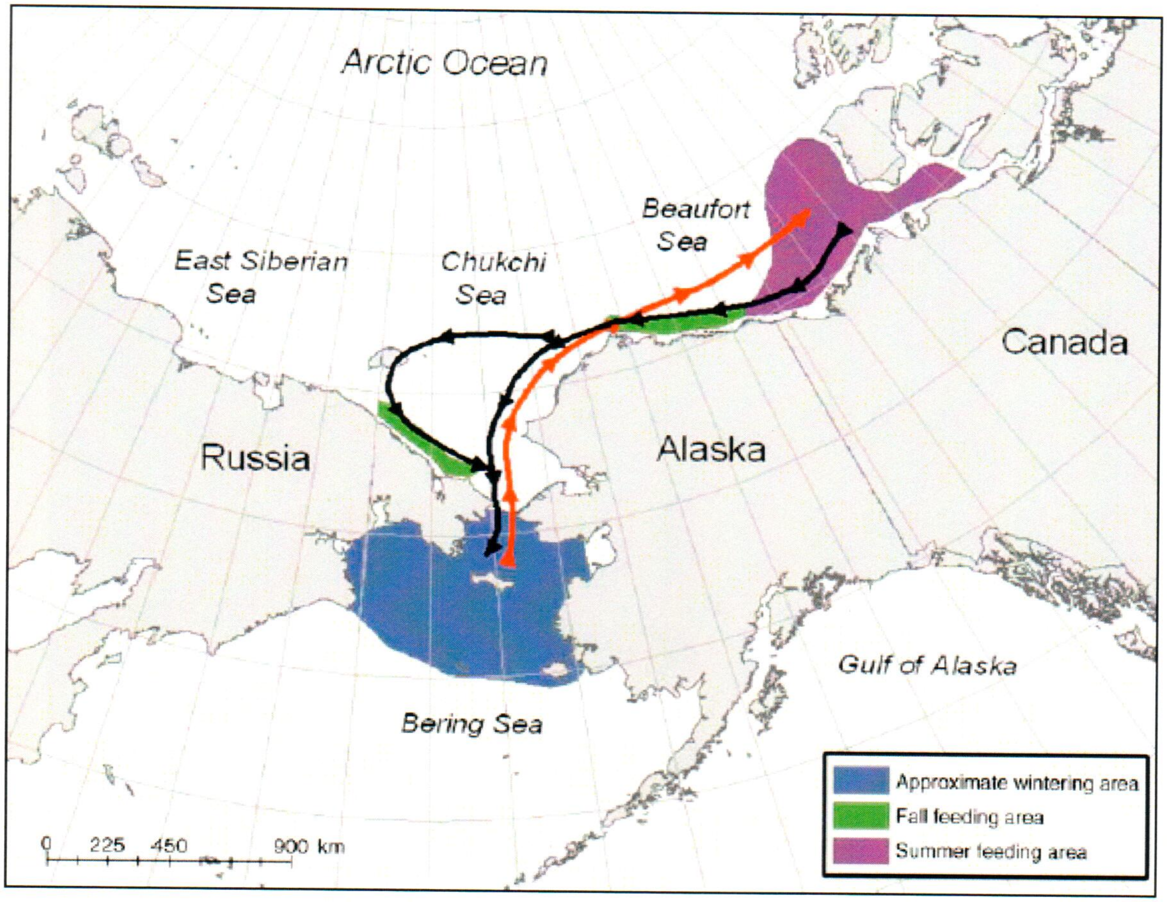


Figure 1. The migration route of the western-Arctic stock of bowhead whales; the red line shows the spring migration, while the black line shows fall migration (Moore and Laidre, 2006).

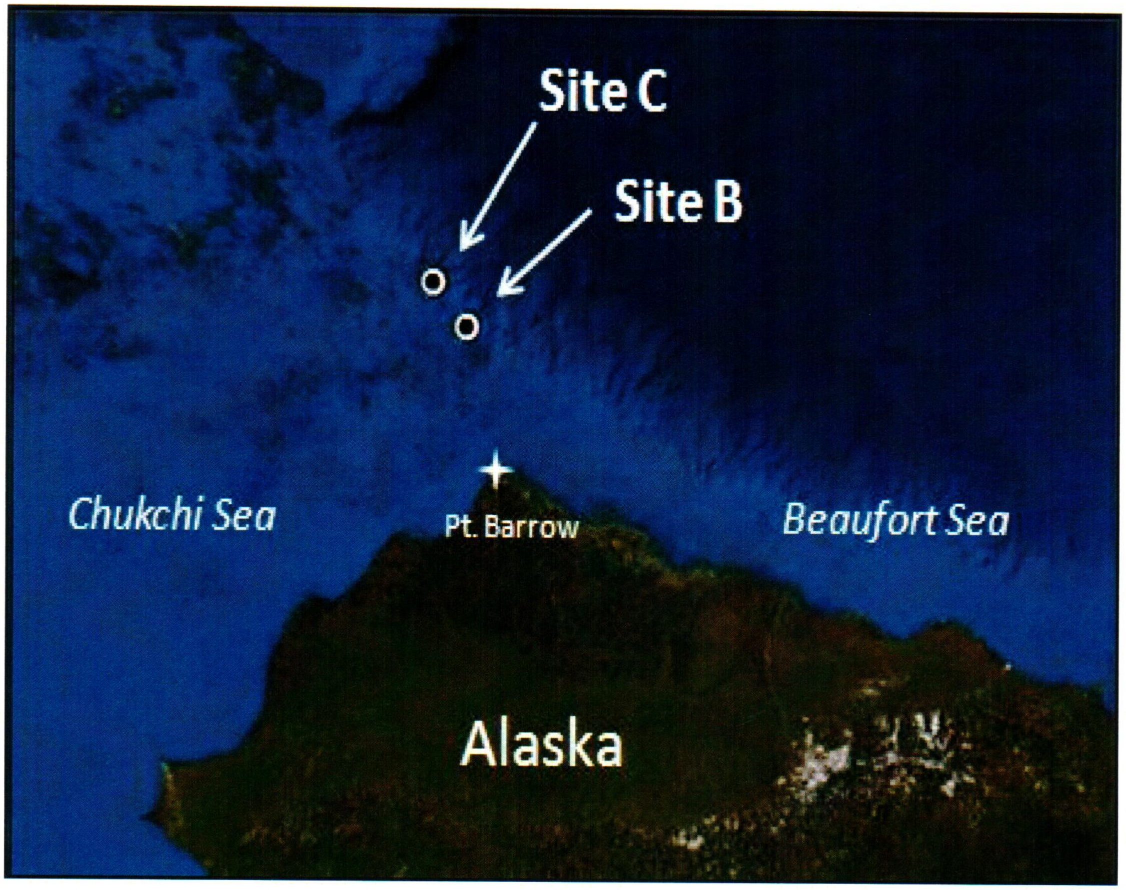


Figure 2. Study Site; two High-frequency Acoustic Recording Packages (HARPs) at Site B and Site C were deployed at the edge of the continental slope north-northwest of Point Barrow, Alaska between the Beaufort and Chukchi Seas.

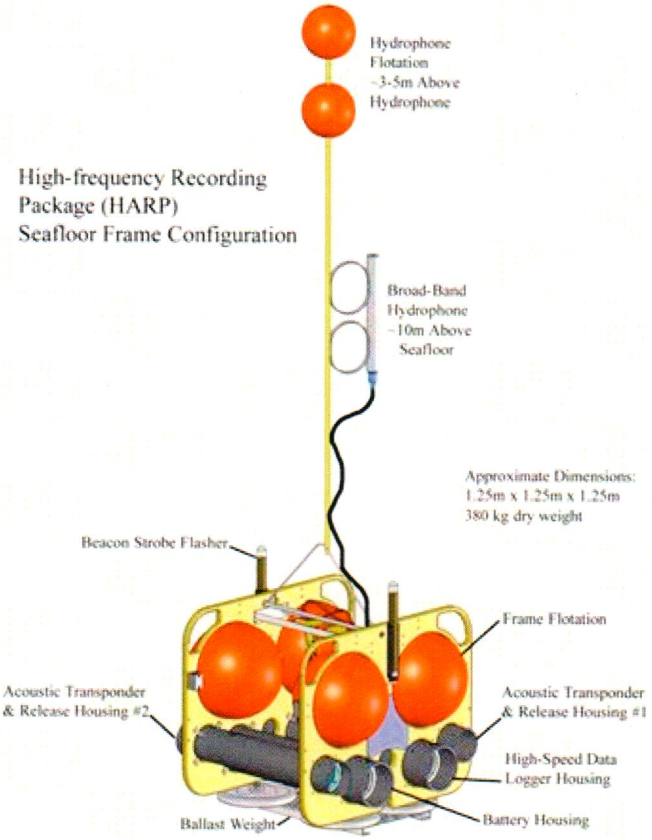


Figure 3. High-frequency Acoustic Recording Package (HARP).

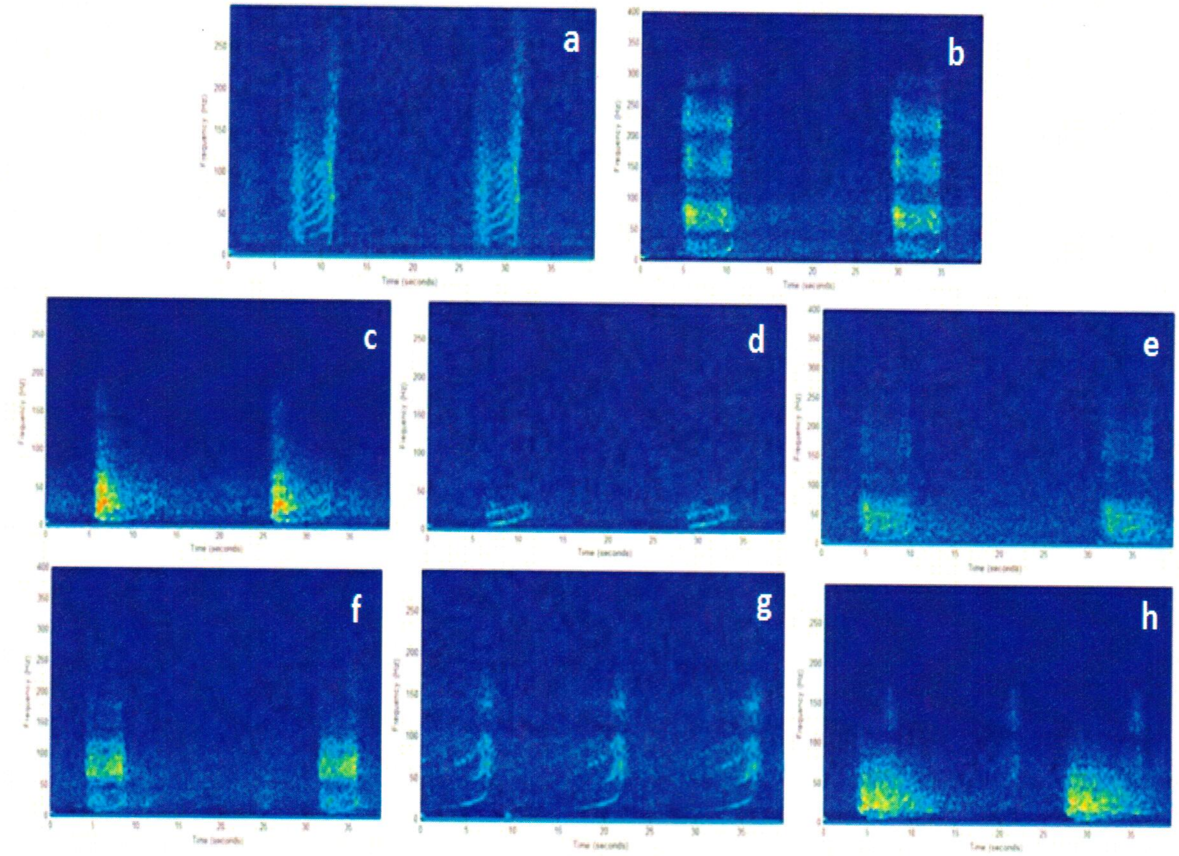


Figure 4. Seismic shot categories: (a) dispersed, (b) multi-banded, (c) L, (d) short, (e) umlaut, (f) corset, (g) J, and (h) other.

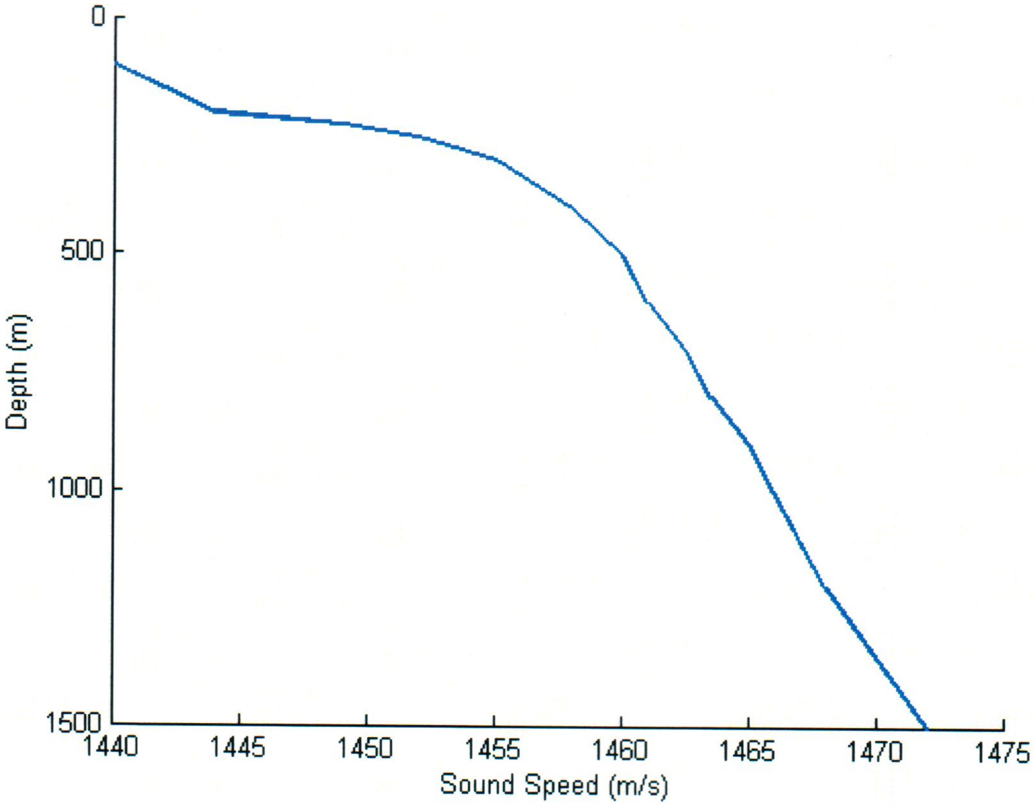


Figure 5. Histogram of sound speed values and depths reported from all the CTD data contained in the World Ocean Database (19,795 casts) at the National Oceanographic Data Center for latitudes greater than 65° N (Roth and Schmidt, 2010). Based on this data, two sound propagation models were developed for this study: Model 1 is the mean sound speed value and Model 2 is the lower limit of the sound speed profile.

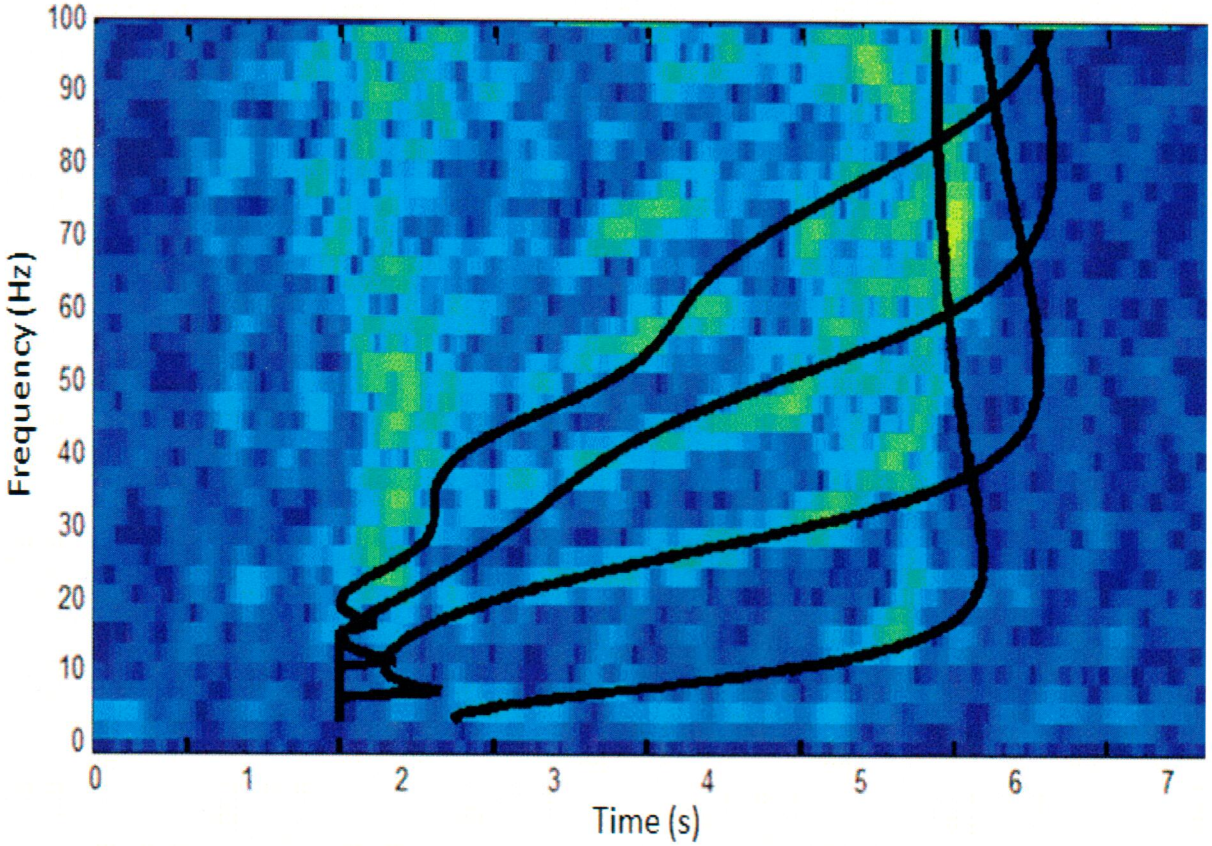


Figure 6. Modes from Model 2 overlaid on a dispersed seismic shot approximately 500 km from the HARPs. The second mode (from the bottom) was used to determine the range to the seismic source and a frequency range from 25-30 Hz was used to calculate the time difference between frequencies on the curve as they arrived at the HARPs.

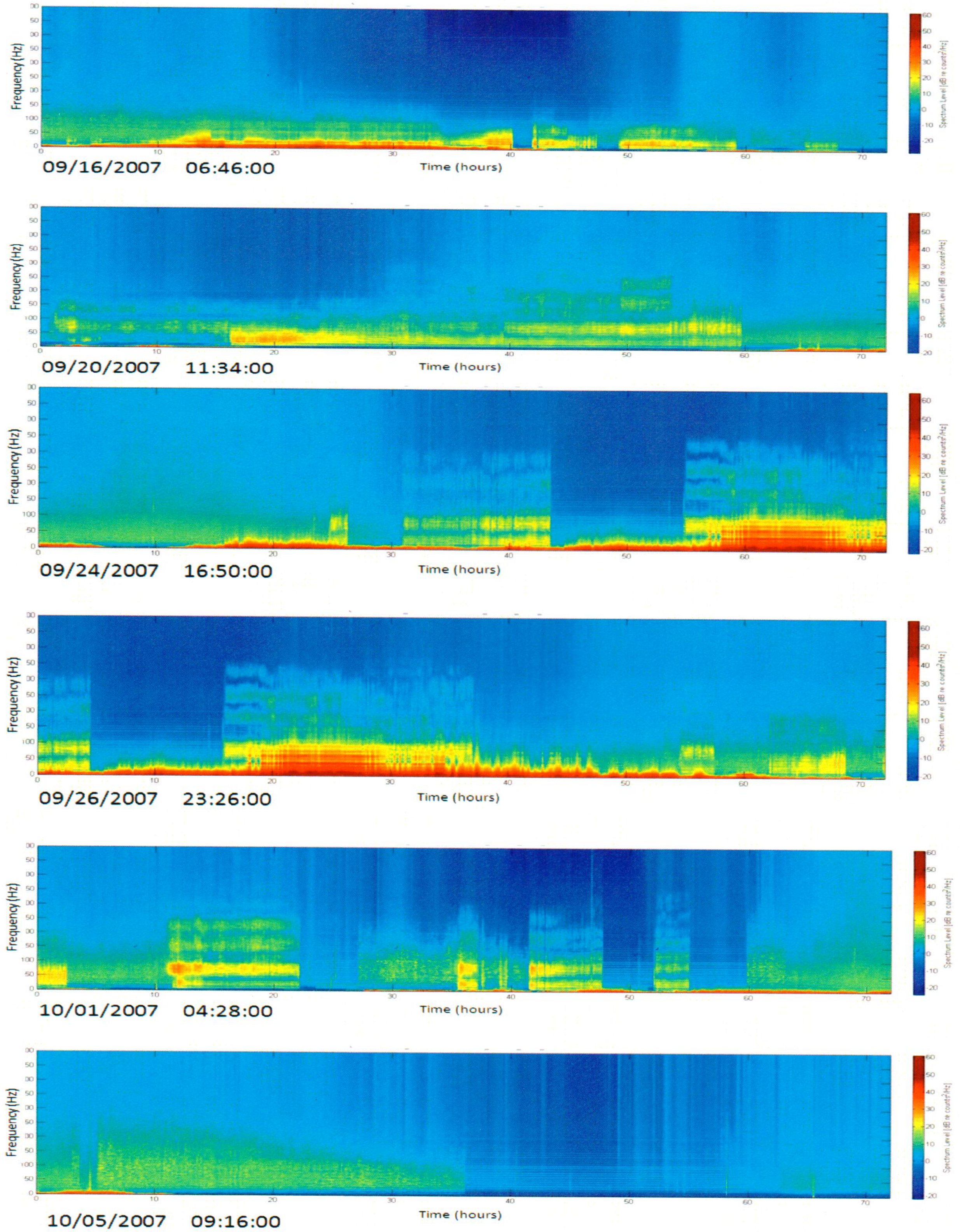


Figure 7. Long-Term Spectral Averages (LTSAs) showing increased noise levels at Site B due to the presence of seismic airgun surveys from September 16 – October 7, 2007.

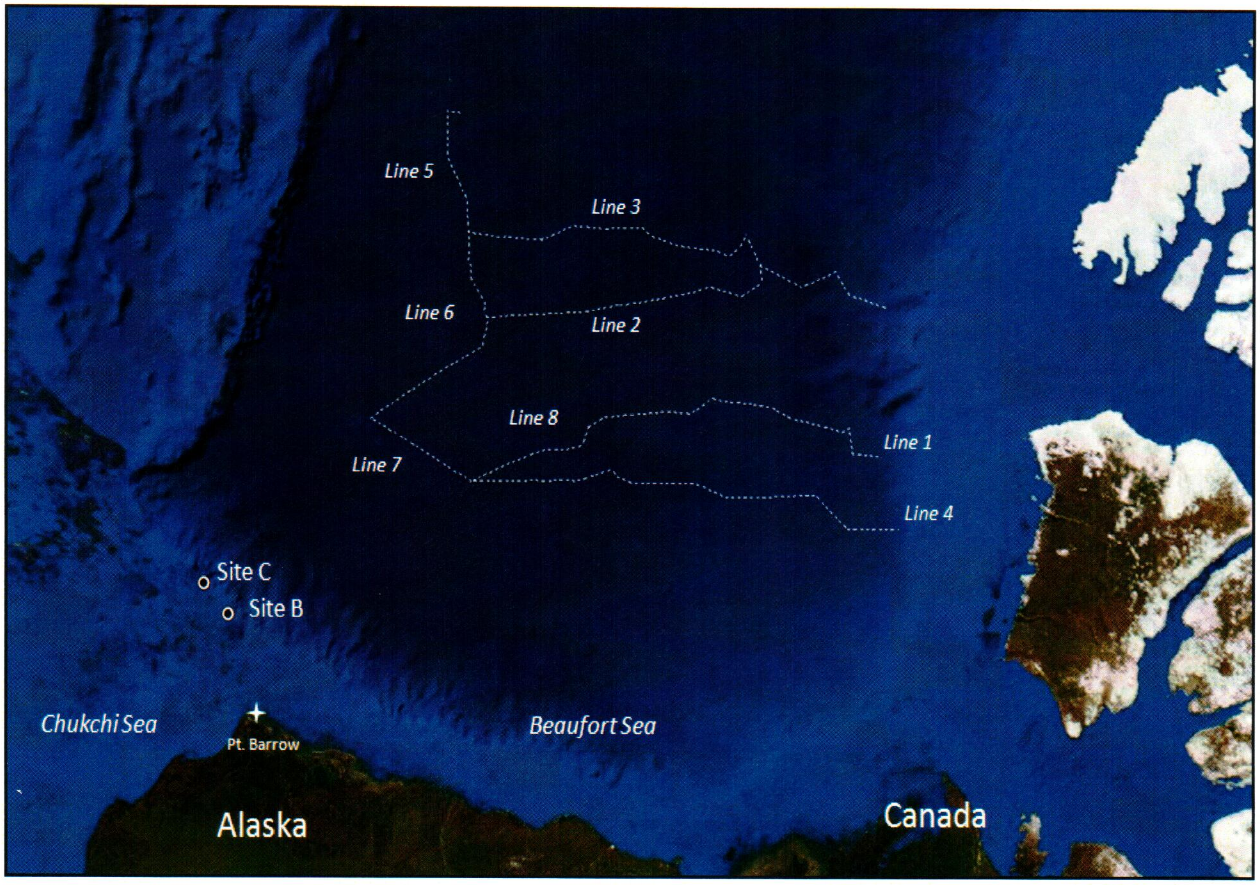


Figure 8. Regenerated track line data from the seismic watch log for the *LSSL* in the deep-water Beaufort Sea.

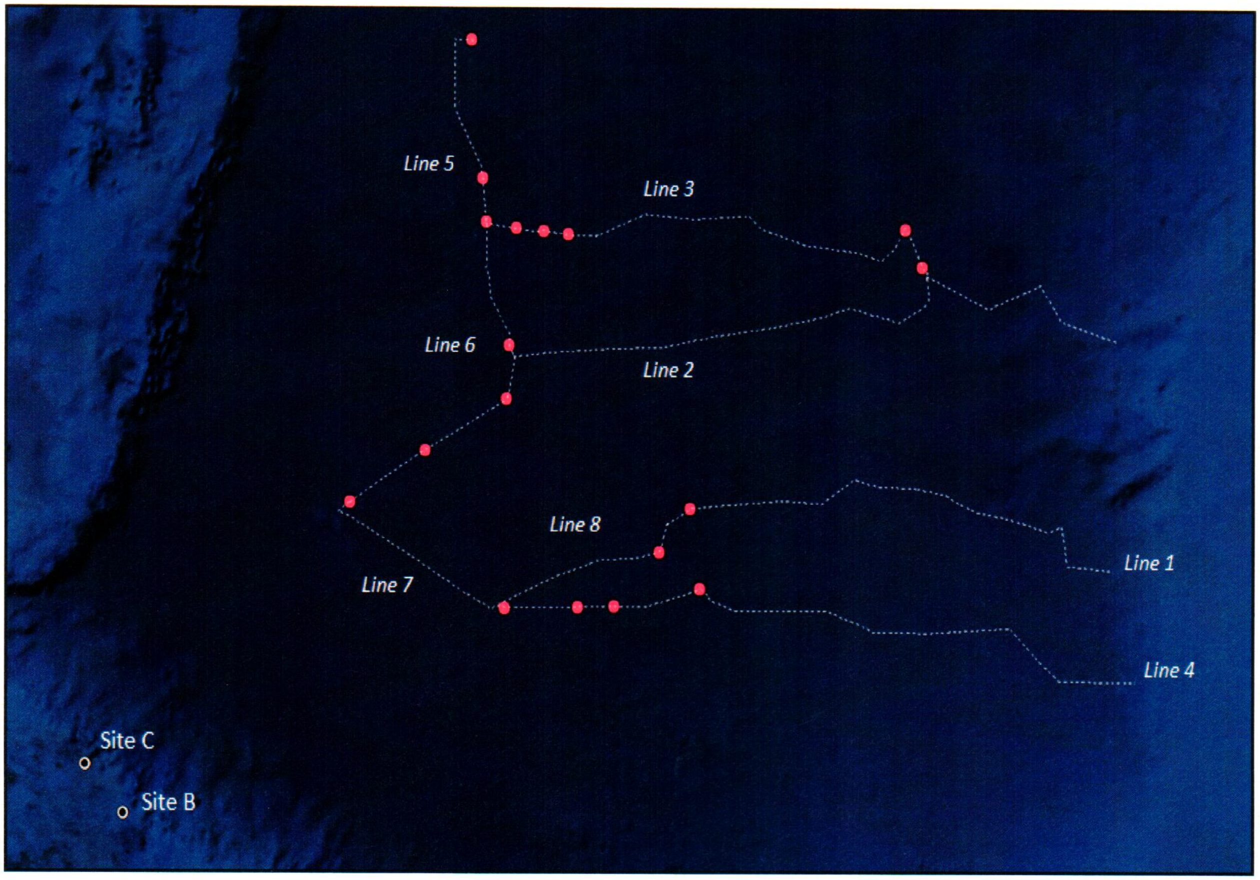


Figure 9. Positions of *LSSL* seismic activity used for comparison against the sound propagation models.

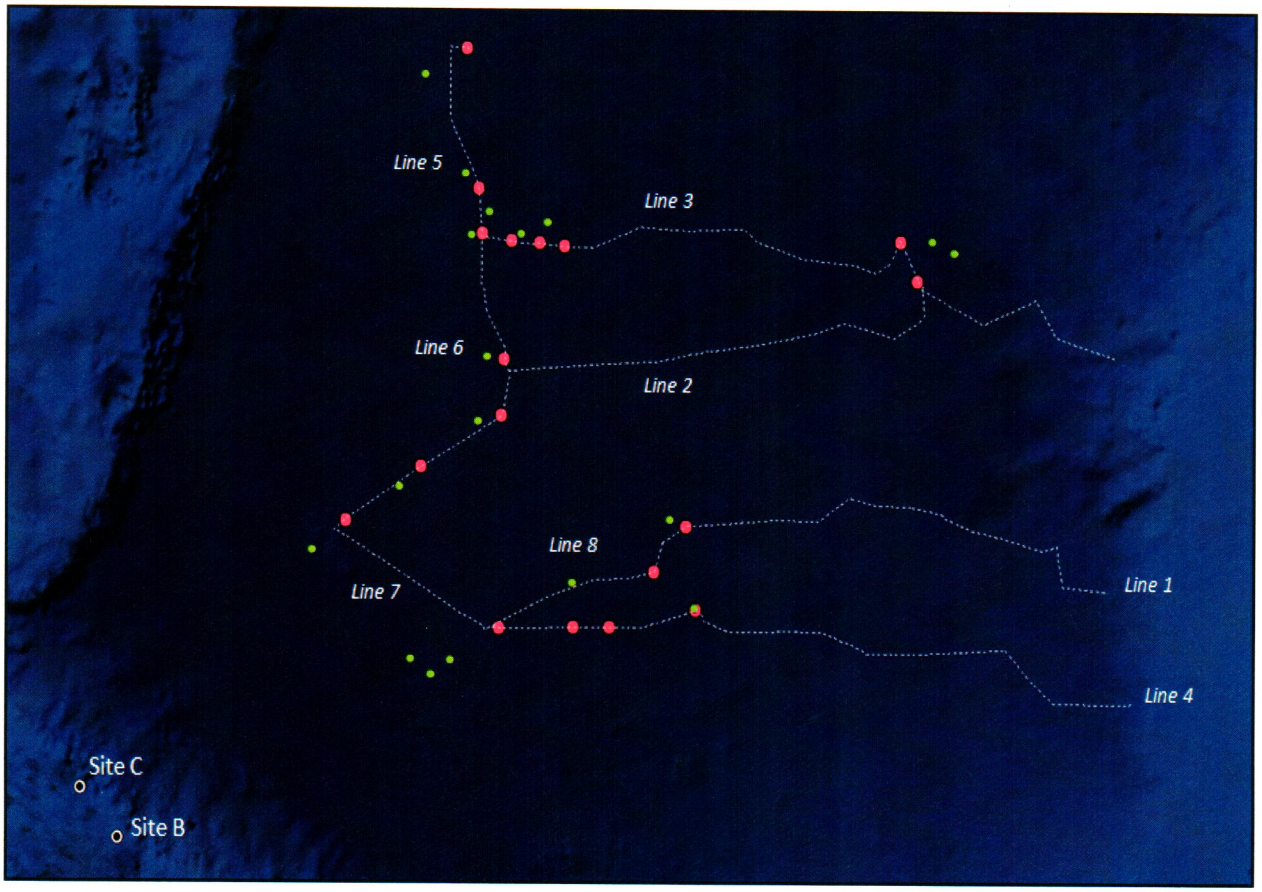


Figure 10. Comparison between positions in the *LSSL* seismic watch log and positions calculated with range estimates from Model 2.

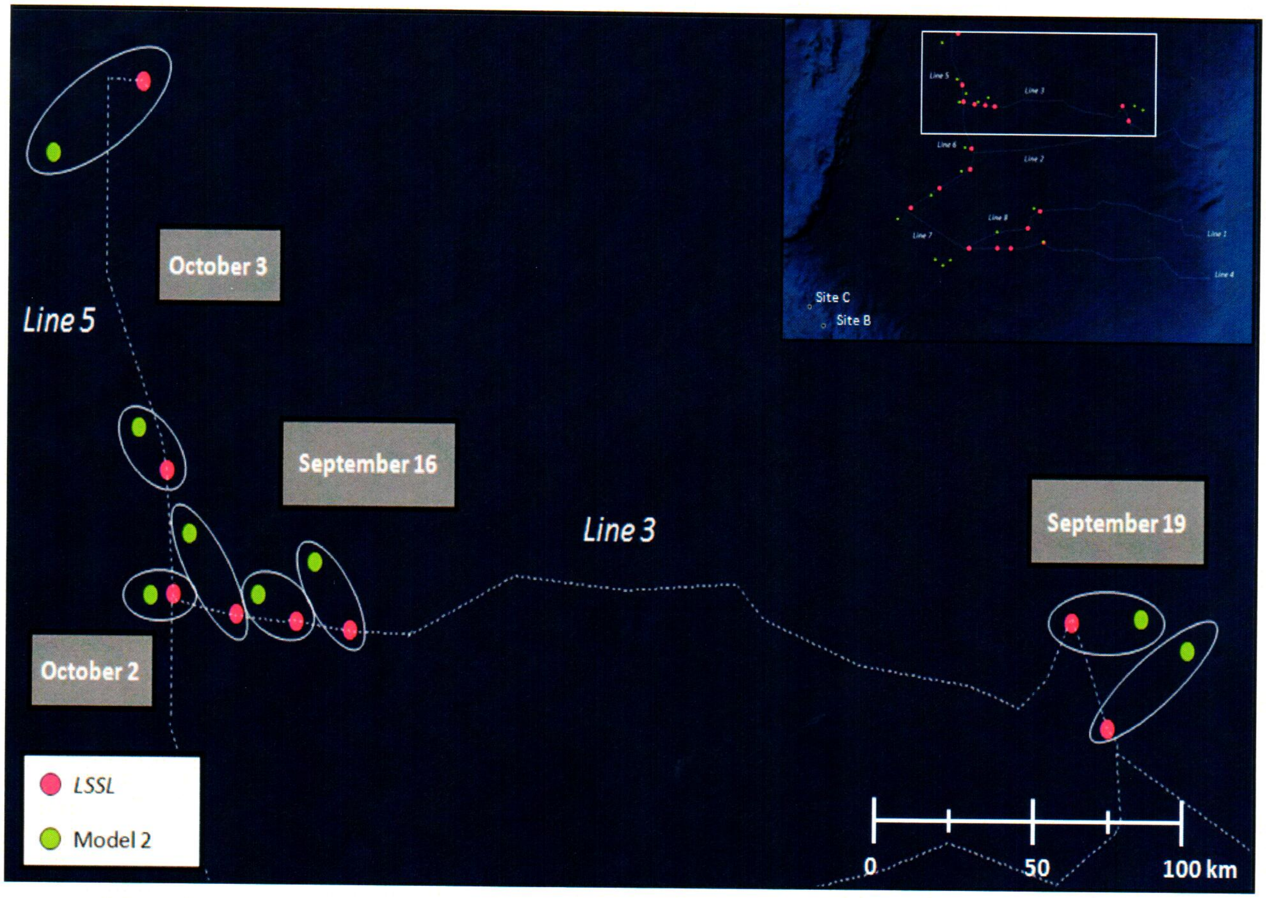


Figure 11. Close up of Lines 3 and 5. The pink circles are positions from the *LSSL* seismic watch log and the green circles are the positions calculated with range estimates from Model 2. White ovals were used to show which positions correspond in time during the survey period.

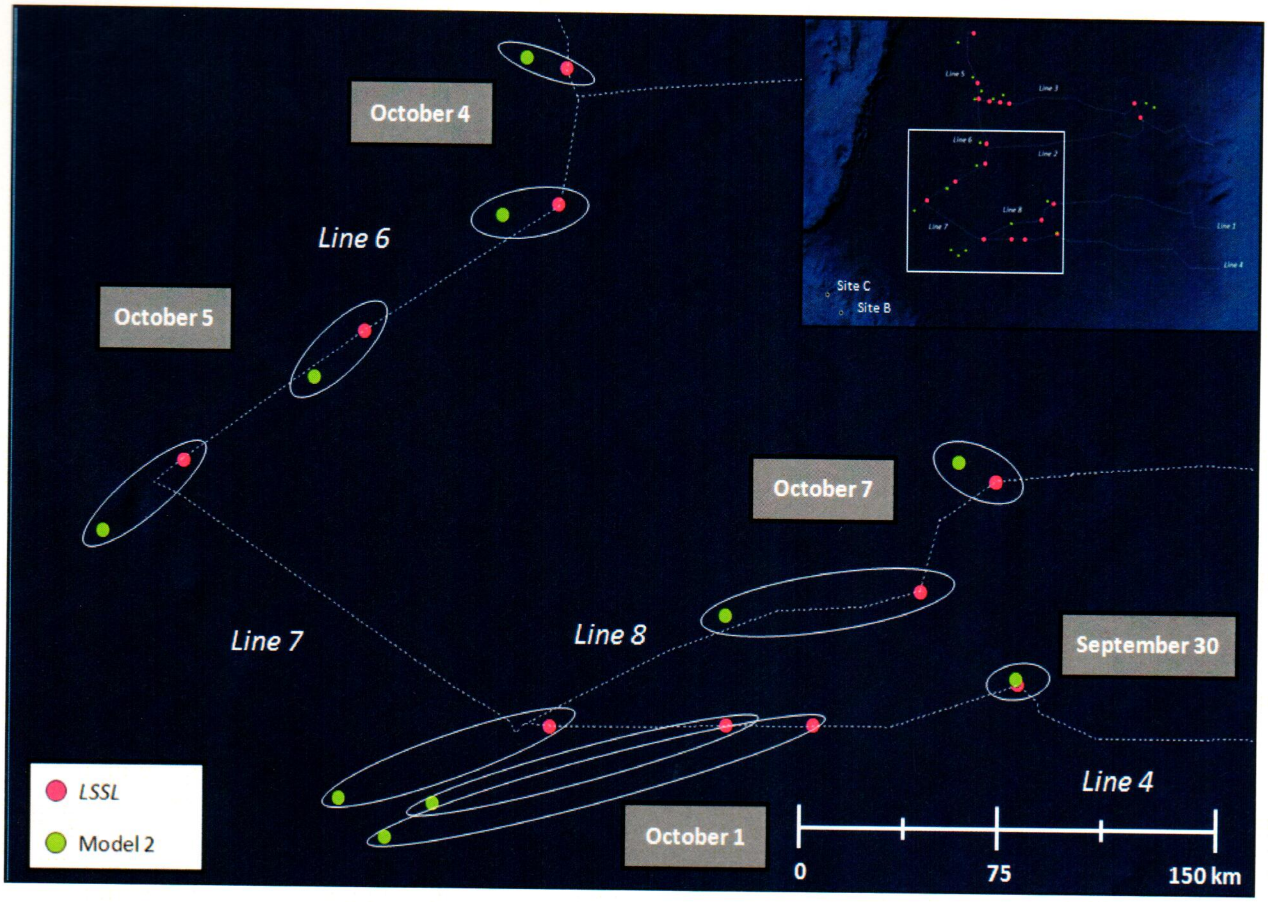


Figure 12. Close up of Lines 4, 6, 7, and 8. The pink circles are positions from the *LSSL* seismic watch log and the green circles are the positions calculated with range estimates from Model 2. White ovals were used to show which positions correspond in time during the survey period.

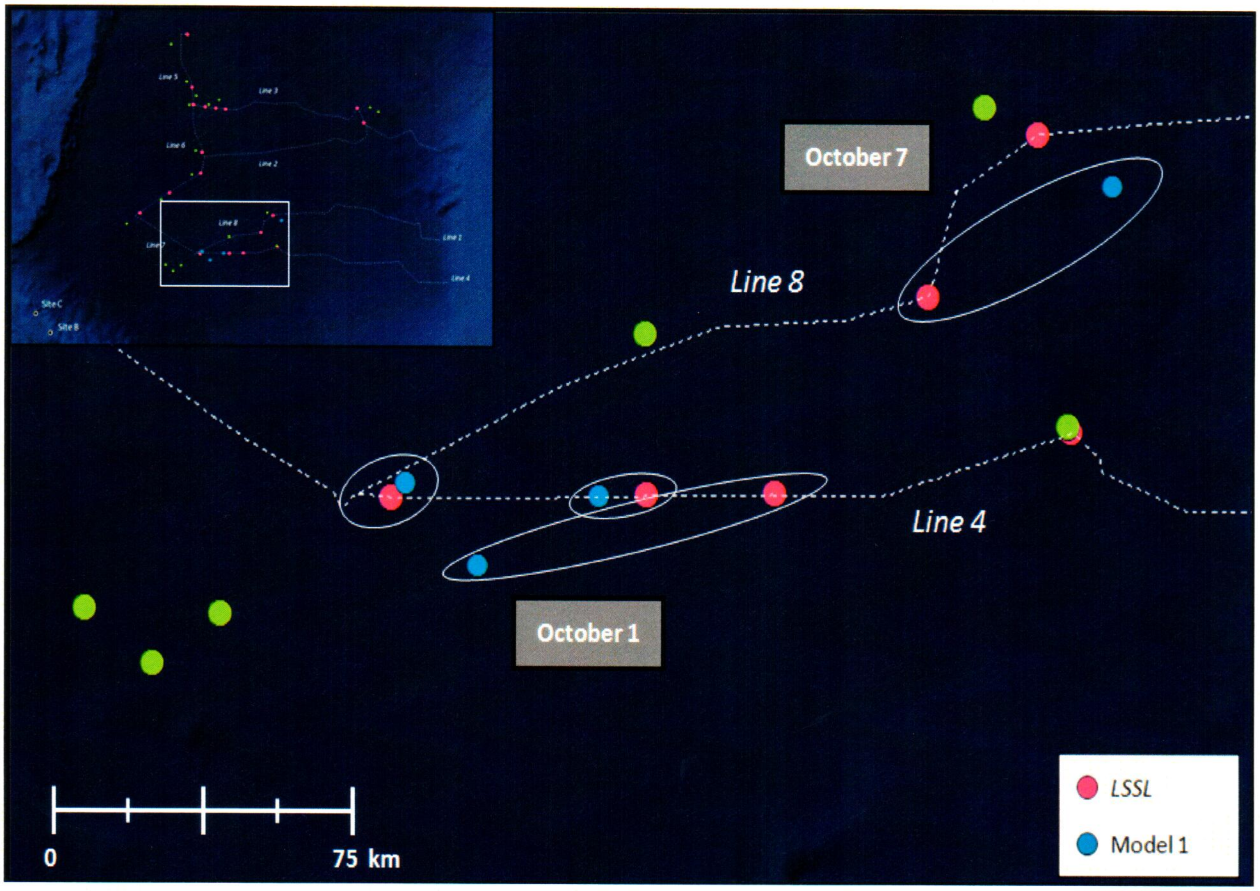


Figure 13. Close up of Line 4 and Line 8. The pink circles are positions from the *LSSL* seismic watch log and the blue circles are the positions calculated with range estimates from Model 1. White ovals were used to show which positions correspond in time during the survey period.

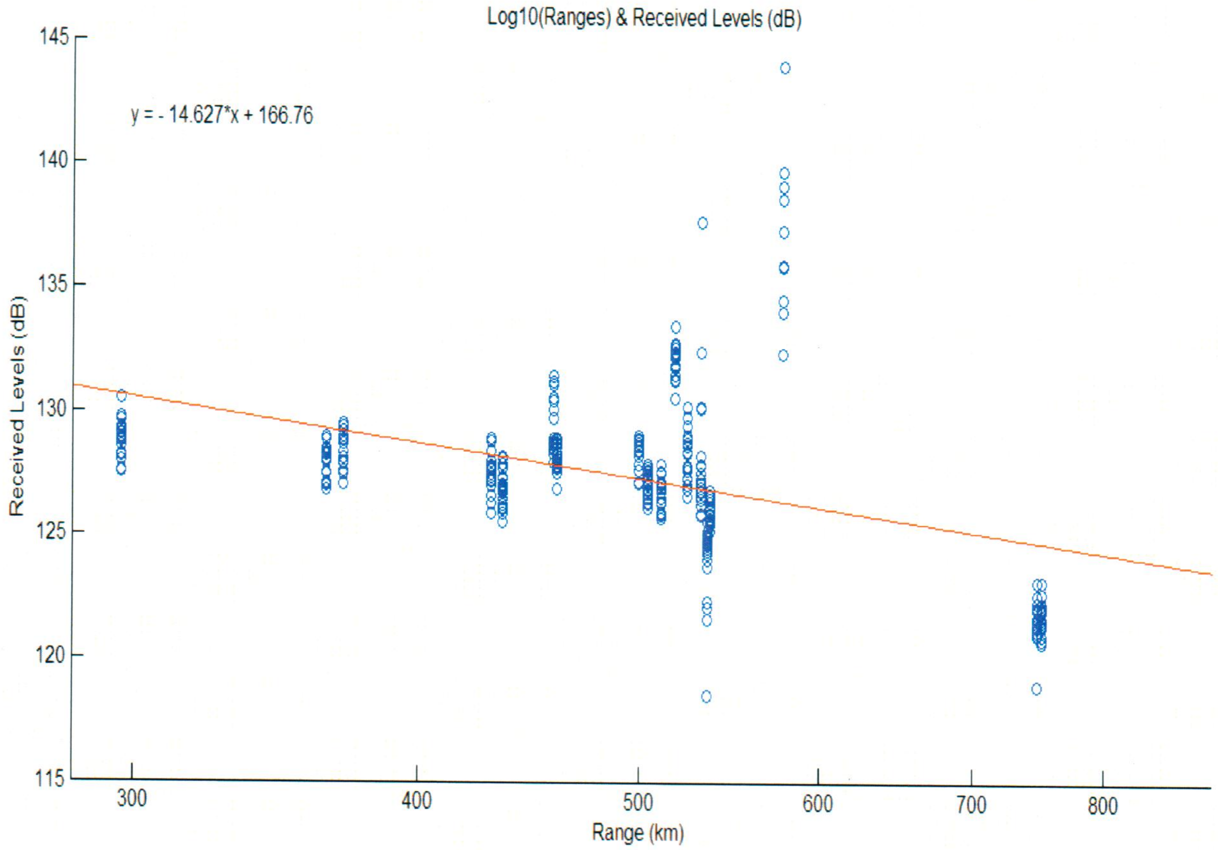


Figure 14. Received levels of sound from seismic surveys decreased with increasing range to the HARPs. Using a linear fit, transmission loss was 14.627*log(10)(range), intermediate between cylindrical and spherical spreading.

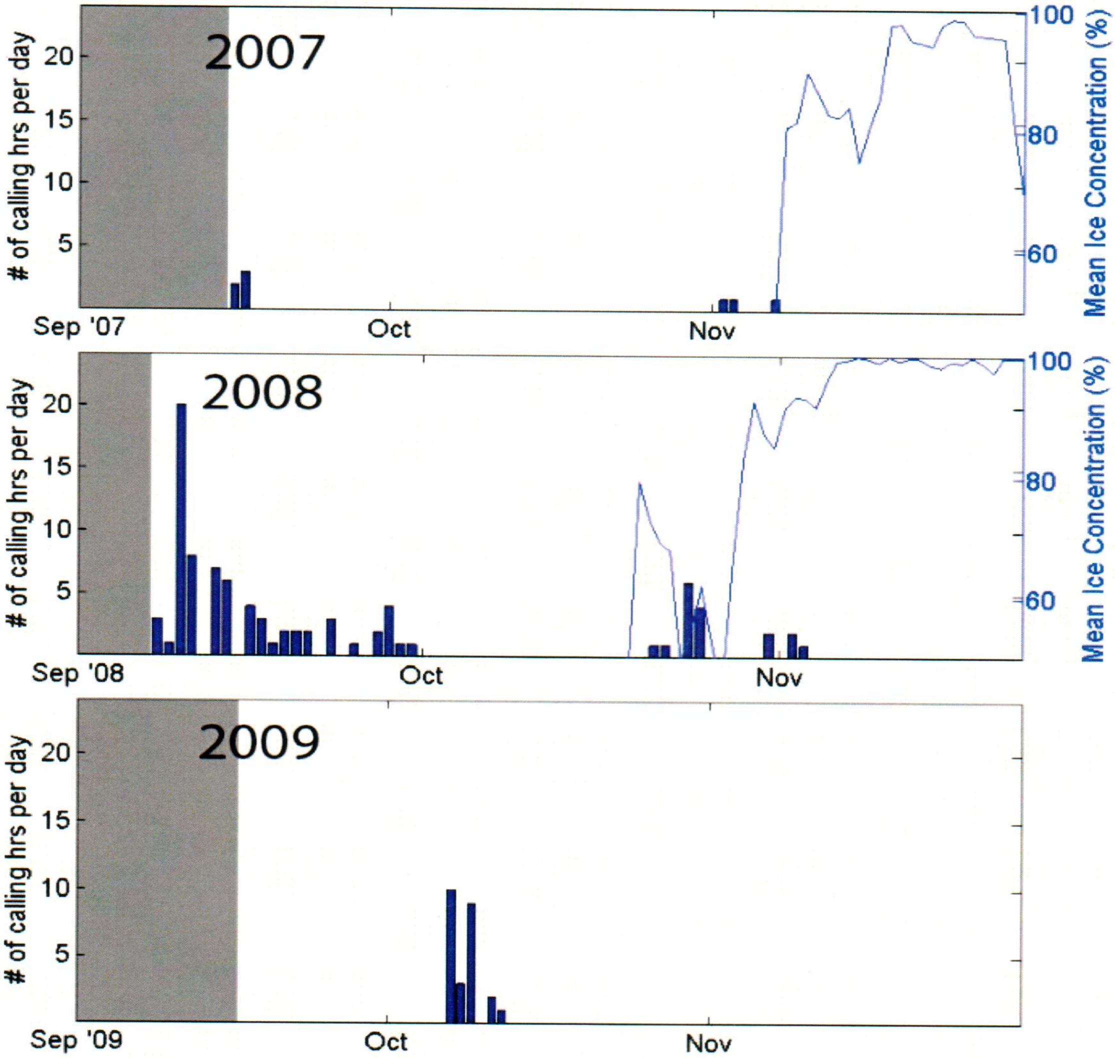
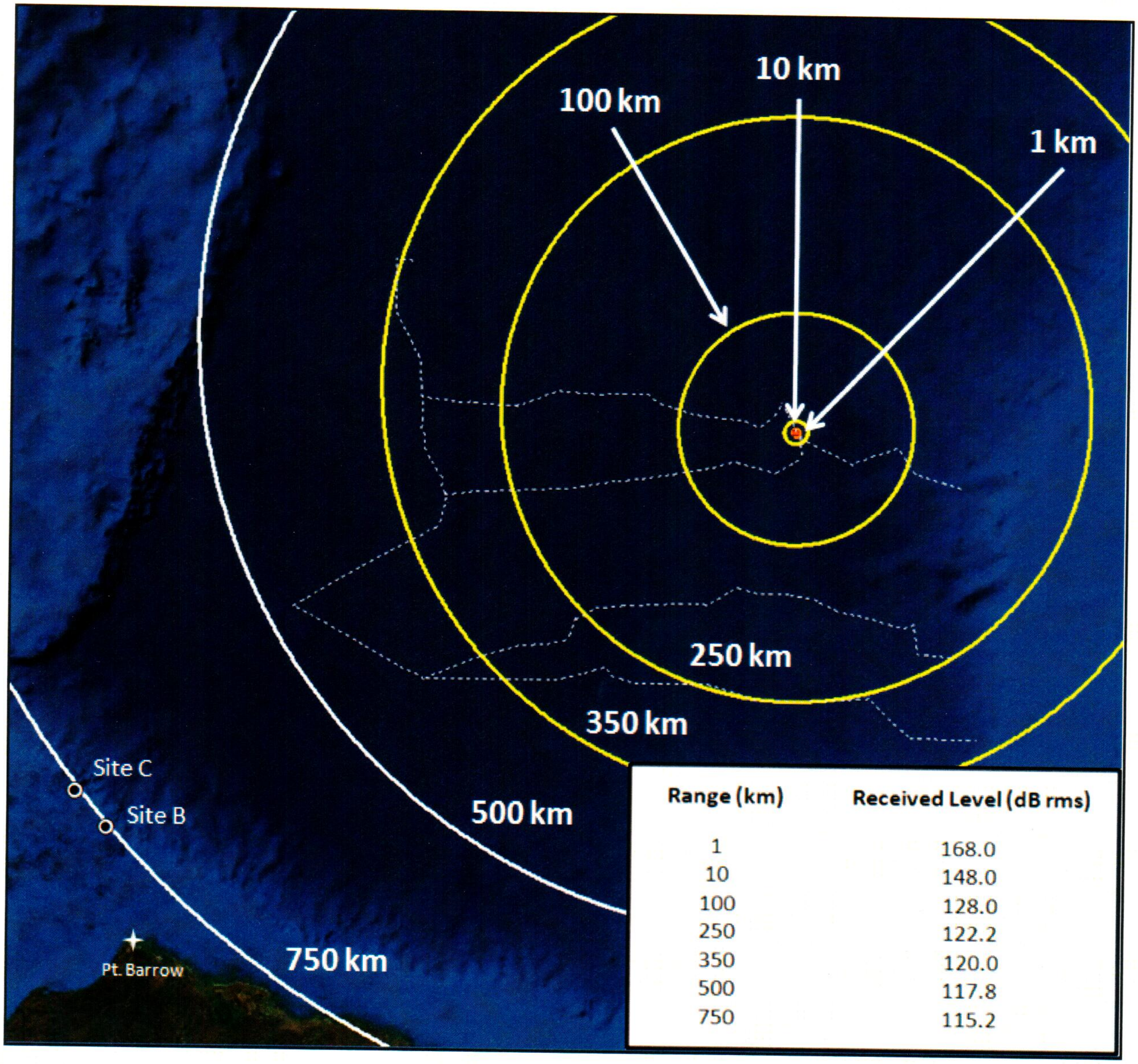


Figure 15. The number of bowhead whale calling hours per day at Site B during the 2007-2009 open-water seasons (Baldwin et al., 2012).



Range (km)	Received Level (dB rms)
1	168.0
10	148.0
100	128.0
250	122.2
350	120.0
500	117.8
750	115.2

Figure 16. Using the information in the 2007 *LSSL* field report, a source level of 228 dB rms @ 1 m was calculated (Jackson, 2008; John Shimeld, pers. com.). Received levels were then calculated based on the transmission loss of the signal as it propagates through the waveguide in the deep-water Beaufort Sea. At distances out to 350 km, received levels fall within the 120 dB monitoring zone (indicated in yellow) used in the United States to mitigate against potential behavioral disturbance to bowhead whales.

Table 1. Descriptive statistics for seismic shots from Site B and Site C.

Site B	Dispersed	Multi-banded	L	Short	Umlaut	Corset	J	Other
Mean Dur (s)	5.1	7.2	7.2	5.8	6.9	5.3	4.5	10.8
Mean Dur Stdv (s)	0.6	4.5	0.7	0.8	0.6	0.5	0.5	0.7
Mean Max Freq (Hz)	180.3	308.6	120.8	53.1	---*	---*	171.2	94.1
% Logged	49.7	23.3	7.0	6.1	5.2	2.2	5.6	0.9

Site C	Dispersed	Multi-banded	L	Short	Umlaut	Corset	J	Other
Mean Dur (s)	5.3	6.6	7.8	6.6	9.9	6.4	6.2	11.9
Mean Dur Stdv (s)	1.2	0.4	1.1	1.8	2.0	0.8	0.7	1.06
Mean Max Freq (Hz)	175.0	275.0	110.8	51.5	155.0	---*	237.9	77.6
% Logged	49.7	23.3	7.0	6.1	5.2	2.2	5.6	0.9

* Indicates features could not be logged

Table 2. Comparison between ranges from the midpoint to positions in the *LSSL* seismic watch log and estimates from Model 2. In addition, the difference between positions was included when Model 2 range estimates were combined with bearings.

Date	**Time**	***LSSL* (km)**	**Model 2 (km)**	**Difference Between Ranges (km)**	**Distance Between Positions (Range + Bearing) (km)**
9/16	8:38:00	511.2	512.5	1.3	23.6
9/16	11:26:00	524.7	518.7	6.0	14.2
9/16	14:14:00	536.9	537.5	0.6	19.1
9/19	2:54:00	747.4	768.7	21.3	23.0
9/19	23:12:00	751.1	781.2	30.1	31.8
9/30	23:34:00	532.1	531.2	0.9	1.4
10/1	10:46:00	460.1	312.5	147.6	153.7
10/1	14:30:00	430.4	325.0	105.4	105.2
10/1	21:58:00	370.9	293.7	77.2	76.9
10/2	20:22:00	499.4	493.7	5.7	7.50
10/3	0:06:00	518.0	518.7	0.7	13.2
10/3	15:02:00	577.7	550.0	27.7	31.3
10/4	17:10:00	458.4	450.0	8.4	12.8
10/4	20:54:00	435.2	418.7	16.5	17.9
10/5	4:22:00	364.7	343.7	21.0	20.7
10/5	11:50:00	296.1	262.5	33.6	33.6
10/7	3:58:00	503.9	437.5	66.4	66.8
10/7	11:26:00	535.8	525.0	10.8	13.4

Table 3. Comparisons between ranges from the midpoint to positions in the *LSSL* seismic watch log and estimates from Model 1. In addition, the difference between positions was included when Model 1 range estimates were combined with bearings.

Date	**Time**	***LSSL* (km)**	**Model 1 (km)**	**Difference Between Ranges (km)**	**Distance Between Positions (Range + Bearing) (km)**
10/1	10:46:00	460.1	400.0	60.1	72.4
10/1	14:30:00	430.4	418.7	11.6	11.6
10/1	21:58:00	370.9	375.0	4.1	4.7
10/7	3:58:00	503.9	550.0	46.1	47.8

Table 4. Using the information in the 2007 *LSSL* field report, an estimated source level of 228 dB rms @ 1 m was calculated (Jackson, 2008; John Shimeld, pers. com.). Received levels (rms and pk-pk) were then calculated based on the transmission loss of the signal as it propagates through the waveguide in the deep-water Beaufort Sea.

Range (km)	**Received Level (dB rms)**	**Received Level (dB pk-pk)**
1	168.0	177.0
10	148.0	157.0
100	128.0	137.0
250	122.2	131.2
350	120.0	129.0
500	117.8	126.8
750	115.2	124.2