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Noise levels generated by research icebreakers and marine seismic sources in the deep-water, Arctic Ocean

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Introduction

This report presents results from several *in situ* shipboard experiments designed to observe and measure acoustic sound pressure levels (SPL) generated by research icebreakers and active sound sources operated in the Arctic Ocean. Sections of this report will be divided up by the icebreaker study (**HLY-0805**) and seismic source experiment (**HLY-0905**).

HLY-0805

Seafloor mapping was the primary science mission for HLY-0805 (chief scientist: Larry Mayer) to support U.S. delineation of an ECS under provisions of the UN Convention on the Law of the Sea (UNCLOS). During the HLY-0805 cruise from August 14 to September 5, 2008, periodic acoustic monitoring of the U.S. Coast Guard Cutter Healy was conducted during ice-breaking operations. These measurements were taken opportunistically by deploying and tracking several omnidirectional sonobuoy hydrophones on a non-interference basis with the main science objective. We have conducted a thorough analysis of these recordings with the goal of determining quantitative noise measurements and examining sound pressure levels during different sea ice conditions and modes of propulsion.

The icebreaker Healy was commissioned in August 2000 and has an overall length of 420 ft (128 m), maximum beam of 82 ft (25 m), full-load draft of 29 ft 3 in (8.9 m), and full-load displacement of 16,400 LT (see Figure 1). The ship's propulsion is diesel-electric with an AC/AC cycloconverter system. The generating plant consists of four Sultzer (12Z AU40S) main diesel engines, while propulsion power is provided by two fully reversing, variable speed, Westinghouse AC Synchronous drive motors (11.2 MW). The ship's control includes two rudders and two fixed pitch, four-bladed propellers with a maximum shaft horsepower of 30,000 HP at 130 RPM. Healy also has a 2500 HP bow thruster with Alstom dynamic positioning system. Cruising speed is 12 knots at 105 RPM, maximum speed is 17 knots at 147 RPM, endurance is 16,000 NM at 12.5 knots, and fuel capacity is 1,220,915 GAL (4,621,000 liters). Icebreaking capability was designed for breaking through 4.5 ft (1.37 m) thick ice of 100 psi (690 kPa) strength at 3 knots continuous, while observed performance is 5.5 ft (1.75m) at 2.6 knots continuous. Healy has proven capable of breaking ice up 8 ft (2.44 m) thick while backing and ramming. (http://www.uscg.mil/pacarea/cgcHealy/ship.asp)

Significant measurements were made on three days, during which time a total of 7 sonobuoys were deployed during moderate-to-heavy ice breaking and while stationary (during deep sea dredging operations). Approximately 14 total hours of sonobuoy recordings were made. Recordings were also made with the ship's in-hull calibrated transducer coincident with the sonobuoy deployments. The acoustic measurements taken were best-effort measurements on a noninterference basis with the ship's primary science mission. Therefore our ability to make quantitative assessments of the ship's radiated noise will invariably be limited. Nonetheless we believe we have a unique data set that may provide valuable guidance for future work. Portions of our recordings in close proximity to the ship were clipped due to high noise levels and are not usable. For this study, we've selected data samples that most accurately reflect Healy's noise signature, and will only present Fourier analyses for unclipped time series.

All of our measurements have been post-calibrated, so estimates of the ship's radiated noise will be given in sound-pressure level referenced to 1 μ Pa RMS at 1 meter. Underice acoustic propagation is an under-studied area of acoustics with many unanswered questions, including scattering effects from ice, absorption of acoustic energy at the icewater interface and the possibility of the transmission of shear waves through ice that might re-radiate into the water column (Etter, 2003). In addition, our measurements require estimations of several key parameters needed to assess the sound pressure field. Therefore, these values are expected to have a wider range of uncertainty (ANSI/ASA S12.64-2009/ Part 1, *American National Standard, Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements*). Nevertheless, we've measured received sound pressure levels at various distances in typical ice breaking conditions, and will report our source level estimates while making comparisons with various ship operations (e.g. shaft RPM, speed over ground, relative heading, etc.)

HLY-0905

HLY-0905 was a joint collaboration between USCGC Healy and the Canadian Coast Guard Ship (CCGS) Louis S. St-Laurent (LSSL) to acquire multichannel seismic reflection and refraction data along positions that serve to establish sediment thicknesses along Canadian and U.S. Arctic continental margins. Part of the geophysics program included a seismic calibration experiment to measure the sound-pressure levels of the seismic airgun signal propagating in deep water out to a distance of 2 km. Upon rendezvous of Healy and LSSL, a two-ship operation was implemented to conduct a seismic-source sound propagation experiment. Though the sound field will be numerically modeled by the Geologic Survey of Canada (GSC) to provide a full 3D perspective of sound pressures, this model will benefit by being validated with direct field-based measurements.



Figure 1 – U.S. Coast Guard icebreaker Healy (foreground) and the Canadian Coast Guard icebreaker Louis S. St-Laurent (background). Credit – USCG photo by Petty Officer Patrick Kelley

Study Setting

HLY-0805

The icebreaker noise study was conducted in the western Arctic Ocean while mapping the seafloor on the northern Chukchi Cap (see Figure 2). Healy's hull-mounted SeaBeam 2102 12 kHz multibeam echo sounder was the primary tool, supplemented by the Knudsen 3.5 kHz sub-bottom profiler and deep sea dredging operations. The significance of exploring this poorly known region is to better understand its morphology and its potential for an extended continental shelf delineation under UNCLOS. Primary targets for mapping were the delineation of the 2500 m (about 8,250 foot) depth contour and the "foot" of the continental slope – the area where the continental margin transitions into the deep seafloor. A total of 3,114 linear nautical miles were surveyed (5767 km) on HLY0805 covering an area of approximately 34,600 km (assuming an average swath width of 6 km) – Mayer, HLY-0805 Cruise Report.



Figure 2 – HLY-0805 ship track 14 Aug –5 Sept. 2008 (dredge sites indicated by small blue icons). Most of our acoustic measurements took place north of the Chukchi Cap in deep water (from Mayer).

HLY-0905

On August 11, 2009, a seismic-source calibration experiment was carried out in open water during low sea state – west of the main ice pack – at the first rendezvous position between the LSSL and Healy (74.8° N, -156.6° W). Implementing a two-ship operation, the LSSL shot the airgun source array in 20 second intervals at known times (see Figure 3), while the sound-pressure field was measured with hydrophone receivers on the Healy, which remained relatively stationary and quiet. Two independent, calibrated hydrophones (GSC and SIO) were hung vertically in the water column from Healy while the LSSL towed the seismic source array (3 Sercel G-guns: $2 \times 500 \text{ in}^3$, $1 \times 150 \text{ in}^3$) in a walk away pattern or figure-eight geometry at a survey speed of 3 to 4 knots – as defined in the Society of Exploration Geophysicists (SEG) standard procedures (Johnston et al., 1988). The straight line transect of the figure-eight pattern was 4 km (2 km on either side of the

center). The evolution took place in an area with an average water depth of approximately 3,860 meters. This report will only present results for the SIO hydrophone and recording system.





Figure 3 – At the top, the LSSL is towing the seismic source in a figure-eight pattern around Healy. Above, you can see the bubble generated by the air expelled from the airguns as it reaches the surface. The airguns were being towed at a depth of 11.8 m (38.7 ft). To the left is the airgun sled being recovered from the water. Below the sled is the 1150 cu in. seismic source array, consisting of one 150 in³ Sercel G-gun and two 500 in³ Sercel G-guns.

Methods

1. Equipment

Sonobuoy Recording System (HLY-0805)

The Sparton AN/SSQ-57B is a Low Frequency Analysis and Recording (LOFAR) sonobuoy that provides omnidirectional passive acoustic signature data to the monitoring unit. The sonobuoy is calibrated and can be used to accurately measure ambient noise, and through post-event analysis, provides sound pressure level measurements. When deployed in seawater, a saltwater battery is activated, a CO_2 cartridge inflates a float bag with a RF transmitter inside, and a 400 ft cable with baffles drops out into the water column with a hydrophone, preamplifier, and weight attached to the tail-end (see Figure 4). The analog acoustic signal is transmitted from the RF transmitter to an omni-directional, vertical line antenna mounted atop Healy's mast, with an antenna splitter/amplifier, two ICOM R100 FM radio receivers, a Sound Blaster Audigy 2NX A/D converter, and laptop recorder set up near the bridge. After 8 hours, the sonobuoy stops transmitting and a burn resistor punctures the float bag, resulting in the unit scuttling. More often though, the sonobuoy would exceed the transmission range for decent RF reception (>5 km), since omnidirectional antennas have lower signal strength compared to directional Yagi antennas.

The data was sampled at 48 kHz and recorded using the real-time data acquisition software Ishmael (Mellinger, 2002). For a portion of HLY-0905, both channels were also simultaneously acquired by a TEAC recording system – which was provided by the LSSL science party – and had a low-pass roll off at 1.5 kHz. The LSSL science party also provided their backup Zypher GPS time clock – synchronized with the primary Zypher clock that was used to provide the seismic airgun shot-time trigger – which output a 100 ms



Figure 4 – Schematic of a Sparton AN/SSQ-57B sonobuoy in a normal 400-ft deployment configuration (Horsley, 1989).

square-wave trigger pulse recorded by the TEAC. With the shot times of the seismic source, it is possible to estimate the range of the sonobuoy by measuring the direct arrival time of the signal. This sonobuoy data from HLY-0905 will be analyzed at a later time. Figure 5 shows the sonobuoy receiver setup on the LSSL during HLY-0905.



Figure 5 – On the top left is a splitter/amplifier, below are the two sonobuoy FM receiver radios, on the top right is the TEAC recorder, and on the bottom right is the Zypher GPS time clock.

Table 1 shows the date/time and position of each sonobuoy deployment. Several field trials took place in between August 18-23 to help establish protocol before commencing with actual data collection. The majority of data recordings were made in between August 27-31 when Healy's navigation presented several opportunities for good acoustic case studies. Because sonobuoys were not designed for ice-covered waters, several deployments failed as the pack ice would tend to reconsolidate aft of Healy's stern at variable rates, and this increase in surrounding pressure is believed to have sometimes caused damage to the surface electronics or hydrophone cable, resulting in data loss. There were also instances where Healy would have to reverse direction due to ice conditions and the sonobuoy was either destroyed or experienced data loss.

Date/Time (UTC)	Latitude	Longitude
18Aug08 1123	81° 58.360	166° 03.900
18Aug08 1138	81° 58.444	165° 55.505
21Aug08 0432	83° 01.884	159° 30.853
23Aug08 0414	81° 26.717	152° 58.808
27Aug08 0455	81° 43.196	144° 27.637
27Aug08 0521	81° 44.226	144° 17.617
28Aug08 2205	82° 04.283	142° 36.016
28Aug08 2245	82° 03.868	142° 27.890
28Aug08 2349	82° 03.440	142° 29.436
29Aug08 0017	82° 03.278	142° 29.773
31Aug08 0746	81° 24.028	151° 57.127
31Aug08 0904	81° 24.164	151° 59.010
01Sep08 0226	81° 18.435	153° 51.701
03Sep08 1830	78° 31.595	156° 40.140

Drop-Hydrophone Recording System (HLY-0905)

The ITC-1042 spherical transducer offers broadband omnidirectional receiving response with high efficiency (see Figure 6). This transducer is fabricated of Channelite-5400 lead zirconate titanate ceramic and is particularly well suited for noise measurements as a broadband hydrophone and applications where an omnidirectional response is required (<u>http://www.itc-transducers.com</u>). For the purposes of this particular recording system, since clipping could be an issue at close distances to the seismic source array, no pre-amplifier was used on the hydrophone's analog side. The transducer was connected to 200 meters of shielded DSS-2 cable to reduce noise interference.



Figure 6 – Specification for the ITC-1042 spherical transducer from the manufacturer. (http://www.itc-transducers.com)

For accurate timing, an IRIG-B time code signal was digitized and the amplitudemodulated 1 kHz sine wave carrier (see Figure 7) was recorded simultaneously with the hydrophone signal on a Fostex FR-2 Field Memory Recorder (Figure 8) sampling at 22.05 kHz and a predetermined gain level. The IRIG-B pulse code contains one frame of 100 elements per second for the time of the year and GPS receiver status.



Figure 7 – Each element length is 10 milliseconds. The three types of elements are defined as a binary zero (0), binary one (1), and position marker (P). (neutrino.phys.washington.edu/~berns/superk/gps/irigcode.html)



Figure 8 – Fostex FR-2 Field Memory Recorder. (http://www.fostexinternational.com)

All components of the hydrophone and recorder ran off DC batteries in order to avoid picking up electronic noise from the ship, but still some of the data appeared to contain 60 cycle noise. Post-processing data analysis will yield absolute sound pressure levels at specified ranges (0.04-2 km) in order to understand the geometrical spreading loss of the seismic source as it attenuates in deep water.

2. Data Processing

Data Selection (HLY-0805)

We used the MatLab GUI package Triton (Wiggins, 2007) for first-level signal processing to determine which data was clipped or not of suitable quality due to poor sonobuoy RF transmission. In general, if the hydrophone was within 1 km of Healy, the data was clipped and not used. If the sonobuoy was greater than 5 km away from Healy, then it became difficult for the radio receiver to acquire good quality continuous data. As the nature of this work is to examine case studies, we selected several transient and continuous acoustic events that would be used for our analysis. Examples of different cases include open water and varying sea ice conditions, propeller cavitation, back-and-ram maneuvers, and discrete active sound sources such as Healy's multibeam echo sounder and sub-bottom profiler.

Acoustic Measurements (HLY-0805 and HLY-0905)

Fourier analysis was performed on all data using the Fast-Fourier Transform (FFT) to produce frequency-domain representations of the acoustic signals. Discrete time-series analysis requires that the input signal has non-zero values that are limited or finite in duration, which is achieved through uniform sampling of the continuous time signal. Conversion from continuous time to discrete-time samples changes the underlying Fourier transform of x(t) into a discrete-time Fourier transform, and generally includes aliasing distortion that should be avoided. The *pwelch* function in MatLab uses the *Goertzel* algorithm to calculate the power spectral density by dividing the input signal vector x into k segments with no overlap. A *Hanning* window is applied to each segment of x, and an FFT the same length as the sample rate is applied to the windowed data to obtain 1 Hz bins of spectral energy. We use one-second time windows to compute high-resolution FFTs for scatter plots, while five-second time windows produce smoother time series curves that represent averaged spectral estimates.

All spectral measurements will either be reported using 1 Hz bins, 1/3 octave, and full octave bands. This is done for comparison purposes since more detail is obtained from 1 Hz bins for the highest resolution, while the ANSI standard prefers 1/3 octave bands for simplification, and auditory perception and physiology literature recommends 1 octave bands as they relate best to mammalian hearing sensitivity (Yost, 2006). We first attain 1 Hz frequency bins by computing each FFT using data chunks at least one-second long, so that the FFT length (or NFFT) can equal the number of samples per second (or sample rate). After correcting for transmission loss to estimate source level, we convert back to units of linear pressure and sum all the pressures within each 1/3 or 1 octave band. The frequency bands are based on a starting frequency of 10 Hz. If f_n is the lower cutoff frequency and f_{n+1} is the upper cutoff frequency, the ratio of band limits is given by

$$\frac{f_{n+1}}{f_n} = 2^k$$

where k = 1 for full octave bands and k = 1/3 for one-third octave bands. An octave has a center frequency that is $\sqrt{2}$ times the lower cutoff frequency and has an upper cutoff frequency that is twice the lower cutoff frequency. When a figure refers to a specific frequency band – say the 100 Hz band for example – though this frequency lies within the band being plotted, this is not actually the center frequency but merely a metric to distinguish and compare various orders of magnitude (i.e. 10^1 , 10^2 , 10^3 , 10^4 Hz). In each case where this occurs, we will specify the bandwidth limits and true center frequency.

In correcting for transmission loss, we assume a range and frequency dependent spreading loss less than 20LogR (where R = source/receiver range). At long ranges the coefficient is adjusted to agree with empirically observed attenuation of Arctic noise transmission during the period of the experiment. This will be elaborated upon further in the discussion section.

Because the sonobuoy drifts due to ice, winds, and current, the exact relative bearing of the sonobuoy to the ship, and hence the aspect of the ship that is measured at any instant is unknown. Therefore, we do not consider azimuthal variations in the ship's radiated noise and acknowledge this as a source of error in those measurements. Directionality in shipgenerated noise has been observed at frequencies > 10kHz (Urick, 1983) with larger amplitudes to the ship's stern. This directionality is expected to be abated at lower frequencies. The limited visual observations of our sonobuoy deployments indicate that the sonobuoy likely remains abaft the beam when transiting which may lead to slightly elevated measurements from those produced in accordance to the ANSI standard (S12.64-2009) which specifies measurements within 30° of the ship's beam.

Sound pressure levels for HLY-0805 are reported as referenced to 1 µPa RMS at 1 meter, while sound pressure levels for HLY-0905 are reported as referenced to 1 µPa Peak-to-Peak (P-P) at 1 meter. We have chosen to use two different measures for pressure levels as the sound pressure of a continuous signal is normally parameterized by a RMS pressure, while the sound pressure of a transient is normally given in terms of peak pressure measures. For a sine wave, the difference between RMS and P-P is given by $10\log((2\sqrt{2})^2) \approx 9.03 dB$, but for discrete, impulsive signals the difference between

RMS and P-P can vary as much as 15 dB or more. RMS measures rely too much on the size of the averaging window for squared pressures, and therefore do not represent the true energy of a sound pulse (Madsen, 2005).

Hydrophone Calibration (HLY-0805 and HLY-0905)

Sparton provides nominal calibration curves for the sonobuoy hydrophone model used in these measurements. However, because actual calibration values may vary in manufacturing, we saved several sonobuoys from the same manufacturing batches as those used in the field and did extensive hydrophone post-calibrations at the Transducer Evaluation Center (TRANSDEC) facility in San Diego, CA (see Figure 9) on October 28-29, 2009. In addition, we also tested the exact ITC-1042 (S/N 1656) hydrophone and recorder used in the seismic-source calibration experiment.



Figure 9 – An aerial view of the U.S. Navy's Transducer Calibration Center.

Several calibration runs were performed at a depth of six meters to measure the received sensitivity of each hydrophone in response to a source transducer transmitting different frequency tones from 10 Hz - 30 kHz at a distance of 2-10 meters. For the purposes of data analysis, a transfer function or frequency response calibration is computed based on the inverse sensitivity of the transducer elements in addition to the signal-conditioning provided by the amplifiers in the hydrophone, radio, and A/D converter (see Figures 10-12). There will invariably be an uncertainty of 1-2 dB associated with the transfer function that should always be considered in our analysis. Once added to the frequency content data, spectral measurements are reported as absolute sound-pressure levels (dB) referenced to 1 µPa at 1 meter.



Figure 10 – Frequency response envelope (red) for a model AN/SSQ-57A sonobuoy corrected for an ICOM R100 radio, and the receive sensitivity of a sonobuoy calibrated at Transdec (blue). The hydrophone has a frequency-dependent gain response up to approximately 10 kHz, then goes flat.



Figure 11 – Receive sensitivity of an ITC-1042 transducer on 200 meters of DSS-2 cable, calibrated at Transdec. Adding a long cable changes the capacitance and drops the sensitivity from the originally specified -202 dB re V/µPa down to approximately -209 dB re V/µPa.



Figure 12 – Receive sensitivity calibrations for both the A/D converters used in this project. The sound card response on the left is added to the sonobuoy response, while the Fostex recorder response on the right is added to the ITC-1042 response.

Source/Receiver Range (HLY-0805)

Ranging from the ship to the sonobuoy is required to estimate acoustic propagation losses. We use ray trace refraction and reflection analysis to estimate the distance between Healy's sonar and the sonobuoy hydrophone. The time difference between arrivals resulting from direct path and first bottom reflection propagation of the ship's 12 kHz echo sounder were measured in the sonobuoy acoustic data. These direct-path/first-reflection time differences were converted to ranges from the ship to the sonobuoy through an iterative procedure in which an acoustic propagation model, incorporating the measured sound speed profile, local water depth and depth of the sonobuoy hydrophone, was adjusted in range until the observed time difference was matched. Figures 13-14 graphically illustrate the procedure.



Figure 13 – This ray path diagram estimates a launch angle for the bottom-bounce. It then adjusts the launch angle for the direct path until it intersects the bottom-bounce path at the sonobuoy depth. The distance at which this occurs becomes our range estimate at the time of the direct path arrival.



Figure 14 – The top two graphs show calculated ranges as a function of the difference in travel time between the direct path and first bottom-bounce arrivals, and based on the average local water depth for Aug. 27 (left) and Aug. 28-29 (right). Using the fitted quadratic equations, the bottom two graphs show estimated ranges for the sonobuoys deployed on Aug. 27 (left) during transit and on Aug. 28-29 (right) during backing and ramming, hence the difference in variation between the two cases.

Source/Receiver Range (HLY-0905)

The evolution took place in an area with an average water depth of approximately 3860 meters. The hydrophone was lowered over the starboard side of Healy to a depth of approximately 150 meters so it would be below any interference from the hull of the vessel, but well above the bottom so as not to record multipath propagation arrivals mixed in with the direct signal arrival. Precise absolute position information of the hydrophone wire placement and source array were measured relative to the ship position GPS and heading (see Figure 15). The hydrophone wire was located 61.3 meters aft of the Master Reference Point (MRP) for the POS/MV GPS antenna, and 12.1 meters starboard of the ship's centerline. Though the tail-end of the hydrophone was weighed down, there will undoubtedly be some uncertainty associated with the exact location of the hydrophone due to the vessel's drift and subsurface currents. The position of the center of the source array on the LSSL was 89 meters astern of the vessel's GPS antenna position, and 11.8 meters deep.



Figure 15 – This schematic of Healy shows the location of the hydrophone deployment relative to the Master Reference Point (MRP).

Figure 16 shows the relative geographic tracks for both Healy and the LSSL based on the GPS coordinate positions of both ships. The LSSL ran the Figure-8 pattern around Healy as it drifted 1266 m northeast throughout the experiment. We can see on three different occasions the two ships came very close to each other, with a closest point of approach (CPA) of 50 meters.

Using the same GPS data, we can subtract the two relative positions to calculate the distance of separation – or range – between the seismic source array and hydrophone. Figure 17 shows the range versus time for the duration of the experiment. For our analysis, we will only consider the airgun shots within 2 km of the hydrophone. We will compare received sound pressure levels over these ranges – corrected with source/receiver location offsets – to see how the source signal attenuates as it spreads geometrically.



Figure 16 – Relative positions of the seismic source (blue) and hydrophone (red) show the walk-away (figure-eight) geometry by the LSSL. Healy was drifting northeast throughout the experiment.



Figure 17 – Range calculated between the seismic source and hydrophone during the experiment.

Ancillary Data (HLY-0805)

Incorporating various factors such as sea ice conditions, water depth, sound speed, and the radiation pattern around the vessel, can help to better understand the characteristics of active sound source propagation in the Arctic Ocean. Healy is equipped with a ship-wide computerized data logging system that records and stores data from the navigation, oceanographic, engineering, and communications systems. The Science Data Network dates and time-stamps all data collected. We found several of these ancillary measurements to be useful for our analysis, namely the items listed in Table 2.

Table 2
Navigation [LAT, LON, HDG, VTG, SOG] (1Hz)
XBT Casts (~2/day)
Wind Speed and Direction (1Hz)
Aloft Conn Camera (still images once per 5 min)
Keel Temperature and Salinity (1Hz)
Mean PORT and STBD Shaft RPM* (~ 1/20 Hz)

* Not part of the ship's normal data collection.

The engineering data provides the time along with corresponding port and starboard shaft speeds averaged from the cycloconverter readings and converted from percentages to pure shaft RPMs.

Results

Icebreaker Source-Level Noise Experiment (HLY-0805)

Ambient Noise

Arctic Ocean ambient noise is unique from most other ocean environments in that the spatial and temporal variability of the probability density function relates directly to sea ice, and in many cases wind. In previous work, autonomous acoustic recorders have been overwintered in the nearby Chukchi Cap region to collect ambient noise data (Roth, 2008). All acoustic events, transient signals, and electronic noise are removed from spectral averages and corrected for received sound pressure levels re 1 µPa (see Figure 18). In summer and early fall, broadband sources like storm-generated winds and surface waves couple with the underwater noise environment, but throughout winter, pack ice dynamics continually influence the relationship between ambient noise and the environment. At 10 Hz, all the spectra converge at 85 dB re µPa. Across the entire lowfrequency band, September is naturally the noisiest month – due to open water conditions - reaching peak noise-levels of 87 dB re μ Pa between 20 and 60 Hz. All other months that were recorded exhibit low spectrum levels, as sound pressure levels decrease about 8 dB/octave. This slope is partly attributed to sea ice coverage in the area around the hydrophone sites. Heavy pack and shore-fast ice act like a rigid boundary for sounds propagating horizontally across the waveguide, except that the underside of sea ice is rough and dispersed with ridges and keels. As frequency increases so does scattering strength and thus transmission loss; plane waves that reflect off ice tend to attenuate rapidly and transmit over shorter distances. All sonobuoy records are contaminated by ship noise and therefore cannot be presented as true ambient noise.



Figure 18 – Low-frequency ambient noise levels in the Chukchi Sea averaged by month (Roth, 2008).

Transient Signals

Besides continuous underwater noise emissions due to Healy prop cavitation, there are several discrete noise sources that contribute to the overall sound pressure field, and should be mentioned if we are to characterize the entire frequency spectrum of icebreaker noise. During most Healy cruises, the 12 kHz (ping) multibeam sonar and 3.5 kHz (chirp) sub-bottom profiler are always running. The chirp is delayed about 0.5 seconds after the multibeam ping, and their transmission rate is depth-dependent. Figure 19 represents a standard sequence of direct path arrivals to a sonobuoy hydrophone. Figure 20 shows a one-minute record of the active sources, which are easily detectable in the beginning when Healy is stopped, but then become masked as the ship speeds up again and the propellers become the dominating noise source.



Figure 19 – Spectrogram (top) and time series (bottom) show the 12 kHz SeaBeam multibeam sonar and 3.5 kHz Knudsen sub-bottom profiler. The mid-frequency SeaBeam echo sounder produces a ping while the Knudsen generates a chirp (or frequency swept) signal.



Figure 20 – Spectrogram shows a one-minute acoustic record of Healy slowing down to a complete stop and then proceeding to speed up again during backing and ramming maneuvers in heavy ice conditions.

Hydrodynamic cavitation results from the dynamic effects of liquid flows. Cavitation of marine propellers is the most prevalent source of underwater sound in the oceans (Ross, 1976). Whenever water flows past the propeller, the fluid must speed up near the propeller blade tip. By Bernoulli's principle, there is a reduction of static pressure below the ambient value, the magnitude of the drop being proportional to the dynamic pressure of the flow velocity and dependent on the shape of the blade tip. If the pressure drop is sufficiently large, then cavitation may occur in which dissolved gases are momentarily released resulting in small bubbles which subsequently collapse as hydrostatic pressure is restored.

Depending on the operating cavitation parameter, each propeller blade would be free of cavitation at all times except for the very short period when the angles of attack are equivalent to operation at values considerably less than the propeller's nominal advance ratio. The resultant burst of cavitation noise would be very short-lived, sounding like a high-pitched click. Since one blade invariably cavitates sooner than the others, the bursts would first occur once per revolution. As the other blades join, the bursts would become more frequent, finally occurring at *blade rate* – the number of blades times rotational frequency. Figure 21 presents sonobuoy data of Healy to illustrate this concept. In the middle of the record there are about 6-7 bursts per second, and knowing Healy's fixed-pitch propellers have 4 blades each, this implies a blade rate of 1.5-1.75 revolutions per second or 90-105 RPM. The engineering logs show that Healy's starboard shaft speed was 85 RPM and port shaft speed was 93 RPM. It is possible we are combining bursts from the two different propellers or seeing certain blades that are cavitating more than others.



Figure 21 –Spectrogram shows propeller noise which is indicative of the blade rate.

If the speed increases and the *cavitation index* (i.e. dimensionless resistance of the flow to cavitation) lowers further, the point would be reached where cavitation noise would be continuous, since at least one blade would be cavitating at all times. The frequency spectrum would still be strongly modulated at blade-rate frequency. Since one blade invariably cavitates more than the others, there is also a superimposed shaft-rate modulation which can be detected by the human ear (Ross, 1976).

There is one other noticeable transient sound source that was found repeatedly throughout the data, and shown below in Figure 22. It occurred consistently in every situation where

Healy was backing and ramming, exactly at the instance after the propeller shafts stopped rotating in one direction and before they started rotating again in the other direction. The typical presumption would be that this noise is related to hydraulics in the propellers, but we know this not to be the case since Healy does not have controllable pitch propellers. Because Healy has AC/AC propulsion, the cycloconverter controls the speed of the propulsion motors by varying the frequency of the power provided to the motors. We suspect that the acoustic signal shown below is in someway related to the cycloconverter reinitializing power to the AC synchronous motors in order to drive the propeller shafts in the desired direction.



Figure 22 – Spectrogram (top) and time series (bottom) show that in between backing and ramming maneuvers – when the vessel is completely stopped – this signal is detected. We suspect these sounds are related to the cycloconverter and drive motors.

Case Studies

In this section we will take a closer look at four different cases to help make distinctions about noise levels during different modes of propulsion. The first case examines Healy during transit from variable ice cover to an open-water polynya. The second and third cases examine Healy during repeated backing and ramming maneuvers in heavy ice cover. The last case examines Healy while keeping station using its bow thruster in heavy ice cover. In each case, we present information pertaining to the ship's position, heading, speed over ground, and propeller shaft speed, as well as environmental information with regard to the local sea ice coverage. Spectral sound pressure levels will be reported for each case in a relevant manner such as source level time series or broadband spectra.

Case 1

A sonobuoy recording was analyzed during approximately 40 minutes of good signal reception on **August 27th**. During this time the ship transited from near 10/10's sea ice cover to an open water polynya. Figure 23 shows the ship's track relative to the sonobuoy deployment, and illustrates the ice coverage with photos taken from the Aloft-Conn camera. The black circle represents the radial range estimate to the sonobuoy at the time corresponding to the ship's position and heading. From our observations, it appears a sonobuoy is capable of drifting over one knot, depending on surface currents, wind, and pack ice dynamics. Figure 24 shows the ship's speed over ground (SOG), as well as both the port and starboard propeller shaft rotational speeds. The transition from ice-breaking to open water is clearly evident at approximately 05:37 when shaft RPMs drop and SOG increases as the resistance to movement abates in open water.



Figure 23 – The top figure shows Healy's relative ship track to the sonobuoy deployment (magenta circle) and current range estimate (black circle) during transit in variable ice cover on August 27, 2008. The still images are taken every 5 minutes (time in upper left corner) from the aloft conn and represent a visual estimate of the local sea ice coverage (x/10 in upper right corner).



Figure 24 – Vessel speed over ground (SOG) and propeller shaft rotational speed during the sonobuoy deployment.

Figure 25 provides a time series – over the course of the sonobuoy recording – of source level estimates, centered around 55.6 Hz (49-62 Hz band) for 1/3 octave bands and 56.6 Hz (40-80 Hz band) for full octave bands. Each FFT is computed over a 5-second time window. Constructive interference from multipath propagation can result in up to 6 dB of variation – or a doubling of amplitude – in our spectral energy estimates (see Appendix A). Recalling that the transition from ice-breaking to open water occurs at approximately 05:37, we can see a small decrease in mean noise levels within this frequency band. Moreover, large amplitude peaks such as those occurring at 05:22 and 05:24 are reduced when the ship is operating in open water and does not have the resistance of sea ice to contend with. This correlation of high amplitude peaks in substantial ice cover becomes more apparent in noise samples from later recordings, especially during backing and ramming maneuvers.



Figure 25 – Source level estimations (re @1m) centered around 55.6 Hz (49-62 Hz band) for 1/3 octave bands and 56.6 Hz (40-80 Hz band) for full octave bands.

As this is a good case to observe Healy continuously transiting through variable ice-cover and transitioning into open water, we selected two representative 5-second sample windows to compute the power spectral density (PSD). Figures 26-27 show source level PSDs while Healy is breaking through nearly 9/10's ice cover and while in open water, respectively. In ice-covered waters, the SOG was between 4-6 knots and both propeller shafts varied between 80-110 RPM, while in open water the SOG was nearly 8 knots and both propeller shafts varied between 70-80 RPM. At 10 Hz, the source spectra both exhibit the same sound pressure levels. Above 20 Hz, the slopes differ substantially up to 10 kHz, and there is an approximate 10 dB difference on average between the two source spectra. In Figure 25, the full octave band remains more or less flat at 190 dB up until approximately 300 Hz, while in Figure 26 the full octave band is never flat but instead slopes steadily downwards across the frequency band until 2 kHz. Notice in both figures the elevated spectral levels between 3-5 kHz due to the sub-bottom profiler (chirp), and the narrowband peak at 12 kHz due to the multibeam echo sounder (ping).



Figure 26 – Representative source spectra during Healy transiting in > 5/10's ice cover. Range to sonobuoy at this time was approximately 2 km.



Figure 27 – Representative source spectra during Healy transiting in < 5/10's ice cover. Range to sonobuoy at this time was approximately 4 km.

Case 2

On August 28th a sonobuoy recording was made for several hours during multiple backing and ramming maneuvers. In this case study, we analyzed the first 25 minutes of the recording. During this time the ship was in consistent 8/10's ice cover (see Figure 28), backing and ramming in slow progression. The ship's track relative to the sonobuoy deployment is illustrated in Figure 28, while the SOG and both the port and starboard propeller shaft speeds are shown in Figure 29.



Figure 28 – The top figure shows Healy's relative ship track to the sonobuoy deployment (magenta circle) and current range estimate (black circle) during backing and ramming in 8/10's ice cover on August 28, 2008. The still images are taken every 5 minutes (time in upper left corner) from the aloft conn and represent a visual estimate of the local sea ice coverage (x/10 in upper right corner).

In Figure 29, one can see that the port and starboard screws are not operated simultaneously in the same direction, as the ship attempts to change heading in the ice. The non-synchronous operation of the two screws complicates any attempt to correlate RPMs with sound levels during this recording.

Also apparent are the backing and ramming maneuvers made by Healy while breaking heavy ice. Positive (i.e. forward) RPM movement and subsequent increases in SOG up to 6-7 knots characterize ramming. Negative (i.e. sternward) RPM movement and subsequent increases in SOG only up to 3 knots characterize backing. In other words, the ship reaches 6-7 knots before forward progress is stopped by the ice pack. Reversing the direction of the screws, the ship backs up, reaching speeds around 3 knots before making forward progress again. This alteration in SOG indicates that the ship is breaking heavy ice while making little forward progress into the hole created by the previous ram.



Figure 29 – Vessel speed over ground (SOG) and propeller shaft rotational speed during the sonobuoy deployment.

The modulation in SOG over the course of the sonobuoy recording is reflected in several SPL time series shown in Figure 30, and for this case study we examined frequency bands at various orders of magnitude – i.e. centered near 10^1 , 10^2 , 10^3 , and 10^4 Hz – to see whether variation in the distribution of sound pressure levels is frequency dependent. The actual center frequencies and corresponding bandwidths for 1/3 and full octave bands are given in Figure 30. Each FFT is computed over a 5-second time window.

In general, for the spectral time series centered near 10, 50, and 100 Hz, we measured source levels quickly increase 10 dB higher in several instances, correlating with negative RPMs of one or both of the ship's propeller shafts. The effect is seen to a lesser extent in frequency bands centered near 1 and 10 kHz. The maximum source level for all frequency bands during this recording reached about 195 dB.



Figure 30 – From the top left down, then to the right side and down, these are source level estimations (re @1m) centered around 11.3 Hz (10-13 Hz band), 55.6 Hz (49-62 Hz band), 111.2 Hz (98-123 Hz band), 1.12 kHz (0.985-1.24 kHz band), and 11.27 kHz (9.93-12.51 kHz band) for 1/3 octave bands, respectively. Spectral estimates for full octave bands are centered around 14.1 Hz (10-20 Hz band), 56.6 Hz (40-80 Hz band), 113.1 Hz (80-160 Hz band), 0.905 kHz (0.640-1.28 kHz band), and 7.24 kHz (5.12-10.24 kHz band), respectively.

Case 3

The same sonobuoy deployment from August 28th was also used for the **August 28-29th** case-study. Again, this recording was made during several hours of Healy making backing and ramming maneuvers in heavy ice cover. We analyzed 35 minutes in the middle of the recording, during which time the ship was in 9/10's ice cover (see Figure 31), backing and ramming in slow progression. The ship's track relative to the sonobuoy deployment is illustrated in Figure 31, while the SOG and both the port and starboard propeller shaft speeds are shown in Figure 32.



Figure 31 – The top figure shows Healy's relative ship track to the sonobuoy deployment (magenta circle) and current range estimate (black circle) during backing and ramming in 9/10's ice cover on August 28-29, 2008. The still images are taken every 5 minutes (time in upper left corner) from the aloft conn and represent a visual estimate of the local sea ice coverage (x/10 in upper right corner).

The modulation in SOG over the course of the sonobuoy recording is reflected in several SPL time series shown in Figure 33, and for this case study we examined frequency bands at various orders of magnitude – i.e. centered near 10^1 , 10^2 , and 10^3 Hz – to see whether variation in the distribution of sound pressure levels is frequency dependent. The actual center frequencies and corresponding bandwidths for 1/3 and full octave bands are given in Figure 33. Each FFT is computed over a 5-second time window.



Figure 32 – Vessel speed over ground (SOG) and propeller shaft rotational speed during the sonobuoy deployment. The gray section is where intermittent acoustic data loss occurred.

In general, for the spectral time series centered near 50, 100, and 1000 Hz we measured source levels quickly increase 10-15 dB higher in several instances, again correlating with rapid deceleration of the ship from forward movements reaching higher speeds and sternward operation of the screws. In this case, the same effect is seen to a similar extent with the higher frequency band centered near 1 kHz. The maximum source level for all frequency bands during this recording reached about 200 dB.



Figure 33 – From the top left to the right, then down, these are source level estimations (re @1m) centered around 55.6 Hz (49-62 Hz band), 111.2 Hz (98-123 Hz band), and 1.12 kHz (0.985-1.24 kHz band) for 1/3 octave bands, respectively. Spectral estimates for full octave bands are centered around 56.6 Hz (40-80 Hz band), 113.1 Hz (80-160 Hz band), and 0.905 kHz (0.640-1.28 kHz band), respectively. The gray section is where intermittent data loss occurred.

Case 4

On **August 31st** a sonobuoy recording was made for several hours during deep sea dredging operations. In this case study, we analyzed 25 minutes of the recording. During this time the ship was using its bow thruster and propellers in 9/10's ice cover (see Figure 34). The ship's track relative to the sonobuoy deployment is illustrated in Figure 34, while the SOG is shown in Figure 35. Healy never exceeds one knot during the duration of the recording, which is usually achieved by a large vessel by intermittingly applying short bursts to the throttle. There is no propeller shaft speed data displayed for this case study as our goal here is to characterize Healy's source level while using its bow thruster to operate in a dynamic positioning mode. Dynamic positioning is an important feature for a research vessel that needs to meet the demands of science and keep precise station.



Figure 34 – The top figure shows Healy's relative ship track to the sonobuoy deployment (magenta circle) and current range estimate (black circle) during deep-sea dredging operations on August 31, 2008. The still images are taken every 5 minutes (time in upper left corner) from the aloft conn and represent a visual estimate of the local sea ice coverage (x/10 in upper right corner).



Figure 35 - Vessel speed over ground (SOG) during the sonobuoy deployment.

While the propellers were turning as the ship was dragging the dredge up the slope of the seafloor, Healy was only moving variably at half a knot. The propeller blades would have been far below cavitation inception and we can consider this contribution to the sound field to be essentially absent in this case. Figure 36 shows a source level PSD – computed over a 5-second sample window – that represents Healy's sound field while operating the bow thruster in heavy ice cover. The bow thruster contributes significant narrowband spectral peaks at 30 and 55 Hz, reaching sound pressure levels over 190 dB in the full octave band. There are several harmonics associated with the 55 Hz peak at 110 Hz, 165 Hz, etc. Above 200 Hz, source levels drop to similar sound pressures as seen in the openwater source spectra (see Figure 27), except for frequencies > 10 kHz.



Figure 36 – Representative source spectra of Healy while using its bow thruster in 9/10's ice cover. Range to sonobuoy at this time was approximately 500 m.

Seismic Source Calibration Experiment (HLY-0905)

This section includes results from the two-ship experiment to measure the attenuation of the seismic source array signal as it propagates out to 2 km in open water conditions.

Physical properties like pressure, temperature, and salinity determine the vertical structure of sound speed in the water column, so it is important for our analysis to measure these properties with a CTD sensor. Healy conducted a full ocean depth CTD cast in the area where the experiment took place. Temperature and sound speed profiles for the top 250 m are presented in Figure 38. We believe the temperature profile from CTD122 more accurately reflects the oceanographic conditions during the experiment, yet nearby XBT17 shows how variable the Arctic water column can be during summer. There is a mixed layer in the top 100 m that affects the sound speed structure. A shallow, thin, high-velocity layer (1,444 m/s) is present at 10 m depth, followed by a velocity low (1,437 m/s) from 20-35 m, and finally another velocity high (1,443 m/s) between 60-70 m depth. Below 100 m depth is a typical, positive sound-speed gradient found in Arctic waters. Notice that in the full ocean depth plot, both temperature and salinity change abruptly at a thermocline above 400 m.

During the experiment, the LSSL shot the airgun source array in 20 second intervals on the top of the minute. Our analysis only includes shots from the full (3) airgun array of 1150 in³. The fact that the airguns are fired synchronously allows us to consider the array as a point source. We assume propagation of the source array to be symmetric and spherically concentric, regardless of frequency. Due to the figure-eight pattern, the amplitudes of the incoming signals would either ramp up or down depending on the distance of separation between the source and receiver (see Figure 37). Background noise levels were fairly low, although it appears a 12 kHz echo sounder was running during most of the experiment.



Figure 37 – Large amplitude pulses are incoming airgun shots on a regular 20 second interval. The smaller amplitude pulses at shorter intervals are from a 12 kHz echo sounder.



Figure 38 – Sound speed profile (upper left) from a CTD cast taken near the site of the seismic source calibration experiment, a comparison between the temperature profiles of the CTD and a nearby XBT cast (upper right), and vertical profiles down to almost 3,860 m for salinity, oxygen, temperature, and fluorescence (bottom).

Amplitudes were converted from counts to volts to sound pressures re 1 μ Pa at 1 m, which is described in the section on hydrophone calibration. We first examined the pressure signature of a single, incoming airgun shot when the source array and hydrophone were fairly close together. It is very important for geophysicists to determine the shape of the seismic source wavelet and maximum sound pressure generated by the particular seismic source array, as this information is used for seismic data processing purposes. Figure 39 displays the discrete waveform pulse in the upper time-series plot, while the lower plot is the power spectral density of the measured pulse (0-peak). In the time series, sound pressures are reported in units of Bar-m to be consistent with GSC's analysis. Source levels have been corrected to 1 m by adding 20LogR to the received sound pressure levels. For this case, the range was approximately 300 m, so the seismic source array can certainly be considered a point source. The peak source level of the PSD is 235.7 dB around 72 Hz.



Figure 39 – Time series (top) and frequency spectrum (bottom) of the measured source signature. The peak source level is 235.7 dB re 1 μ Pa at 1 meter. The primary pulse peak amplitude is +6.1 Barm and source ghost peak amplitude is -6.3 Bar-m. For reference, 220 dB re 1 μ Pa at 1 m = 1 Bar-m = 0.1 MPa.

Taking a closer look at the signal in Figure 39, the initial positive peak reaching +6.1 Bar-m is known as the primary pulse, or the direct path arrival of the seismic source signal. The larger negative peak reaching -6.3 Bar-m and following the primary is known as the source ghost, which results from the seismic source signal reflecting off the water surface before arriving to the hydrophone. The acoustic impedance mismatch of the airwater interface causes a 180° phase shift of the primary signal, which explains why the source ghost is a negative peak. The difference in arrival time between the primary and

ghost is 8.21 ms, which is 11.8 m using an average sound speed of 1,440 m/s. Recall that the horizontal distance between the source and receiver is about 300 m, the source is 11.8 m deep, and the receiver is 150 m deep. With this information, simple trigonometry shows that the direct ray path is 330 m long and the reflected ray path is 341 m long, therefore the difference in ray path length is 11 m. That is less than a meter off from our arrival time calculation, verifying that the larger negative peak is truly the source ghost reflected off the water surface.

The third component of a typical seismic source pressure signature are the bubble pulses produced by the cyclical expansion and collapse of the air bubble created in the water when the airguns fire. Each bubble pulse consists of a direct arrival from the bubble, followed by a reflected arrival of the bubble off the water surface.

What is unusual about this pressure signature is the fact that there is a smaller negative peak that arrives before the ghost and causes interference. In the GSC cruise report, Mosher explains that an unconventional towing arrangement is necessary because the array is towed in ice-covered waters, and therefore a massive sled is used to keep it 11.8 m deep and very close behind the stern of the vessel. He suggests that the reflection is off either the tow sled or the hull of the LSSL. We believe this to be a reflection off the ship since the difference in arrival time between the primary and reflected path is 2.54 ms, which is 3.7 m using an average sound speed of 1,440 m/s. The ship's draft is typically 9.9 m, so the vertical distance between the bottom of the hull and the source array is 1.9 m, making it very plausible that the source signal reflects off the ship somewhere. This reflection results in a negative peak since the source array generates low frequencies with wavelengths much longer than the hull thickness, causing the ship to appear acoustically as a giant air bubble. A negative impedance contrast shifts the phase 180° and the signal flips. Due to the unique shape of the ship's hull (see Figure 3), a great deal of scattering may occur, which might explain the loss in energy.

Taking all the waveforms, the arrival time of each airgun pulse in the data was selected, and the corresponding shot time was subtracted to yield the travel time. Measured ranges were derived from both ships' GPS positions (see Figures 16-17) and adjusted for the locations of the source and receiver. A comparison of range as a function of travel time is shown in Figure 40, and the data is fitted with a linear regression that gives a slope or average sound speed of 1,447.6 m/s. Clearly there are aspects of deep-water sound propagation that are responsible for the signal spreading, yet it is difficult to sort out these complexities in sound velocity due to the distinct change in temperature near the surface as shown in Figure 38.



Figure 40 – Ranges between the source and receiver are plotted as a function of travel time. A linear regression provides an average sound speed of 1,447.6 m/s.

The goal of the two-ship, seismic source calibration experiment was to empirically measure the range-dependent attenuation of the seismic source signal in deep water out to 2 km. This report presents those measurements for the expanding wavefront, as shown in Figure 41. For each clean shot with a good signal-to-noise ratio (SNR), absolute received sound pressures (peak-peak) were computed over a 1-second window with a FFT length equal to the sample rate ($f_s = 22.05$ kHz). The resulting 1 Hz bins are used to sum pressure levels together within different frequency bands. Peak source levels are given for both 1/3 and full octave bands. Also shown in Figure 41 for comparison is a 235 dB re 1 µPa marine source at 1 m, which in theory would expand concentrically along a spherically divergent wavefront, and sound pressures would dissipate by 20LogR (where R is the radius of the sphere). Most of the energy is absorbed within 500 m of the source.

Although there is variability in our results, this can be attributed to constructive and destructive interference of multiple ray paths due to the complex sound speed profile near the surface. Within 1 km, received sound pressure levels agree quite well with expected source propagation and 20LogR spreading loss. Beyond 1 km, there is much more variability in our measurements, yet 20LogR still seems to be the mean fit.

The 180 and 190 dB radii are the zones of marine mammal mitigation for purposes of IHA permitting, as stated by the U.S. National Marine Fisheries Service (NMFS) under the authority of Section 101(a)(5)(D) of the Marine Mammal Protection Act (16 U.S.C. 1361 et seq.). NMFS has determined that temporary threshold shift (TTS) of cetacean hearing sensitivity occurs at sound exposures of 180 dB re 1 μ Pa (RMS), and for pinnipeds at 190 dB re 1 μ Pa (RMS). We report safety levels for transients as received

peak-peak sound pressure, since RMS does not represent the energy of the noise pulse and therefore may not prevent exposure to high peak pressures (Madsen, 2005). For this particular seismic source array, it appears that for full octave bands the 180 dB sound pressure level is reached at 550 m from the source, and the 190 dB sound pressure level is reached at 200 m from the source. In addition, NMFS uses the 160 dB re 1 μ Pa (RMS) isopleth for both cetaceans and pinnipeds to indicate where behavioral harassment begins for acoustic sources, which in this case occurs beyond 2 km. As shown earlier in the data processing section on acoustic measurements, RMS for a sine wave is approximately 9 dB less than peak-peak.



Figure 41 – Measured peak sound pressure levels as a function of range for 1/3 and full octave bands. The blue line shows theoretical spherical spreading loss for a 235 dB marine source as a comparison.

From our analysis, we believe that the propagation pattern for this particular marine seismic source is more complicated than a concentric, spherically diverging wavefront at distances greater than 1 km. We need to consider the effects of a complex sound speed profile and the fact that the acoustic signature of each source signal consists of a positive primary pulse, negative ship reflection, and negative water-surface reflection, finally followed by bubbles. It seems that measuring sound pressures at distances greater than 1 km from the source will lead to greater variability in the interference pattern due to multipath propagation, and ultimately may affect the peak pressure level.

Discussion

A combination of sonobuoys and static recording equipment has been used to characterize Healy's noise signature in several modes of operation. These modes include open water transiting, ice-breaking (backing and ramming) in 10/10's ice cover, and while stationary with the bow thruster in operation. In addition we have measured the waveform and received levels of the seismic source array operated from the LSSL during collaborative operations with Healy in the summer of 2009.

We find that – compared to open water transit – Healy's noise signature increases approximately 10 dB in the frequency band between 20 Hz and 2 kHz while breaking ice. In addition, while the ship is engaged in backing and ramming maneuvers, the largest modulation in Healy's noise signature results from severe cavitation of the propellers while operating astern. In bands centered near 10, 50, and 100 Hz, source levels were shown to increase 5-15 dB during such modes of propulsion.

Variability in Icebreakers (HLY-0805)

After plotting spectral time series for several different frequency bands, we began to suspect that direct correlations may exist between source levels and a dynamic ship metric that effectively characterizes or reflects the ship's overall performance whether in ice-covered or open waters. To reiterate this difference, we have overlaid the source spectra (1 Hz bins) from Figures 26-27 to compare source level PSDs in open water and while breaking ice (see Figure 42). In addition to the general increase in noise levels while breaking ice in the forward direction, we find a marked increase in noise levels resulting from astern operation of the screws while backing and ramming. Specifically, noise levels increase 10-15dB in the 50 Hz and 100 Hz bands while operating astern propulsion as compared to operating forward propulsion while breaking ice.



Figure 42 – Comparison of source spectra in open water and while breaking moderate ice. Spectral levels are seen to increase as much as 15 dB between 20 Hz and 2 kHz.

From a classical mechanics perspective, velocity (V) is analogous to SOG, force (F) is analogous to the first-differenced absolute value of total shaft RPMs, therefore power ($P = V \cdot F$) would be the product of SOG times the derivative of total shaft RPMs. In reality though, icebreaking and the unique maneuvering required to do so introduces many complexities to the resistance associated with a solid body interacting with fluid (Jones, 2006). In another past study on icebreaker noise levels, Cosens and Dueck (1993) found that received levels for one icebreaker were noticeably more variable than those recorded for a different icebreaker, presumably because they sampled noise during different types of vessel activity. A playback study (Richardson et al., 1995) observed that the lack of correlation with distance was related to the highly variable levels of icebreaker sound at different times. Since we measured the source levels of Healy during different modes of propulsion at various times and distances, we expect that variability is inherent due to maneuvers associated with these specific modes of propulsion, and that different modes of propulsion should not necessarily be compared to each other when trying to observe correlations with source levels (see Appendix A). We will first examine Case 1 (Aug 27th) when Healy is transiting from ice-covered waters to an open-water polynya, and then Case 2 (Aug 28th) and Case 3 (Aug 29th) combined when Healy is backing and ramming in heavy ice.

For the ancillary data available to us for this study, we found SOG could be indirectly related to the ship's power output as well as sea ice conditions – e.g. sudden decreases in SOG are indicative of high shaft RPMs and heavy ice cover. Figure 43 shows source levels, centered around 111.2 Hz (98-123 Hz band) for 1/3 octave bands, plotted with the corresponding SOG throughout the 40 minute recording. Each FFT is computed over a 1-second time window to obtain the maximum number of samples for the scatter plot. What we see is that SOG really relates to the distribution of sound pressure levels depending on ice cover, rather than directly determining the noise level. As SOG increases, so does the variability of sound pressures, as illustrated by the lower and upper envelope limits (red lines). Operating at SOGs between 2-6 knots in greater than 5/10's ice cover (light blue dots) result in a mean sound pressure level of 185 dB, while SOGs between 6-8 knots in less than 5/10's ice cover (dark blue dots) result in mean source levels decreasing from 180 to 175 dB, respectively. The maximum threshold for Healy's source level in this case is about 193 dB.



Figure 43 – Source level estimations (re @1m) centered around 111.2 Hz (98-123 Hz band) for 1/3 octave bands. The red lines are the lower and upper limits of the SPL envelope, and the blue line is fitted to the entire scatter plot data.

Figure 44 shows source levels, centered around 111.2 Hz (98-123 Hz band) for 1/3 octave bands, plotted with the corresponding SOG throughout the 25 minute recording from August 28th in addition to the 35 minute recording from August 28-29th. Each FFT is computed over a 1-second time window. There are some outliers between 191-200 dB that occur on August 29th from 00:09 to 00:11 when the ship is transitioning from reverse to forward motion and the speed of the propeller shaft rotations quickly shift from one direction to the other (i.e. counter-clockwise to clockwise).

Measurements reaching 190 dB match the large positive peaks from the time series curves (100 Hz band) shown in Figures 30 and 33, and correlate with sternward operation of the screws during backing maneuvers. Source levels well within the distribution envelope (red dashed lines) are due mostly to the impact of the ship with the ice – e.g. ice on hull noise, ice-breaking and increased propeller cavitation. This makes sense because SOG increases to 6-7 knots on forward runs but never exceeds 3 knots when reversing. We interpret this to mean that Healy impacts the ice hard and breaks some amount of it, and then the ship backs up and proceeds to make forward progress in the hole just created, repeating as necessary. A past study noted that the highest noise levels occurred when the icebreaker was going into reverse (Cosens and Dueck, 1993).

Also apparent is the reversal in variability of the measurements from those recorded on August 27^{th} (shown in Figure 43) as a function of SOG. As SOG increases, the variability of sound pressures is reduced, as illustrated by the lower and upper envelope limits (red dashed lines). Operating at SOGs between 0-7 knots in 8/10's ice cover results in mean sound pressure levels increasing from 180 to 183 dB, respectively. This effect on the SPL distribution is due largely to the fact that the ship operated almost exclusively at slower speeds during this recording and does not indicate a meaningful difference in regimes. However, it does suggest that the distribution of sound pressures and SOG may be related to specific modes of propulsion – i.e. transiting in variable ice cover or open water, backing and ramming in heavy ice cover, or keeping station with dynamic positioning. The maximum threshold for Healy's source level in this case is about 191 dB.



Figure 44 – Source level estimations (re @1m) centered around 111.2 Hz (98-123 Hz band) for 1/3 octave bands. The red dashed lines are the lower and upper limits of the SPL envelope, and the blue line is fitted to the scatter plot data.

Icebreaker Cavitation and Noise (HLY-0805)

Healy is one of the world's largest non-nuclear polar icebreakers, and was designed from the keel up for the primary mission as a high-latitude research platform for conducting a wide variety of research tasks in diverse fields of science and engineering. As the Coast Guard's only dedicated research vessel, Healy must meet the diverse needs of the U.S. science community in polar regions with an equivalent level of service to that which is provided by large UNOLS research vessels in other parts of the world. The ship is equipped with a highly automated engineering plant, a state-of-the-art array of navigational equipment, extensive communication and computer systems, a voyage management system, and a modern suite of science systems (Berkson ,1998).

Propeller cavitation is the dominant noise source for ships at cruise speeds, and it has been estimated that propeller cavitation produces at least 90% of all ship generated ambient noise (Ross, 2005). Cavitation is such a dominant noise source because not only does the collapse of many individual bubbles produce a continuous spectrum that extends from 50 Hz to several kilohertz, but also pulsations of the aggregate volume of cavitation radiate strong tonals at frequencies below 70 Hz. (Ross, 1976)

The effect of wake operation on cavitation inception is so dramatic that the critical inception index usually depends more on the wake than on the design of the propeller. For severe wakes, stall is likely to occur when the propeller blade passes behind the stern post, or so-called "shadow zone" (Ross, 1976). Icebreakers are unique in this regard as they invariably encounter a particular situation during backing and ramming maneuvers where the ship's propeller shafts are rotating at nearly full speed, yet the speed over ground of the vessel can be quickly reduced due to increased resistance from pack ice. At this moment, there is not only stagnant fluid flow in the shadow zone, but it is everywhere around the propeller. The drop in dynamic pressure of flow velocity around more surface area of the propeller blades will cause increased cavitation inception simultaneously for all the propeller blades, thus producing perhaps the highest noise levels achieved by an icebreaker. Furthermore, we should consider how the bow of the ship rides up on top of the ice to break it, and how this could momentarily lower the depth of the propellers by altering the ship's draft.

Other noise sources are propulsion machinery and diesel generators. Diesel-electric drives – like the propulsion system found on Healy – employ four-stroke medium speed diesels which are quite noisy and produce multiple tones attributed to piston slap. These four-stroke medium speed diesels can radiate as many as 100 harmonics of their rotational frequencies (Ross, 1976). This noise source usually becomes important when a ship is operating at slow speeds, which is very relevant in the case when icebreakers maneuver through substantially thick, ice-covered waters. Interestingly enough, Healy's engines are located on the main deck to reduce noise for the sonar systems.

Ross has suggested that the total noise radiated by a surface ship be estimated from:

 $SPL = 126 + 15\log(HP)$ in dB re 1µPa at 1 meter.

where HP = horsepower. For modern ships near their design speeds, the noise radiated below 100 Hz exceeds that radiated above that frequency by approximately 6 dB. As an

example, if Healy's maximum shaft horsepower is 30,000 HP at 130 RPM, then the sound pressure level would be about 193.2 dB re 1 μ Pa at 1 m. This is actually a reasonable peak estimate for low frequencies, considering the vessel rarely transits at high speeds when operating in the pack ice, and the fact that little is known about the transmission effects of the ice itself (see Appendix A).

Future Work

As a first priority, we hope to analyze the existing sonobuoy data collected during the HLY-0905 seismic survey, as a number of factors make this a promising dataset. From August 24-27, 2009, the receiver station was set up on the LSSL while every few hours, two sonobuoys were deployed off Healy (in the lead breaking ice) with about 20-30 minutes lag time in between deployments. Additionally, there was one day where the LSSL was not conducting their seismic survey and instead was in the lead breaking ice for Healy. Sonobuoys were deployed off the LSSL to measure the noise radiation pattern of Healy off the bow and stern to see how the ship's aperture in relation to the hydrophone relates to frequency-dependent noise emissions.

In addition, we possess the shot times of the seismic source during the duration of our recordings, thanks to the GSC. This makes it possible to estimate the range of the sonobuoy by measuring the direct arrival time of the signal. If the range between the hydrophone and source is known more accurately, then sound pressures can be quantified with much less uncertainty. Incorporating various factors such as sea ice conditions, water depth, sound speed, and the radiation pattern around the vessel, this data can help us to better understand the characteristics of near-field active sound source propagation in the Arctic Ocean.

There is also one additional existing dataset of relevance to this work. During the joint U.S./Canadian seismic survey in September of 2008, our autonomous seafloor recorders that were mentioned earlier, detected long-range propagation and modal dispersion of several seismic surveys simultaneously taking place in the Chukchi and Beaufort Seas, one of which we believe to originate from the LSSL seismic source array. Besides using the time difference of arrival to estimate bearing from the receiver pair, we can develop a normal mode model to estimate the range to the source as well. Such an empirical based model could expand our understanding of far-field active sound source propagation in the Arctic Ocean.

As trends in Arctic sea ice dynamics continue to shift and allow for increased vessel activity, geophysical exploration, and resource extraction, further monitoring of sound sources and ambient noise in the underwater acoustic environment are warranted. We hope that our efforts will help to serve future studies in any manner from experimental setup to analytical techniques. Although there is currently no precedence or noise regulations for ships, the ANSI/ASA standard was a major step in helping to establish protocols for open-water regions. It is important though that this work also be extended specifically to polar regions with ice-covered waters, and in the context of noise and sound exposure to marine mammals.

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Appendix A – Arctic Ocean Sound Propagation (HLY-0805)

The deep-water Arctic waveguide is typically defined by a relatively isothermal water column, an ice canopy at the sea surface that is spatially and temporally variable, and a positive sound speed gradient below 500-800 m. Figure 45 illustrates a composite sound speed profile for the entire Arctic Ocean. Since the summer of 2007, the western Arctic Ocean has been on the verge of a fundamental shift towards seasonal ice cover as we have witnessed record lows for not only sea ice extent, but ice thickness – the main proxy for multiyear ice. Perennial ice is vanishing while more prevalent frail and thin, seasonal ice is more easily disturbed by low-pressure winds and warmer sea temperatures.



Figure 45 – This 2D histogram of sound speed values and depths (color indicates the number of measurements) is 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.

In an Arctic waveguide, acoustic ray paths are usually refracted upwards and subsequently reflected off the surface (for low frequencies) or scattered from the rough underside of sea ice (for high frequencies), as illustrated in Figure 46. Even low-frequency (10-100 Hz) transmission loss is more substantial than most free-surface scattering theories since acoustic waves interfere regularly due to this strongly upward refracting surface duct (LePage and Schmidt, 1994). Reflection loss is not only a function of frequency but depends on the change in acoustic impedance between the two mediums (i.e. water-air or water-ice), as well as the depth of the ice (Diachok, 1976). Because of the combination of upward refraction, surface or under-ice reflection, and high scattering strength, long-range sound propagation in the Arctic is highly dependent on the local sea ice conditions. Transmission loss increases as frequency increases at a rate faster than cylindrical spreading (10LogR) and even spherical spreading (20LogR) at distances greater than 100-1,000 km, therefore high-frequency acoustic waves attenuate rapidly with increased range (Yang, 1981).



Figure 46 – Typical ray diagram and corresponding sound-speed profile for acoustic propagation in the Arctic Ocean (Diachok, 1976).

Due to the surface duct formed by a shallow thermal gradient, sound waves tend to refract off the duct and propagate towards the surface, which then reflect off the air-water interface (for low freq.) or rough underside of ice (for high freq.), characteristic of high scattering strength. Therefore sound will attenuate rapidly the more it reflects off the ice and as a function of frequency – as it increases so does reflection loss and surface scattering (see Figure 47). Reflection and transmission coefficients are generally proportional to the thickness of sea ice (if present), determining the frequency dependent shape of the ambient noise spectrum (Diachok, 1974). This suggests high frequency sound cannot travel long distances and the hydrophone mostly receives locally produced signals at frequencies > 1 kHz.



Figure 47 – Transmission loss measurements versus range in the Arctic Ocean for various frequencies (Buck, 1968 and later modified by Ross).

However, lower frequencies around 10 Hz contribute from much farther distances, with wavelengths in excess of the scale size for under-ice projection (Milne and Ganton, 1964). With the effect of the upward-refracting surface channel on low frequency sound transmission, it appears that transmission loss for a surface ship in the deep-water Arctic is less than the theoretical spherical spreading equation -20LogR.

In a past study, Richardson et al. (1995) found that the movements and behavior of migrating Bowhead whales – exposed to playbacks of variable icebreaker noise – were altered subtly but statistically significantly when the received levels of icebreaker sound exceeded 100 dB re 1 μ Pa. The conclusion drawn was that bowheads would react at distances up to 10-50 km from an actual icebreaker.