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OCEAN ENVIRONMENTAL EFFECTS ON WALRUS COMMUNICATION

A Dissertation in

Acoustics

by

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ABSTRACT

This work aimed to develop source characteristics and transmission effects for the acoustic breeding displays of male Pacific walrus (*Odobenus rosmarus divergens*). Pacific walrus breeding activities occur in late winter in the Bering Sea, an area renowned for extreme weather conditions and high biological productivity. During the breeding season, males perform acoustic displays while swimming in the vicinity of females hauled out on ice. Underwater vocalizations heard by individuals hauled out on ice may be important in the mate selection process. The extreme environment in which walrus breeding activities occur precludes direct observation of these animals during this important period and has resulted in a lack of data. A combination of remote-sensing data, captive animal research, controlled environment experiment, and computational modeling was used to increase our understanding of the acoustic displays of Pacific walrus.

Analysis of recordings of captive and wild male Pacific walrus vocalizations during breeding season provided quantification of source characteristics. Working with a captive animal provided the ability to make direct observations of a male producing breeding vocalizations and the direct calculation of source level. The mean peak to peak source level of the impulsive knocks produced by the captive male was 183 dB (re: 1 µPa) with the middle 95% of the knocks between 168 dB and 195 dB. The broadband knock signals contained significant acoustic energy up to 13 kHz. To estimate source level from wild vocalizations, the location of the source walrus first needed to be determined. Using a method of relative multipath arrival time, more than 37,000 knocks were localized from six years of data from autonomous recorders deployed in the Bering Sea. The mean peak-peak source level from the wild recordings was 177 dB (re: 1 µPa) with 95% of the knocks between 163 dB and 189 dB. For both wild and captive vocalizations, a significant relationship between ambient noise level and source level was identified. The Lombard effect, the increase in source level in response to an increase in noise level has not previously been identified in any pinniped species. In both datasets, an increase of approximately 5 dB in source level was found for an increase in 10 dB of noise level.
A propagation experiment was conducted to measure the transmission of an impulsive acoustic signal, similar to a walrus knock, from an underwater source through ice and into air. Peak to peak pressure measured in air was approximately 2,500 times lower than pressure measured in water separated by two meters of shorefast ice. The results from this experiment were used to verify the adequacy of a wavenumber integration acoustic propagation model for determining transmission loss in this multi-media environment. Propagation model environments were generated from historical ice thickness and oceanographic data. Modeled received signals were compared with walrus audiometric data to determine what factors impact signal detectability with source level, ice thickness, and range having the greatest impact.

The findings of this work suggest that the underwater vocalizations of males making breeding vocalizations are received by females hauled out on ice at audible levels when the females are within a few hundred meters of the males. As the signals exceed the levels estimated to be perceived, these signals may play a role in mate selection by the females. If climate change affects the ice conditions, water depth, and bathymetry where walrus congregate for breeding, mate selection and therefore offspring fitness may be impacted.
Table of Contents

List of Figures .......................................................................................................................... x

List of Tables ........................................................................................................................... xxi

Acknowledgements .................................................................................................................. xxiii

Chapter 1 Introduction .............................................................................................................. 1

Walrus Natural History ............................................................................................................ 3

Vocalizations ............................................................................................................................... 5

Walrus as Receivers ................................................................................................................... 6

Bering Sea Environment .......................................................................................................... 8

Acoustic Environment ............................................................................................................ 10

Acoustic Propagation .............................................................................................................. 12

Approach .................................................................................................................................. 14

Chapter Organization ............................................................................................................. 15

Chapter 2 Captive Walrus Vocalizations ............................................................................... 17

Introduction .............................................................................................................................. 17

Methods .................................................................................................................................. 22

SeaWorld San Diego .................................................................................................................. 26

Signal Processing ..................................................................................................................... 27

Localization ............................................................................................................................... 30

Statistics .................................................................................................................................. 31

Results ..................................................................................................................................... 32
PAL Signal-to-Noise Ratio .................................................................................................................. 76
AURAL Source Level .......................................................................................................................... 81
AURAL Signal-to-Noise Ratio ............................................................................................................. 83
AURAL Timing .................................................................................................................................... 85
Comparison between Recorders .......................................................................................................... 90
Comparison with Captive Data ........................................................................................................... 91
Discussion ........................................................................................................................................... 94
Source Level ....................................................................................................................................... 94
Signal-to-Noise Ratio ......................................................................................................................... 95
Timing .................................................................................................................................................. 95
Persistent Localizations ...................................................................................................................... 96
PAL ...................................................................................................................................................... 96
Conclusions ......................................................................................................................................... 98
Chapter 4 Water-Ice-Air Propagation Measurements and Modeling .................................................. 99
Introduction .......................................................................................................................................... 99
Methods .............................................................................................................................................. 102
Equipment ......................................................................................................................................... 104
Signal Processing ............................................................................................................................... 108
Modeling ........................................................................................................................................... 108
Statistical Analysis ............................................................................................................................. 110
Results ............................................................................................................................................... 111
Discussion

Chapter 5 Modeling of Detectability of Walrus Knocks

Introduction

Bering Sea Ice

Walrus and Sea Ice

Detectability

Walrus Hearing

Methods

Open Water Propagation Experiment

Acoustic Source Equipment

Propagation Model Parameters

Ice Estimation

Source Knocks

Walrus Hearing

Detectability

Statistics

Results

Open Water Propagation Experiment

Environment

Modeled Received Level

Detectability
List of Figures

Figure 1-1 Spectrogram of knock vocalizations from a 2 second segment of a PAL recorder file deployed at PMEL mooring M5 in the southeastern Bering Sea. Dominant energy is below 5000 Hz. Multipath arrivals can be seen. .......................................................... 6

Figure 1-2 In-air audiograms of an adult male Pacific walrus (Kastelein et al., 1996). .......... 7

Figure 1-3. Underwater audiogram of an adult male Pacific walrus (Kastelein et al., 2002). .... 8

Figure 1-4. Map of Bering Sea with recorder location (M5). NOAA PMEL maintains a series of oceanographic monitoring moorings along the 70 m isobaths in the southeastern Bering Sea. Acoustic recordings of walrus vocalizations were collected from recorders deployed on one of the moorings, M5, southeast of St. Matthew Island. ........................................................................................................................................................................................................... 10

Figure 2-1. Time series of walrus vocalizations in (a) bouts, (b) coda, and (c) sequences. Individual knocks can be seen as vertical lines in the sequence (c). Bells can be seen as decaying signals around 00:18:35 in the sequence.......................................................... 19

Figure 2-2. Simplified three dimensional model of walrus enclosure. Red stars represent locations of cameras for monitoring. ......................................................................................................................... 23

Figure 2-3. Point locations of calibrations relative to the outline of the surface and depth of the walrus exhibit pool at SeaWorld San Diego. Receiver location marked with red square. Axes are in meters.................................................................................................................. 25

Figure 2-4. Frequency dependent transmission loss measurements for each of the 8 locations and 3 depths per location. Location, corresponding to Figure 2-3, is given by the first number in the legend, and ordinal depth by the second number. Peaks at low frequency were attributed to the resonance of the feeding tube.............................................................................................................................................................................. 25
Figure 2-5. Example of a knock showing noise and signal periods in red and blue respectively. Spectra calculated from noise before and during the knock. Peak and maximum frequencies, and spectrum slope are identified. .................................................................29

Figure 2-6. Location of walrus’ head (magenta triangles) for recorded knocks determined relative to outline of pool. Hydrophone location is represented as black square. Axes are in meters. ...............31

Figure 2-7. Calibrated waveform and spectrogram for characteristic knock from walrus recorded at SeaWorld San Diego Wild Arctic facility. The signal was clearly above the background noise for 0.06 seconds. Most of the energy was below 10 kHz. .................................................................33

Figure 2-8 Source level estimates grouped by distance from hydrophone. Knocks were grouped into 3 m slant distance bins. Elevated source levels identified in the 7.5 m bin. .........................35

Figure 2-9 Screen capture of video with walrus subject knocking while under platform. Walrus would remain stationary under platform and produce knocks with mean source level greater than at other locations. ........................................................................................................35

Figure 2-10. Source level estimate for distance of 7.5 meters from hydrophone, grouped by whether or not the walrus was underneath the platform. A Kruskal-Wallis test for variance of non-parametric distributions showed that the source level under and not-under the platform were significantly different..........................................................................................36

Figure 2-11. Average spectra of recorded knocks. Average noise spectra from period immediately preceding the knock is given in red. NFFT = 1024, 50% overlap, Hann window. Noise duration was selected to be equal to the knock duration. Average frequency with the maximum band level was 833 Hz. The average frequency at which the signal was equal to the noise was 12,928 Hz. ....37

Figure 2-12. Knock level (peak-peak and RMS) plotted against RMS noise level. Linear regressions fit to the data are represented by lines of the same color as each data point. The positive slope of the regression lines indicate that there was a positive relationship between the noise and source level.39
Figure 2-13. Signal to noise ratio of the peak level plotted against the ambient noise level. The negative trend between SNR and noise suggests that even though the source level increases with increasing noise, that the signals become less detectable with increasing noise.

Figure 2-14. Frequency based signal-to-noise ratio averaged in each frequency bin across the 3,462 knocks. The dominant energy in the knocks was below 5 kHz and that is where the greatest SNR was. Spectra were calculated over the duration of the knocks and noise with FFT size of 1024 points, 50% overlap, and a Hann window.

Figure 2-15. Histogram of durations of recorded walrus knock signals. Despite a fairly Gaussian appearance in the histogram, the distribution was determined to not be normal from a Shapiro-Wilk’s test for normality.

Figure 2-16. Box plots of duration of knock recordings by date of recording. The non-parametric Kruskal-Wallis test for variance showed that the duration of the knocks were significantly different between days.

Figure 2-17. Plot of peak amplitude as a function of source duration. Secondary grouping around 0.02 seconds was isolated and regressions calculated for all knocks and for knocks with less than 0.015 s. Solid squares used for both regressions, hollow squares excluded for regression with durations less than 0.015 s (red line).

Figure 2-18 Lag between knocks within the same sequence. The lag between most knocks was less than 2 seconds. Change-point analysis identified a change in regime at 2 second lag. Two seconds was used as the threshold for associating knocks within a sequence.

Figure 2-19 Number of knocks per sequence aggregated over all recording days. Knocks were assigned to the same sequence if there was less than 2 seconds separating them. Sequences had up to 27 knocks, with the majority of sequences containing less than 10 knocks.

Figure 2-20. Box plot of knock duration grouped by sequence number. A significant difference in knock duration grouped by sequence number was found (Kruskal-Wallis: N = 3381, p < 0.005, F (15)
A trend of increasing duration with increasing sequence number can be seen, especially above sequence number 10.

Figure 2-21. Box plot of knock duration grouped by sequence number for the first 9 knocks of the sequences. Despite limiting analysis to the first nine knocks of the sequences, a significant difference in duration between knocks from different sequence numbers was still identified (Kruskal-Wallis: N = 3226, p < 0.005, \( \chi^2 = 134.6 \)).

Figure 2-22. Inter-knock-interval within a sequence plotted against sequence number.

Figure 2-23. Distribution of slopes of inter-knock-interval as a function of sequence number. The slope of the inter-knock-interval measured whether the lag was changing within a sequence. For most of the knocks, the lag remained the same from previous knocks, thus the peak at 0.

Figure 3-1. Spectrogram, kurtosis, and pressure waveform of a sequence of knocks. Red circles identify kurtosis peaks above threshold of 10 and corresponding peaks in the waveform. Knocks were detected if the kurtosis of the time series was greater than 7.5. Knock detections were validated to insure that the signals were knocks and were not corrupted by other transient signals.

Figure 3-2. Pressure waveform, normalized Teager-Kaiser energy time series and cumulative normalized TK energy series for knock 26 from example sequence. The 99% level of the cumulative Teager-Kaiser energy was used to determine the length of the extracted knock signal used in the knock localization algorithm.

Figure 3-3. Plot of multipath arrivals (solid lines) with isovelocity sound speed profile and identified image receivers (dashed lines). This is a cartoon of the situation documented in Figure 3-4, showing the longer propagation paths travelled by the higher order reflected paths.

Figure 3-4. Plot of idealized, synthetic peak arrivals from a source located 32 m deep and 800 m in range from receiver deployed to 65 m. Assuming an isovelocity environment with sound speed of 1450 m/s, each peak represents the time lag for an arrival relative to the direct path propagation (D).
Arrivals are labeled with the reflections from the propagation path in the order they occur: B – bottom reflected; S – surface reflected; BS – bottom and surface reflected; SB – surface and bottom reflected

Figure 3-5. Localizations of walrus knocks from example sequence (Figure 3-1) of walrus knocks from a 7 second sample. The localizations except those associated with the 7th, 27th, and 28th knocks were all at about 800 m range and 15 m depth, with a general downward trend. The incongruous knocks 7, 27, and 28 were excluded from source level estimation. The localized points at 800 m showed the walrus traveling away from the recorder and towards the surface.

Figure 3-6. Example of multipath knock arrivals, normalized TK energy, and localization index map for a poorly localized knock. There is no clear location that indicates where the vocalizing walrus was.

Figure 3-7. Example of multipath knock arrivals, normalized TK energy, and localization index map for an average knock localization. There are a couple locations, within a small range, where it was likely the vocalizing walrus was.

Figure 3-8. Example of multipath knock arrivals, normalized TK energy, and localization index map for a well localized knock. There is one clear location that indicates where the vocalizing walrus was.

Figure 3-9. Sound speed profile as a function of date from deployed temperature and salinity meters in the winter of 2009 at M5. After sea ice cover was present, the water column was relatively stable with isovelocity sound speed profile. Measurements were limited to below 19 m depth as instruments cannot be deployed safely above that depth due to possible ice keels.

Figure 3-10. Knock count per 4.5 s PAL file. The number of knock per file recorded by the PAL. Each file contained only a portion of a sequence ranging anywhere from 1 to 21 knocks.

Figure 3-11. Histogram of Inter-knock-interval for knocks detected on the PAL recorder. The majority of successive knocks had less than 0.5 seconds between them.
Figure 3-12. Average spectrum from knocks recorded on the PAL. N = 966, FFT size 1024, 50% overlap, Hanning window. Frequency bins were averaged over the duration of each knock, and then the average of each knocks spectra was used to generate an overall average. Dominant energy was contained below 10 kHz.  

Figure 3-13. Source level versus year from the PAL. A Kruskal-Wallis test of source level and year showed significant differences in the mean ranks of source level by year. Some years were louder than others. 

Figure 3-14. Plot of source level from PAL against noise level aggregated for all years. The increase in source level with a correlated increase in noise level is indicative of Lombard effect. 

Figure 3-15. Source level versus noise level for each year of data from the PAL. All years except 2009 had a positive relationship between source level and noise level, and all years except 2009 and 2013 had significant regressions. 

Figure 3-16. Average source level by year plotted as a function of average noise level associated with knocks for each year. A positive regression with similar effect size of 5 dB increase in source level per 10 dB increase in noise level was identified. 

Figure 3-17. Calculated source level estimates from AURAL recordings. Source levels were calculated by correcting received levels for losses associated with spherical spreading over the propagation from the localized knocks from the multipath arrivals. A very slight increase in the source level with range was observed. 

Figure 3-18. Calculated source level estimates by date. A regression fit to the scatterplot of source levels by date showed a slightly decreasing source level as a function of date in the AURAL recordings from 2009. The effect was small with the source level dropping less than 3 dB over the course of the data collection period.
Figure 3-19. Calculated source level estimates by depth of walrus. The distribution of localizations by depth shows that most of the knocks were made by walruses in the top 50 m of the water.

Figure 3-20. Calculated source level as a function of noise level on recording.

Figure 3-21. Signal to noise ratio as a function of noise level.

Figure 3-22. Source level versus noise level for knocks localized to within 200 m range of the AURAL. Limited range results in lower source level knocks detected, and increases the likelihood that the noise at the receiver is similar to that at the walrus. The 95% confidence interval for the slope of the effect was (0.0041, 0.047).

Figure 3-23. Histogram of inter-knock-intervals from any 9 minute sampling period. The time between the knocks was calculated and almost all of the knocks were within 100 seconds of a successive knock. Most knocks occur within a long sequence of knocks.

Figure 3-24. Histogram of counts for inter-knock-intervals less than 2 seconds. The highest proportion of the knocks actually had less than 2 seconds between successive knocks. This 2 second threshold was used as the cut-off for determining sequences of knocks.

Figure 3-25. Scatter plot of inter-knock-interval versus sequence number from AURAL data.

Figure 3-26. Histogram of the slope of regression of the inter-knock-intervals. The slope of the inter-knock-intervals is a measure of whether the intervals are changing. With most knocks occurrences around a value of 0, the knocks intervals are constant within a sequence.

Figure 3-27. Histogram of knock detections by hour from the AURAL in 2009. Knocks were detected at all hours of the day with peaks at 0500, 1300, and 2100 which is an 8 hour interval.

Figure 3-28. Probability distribution functions for the hour of the knock by date of detection. Each PDF represents the distribution in time of when the knocks were detected on the AURAL for a given day in 2009.
Figure 3-29. Difference in spectral levels from recordings made by the PAL and AURAL at similar time periods. The values represent the difference in decibel levels of power spectral density between the PAL and AURAL. The thick black line represents the average difference spectrum .......... 91

Figure 3-30. Probability distribution functions for source level calculated from wild and a captive walrus................................................................. 92

Figure 3-31. Source level versus noise level for both wild recorders and the captive recordings. All three datasets exhibited a positive relationship between source level and noise level of about 5 dB increase in source level for every 10 dB increase in noise level......................................................... 93

Figure 3-32. Plots of localizations from a 40 hour period with clusters of localizations. Red outlines highlight localization clusters that appear over multiple hours. Blue dots represent localizations from the first half hour, black dots represent localizations from the second half hour....................... 97

Figure 4-1. Diagram of experimental design. Magenta triangles are geophones, red stars are microphones, black circles are hydrophones, and the black squares are the sources. The Compressional sound velocity profile is presented on the right, with a zoomed view of the measured profile in water to the extreme right. ................................................................................................................................................. 103

Figure 4-2. Picture of Recording equipment housing (insulated cooler) and deployed transducers at station 2. The geophones were housed in the black cases with the orange caps, and the microphones were mounted on an aluminum rod, 0.5 meters above the ice with a spherical windscreen. The hydrophones were deployed through a 10 inch borehole, to the left of surface transducers. ............... 104

Figure 4-3. Photo of field crew drilling borehole through the ice. Hydrophones and the source were deployed through the holes drilled by the 10 inch auger. Ice thickness was measured by determining the depth of the auger when water came up through the borehole.......................... 106

Figure 4-4. Waveform and spectrogram of source signal used for experiment. Spectrogram level is in relative dB. The source signal was created by recording a hammer blow to a block of wood in a
laboratory setting. The amplitude of the source signal was limited to below 160 dB to avoid additional permitting processes.

Figure 4-5. Sample waveforms and spectrograms from a microphone (L) and shallow hydrophone (R) for a broadcast with the source at the shallow depth. The impulsive nature of the signal resulted in a broadband signal with short duration. The amplitude of the in air signal was five orders of magnitude smaller than the underwater signal.

Figure 4-6. Example waveforms from one broadcast of the shallow source at the 12 receivers. First row has the microphones, second row has the geophone plots, third row has the shallow hydrophone, and fourth row has the deep hydrophone. X-axes are all the same, and referenced to the same time. Y-axes for the 2nd row of plots are in m/s; all others are in µPa. The red line represents the amplitude envelope used to calculate duration above background.

Figure 4-7. Modeled time series of source signal convolved with transfer functions for each of the transducers for the shallow broadcast. Amplitude envelopes in red. The underwater signals were peakier than signals recorded on microphones and geophones. The reduced peakiness may be due to attenuation of the higher frequencies for signals propagating through the ice.

Figure 4-8. Transmission loss as a function of frequency relative to the deep hydrophone located 10 m in range from the source. a) Transmission loss averaged over the 20 broadcasts for each signal with the source at the shallow deployment. b) Modeled transmission loss for the source at the shallow depth. c) Measured transmission loss averaged over the 20 broadcasts for the source at the deep deployment. d) Modeled transmission loss for the source at the deep depth.

Figure 5-1. Bering Sea ice area from 1978 - 2012. (NSIDC 2014) The Bering Sea is seasonally ice covered. In the winter the Bering Sea is covered by ice; in the summer the Bering Sea is ice free. In 2012, the ice coverage in the Bering Sea reached the greatest recorded extent.

Figure 5-2. Ice area anomaly for Bering Sea (blue) and all of the Arctic (green). Anomaly is the difference between the monthly area covered and the monthly mean area covered. (NSIDC 2014)
years from 2008 to present, the Arctic experienced reduced sea ice coverage, while the Bering Sea saw increases in the ice extent. ................................. 127

Figure 5-3. NASA image by Rob Simmon based on data from Jeff Schmaltz, LANCE/EOSDIS MODIS Rapid Response Team at NASA GSFC. Ice in the Arctic is solid white indicating thicker, more contiguous ice. Ice in the Bering Sea has variable reflectivity indicating variable thinner ice and greater variability in percent coverage. The ice edge can be seen just below the location of the M2 mooring. Clouds and snow covered islands comprise the white regions below the ice edge. ................................. 131

Figure 5-4. Pacific walrus audiograms (underwater – blue, in-air – red) and magnitude response of C-weighting filter used to approximate walrus hearing perception. The high and low frequency roll-offs in the walrus audiograms are similar to the roll-offs in the C-weighting filter. Decibel references are 1 µPa for underwater, 20 µPa for air, and 1 for frequency response. .......................................................... 140

Figure 5-5. Sound velocity profiles measured at the sites of the propagation experiments for M2 (left) and M5 (right). The sound velocity profiles were calculated from the casts of the on-board SeaBird Electronics SeaCAT made at the same location as each of the broadcasts. ......................................................... 142

Figure 5-6. Sequence of FM sweeps and CW tones recorded on AURAL at M5 on 20 May 2011. The Nyquist frequency of 4096 Hz resulted in the aliasing of the high frequency end of the linear FM sweep. This plot shows two FM sweeps and three CW tones at 1250 Hz, 2 kHz, and 4 kHz. .......................... 143

Figure 5-7. FM sweep recorded on AURAL at M5. This is a zoomed in view of the FM sweep up to the Nyquist frequency. ................................................................. 144

Figure 5-8. CW tone recorded on AURAL at M5. This is just the 2 kHz signal. The noise environment was consistent over the broadcast of the acoustic signals. ................................. 144

Figure 5-9. Source levels, and measured and modeled received levels for open water propagation experiments in the Bering Sea. Source levels are in blue and referenced to the right vertical axis. Received levels are in red and referenced to the left vertical axis. Modeled results have solid markers. M5 markers are triangles. M2 markers are squares. ................................................................. 146
Figure 5-10. Sea ice thickness (blue) and concentration (green) for the region around the M5 mooring from NOAA Sea Ice Desk. Solid lines are the mean values. Dashed and dotted lines are the minimum and maximum estimated values. NOAA published values approximately every 2 days. Sea ice thickness measured from an Acoustic Water Column Profiler (AWCP) (red line). AWCP estimates were made based on the average value calculated from 5 minutes of sampling every half hour. .................... 147

Figure 5-11. Binary detectability of average received level 0.5 m above ice for walrus knocks for a walrus at 10 m depth in 100 m of water varying with range (x) and ice thickness (y). Knock is detectable for red cells. ........................................................................................................................................................................... 148

Figure 5-12. Binary detectability of average received level 0.5 m above ice for walrus knocks for a walrus at 70 m in 100 m of water varying with range (x) and ice thickness (y). Knock is detectable for red cells. ........................................................................................................................................................................................................................................................................... 149

Figure 5-13. Detectability of walrus knocks in 100 m of water with four different ice thicknesses modeled a) 20 cm; b) 80 cm; c) 140 cm; d) 200 cm. ........................................................................................................................................................................................................................................................................... 150
List of Tables

Table 3-1. Range, depth, travel distance, and arrival lag for a synthetic vocalization. Calculation of distances and lags are based on a source 32 m below the surface 800 m in range from a receiver deployed to 65 m depth in 70 m of water. Water column is assumed uniform with sound speed of 1450 m/s. Time lag is the time in seconds between the arrival specified and the direct path arrival. .................. 66

Table 3-2. Estimates of Lombard effect size by year, and for average yearly SNR with 95% confidence intervals. If the confidence interval does not include 0, an effect is present. ...................... 77

Table 4-1. Input parameters for the OASES propagation model (OASP). J - Complex integration contour; N - normal stress; f - full Hankel transform; c – compressional speed (m/s); cs – shear speed (m/s); ac – compressional attenuation (dB/Λ); as – shear attenuation (dB/Λ); ρ – density (g/cm3); R – RMS roughness (m)........................................................................................................................................ 109

Table 4-2. Results from the generalized linear model comparing the difference in predicted and measured amplitudes to the predictors of transducer type, range, and depth. Range and transducer type had a significant effect on the difference, but source depth did not......................................................... 111

Table 4-3. Average and standard deviation of levels for each transducer from the shallow and deep projections. Averages and standard deviations were computed in the linear domain. ......................... 115

Table 4-4. Peak and RMS modeled received levels at the transducers for the deep and shallow sources. ........................................................................................................................................ 115

Table 4-5. Student's t-test statistic to determine if the measured value distribution varies from the modeled value. Green indicates the modeled values are not significantly different from the measured values. ........................................................................................................................................ 115

Table 4-6. Student's t-test results comparing modeled and measured durations at each transducer for the shallow broadcast. The t-statistic, t, is a ratio of the departure for the estimated parameter, here duration, from its notional value and standard error. The degrees of freedom, df, are the number of
parameters that are free to vary. The standard deviation is given by sd. P is the probability that the
durations are actually the same but the results were obtained merely by randomness. P values less than
0.05 were considered significant.

Table 4-7. Student's t-test results comparing modeled and measured durations at each transducer
for the deep broadcast. The t-statistic, t, is a ratio of the departure for the estimated parameter, here
duration, from its notional value and standard error. The degrees of freedom, df, are the number of
parameters that are free to vary. The standard deviation is given by sd. P is the probability that the
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0.05 were considered significant.

Table 5-1. Input parameters for the OASES propagation model (OASP). J - Complex integration
contour; N - normal stress; f - full Hankel transform; cc - compressional speed (m/s); cs - shear speed
(m/s); ac - compressional attenuation (dB/Λ); as shear attenuation.

Table 5-2. Source level by frequency for signals recorded during propagation experiments from
the ship.

Table 5-3. Measured and modeled transmission loss for each location.

Table 5-4. Results of a GLM comparing detectability by a walrus in air with water depth, walrus
depth, ice thickness, source signal, and range. Source signal amplitudes were normalized to 177 dB_{pp}.

Table 5-5. Results of a GLM comparing detectability by a walrus in water with water depth,
source walrus depth, ice thickness, source signal, range, and receiver walrus depth. Source signal
amplitudes were normalized to 186 dB_{pp}.

Table 5-6. Reported octave band levels from a herd of Atlantic walrus hauled out on a gravel
beach (Kastelein et al., 1993).
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Chapter 1

Introduction

The eastern Bering Sea is a highly productive ecosystem known for its commercial fisheries and extreme environment. Many species of cetacea and pinnipedia are found in the region at varying times of the year. This dynamic region is subject to an extreme change in environmental conditions over the course of a normal year. Much of the Bering Sea experiences coverage by sea ice, historically, from January through April or May. Global climate change will affect environmental conditions like sea ice and primary productivity in the Bering Sea (Grebmeier et al., 2006). This poses a serious threat to the many species dependent upon the ice and requires an increase in the understanding of the ecology of these animals (Moore and Huntington, 2008).

The dependence of different species on sea ice is as varied as the individual species. Depending on the species, ice can serve as a refuge, home, resting platform, or nursery. Arctic pinnipedia are some of the most visibly ice dependent marine mammals. Bearded (Erignathus barbatus), ribbon (Histriophoca fasciata), ringed (Pusa hispida) and spotted seals (Phoca largha), along with Pacific walrus (Odobenus rosmarus divergens), are, even to the casual observer, dependent on this ice (Marz, 2006). A reduction in the duration and extent of the sea ice coverage over different seasons could affect these species dramatically. Pacific walrus, in particular, use the ice floes for many functions in addition to relying on the prey controlled by the presence of the ice and its biological processes (Kastelein, 2002). Walrus use ice platforms to rest during migration and foraging. Females nurse young while hauled out on the pack ice, and males attend to groups of females hauled out on the ice during the breeding season. The seasonal sea ice is also a factor in supporting the benthic prey upon which walrus feed. The large spring bloom of algae and phytoplankton is the basis for the carbon cycle in which dead organisms from the
photic zone settle to the sea floor where benthic invertebrates, which are the primary prey of walrus, can feed on them (Grebmeier et al., 1988).

Walrus are perhaps already feeling the effects of a changing climate. As the ice recedes north of the continental shelf in the Arctic Ocean, walrus are forced to rest on ice or beaches and swim to their foraging grounds at an increased energetic cost (Marz, 2006; Moore and Huntington, 2008). In order to better understand the effects of global climate change on the Pacific walrus, better knowledge of their ecology is required. One aspect of walrus ecology in which we can increase our understanding is their acoustic ecology. Walrus are a vocal species, producing underwater sounds year round. In the breeding season from January through March, male walrus produce an acoustic display while tending to a group of females. The exact function of the display remains unknown, but the timing and location of these displays suggest a role in breeding (Sjare et al., 2003).

Oceanographic instrumentation has been deployed to study the physical environment of the Bering Sea where Pacific walrus breed. The results from the remotely sensed environmental parameters allow the computation of the sound velocity profile. From this work, it is possible to predict how perturbations in the physical environment will affect the propagation of acoustic signals and will contribute to understanding the impacts of climate change on this species. Additionally increased human activity in the Pacific walrus’ habitat is cause for concern. Increasing oil and gas production activities throughout the range of the Pacific walrus from the Beaufort and Chukchi seas, to Bristol Bay in the southeastern Bering Sea, along with increasing commercial shipping activity from the opening of the Northwest Passage will result in changes to the Pacific walrus’ acoustic environment. The overarching goal of this research is to synthesize walrus acoustic parameters for integration into acoustic propagation models to estimate the effective range of detection by walrus in different acoustic environments.
Walrus Natural History

Walrus are a species of large pinniped found in the Arctic and sub-arctic regions. The species is divided into two or three sub-species, the Pacific, Atlantic (*O. r. rosmarus*), and a still debated population in the Laptev sea (*O. r. laptevi*) (Lindqvist *et al.*, 2009). Pacific Walrus are historically found in the Bering, Chukchi, and Beaufort seas at different times of the year. These animals are characterized by their prominent tusks, whisker-like vibrissae on their snout, and large size. Pacific walrus are larger than the Atlantic sub-species, with males weighing between 800 and 1800 kg, females weighing 1/3 less, and the Atlantic counterparts weighing approximately 90% as much (Kastelein, 2002). For the majority of its life, a Pacific walrus lives at sea. However, no more than 2/3 of the time are walrus in the water. The remaining time walrus spend hauled out. Walrus predominantly haul out on snow covered ice floes when available. In recent years, walrus summering in the Chukchi and Beaufort seas have been observed hauling out on the Northern Alaskan coast as the pack ice receded north of the continental shelf inhibiting access to foraging grounds from the ice platforms (Jay *et al.*, 2008). Most important life cycle events occur at sea, including feeding, mating, breeding and migration. Due to the high use of sea ice throughout their lives, walrus are considered an ice dependent marine mammal (Fay, 1982). The recent trends of reduced extent and duration of sea ice coverage is cause for concern and has been linked to reduced recruitment (Cooper *et al.*, 2006).

Pacific walrus are most often distributed around both Russia and Alaska in waters up to 100 meters deep on the continental shelf allowing benthic foraging for invertebrates. Over the course of a year, Pacific Walrus can be found from the Beaufort and Chukchi seas in the Arctic to the Aleutian Islands on the southern border of the Bering Sea. Females, their young, and sub-adult males follow the edge of the pack ice throughout the year. Their migration is coupled to the availability of suitable characteristics of ice near the edges of the extent or polynyas and open leads. Due to seasonal variations in the extent of the ice, these walrus migrate north in the summer and south in the winter. Most adult male Pacific walrus tend to summer in the southeastern Bering Sea in and around Bristol Bay (Fay *et al.*, 2006).
During fall and spring, Pacific walrus can be found throughout the Bering Sea. In the winter, they congregate at breeding grounds near open water leads and polynyas historically throughout the southeastern Bering Sea.

In winter, walrus are found in regions of relatively thin or broken ice in water depths of less than 100 m. The characteristics of this thin ice allow the walrus to maintain breathing holes by breaking through; however, the ice must also be strong enough to support their weight. The walrus are therefore often found near polynyas and divergent ice, regions where ice sheets are separating during these periods (Fay, 1982). Distribution, density, and foraging success are closely coupled to these ice characteristics.

Until the 1950s, it was assumed that mating took place at the same time as calving - in late spring and early summer (Fay, 1982). It is now known that the herds during the calving season are generally separated by sex, with females and juveniles following the ice edge and males heading south (Fay, 1974; Fay, 1985). Walrus breed during the winter, primarily from January to March, when breeding females congregate on pack ice and are at the peak of ovulation. These groups of females hauled out on the ice are attended by adult males positioned in the water just off the ice at the edge of the group. While the males are attending these females, they produce extensive vocal displays both in air and underwater. These acoustic displays have been hypothesized to be courting displays as well as territory defense (Ray and Watkins, 1975).

The rationale for using Pacific walrus as the focus of this study include their position as a keystone species in the highly productive Bering Sea ecosystem and the vulnerability of the species (Grebmeier et al., 2006; Moore and Huntington, 2008; Meehan, 2009). These animals have a large effect on their prey and their ecosystem. Individuals can eat up to 50 kg of food per day, their feeding mechanism of rooting through the seafloor mixes bottom sediments and can create microhabitats and leave food for scavengers (Oliver et al., 1983; Born et al., 2003). Walrus are regarded as a keystone species as their only known predators are killer whales and humans. Polar bears are known to eat walrus carrion, but successful predation has never been documented. As a result of being an upper trophic level animal, walrus may be disproportionately affected by environmental changes and can serve as an
indicator for the system. The expected impact of climate change on the species’ environment has led to a consideration of listing walrus as a threatened species by the US Fish and Wildlife Service (Meehan, 2009).

The International Union of Concerned Naturalists (IUCN) list walrus as a data deficient species (Lowry, 2008). Population assessments show that Pacific walrus increased in number from minimums in the 1950s to peaks in the 1980s (Fay et al., 1997). However, because the Bering Sea is a difficult region in which to conduct population surveys, low accuracy is assumed in the estimates (Gilbert, 1999). Global climate change is considered a major threat to walrus. Any reduction in the extent, timing, and characteristics of sea ice could have large impacts on Pacific walrus. Reduced sea ice will inhibit access to offshore feeding grounds, limit the available platforms for calving and breeding, and impact the carbon cycle upon which walrus depend (Tynan and DeMaster, 1997; Moore and Huntington, 2008).

Vocalizations

Walrus make at least four types of underwater sounds: knocks, rasps, grunts and bells. The mechanisms by which walrus create these sounds is unknown. The knocks are impulsive, broadband sounds with most of their energy below 2 kHz (Schevill et al., 1966; Ray and Watkins, 1975; Stirling et al., 1983). Knocks are alternatively known as taps or clicks. The bell tones are tonal, consisting of one or two frequencies. They are thought to be produced only by mature males and are hypothesized to be a result of the pharyngeal air sacs resonating (Schevill et al., 1966). Walrus also produce a number of vocalizations in air. Roars, grunts and guttural sounds are associated with agonistic behavior (Miller, 1985). During mating season, males whistle at the surface as they attend a group of females (Verboom and Kastelein, 1995). Barks are used by calves as distress calls, and also by older animals as a sign of submission (Miller, 1985).

The male vocal displays are comprised of impulsive and tonal sounds (Stirling et al., 1987). There are two distinct portions of these displays – surface and underwater. The surface portion occurs
with the male walrus tilting his head back and emitting whistles and pulsed sounds. These vocalizations occur a number of times alternating with the male walrus briefly dipping its head into the water for 1-2 minutes. The sub-surface portion is a longer and more intricate series of vocalizations. Made up of a combination of knocks and bells, the sub-surface vocalizations last on average 4-6 minutes. These calls have been identified in both captivity and the wild, as well as for both Pacific and Atlantic walrus (Schevill et al., 1966; Ray and Watkins, 1975; Sjare et al., 2003). The diving vocalizations are stereotyped; they have a general pattern that the walrus follow. Each walrus exhibits variations in their calls enabling the identification of individuals. A single, male Atlantic walrus was identified over the course of two breeding seasons by its vocalization coda, with visual confirmation by an identifiable appearance (a broken tusk) (Stirling et al., 1987).

![Spectrogram of knock vocalizations from a 2 second segment of a PAL recorder file deployed at PMEL mooring M5 in the southeastern Bering Sea. Dominant energy is below 5000 Hz. Multipath arrivals can be seen.](image)

**Walrus as Receivers**

Measures of received acoustic levels, regardless of metric, are only important as they relate to the ability of the subject to perceive them (Yost, 1994). Different animals are able to hear different ranges of acoustic pressure waves in frequency, amplitude, and duration. For example, humans nominally have a hearing range of 20 Hz to 20 kHz, with an absolute sensitivity of 0 dB (re: 20 µPa) at 1 kHz in air, while a
common canine can hear as high as 50 kHz with best sensitivity of -4 dB (re: 20 µPa) at 4 kHz (Heffner, 1983). The medium in which an animal is in has a large effect on its ability to hear sounds. Being amphibious, audition in walrus is complex. The relative difference in impedances between media (air or water) and the physiological structures plays a large role in an animal’s ability to perceive a pressure wave in each medium.

The maximum sensitivity range of the in-air hearing for a single adult male walrus has been determined to be within the range of 500 Hz to 8 kHz, (Figure 1-2)(Kastelein et al., 1996). Over this range, the walrus had sensitivity to signals of approximately 60 dB (re: 20 µPa), which was within 20 dB of the noise background. The underwater audiogram (Figure 1-3) obtained from the same walrus shows effective hearing from 1-12 kHz underwater, with the greatest sensitivity down to approximately 70 dB (re: 1 µPa) at 10 kHz (Kastelein et al., 2002). Both the in-air and underwater audiograms include the range of walrus vocalizations, as well as many anthropogenic noises.

![Figure 1-2 In-air audiograms of an adult male Pacific walrus (Kastelein et al., 1996).](image)
Bering Sea Environment

The eastern Bering Sea bathymetry is dominated by the continental shelf with moderately constant water depths (Figure 1-4). The shelf extends away from the coast of Alaska and its gradual slope results in depths of approximately 100 m at ranges of 500 km from the Alaskan coast (Niebauer and Day, 1989). This bathymetry is the dominant driver of primary productivity in the region because the cool, nutrient rich waters of the abyssal region mix with the warmer waters of the shelf enabling high levels of phytoplankton production (Muench and Schumacher, 1985). Another driver of productivity in the Bering Sea is the sea ice. Each year as the ice melts, the fresh water melt mixes with the sea water which stabilizes the water column and promotes plankton production. From this principal level of production,
an entire ecosystem is supported. Primary production is nutrient limited as late summer approaches. In warmer years when ice extent is at its lowest, there is reduced production on the shelf after the spring ice-edge bloom. Therefore, increased insolation does not necessarily lead to increased production. The change in production and associated alterations of the nutrient load may have impacts at higher trophic levels. The benthic invertebrates on which grey whales (Eschrichtius robustus), walrus, and bearded seals feed, rely on ungrazed ice algae and plankton that settle to the sea floor (Alexander and Niebauer, 1981). This detritus feeds the benthic community which in turn feed the upper trophic predators.

Although a trend of warming and reductions in ice extent have been observed in the polar and sub-polar regions, complex inter-annual and decadal cycles exist. For example, between 1976 and 1979 annual sea ice coverage transitioned from 10-15% above normal to 10-15% below normal, corresponding to a reversal of strong winds out of the north to strong winds out of the south (Niebauer, 1983). Climate models predict an increase in the temperature in the Arctic and sub-arctic region of about 3°C during this century (Bernstein, 2007). In the Bering Sea, the inter-annual ice extent is linked to an interaction between the El Nino-Southern Oscillation (ENSO) events and the winter position of the Aleutian Low (Niebauer and Day, 1989). ENSO is a quasi-periodic climate pattern of warming and cooling of the surface waters in the tropical eastern Pacific Ocean. The temperature variations associated with ENSO cause extreme weather events. These processes have longer cycles related to the Bering Sea ice cover, however the strongest signal is the interannual variations in ice cover (Stabeno and Overland, 2001).
NOAA PMEL maintains a series of oceanographic monitoring moorings along the 70 m isobaths in the southeastern Bering Sea. Acoustic recordings of walrus vocalizations were collected from recorders deployed on one of the moorings, M5, southeast of St. Matthew Island.

**Acoustic Environment**

There are many sources of acoustic signals in the ocean. Sources can be grouped into three broad categories: biotic, geophysical and anthropogenic. Biotic sources are comprised of marine mammals, fish, shrimp, and other invertebrates. Rain, wind, waves, earthquakes, tides, and ice cracking and melting
are all geophysical sources of sound. Anthropogenic sources include, but are not limited to, SONAR, propellers, motors, oil and gas exploration and production, and aircraft. The mechanism by which each source creates its acoustic signal varies, and the acoustic signal itself varies greatly.

Long term observation of marine mammals in the Bering Sea is complicated by the extreme temperatures and weather events, as well as the instability of the ice platforms (Gilbert, 1999). To enhance year round data collection on presence, distribution, and behavior of these animals, autonomous acoustic recorders have been deployed on oceanographic moorings and bottom mounted installations. Principally, continuous recorders have been used to collect acoustic recordings over an entire deployment with durations of 6 months or more. By collecting data continuously, these recorders provide a detailed time history of the acoustic events related to marine mammal vocalizations and anthropogenic activity; however, they also consume large amounts of memory and energy which limits bandwidth to below 5 kHz. Recently, acoustic recorders with an adaptive sub-sampling protocol have been implemented to collect acoustic recordings with larger frequency bandwidths sacrificing the continuous time series for a sub-sampled one (Miksis-Olds et al., 2010).

With these technological innovations permitting increased sampling in new regions, additional questions can be addressed. The inherent limitation of sub-sampled data is that transient events not occurring during a sampling period are indistinguishable from events that do not actually occur. Analysis can only be conducted for which data exists. Detections from recorders operating on different sampling protocols can be comparable if the temporal sampling parameters are chosen carefully with respect to species’ vocalizations (Denes et al., 2014). In addition to the relationship between detection probability of continuous and sub-sampled recorders, the capability of a deployed unit to detect vocalizations is dependent upon the propagation of the signal from source to receiver.

Interpreting detections of marine mammals requires the understanding of the environment through which the signals have propagated (Urck, 1983). The environment has a large impact on the propagation of acoustic signals. The highly dynamic environments of the polar and sub-polar regions where walrus are found will have a varying effect on the signal due to the normal changes in the
environment. The environment can be characterized by the water column and the boundaries. In addition to the propagation medium, knowledge of the source and receiver characteristics allows range and location of the source to be estimated.

**Acoustic Propagation**

Characteristics of an acoustic system are required to determine the detection of the signal at a single point within the system. The system is comprised of the source, receiver, and medium through which the signal propagates. The amplitude, frequency content, temporal patterns, location, and directivity are all important in the propagation of sound waves and where, when, and by which receivers the sound may be heard. The source can be characterized by its physical location and acoustical properties.

Receivers can be natural (animals) or man-made (transducers). Like sources, receivers have acoustical properties that affect the detection of signals. Receivers can have responses that vary with frequency and require certain duration of stimulus. In addition, directivity in receivers is also a consideration, just as it is in sources. An often used simplification of to the acoustic wave equation for propagation is the SONAR equation. The characteristics of the medium, source, and receiver are combined algebraically in the SONAR equation and can result in a measure of detectability (Urick, 1983). The passive sonar equations used are

\[
SNR = SL - TL - NL - DI_s - DI_R
\]  

1-1

\[
SNR \begin{cases} < DT & \text{not detected} \\ \geq DT & \text{detected} \end{cases}
\]  

1-2

\( SL \) is the source level 1 meter from the source on its acoustic axis. \( TL \) is the transmission loss, or the reduction in amplitude at a point relative to the source level. \( NL \) is the noise level at the receiver. \( DI \) is the directivity index, a measure of amplitude in a direction, relative to the level on the axis, for both source and receiver. \( SNR \) is the signal to noise ratio. For detection to occur, the detection threshold (\( DT \))
must be greater than the SNR (Eq. 1-2). To determine whether a signal is detectable this equation is evaluated for specific cases of interest. The use of the SONAR equation here is illustrative, the received level detailed in this work was calculated by the implementation of a computational propagation model.

The source level, directivity indices, and detection threshold are all factors of the source and receiver, and can be quantified separate from the environment. Transmission loss and noise level are factors of the environment. The noise level can be obtained from acoustic sampling and inferences about the nature and probability of noise levels when sampling is not actually done. Transmission loss can be modeled in a number of different ways to determine effects of the environment on amplitude, frequency content, and temporal factors. All methods used to predict transmission loss are based upon estimates of the solution to the wave equation. The simplest of propagation models, spherical and cylindrical spreading, are based solely on the range of transmission. These are useful for rough estimates accounting for the increasing area ensonified by a propagating signal while adhering to the conservation of energy over the area. More complicated models allow for variability within a medium and make estimates of the solution to the wave equation in different ways.

The role of computational acoustic models to characterize propagation has increased along with the increase in the computing power available. To model transmission loss well, an algorithm needs to adequately sample the space. The algorithm needs to assess the acoustic field at points between the source and receiver, and to do so, field variables for each point are needed. The number of variables (sound speed, attenuation, absorption, density, currents) needed at each point depends on the accuracy required in the medium and boundaries.

Propagation models incorporate various levels of complexity to determine the transmission loss related to a specific signal in a given environment. The mathematical basis for these models vary based on the application. The signal from a male in water to a female on ice propagates through three different media – water, ice and air. For computational simplicity, this environment is roughly approximated as horizontally stratified. Each media could be represented as a layer: A layer of air above a layer of ice above a layer of water. The wavenumber integration technique is a method that has been used to
numerically solve the depth separated wave equation for these environments (Pekeris, 1948; Ewing *et al.*, 1957). To predict the effects of the environment on the received acoustic signal from the underwater source to receivers hauled out on ice a wavenumber integration algorithm was employed. The wavenumber integration technique can be straightforwardly applied to problems of depth dependent sound speeds and elastic layers, such as ice (Jensen *et al.*, 1994).

**Approach**

The result of this research provides quantification of the current acoustic environment for Pacific walrus, as well as the ability to predict how changes in the environment will impact walrus acoustics. Each step of this project results in improved estimation of acoustical quantities to determine detectability of walrus vocalizations by conspecifics.

Collection of recordings of captive male vocalizations using simultaneous acoustic and video recorders provided an estimation of source level for underwater walrus vocalizations. The limited sample size of captive animals and the influences from the artificial environment required estimation from wild individuals. Due to the remote nature of Pacific walrus breeding grounds, recordings of wild individuals with direct observation was unfeasible. To estimate source characteristics from recordings of wild walrus, the vocalizations were localized and source estimates calculated from calibrated received levels and transmission loss estimates. Using a recording from a single hydrophone and environmental data, it has been demonstrated that the location of the source vocalization can be determined (Mouy *et al.*, 2012).

To determine the audibility of walrus vocalizations during the breeding season for situations in which the receiver was either in the water or hauled out on ice, computational propagation models were used. The propagation of walrus vocalizations over short and long ranges was required, as there are receivers of interest in each paradigm. When males attend hauled out females, the impacts of the environment on the signal propagation that need to be considered are different from those propagating over many kilometers from the male to an underwater conspecific or deployed receiver. In addition to
propagation to receivers hauled out on ice, the range of detection for receivers in the water was also of interest. Despite differences in the overall range examined, both regimes – long range and short range – were well characterized as horizontally stratified. This layered environment – air over ice over water – was well handled by wavenumber integration techniques. The same computational model was used for both paradigms with receivers on ice or in the water to estimate the transmission loss of the signal for varying environments.

Predictions from the computer models were validated during controlled source/receiver experiments. In a region of stable ice, calibrated sources and receivers were placed in a linear configuration. Measurements of the ice thickness and water column parameters were made and used as inputs into the computer models. Utilizing the recorded output from the receivers, the transmission loss from the experiment was compared to predictions from the model with the given configuration.

Transmission loss estimates from a source to a conspecific receiver are most useful when compared with the sensitivity of the animal to the stimuli. Using previously determined auditory thresholds (Figure 1-2 & Figure 1-3) a measure of detectability was obtained as functions of environmental parameters of ice thickness, water depth, caller depth, receiver depth, and range.

**Chapter Organization**

Chapter 2 details recordings and estimation of source characteristic from a captive adult male Pacific walrus. Acoustic and video recordings were analyzed to provide estimates of source level, spectral content, and temporal characteristics of knocks and knock sequences. In Chapter 3, source characteristics of walrus knocks were estimated from recorders deployed in the Bering Sea. Walrus knock recordings were extracted, and the sources were localized from acoustic arrivals resulting from multipath propagation. A propagation experiment for acoustic signals propagating from an underwater source, through ice, and into air was documented in Chapter 4. The results of the experiment were compared to the results from a wavenumber integration computational model. The favorable comparison of the
measured and modeled results indicated that the computational model would be useful for estimating the effects of ice on a signal that originated underwater and was received in the air. Chapter 6 combined the results from the source estimation of Chapters 2 and 3 with propagation modeling to estimate the received signal parameters for different environments. The received signal parameters were compared to audiograms for Pacific walrus to estimate whether or not the signal would be detectable.
Chapter 2

Captive Walrus Vocalizations

Introduction

Pacific walrus breed during the winter, from January through March, when males and females congregate at open water leads and polynya in the Bering Sea (Fay, 1982). Limited sample studies have shown that female walrus are at the peak of estrus during this period (Fay, 1982). However, there has been no systematic study of the endocrinologic data for wild populations of this species to date. Outside of the breeding season walrus are generally separated by sex, with females and juveniles following the ice edge into the Arctic and males heading south to occupy small isolated islands in the Bering Sea to rest and feed (Fay, 1974; Fay, 1982; 1985). During the breeding season males produce extensive vocalization displays both in air and underwater at the edge of the ice on which females are hauled out. It has been hypothesized that these vocalizations act as courting displays as well as territory defense (Ray and Watkins, 1975). Pacific walrus exhibit lek-like breeding behavior, in which several mature male walruses remain in the immediate vicinity of a herd of females, producing vocalization displays and guarding a small territory. In a few instances, females have been observed to approach, consort, and possibly mate with an individual male in water (Ray and Watkins, 1975; Fay, 1982; Fay et al., 1984). These displays are comprised of vocalizations made at the surface and underwater. The surface portion occurs with the male walrus tilting his head back and emitting pulsed sounds and tonal sounds. The surface vocalizations occur over 1 – 2 minutes with the male alternating between producing the sounds and dipping his head in the water. The longer underwater component lasts 4 – 6 minutes and includes more intricate series of vocalizations. Both Pacific and Atlantic walrus, in the wild and captivity, have been documented to produce these (Schevill et al., 1966; Ray and Watkins, 1975; Sjare et al., 2003).
Both impulsive and tonal sounds, knocks and bells, respectively, are produced during the underwater vocal displays (Stirling et al., 1987). The walrus knock is an impulsive, broadband sound, deriving its name from the similarity of the sound to a knock on a door. Most of the energy in the knocks is contained below 2 kHz (Schevill et al., 1966; Ray and Watkins, 1975; Stirling et al., 1983). The knock is the predominant vocalization type produced by males during breeding season. The less frequent bells are tonal, with one or two narrow band frequency components. The bells are hypothesized to be related to the resonance of the inflated pharyngeal sacs of mature males (Schevill et al., 1966). It is unknown by what mechanism the walrus produce these sounds. Walrus also produce roars, grunts, and guttural sounds in air associated with agonistic behavior (Miller, 1985). The surface portion of the breeding displays include whistles not identified at other times of the year (Verboom and Kastelein, 1995).

The vocalizations are defined at different temporal scales (Figure 2-1): individual vocalizations; sequences of individual vocalizations; coda; and bouts (Sjare et al., 2003). The individual vocalizations are the knocks, bells, grunts, surface whistles and other vocalizations that are emitted by the walruses. A sequence consists of knocks that can be associated with one another temporally with relatively short intervals between successive vocalizations within the sequence. The sequences of the coda may vary in length and pattern of component knocks. The codas have been defined as the song of the walrus (Ray and Watkins, 1975). The underwater breeding codas are stereotyped; they have a general pattern of sequences that is consistent among the codas for one walrus. Variations in the stereotyped displays may permit the identification of an individual from his coda (Sjare et al., 2003). The coda from one male Atlantic walrus was consistent enough to identify him over the course of two breeding seasons confirmed by an identifiable broken tusk (Stirling et al., 1987). The bouts are periods of time when a walrus vocalizes consistently, comprised of multiple repetitions of the codas.
This work focuses on the most ubiquitous and loudest of the walrus vocalizations, the knock. The objective of the work detailed in this chapter was to characterize the level, frequency content, and timing parameters of the knocks of a captive walrus. Collection of parameters from this controlled environment refined the source inputs for propagation modeling related to this species. Additionally, this provided metrics of level, frequency content, and timing to benchmark the parameterization of knocks from wild walruses obtained from autonomous recorders. As this is a common sound, various research projects have been conducted to gain a better understanding of the purpose and characteristics of the sound. However, due to the remote nature and often harsh environmental conditions in the Arctic and sub-Arctic, the research efforts are often limited to remote sensing or ideal weather conditions.

Two recent studies have estimated the source level of walrus knocks from walrus that were not mature adult males. One study analyzed knocks from wild walruses recorded on two recorders in the Chukchi Sea (Mouy et al., 2012). The recordings analyzed as part of Mouy et al. (2012) were collected over summer. Historically, the walrus in the Chukchi Sea do not include many adult males (Fay et al., 1984). Mouy et al. (2012) used the relative multipath arrival times at single hydrophones to localize
vocalizing walruses. The authors were also able to estimate the source levels for the walrus knocks recorded by correcting for the effects of propagation. Source levels of knock vocalizations were estimated at 176 dB (re: 1µPa at 1 m). The levels estimated there may be influenced by the walrus demographics in the study area. The diving behavior documented by Mouy et al. (2012) was different from that described by Sjare et al. (2003) associated with adult male Atlantic walruses during the breeding season. Although all walruses are known to produce knocks throughout the year, only adult males produce the stereotyped codas associated with the breeding season, and only during the breeding season (Ray and Watkins, 1975; Stirling et al., 1983; Fay et al., 1984; Sjare and Stirling, 1996; Sjare et al., 2003). It has been recently documented that female walrus produce knocks but not the stereotyped breeding codas (Schusterman and Reichmuth, 2008). Both females and sub-adult males, those most likely responsible for the knocks analyzed by Mouy et al. (2012), are smaller than adult males.

Another study (Reichmuth et al., 2009; Hughes et al., 2011) estimated the source level from a captive sub-adult male walrus. From knock recordings of a male walrus at Six Flags Discovery Kingdom in Vallejo, CA, the authors estimated the source level of the knocks to be 186 dB (re: 1µPa at 1 m) (Hughes et al., 2011). The male walrus ranged in age from 11-13 years old over the course of the data collection. The 10 dB difference in level between the two studies was indicative of a 10 fold increase in intensity for the captive male from the wild estimates. With a source level estimate difference of 10 dB, a simple estimate for range of detection would also exhibit a 10 fold increase for the louder vocalization.

The impact of noise level on the source level of the vocalizations has not been investigated. Neither Mouy et al. (2012) nor Hughes et al. (2011) published noise levels along with their source level estimates. Numerous other species, including terrestrial and arboreal mammals, humans, whales, and bats have been documented to modify vocalizations due to exposure to changing noise conditions (Hotchkin and Parks, 2013). The most often investigated vocal modification to noise is elevation of source level. However, other modifications such as increasing the duration, shifting the frequency, and combinations of multiple modifications have been documented in humans, terrestrial mammals, birds, and cetaceans.
Increasing the source level of the vocalization in response to noise may increase the detectability of the signal in a noisier environment.

Accurately modeling the propagation of the walrus vocalizations in various media requires quantification of the acoustical characteristics of the source signal. Previous work regarding walrus vocalizations has documented that while most of the acoustical energy is contained in frequencies below 2 kHz, there is some energy as high as 10 kHz (Schevill et al., 1966; Ray and Watkins, 1975). Reported frequency ranges for knocks recorded from wild Atlantic walrus showed substantial energy up to 5 kHz (Sjare et al., 2003). Recordings from a captive Atlantic walrus yielded variable fundamental frequencies of the bell vocalization ranging from 400 Hz to 1200 Hz, with occasional harmonics identified up to 10 kHz (Schevill et al., 1966). The inter-knock-interval often changes within a sequence of knocks. Sjare et al. (2003) identified that the knock rate increased to the point where individual knocks were no longer detectable, resulting in a buzz. Mouy et al. (2012) described the knock rate from two walrus tracks as 59.8 knocks/min and 75.4 knocks/min. Though they did not report finer temporal scale knock production rates.

Obtaining recordings of wild vocalizing male Pacific walrus with an observer present is logistically unfeasible due to the remote and dangerous nature of the breeding ground location. Access to animals in a captive environment provides the ability to collect higher resolution behavioral and acoustical data but from fewer individuals. Ideally, recordings would be collected from multiple individuals in their natural environment. Therefore, the characterization of the source signal will rely partly upon recordings from a captive animal. Inherent with collection of vocalizations from captive individuals are caveats related to the ability to generalize findings to the wild populations. The acoustical characteristics of the captive environment vary greatly from these animals’ natural environs. The noise conditions in the enclosure are different than those in the wild. If walrus adjust source levels or other vocalization characteristics in response to noise, the measurements made in captivity will necessarily be different than those in the wild under completely different noise conditions. Additionally, ecological, physiological, and social cues from which wild walrus are informed are lacking in a captive situation in
which there is only one male, food is available consistently, and environmental conditions are relatively
stable. In an attempt to validate the vocalization characteristics from a captive individual, comparisons to
wild vocalizations are made based on estimates detailed in Chapter 3. As observed recordings of wild
c vocalizations are unavailable (the motivation for the work of this chapter), estimates were made from
remotely deployed autonomous recorders (Chapter 3).

Methods

Vocalizations were collected from a hydrophone deployed in a walrus enclosure at a
collaborating aquarium – SeaWorld San Diego, under The Pennsylvania State University IACUC
protocol 37002 and SeaWorld research proposal RR2011-16 (Appendix A). Deployment of the
hydrophone was made with consideration of acoustical needs as well as those of the animals’ welfare.
Video cameras monitored the orientation and location of the individual relative to the hydrophone to
determine range and directionality. Observations of the collection period were made in order to document
any changes in behavior that may be associated with variations in the acoustic signal.

Vocalizations were recorded using a High-Tech Instruments HTI-96-Min hydrophone, with a flat
frequency response up to 30 kHz, deployed through an exhibit feeding tube, with the hydrophone
remaining completely within the feeding tube. Spacers were attached to the hydrophone cable to prevent
contact between the hydrophone and feeding tube. The recordings were collected with an Edirol R-4
audio recorder sampling at 48 kHz with 16 bit depth resolution. Recordings were made during normal
park operating hours. The hydrophone remained deployed throughout the recording period. Two video
cameras were used to record the location of the walrus while audio recordings were made. To ensure
measurements taken from video recordings correspond to the acoustic signals, a time-sync signal was
recorded on the video cameras and audio recorder at the beginning and end of each day’s recordings. One
camera was placed above water to record the horizontal position of the walrus; and one camera was
placed behind an acrylic viewing window below water to determine depth (Figure 2-2).
The recording system was calibrated prior to the beginning of data collection using a comparison method (Urick, 1983). Tonal and broadband signals were delivered to the research hydrophone as well as a calibrated reference hydrophone to determine the sensitivity of the system. The calibration was conducted in a fresh water cement pool in the basement of the Applied Sciences Building on the campus of The Pennsylvania State University. The pool is 20 feet deep by 20 feet wide by 18 feet long.

Propagation characteristics of the exhibit pool were determined by moving an underwater speaker (Lubell Labs LL9162T) to different locations and depths in the exhibit pool while animals were off exhibit. Impulsive, tonal, and frequency modulated signals were broadcast. The signal was recorded by a reference hydrophone fixed to the speaker with a 1 m length of PVC, and by the hydrophone deployed in the feeding tube. At each location, the acoustic source was oriented so the reference hydrophone was in between the source and the feeding tube opening. Transmission loss for impulse and tonal signals was calculated for each location and depth. The impulse used was a recording of hammer strike on a wood block recorded in air. The impulse signal was broadband and contained energy up to 10 kHz. The tonal
signals were half second duration sinusoids with frequencies of 100 Hz, 200 Hz, 400 Hz, 800 Hz, 1 kHz, 1.5 kHz, 2 kHz, 2.5 kHz, 3.5 kHz, 4 kHz, 4.5 kHz and 5 kHz. The transmission loss for each location and signal type was calculated (Equation 2-1). A reference sequence was collected in which the hydrophones were co-located 1 m from the underwater speaker. The received signal during this reference sequence was the same at both hydrophones and the transmission loss estimates were made relative to this sequence. The corrections as a function of frequency for the propagation losses were calculated from the impulsive calibration signal. The calibration values from the tonal signals were used to confirm the values from the impulsive signal.

\[ TL_i = 10 \ast \log_{10} \frac{\bar{f}_i}{f_{tube}} \]  

Calibration recordings were made from 8 locations within the SeaWorld San Diego walrus exhibit pool. At each location, the speaker was placed at 1 m below the surface, 3 m below the surface, and just above the pool floor (Figure 2-3). This resulted in propagation characteristics determined for 24 locations in the pool. Transmission loss was determined to be dependent on both location and frequency. The transmission loss estimates showed frequency dependent increase in transmission loss around 1500 Hz, 2500 Hz and 4500 Hz (Figure 2-4). The transmission loss estimates were made by comparing the spectrum of broadband synthetic knocks recorded 1 m from the source and at the receiver deployed in the feeding tube.
Figure 2-3. Point locations of calibrations relative to the outline of the surface and depth of the walrus exhibit pool at SeaWorld San Diego. Receiver location marked with red square. Axes are in meters.

Figure 2-4. Frequency dependent transmission loss measurements for each of the 8 locations and 3 depths per location. Location, corresponding to Figure 2-3, is given by the first number in the legend, and ordinal depth by the second number. Peaks at low frequency were attributed to the resonance of the feeding tube.
SeaWorld San Diego

The walrus exhibit at SeaWorld San Diego is part of the Wild Arctic animal care unit. The exhibit is entirely outdoors. The outdoor exposure includes noise from other SeaWorld activities as well as air traffic from San Diego International Airport. The pool has a maximum depth of 16 feet and a roughly pentagonal outline (Figure 2-2). The pool has fake rock walls made from reinforced cement. The rock work resulted in varying wall roughness and contour. The rock work covers all of the sides of the pool except where 6 inch thick acrylic windows are present. There are four acrylic windows, two each for lighting and guest viewing. The volume of the pool is 16,042 cubic feet.

The hydrophone was deployed through an 8 inch diameter PVC pipe designed as a feeding tube. The tube is 20 feet in length and enters the pool near the deepest area about 4 feet above the bottom. A video camera was placed in an underwater lighting well nearest the feeding tube opening, oriented such that the feeding tube opening was positioned at the far left of the underwater camera’s field of view, with the pool extending to the right. A second camera was placed on the catwalk overlooking the pool (Figure 2-2).

The male walrus subject studied was a rescued orphan Pacific walrus. At the time of recording, the walrus was 26 years old and weighed between 3000 and 3100 lbs. He has successfully mated with two different female walruses at SeaWorld a total of four times. Viable offspring were born from two of the four pregnancies. This adult male has sired two of the eleven captive born walrus in American zoological facilities (Oland, 2008). During the recording period, the male walrus subject was separated from the female housed in the same facility to prevent pregnancy as part of the breeding plan. This individual produces very few vocalizations throughout the year except for short periods in the spring.
Ishmael software was used to extract periods for the detection of signals within the audio recordings that contained high amplitude signals (Mellinger, 2001). A band limited energy sum detector with a low threshold was used to detect elevated energy in the 1 kHz to 2 kHz range. Knocks, bells and surface whistles made by the subject contained elevated levels of energy within this frequency band, permitting the identification of all vocalizations, while limiting false detections due to noise at frequencies below 1 kHz. This low threshold permitted detection of lower amplitude knocks, bells, and whistles, at the expense of a 35% false detection rate. Custom Matlab scripts were used to visually review the waveform and spectrograms, and to listen to the detected signals. Detections were classified into one of five categories: false detections, noise masked knocks, good knocks, multiple knocks or other. For good knocks, the script selected the maximum and minimum peak amplitudes which were validated visually in the waveform plot.

For each knock identified, two durations were calculated – the source duration and the recorded signal duration. Due to the reverberant nature of the cement pool, the duration of the source knock could not be measured directly, as multipath arrivals were received before the signal amplitude returned to baseline. The source duration estimated the duration of the source signal without reverberation. The recorded signal duration was the total time the signal, including reverberation, was detectable above the background noise. Compensating for the effects of reverberant environments on communication signals is an active field of research. One method to extract signal feature parameters from a reverberant signal is based on the use of the amplitude envelope of the signal. Identification of the envelope maximum and local minima following the maximum permits the extraction of signal features on a subset of data related to the direct path signal (Krishnamoorthy and Prasanna, 2009). To estimate the duration of the source knock, the slope of the amplitude envelope from the peak to the first local minimum after the peak was calculated. The end of the source knock duration was estimated as the sample at which the line from the peak with the calculated slope crossed the background amplitude. The energy contained in the source
signal was calculated as the mean-square amplitude of the signal multiplied by the recorded duration of the signal. The received signal duration of each knock was determined by computing the waveform envelope of the signal and finding the last sample prior to the peak where the envelope exceeded 5 times the amplitude of the median envelope amplitude of a quiet period before the knock. This sample identified the beginning of the recorded signal. The end of the recorded signal was considered to be the first sample after the peak where the waveform envelope was less than five times the median amplitude of the quiet period before the knock. The received signal duration was the result of the highly reverberant environment of the concrete pool. The received signal duration was of interest as the energy contained within the recorded signal should be a function of the recorded duration. The root mean square amplitude was calculated for the received signal duration (including multipath) of each knock determined by the above process. To characterize the ambient noise in which each knock occurred, a period of duration equal to the received signal duration was selected immediately prior to the knock.

The frequency content of each knock, and the noise preceding it, was calculated by computing the average spectra of the knock for the recorded signal duration (including multipath). The peak frequency, maximum frequency, and slope of the spectrum were calculated. The maximum frequency was identified as the first frequency above the peak frequency where the SNR was less than 0 (Figure 2-5). The spectral slope, calculated here as a measure of roll-off above the peak frequency, was the slope of the spectrum from the peak frequency to the maximum. The spectra were calculated using a Fourier transform length of 1024 samples, a Hanning window, and 50% overlap. This resulted in a frequency resolution of approximately 46 Hz. The ambient noise spectra were calculated using the same parameters.
Figure 2-5. Example of a knock showing noise and signal periods in red and blue respectively. Spectra calculated from noise before and during the knock. Peak and maximum frequencies, and spectrum slope are identified.

The knock timing characteristics that were calculated included knock duration, inter-knock-interval, and number of knocks per sequence. The duration of each knock was calculated as described above. The inter-knock-interval was calculated as the time difference between successive peaks identified for each knock. This inter-knock-interval between the peaks was used to determine whether knocks were temporally associated. The R-project package “change point” was used to identify the binary segmentation of the histogram of inter-knock-intervals and provided the point at which the inter-knock-intervals entered a different regime (Killick et al., 2014; R Core Development Team, 2014).

Utilizing the change-point from this analysis, the number of knocks within a sequence was calculated as the number of knocks before the inter-knock-interval exceeded the change-point determined from the analysis. The number of the knocks within a sequence was used for analysis of the relationship with other factors including level, inter-knock-interval, and knock duration.
Localization

To determine the location of the walrus for each good knock detection, a Matlab script was used to access the video files at the recorded time of detection. Graphical inputs of the location of the walrus’s head were recorded from each of the camera views. The field of view of each camera was transformed into a planar view of the three dimensional engineering drawing of the walrus enclosure. The graphically selected location of the walrus was combined with the location of the camera to create a line in 3-D space for each camera/location pair. The intersection point of the two lines in 3-D space indicated the location of the walrus. For most line pairs, there was no intersection; small errors in graphical inputs and limitations due to camera resolution contributed to slight errors in localization. The closest point of approach for the lines was determined by calculating the minimum of the distance between the lines. This minimum separation in the lines was used as a proxy for the walrus’ location (Figure 2-6). Each knock location was then assigned to the nearest calibration point (Figure 2-3). The uncertainty in the localization from the minimum distance between the lines was less than the spacing between calibration locations. The amplitudes of the knocks were corrected for the location of the walrus based on the calibration of the pool. Source level of the walrus vocalizations was determined by computing the received level at the calibrated hydrophone and adjusting the level by values determined from the pool calibration process. The complex spectra of the knocks were multiplied by the correction based on the calibration. The inverse Fourier transform was calculated and the peak amplitudes were determined.
Figure 2-6. Location of walrus’ head (magenta triangles) for recorded knocks determined relative to outline of pool. Hydrophone location is represented as black square. Axes are in meters.

Statistics

To determine the normality of the distributions of continuous variables, a Shapiro-Wilk’s test for normality was implemented. The Shapiro-Wilk’s test has been shown to have the greatest power of the tests for normality for a given significance level (Razali and Wah, 2011). To determine the relationship between groupings by sequence number or walrus location, and measured knock parameters such as level, duration, and peak frequency, one of two tests was used. Either a one-way ANOVA for normally distributed values, or a Kruskal-Wallis test for variance when the distributions were not normal. The ANOVA test compares the means of a group of populations and determines whether the sample means of the groups are equal. For distributions that are not normal, the ANOVA cannot be used and the Kruskal-Wallis non-parametric test for variance was used. Like the ANOVA, Kruskal-Wallis tests determine whether the samples in multiple groups all belong to the same distribution. Rather than using the values,
the Kruskal-Wallis test assigns an ordinal rank to each value, and tests whether the mean ranks of each group are the same. For continuous variables, like range from the hydrophone, or duration of the knock compared to either duration or level, linear regressions were fit to the data and significance tested using a Student’s t-test. This test uses the variance of the observed data to determine if the modeled regression can be applied to the observed data. If the null hypothesis, the slope of the regression is 0, is rejected it is determined that there is a relationship between the predictor and output variables.

Results

Recordings of walrus vocalizations were made from May 9th through May 17th of 2013. A total of 58 hours of concurrent audio and video recordings were made during daylight hours over that time period. No recordings were made on May 12th. Automatic detection of knocks conducted in Ishmael resulted in 34,732 extracted audio clips. Selecting only audio clips with a kurtosis level above a threshold of 7 the number of detections was reduced to 28,996. The resulting audio clips were at minimum 0.2 seconds in duration (Figure 2-7). Of those detections, 7,456 were false detections and 46 were masked by other signals, resulting in 21,494 good knock detections where an individual knock signal could be clearly identified in the waveform and spectrogram and was not masked by another loud signal. Excluding detected signals for which corresponding video recordings were not collected reduced the number of detections to 9,494. The walrus was in view of the cameras and his location was determined for 5,810 knocks. Analysis of video time-synced to the extracted audio recordings resulted in 3,462 recorded knocks for which the walrus was in full view of the video cameras, and facing in the general direction of the hydrophone.
Figure 2-7. Calibrated waveform and spectrogram for characteristic knock from walrus recorded at SeaWorld San Diego Wild Arctic facility. The signal was clearly above the background noise for 0.06 seconds. Most of the energy was below 10 kHz.

**Source Level Estimation**

The mean source level of all knocks for which the walrus' location was determined was 184 $\text{dB}_{pp}$ (re: 1 $\mu$Pa) regardless of the orientation of the walrus with the middle 95% of all knocks between 168 $\text{dB}_{pp}$ and 195 $\text{dB}_{pp}$ (re: 1 $\mu$Pa) ($N = 5,810$). The mean estimated source level of walrus knocks corrected for location of the walrus was 186 $\text{dB}_{pp}$ (re: 1 $\mu$Pa) when the walrus was facing the hydrophone ($N = 3,462$). The greatest source level recorded, corrected for location, was 199 $\text{dB}_{pp}$ (re: 1 $\mu$Pa). When the knocks were grouped into 3 meter slant distance bins (Figure 2-8), the variance in source level was statistically significant when grouped by distance from the hydrophone (Kruskal-Wallis: $N = 3462$, $p < 0.005$, $\chi^2 = 309.24$, df = 4). However, when the 7.5 m distance was excluded, the variance between the groups was not statistically significant (Kruskal-Wallis: $N = 2019$, $p= 0.18$, $\chi^2 = 4.93$, df = 3). At 7.5 m
from the hydrophone, the recorded source level was higher than at other distances. The knocks recorded at this distance, included those for which the walrus was underneath an overhang (Figure 2-9).

Comparing the calculated levels from 7.5 m, grouped as either under overhang or not (Figure 2-10), there was a significant difference between the levels, with the under overhang source level estimated at 190 dB$_{pp}$ (re: $1 \mu$Pa) ($N = 893$) compared to 183 dB$_{pp}$ (re: $1 \mu$Pa) not under the platform ($N = 551$) (Kruskal-Wallis: $N = 1444$, $p < 0.005$, $\chi^2 = 374.92$, df = 1). Excluding the knocks for which the walrus was underneath the overhang, the mean estimated source level was 183 dB$_{pp}$ (re: $1 \mu$Pa) when facing the hydrophone ($N = 2569$). Including all orientations of the walrus relative to the hydrophone and excluding those knocks when the walrus was under the overhang mean source level was 182 dB$_{pp}$ (re: $1 \mu$Pa) with the middle 95% of values between 168 and 195 dB ($N = 4,917$). Due to the limited dependence of source level on orientation of the walrus, analysis will be based on the knocks when the walrus was facing the hydrophone.

Peak levels were compared with the calibration location to determine if the source level estimates varied with calibration coefficients. There was a significant difference in level between the calibration locations (Kruskal-Wallis: $N = 3462$, $p < 0.005$, $\chi^2 = 204.17$, df = 23). Removing the knocks when the walrus was under the overhang removed the significant difference (Kruskal-Wallis: $N = 2569$, $p = 0.12$, $\chi^2 = 25.05$, df = 22). The energy within each recorded knock was the product of the square of the mean pressure and the duration. The average energy in the recorded knocks was 174 dB (re: $1 \mu$Pa$^2$/s).
Knocks were grouped into 3 m slant distance bins. Elevated source levels identified in the 7.5 m bin.

Walrus would remain stationary under platform and produce knocks with mean source level greater than at other locations.
Figure 2-10. Source level estimate for distance of 7.5 meters from hydrophone, grouped by whether or not the walrus was underneath the platform. A Kruskal-Wallis test for variance of non-parametric distributions showed that the source level under and not-under the platform were significantly different.

Frequency Content

The average spectrum of each knock was computed over the signal duration of each knock signal (Figure 2-11). From the plot, it is clear that the knocks are broadband with the dominant energy content below 5 kHz, with frequency levels more than 20 dB higher than the background up to approximately 10 kHz. The average of the peak frequencies of each recorded knock was determined to be 755 Hz (SD: 208 Hz). The peak frequency recorded was not affected by the location of the walrus. Comparing the peak frequency of the knocks with the knock sequence number using a one-way ANOVA there was no effect of sequence number on the peak frequency (N = 3462, p = 0.81, F = 0.68, df = 15). The peak frequency content did not change with successive knocks in a sequence.
Figure 2-11. Average spectra of recorded knocks. Average noise spectra from period immediately preceding the knock is given in red. NFFT = 1024, 50% overlap, Hann window. Noise duration was selected to be equal to the knock duration. Average frequency with the maximum band level was 833 Hz. The average frequency at which the signal was equal to the noise was 12,928 Hz.

The maximum frequency was calculated as the frequency where the spectra dropped below the spectral noise for each knock. The average maximum frequency was calculated to be 12,928 Hz ± 3623 Hz. For 95 of the 3,462 knocks, the spectrum of the knocks never crossed the noise spectrum. For those instances, the maximum frequency was not included in the analysis though the impact was apparent in Figure 2-11, with the average spectrum not crossing the noise spectrum.

The average slope of the spectra from the peak to the maximum frequency was -6.0 dB per octave (±0.7 dB per octave). The average spectral-roll off point, the frequency under which 95% of the energy was contained, was 1,554 Hz ± 678 Hz. Even though the knocks were broadband, with energy up to 13 kHz, most of the energy was contained below 2 kHz.
Signal-to-Noise Ratio

The signal to noise ratio (SNR) of the walrus knocks were computed two different ways. The peak and RMS levels of each knock were compared to the RMS ambient noise immediately preceding the knock, and by comparing the spectra of the recorded knocks with the spectra of the noise immediately preceding the knock. The SNR\textsubscript{peak} was 22.5 dB (95%: [14, 28]) and the SNR\textsubscript{rms} was 12.6 dB (95%: [5, 18]). Linear regressions were fit to the peak and RMS knock levels as a function of noise level. Both the linear regression of the RMS levels with noise and the linear regression of the peak levels with noise were found to be significant (N = 3462; RMS: \(R^2 = 0.06, F = 1294.5, p < 0.001\); peak: \(R^2 = 0.13, F = 508.1, p < 0.005\)). The regression residuals had a random distribution as a function of noise level for both measures of source level. The walrus increased peak level of his knock by 5.8 dB per 10 dB increase in noise and the RMS level of his knocks 4.5 dB per 10 dB increase in noise level (Figure 2-12). The 95% confidence interval for the effect of noise on the peak level ranged from 5.4 to 6.3 dB, and 4.1 to 4.8 dB for the RMS value. Despite an increase in peak level with noise level, a slope of less than one resulted in decreasing SNR with increasing noise level. This relationship can be seen in a plot of SNR\textsubscript{peak} against the RMS noise level (Figure 2-13). The average SNR in the frequency domain, obtained by subtracting the spectra of each knock from the noise associated with each knock, shows two regimes (Figure 2-14). Below 1 kHz, the SNR increases. In this frequency range, the noise level was high relative to the rest of the bandwidth sampled. Above 1 kHz, the SNR decreases linearly with the logarithm of the frequency. This \(-\log(f)\) relationship was the result of a \(-\log(f)\) behavior in the knock spectra, as the energy in the noise spectrum was flat at the higher frequencies.
Figure 2-12. Knock level (peak-peak and RMS) plotted against RMS noise level. Linear regressions fit to the data are represented by lines of the same color as each data point. The positive slope of the regression lines indicate that there was a positive relationship between the noise and source level.

Figure 2-13. Signal to noise ratio of the peak level plotted against the ambient noise level. The negative trend between SNR and noise suggests that even though the source level increases with increasing noise, that the signals become less detectable with increasing noise.
Figure 2-14. Frequency based signal-to-noise ratio averaged in each frequency bin across the 3,462 knocks. The dominant energy in the knocks was below 5 kHz and that is where the greatest SNR was. Spectra were calculated over the duration of the knocks and noise with FFT size of 1024 points, 50% overlap, and a Hann window.

**Knock Timing**

The average duration of the received signals was 0.059 s (SD: 0.0121 s) with a non-normal distribution (Shapiro-Wilk's test, W = .99, p < 0.005, N = 3462) (Figure 2-15). Over the course of the data collection, there was a significant difference in duration associated with date (Kruskal-Wallis: N = 3462, p < 0.005, $\chi^2 = 55.6$, df = 4) (Figure 2-16). There was no effect of distance from the receiver, grouped into 3 m bins, with the recorded duration of the vocalizations (Kruskal-Wallis: N = 3462, p = 0.12, $\chi^2 = 1.8$, df = 4). The recorded duration, which was used to calculate the energy in the recorded signal, was not significantly related to the range of the walrus from the hydrophone.
Figure 2-15. Histogram of durations of recorded walrus knock signals. Despite a fairly Gaussian appearance in the histogram, the distribution was determined to not be normal from a Shapiro-Wilk’s test for normality.

Figure 2-16. Box plots of duration of knock recordings by date of recording. The non-parametric Kruskal-Wallis test for variance showed that the duration of the knocks were significantly different between days.
The source durations calculated by comparing the waveform envelope and the background resulted in durations that were dependent upon multiple arrivals of the same knock. Duration estimated from the zero crossing of the amplitude envelope resulted in average duration of the knocks of 0.0086 s (SD: 0.004 s). The short duration on different days had significant differences (Kruskal-Wallis: N = 3462, p < 0.005, $\chi^2 = 175.6$, df = 4). There was a negative relationship between peak level and source duration. The linear regression was significant (N = 3462, $R^2 = 0.024$, $F = 84.67$, p < 0.005) (Figure 2-17). Analyzing only the first cluster of peak amplitudes with source durations less than 0.015 s was also significant (N = 2985, $R^2 = 0.20$, $F = 741.3$, p < 0.005).

![Figure 2-17. Plot of peak amplitude as a function of source duration. Secondary grouping around 0.02 seconds was isolated and regressions calculated for all knocks and for knocks with less than 0.015 s. Solid squares used for both regressions, hollow squares excluded for regression with durations less than 0.015 s (red line).](image)

Knocks often occur as part of stereotyped sequences. The temporal relationship of the knocks was investigated by comparing the inter-knock-interval between peaks of successive knocks. The natural break for the lag between knocks, determined by change point analysis, was approximately 2 seconds (Figure 2-15). Therefore, if the lag between successive knocks was greater than 2 seconds, the knock was considered to be part of a new sequence. 84% of all the knocks had less than a 2 second lag between successive knocks. Using this 2 second cut off, the knocks were grouped into 1509 sequences, and the
number of knocks per sequence was determined (Figure 2-16). The mean and standard deviation of the number of knocks per sequence was 6.2 ± 4.5. The sequence with the greatest number of knocks contained 27 knocks.

![Figure 2-18 Lag between knocks within the same sequence. The lag between most knocks was less than 2 seconds. Change-point analysis identified a change in regime at 2 second lag. Two seconds was used as the threshold for associating knocks within a sequence.](image1)

![Figure 2-19 Number of knocks per sequence aggregated over all recording days. Knocks were assigned to the same sequence if there was less than 2 seconds separating them. Sequences had up to 27 knocks, with the majority of sequences containing less than 10 knocks.](image2)
To determine whether the recorded knock durations changed as a function of the relative position in the sequence, that is the count of the knock within a sequence of knocks with inter-knock-interval less than 2 seconds, a Kruskal-Wallis non-parametric test of variance was computed for knock duration grouped by sequence number for a knock sequence number up to 16. It was found that the knock duration was significantly different between knock sequence numbers \((N = 3381, \ p < 0.005, \ \chi^2 = 183.7, \ df = 15)\) (Figure 2-20). It appeared that knocks after the first 9 might be influencing this result, so a Kruskal-Wallis test of the source duration and sequence number for the first 9 knocks was conducted and revealed that there was still a significant difference \((N = 3226, \ p < 0.005, \ \chi^2 = 134.6, \ df = 8)\) (Figure 2-21).

**Figure 2-20.** Box plot of knock duration grouped by sequence number. A significant difference in knock duration grouped by sequence number was found \((\text{Kruskal-Wallis}: \ N = 3381, \ p < 0.005, \ F (15) = 6.5)\). A trend of increasing duration with increasing sequence number can be seen, especially above sequence number 10.
Despite limiting analysis to the first nine knocks of the sequences, a significant difference in duration between knocks from different sequence numbers was still identified (Kruskal-Wallis: N = 3226, p < 0.005, $\chi^2 = 134.6$).

The inter-knock-interval was constant with sequence number. It has been reported that some wild walruses decrease the time between the successive knocks as the number of the knock increases (Sjare et al., 2003). A similar effect was not found in the captive subject. The linear regression between the inter-knock-interval and the number of the knock within a sequence was not statistically significant (N = 2472, $R^2 = 3.7 \times 10^{-5}$, $F$ (1) = 0.09, p = 0.76) (Figure 2-22). To determine if a change in inter-knock interval was consistent within sequences, a linear regression was calculated between inter-knock-interval and sequence number for each sequence with at least three knocks. The slopes of the regressions relate the change of the inter-knock-interval to the sequence number. The slopes had an approximately bimodal distribution with peaks at 0 and 0.5 (Figure 2-23). Out of the 741 sequences analyzed, only 11 of the regressions were found to be significant at the p = 0.05 level so the inter-knock-interval was considered constant within a sequence.
Figure 2-22. Inter-knock-interval within a sequence plotted against sequence number.

Figure 2-23. Distribution of slopes of inter-knock-interval as a function of sequence number. The slope of the inter-knock-interval measured whether the lag was changing within a sequence. For most of the knocks, the lag remained the same from previous knocks, thus the peak at 0.
Over the course of the observation period, 16 bouts of sustained vocalizations were recorded with a minimum duration of 5 minutes. The average duration of the 16 bouts was 47.1 minutes with a standard deviation of 29.3 minutes. The knock rate over all bouts was 28.8 knocks per minute or approximately 1 knock every 2 seconds. The total bout duration includes brief periods of no vocalizations as well as bell and whistle vocalizations. Although a few repeated patterns were identified within the bouts, the patterns were generally not consistent between days. The lack of a highly stereotyped, consistent pattern prevented the identification of a coda for this walrus.

**Discussion**

Source characteristics are an important input to acoustic propagation models. Source level, frequency content, and timing characteristics are all important to understand how a signal propagates through a specific environment and at what level the signal will be received at a given location. Two recent studies of walrus knock source levels reported a 10 dB difference in mean level (Hughes *et al.*, 2011; Mouy *et al.*, 2012). In addition to individual variation, the work presented in this chapter determined changes in source level associated with noise level and swimming activity of the walrus. The captive walrus subject in the current study produced knocks with mean source levels greater than the wild estimates (Chapter 3), but lower than the other captive study (Hughes *et al.*, 2011). However, the maximum source level measured as part of this study was higher than the other captive study. The knock rate and durations of knocks are valuable to understand how signal detection in a noisy environment can be impacted. Furthermore, the timing characteristics of knocks can provide insight into possible timing characteristic adaptations and their energetic implications in response to changing environmental conditions, although no relationship between timing and behavioral or noise conditions in the captive environment were detected.
Source Level

The estimated source level was 183 dB$_{re}$ (re: 1 µPa). Hughes et al. (2011) estimated the source level for knocks from a captive sub-adult male Pacific walrus to be 186 dB$_{re}$ (re: 1 µPa). The difference between the two estimates could be caused by differences between the two individuals or related to the effect of age on the individuals. The male subject in Hughes et al. (2011) was approximately 11-13 years old during that study, while the subject in this research was 26 years old. Fay (1982) determined that adult males become physically mature around the age of 15 years old at which point they are able to compete for females. The only data regarding this walrus’ hearing was anecdotal from the SeaWorld San Diego Wild Arctic staff. It was reported that the walrus responds readily to verbal as well as non-verbal acoustic cues, such as whistles. The walrus has no history of ototoxic medication. From this anecdotal data, it would appear that this individual could hear well and was not vocalizing at artificially high levels due to a hearing deficit.

The higher source level recorded when the walrus was underneath the platform was investigated. During calibration of the enclosure, a source was moved throughout the pool including underneath the platform. Transmission loss corrections from this calibration were incorporated into the source level estimates in this study. It is possible that the increased level was related to the lack of motion on the part of the subject. While the walrus was underneath the platform, the subject was mostly stationary. By resting underneath this platform, the individual may have been able to devote more effort to the knocks compared to those when he was swimming in open water. It may also be the case that by making contact with the underside of the platform, more of the acoustic energy was directed towards the hydrophone. A third hypothesis for these higher levels is that the walrus instinctively increased the level of the knock while resting under the platform. In the wild, vocalizing males could make contact with ice platforms and increase the level of the vocalizations so that higher levels of acoustic energy are coupled to the ice and reach the females hauled out on the ice. Greater research of wild walruses during breeding season, including the use of acoustic tags could shed light on this interesting effect.
The walrus produced louder knocks when the background noise level was higher (Figure 2-12). The vocal modification of increasing the level of the source signal in response to noise, the Lombard effect, has not been reported in any pinniped species to date (Hotchkin and Parks, 2013). Changes in the duration of the knocks would likely not have a large impact on their perceptibility as the impulsive nature of the knocks result in very short durations. Likewise, the impulsive nature results in broadband signals and thus spectral changes are unlikely. Modifications that would more likely be successful to compete with noise for walrus would be to increase the source level, change the timing characteristics, or change the types of vocalizations produced. The work here suggests that walrus do increase source level in response to noise.

The increase in knock source level was not greater than the increase in noise, similar to that found in other studies (Hotchkin and Parks, 2013). This suggests that if noise levels were to continue to increase, the signal-to-noise ratio would decrease (Figure 2-13). The ability to produce louder vocalizations is most likely limited; there is some maximum source level that walruses are not able to exceed. This correlation between the signal level and the noise level suggests that it may be possible that walrus use an amplitude modification to the knock vocalization to increase detectability in noise. A lack of research on vocalization source levels for pinnipeds may have contributed to the lack of observation of this effect. As the mechanism by which walrus produce this vocalization is still unknown, it remains unclear how the source level can be increased. Furthermore, the energetic cost of increasing the amplitude of the vocalization is unknown. As the vocalizations are quite ubiquitous, with up to 75 knocks per minute (Mouy et al., 2012), any energetic increase for an individual knock could result in a large cumulative effect on an individual walrus producing hundreds of knocks per hour. If the noise levels in the eastern Bering Sea increase and lead to walrus vocalizing louder, effects could include changes in activity budgets, increases in stress level, and inability to find a suitable mate. Male walruses may have to spend a larger portion of their time foraging or resting, and not tending to females and attempting to mate, or be less fit. The walrus studied here, and reports from previous studies, show that the males produce vocalizations in bouts. The walrus produced vocalizations for sustained periods of up
to two hours, and then did not produce vocalizations for another sustained period of time. In Atlantic walruses, sustained singing bouts of up to 81 hours have been observed followed by intervals lacking singing on the order of the same duration as the previous bout (Sjare et al., 2003). The purpose of these break periods is not known, but if the vocalizations are energetically expensive, these periods could be used for resting or foraging. Increasing the level of vocalizations may also result in increased stress levels within the vocalizing individual, degrade the reception of signals by females resulting in changes to mate selection, or with enough noise increases completely mask the vocalizations.

**Knock Timing**

The duration of the recorded knock signals were short. However, the reverberant pool prevented the direct measurement of the duration of a single arrival of a knock. From the decay in the amplitude envelope of the waveform, the duration of the knocks was estimated to be 0.0086 s. The temporal integration time for hearing in walrus has not been measured underwater or in-air. The underwater temporal integration time of harbor seals (*Phoca vitulina*) have been shown to be related to the number of cycles of a tone; the temporal integration time was frequency dependent (Terhune, 1988; Kastelein et al., 2010). In the only study of in-air temporal integration time in pinnipeds, detection thresholds decreased with increasing tone durations from 25 to 300 ms in a California sea lion (*Zalophus californianus*) (Holt et al., 2012). These temporal integration times are longer than the calculated duration of the knocks. The perceived level of the knock would be lower than that calculated here. However, for those species for which there are more data, humans and other mammals, the temporal integration time for broadband signals was shorter than the temporal integration time of tones (Au et al., 1988; Zwislocki, 2005). The duration of these signals were on the order of the 1/3 the shortest tonal signals detected by a California sea lion in air. This factor of 1/3 was greater than that determined in humans and cetaceans, suggesting that the duration of the walrus knock would not limit perception, if inferences from California sea lions, humans, and cetaceans are valid for walrus temporal integration.
The duration of the knock was shown to be related to the sequence number of the knock with increased duration as the sequence progressed. However, the effect was small especially for the first 10 knocks. It has been documented that walrus knocks are often emitted in sequences of repeated knocks (Schevill *et al.*, 1966; Ray and Watkins, 1975; Sjare *et al.*, 2003). By identifying the change point of the inter-knock-interval as 2 s the division of knocks into sequences was formalized. Prior to looking at the change point, the grouping of knocks was subjective. The inter-knock-interval was found to be constant within a sequence. The inter-knock-interval for this captive male did not decrease into a buzz as was reported to occur at the end of some sequences by Sjare *et al.* (2003). The constant interval between knocks measured here does not suggest that the timing of the walrus knocks are related to noise and rather that the interval change may be an individual characteristic not present for all walruses. The presence or absence of interval changes may be useful for attributing knocks from different walruses in the wild when other factors are unable to distinguish the sources.

**Frequency Content**

Previous research has documented that the impulsive nature of the knock resulted in a broadband signal with dominant energy below 5 kHz (Schevill *et al.*, 1966; Ray and Watkins, 1975; Stirling *et al.*, 1983). The recordings of the male walrus in captivity described here support the previous findings with 99% of the acoustic energy below 2 kHz and a decrease of 6 dB per octave from the peak to maximum frequency. The peak frequency was 755 Hz but the spectral levels were comparable up to 1300 Hz. The underwater and in-air audiograms of walruses show maximum sensitivity of hearing in the range of 500 Hz to 12 kHz and 1 kHz to 4 kHz, respectively. The underwater sensitivity of walrus covers most of the band of the knocks. The decrease in energy with increasing frequency is not unique to walruses. Noise in the ocean exhibits similar behavior (Wenz, 1962). The spectral slope of -6 dB per octave represents a decay equivalent to that of wind noise. Noise spectra associated with various wind speeds have the same 6 dB per octave decrease above 1 kHz regardless of wind speed (Wenz, 1962). Unless noise or receivers
lead to conditions favoring higher frequencies, producing a signal with concentration of acoustic energy in higher frequencies does not result in increased detection due to the greater molecular absorption, and interface and volume scattering of the higher frequencies.

Conclusions

The mean source level of 183 dB was similar to the level measured by Hughes et al. (2011) in captivity and higher than the estimate from the wild (Mouy et al., 2012). However, the maximum peak level measured here was greater than the maximum peak level recorded in captivity previously (Hughes et al., 2011). The results here suggest that knock amplitude is increased with an increase in noise level, the first documentation of a Lombard effect in a pinniped.
Chapter 3

Source Estimation from Wild Walruses

Introduction

While the captive environment provides access to animals that may be difficult, dangerous, and expensive to gain access to in the wild, the confinement and lack of various social and environmental cues in captivity need to be addressed. In the captive setting, the environment is relatively stable, food is easily available, and there was no interaction with other walruses while breeding vocalizations were produced. The noise sources and levels, as well as the influence of the exhibit pool on the acoustic propagation, in captivity vary greatly from these animals’ natural environs. In an attempt to validate the vocalization characteristics from a captive individual’s vocalizations, source characteristics of wild vocalizations were quantified.

Much of the knowledge we have regarding animals has come from studies of specimens held in captive collections. Physiology, social structure, behavior, foraging abilities, and vocalizations have all benefited from studies conducted in a captive setting. Corroborating the findings of the studies from captive research with studies of wild animals can provide managers and decision makers the best information on which to affect policy related to these animals.

The captive environment at the Wild Arctic facility at SeaWorld San Diego is very different from the wild environment of the Bering Sea. In the wild, Pacific walrus spend much of their time in water over the continental shelf with depths up to 100 m (Fay, 1982). The facility at SeaWorld had a maximum depth of 16 feet, approximately 5 m. Walrus can travel up to 200 km per day in the wild (Fay, 1982). The captive facility prevents swimming in any one direction more than 10 m. The water temperature in the captive facility is kept at approximately 13°C, while the water temperature in the wild is variable but
at depth is often around freezing, 0 °C. There is no sea ice coverage at SeaWorld San Diego; in the wild, sea ice is the defining characteristic. In the wild, Pacific walrus are believed to have lek-like breeding groups, where multiple males show off to a group of females in order to win a chance to breed (Fay et al., 1984). At SeaWorld San Diego, there is only one adult male and one adult female housed together. During rut, the animals are separated due to the facilities’ breeding program. The urban environment of SeaWorld San Diego affects the noise environment of the facility. The pumps, chillers, and filters that provide and treat the water in the facility lead to high ambient noise levels. Transportation noise is also present. All of these factors may impact the walruses and therefore affect the vocalizations of captive animals.

Direct observation studies of vocalization displays of Atlantic walrus have been conducted during breeding season with researchers stationed on cliffs overlooking polynya in the Canadian high Arctic. These studies focused on the patterns of vocalizations in the displays and the ability to classify individuals from these vocalizations. Unfortunately, similar studies of Pacific have not been conducted. Pacific walrus breeding activities most often take place in polynya in the Bering Sea. The skittish nature of walrus and the remote location of the breeding grounds make direct observation at this time of year almost impossible.

One method for studying the vocalizations of these animals is through the use of remotely deployed autonomous underwater acoustic recorders. These recorders permit the collection of long term acoustic data records of the area without the presence of human observers. However, without human observers, a lot of information is unknown about the sources of the sounds recorded. Physical characteristics of the source individual are not known. There is no data on the size, weight, age, or other factors of the individual vocalizing. The number and location of vocalizers is unknown. A single individual may be dominating the acoustic record, or the recordings may be comprised of the vocalizations from many individuals located within acoustic range of the recorders. Because the location of the source cannot be observed, the range over which the signal has propagated will be unknown, and therefore the effect of the environment on the signal is not known.
A method for estimating the range and depth of a source signal recorded on a single hydrophone was described in Cato (1998). Previous works in localization of sources from multipath arrivals using a single hydrophone rely on the timing of the multipath arrivals and analysis of the phase relationship of the arrivals (Cato, 1998; Aubauer et al., 2000; Rideout, 2012). Multipath arrivals of the vocalizations permitted determination of time of arrival differences. Recent studies have applied these methods to determine the location of a vocalizing walrus from a single hydrophone recording (Mouy et al., 2012; Rideout, 2012). The relative locations of vocalizing walruses were estimated using this method. The source location can then be used to estimate the transmission loss on the recorded signal. From this analysis, source characteristics of wild vocalizations were estimated.

The acoustic arrivals consist of the direct path and different orders of multipath propagation. The different orders are based on the number of times the signal is reflected before arriving at the receiver. In the Bering Sea in winter, the water column is fairly stable with a consistent mixed temperature and salinity profile over the course of the winter. This mixed water column profile indicates that the acoustic rays travel in straight lines, with little refraction. In a homogenous medium, where the sound speed is uniform, there is no refraction of the travelling rays. When refraction is considered insignificant, the multipaths occur due to reflection of the sound at interfaces of different media. In the situation considered here those interfaces are the bottom, which is mostly flat around the recorder at approximately 70 m depth, and the air or ice at the surface. With a uniform sound speed throughout the water column, differences in arrival time are linearly related to the length of the path. Higher order paths, those with more surface and bottom reflections, are longer and always arrive after the direct path arrival.

The two recent studies applying multipath arrival localization to Pacific walrus vocalizations (Mouy et al., 2012; Rideout, 2012) were from recorders deployed in the Chukchi Sea with knocks recorded over summer. The herds of walrus that are found in the Chukchi Sea in the summer are comprised of adult females, their dependent young, and immature males. Rideout (2012) depended on the identification of the peaks based on their paths as either direct, surface reflected, bottom reflected and so on. To identify arrivals, the phase relationship between successive peaks was examined. This depended
on the impact of reflections on the phase of a signal. The surface reflected path was identified from the direct and bottom reflected paths by presence of a phase reversal and time lag. As the data for this work relies on the recordings of walrus vocalizations from the Bering Sea in late winter and early spring, a period characterized by sea ice coverage, open water was not always present. Due to the presence of ice, not all surface interacting paths had a phase reversal.

The methods for determining the location of the source signals from Rideout (2012) and Mouy et al. (2012) were based upon the same fundamentals, but employed different algorithms for source localization. Rideout (2012) directly solved equations for the time difference of arrival of the multipaths given the environmental conditions of the water column depth and sound speed. Rideout’s examination of single hydrophone walrus localization was limited to a short 7 second sequence of knocks, and was not used to characterize the acoustical or temporal qualities of the knocks. Mouy et al. (2012) localized vocalizing walrus by matching the time of arrivals to a set of modeled time of arrival peaks. In Mouy et al. (2012) longer sequences of knocks were analyzed. However, the shallower water in which the deployment took place limited the depths from which the animals were vocalizing. The walrus tracks described by that research document only one instance in which knocks were produced at depths greater than 20 m. Of the three tracks examined, one was at constant depth, one had repeated shallow dives and one was more variable but contained one deeper dive. The authors attribute the patterns to travelling, navigating or foraging. A repeated shallow depth dive profile, classified as Type I dives described in Jay et al. (2001) in which swimming behavior was recorded with time-depth recorders, was associated with travelling behavior. Mouy et al. (2012) estimated source level and timing characteristics of the knocks recorded in the Chukchi Sea. Knock source level was estimated by Mouy et al. (2012) to be 177 dB$_{pp}$ (re: 1 μPa @ 1 m). However, these vocalizations are not those of the breeding displays of adult male walruses.

Estimates of walrus knock characteristics from wild recordings were calculated by correcting the effect of propagation on the received signal. The range and depth of the source walruses was determined
using the multipath arrivals of the knocks. The estimates from this work were used to determine the audibility of walrus knocks in a variety of environmental conditions in Chapter 5.

**Methods**

**Recordings**

Two autonomous passive acoustic recorders with different sampling strategies were collocated on an oceanographic mooring maintained by NOAA’s Pacific Marine Environmental Laboratory as part of the Fisheries Oceanography Coordinated Investigations (Eco-FOCI) Program (Stabeno *et al.*, 2010). The Passive Aquatic Listener (PAL) is an adaptively sub-sampling recorder developed by Jeffrey Nystuen at the University of Washington (Nystuen, 1998) and the AURAL-M2 (Multi-Electronique Inc., Quebec) is a commercially available, programmable passive acoustic recorder. The mooring was located on the 70 m isobath southeast of St. Matthew Island in the eastern Bering Sea (59° 54.285’ N, 171° 42.285’ W) (Figure 1-4) (Stabeno *et al.*, 2008b). The PAL and AURAL were deployed serially in the mooring line at depths of 65 m and 67 m, respectively until 2009. In subsequent years, the PAL was deployed to 67 m depth.

The PAL consists of a wide-band (0-50 kHz), low-noise hydrophone (HTI-96-MIN), pre-amplifier, and recording computer. An internal battery pack provided power for instrument operation. On-board memory consisted of a 2 GB compact flash card. The PAL was programmed to record a 4.5 second audio clip at a sampling rate of 100 kHz every 10 minutes. Eight spectra were created from 10.24 ms subsamples spaced equally throughout the 4.5 sec clip. The spectral values were compressed by integrating the frequency bins over 200 Hz bandwidths from 100 to 3000 Hz and 1 kHz bandwidths from 3 to 50 kHz (Nystuen, 1998). The eight individual compressed spectra, or spectra cluster, were analyzed against predetermined detection thresholds. A signal of interest was detected in the sample if one of three criteria were met: 1) matching predefined spectral patterns for rain, 2) a 12 dB amplitude threshold
difference for sequential samples, or 3) peaks in frequency bins indicating tonal signals (Miksis-Olds et al., 2010). Exceeding any of the criteria resulted in detection and the implementation of the adapted sampling protocol. If the recording was determined to contain a signal of interest, the audio clip and the spectra cluster were saved to memory, otherwise the audio clip was cleared, the spectra were averaged, and only the average spectrum was saved. Additionally, if a signal of interest was present, the PAL reduced the sampling interval from 10 to 2 minutes until a signal of interest was no longer detected. These two sampling intervals resulted in duty cycles of 0.75% and 3.75%, respectively. A daily quota of 6 saved audio clips was selected based upon the expected deployment duration to ensure adequate disk space. If the number of audio clips saved for any day was less than the quota, the excess allocation was made available to subsequent days up to a maximum of 21 total audio clips per day (Miksis-Olds et al., 2010).

**AURAL**

The AURAL-M2 consists of a wide-band (2 Hz- 30 kHz), low-noise hydrophone (HTI-96-MIN), preamplifier and recording computer. Data were saved to a 320 GB internal hard drive. The system has a user selectable sample rate, gain, and duty-cycle. The AURAL was programmed to record semi-continuously for nine minutes every half hour, a 30% duty cycle, at a sampling rate of 8192 Hz. These parameters were selected to ensure battery life and memory capacity was sufficient for a yearlong deployment. Recordings from the AURAL were initially processed by two frequency band energy detectors. Using Ishmael software, audio clips of signals containing elevated energy in the 0.1-1 kHz and 0.9-4 kHz frequency bands were created (Mellinger, 2001). Detection occurred if the average energy over either band exceeded a threshold of 0.025 normalized units, and a 10 second sound clip was extracted. If successive detections resulted in overlapping sound clips, a single non-duplicated sound clip was created. The low threshold was selected to ensure that almost all transients would be detected. For
many of the days, detections from elevated energy in the frequency bands resulted in near continuous detections from the nine minute sampling period.

**Environment**

Additional remote sensing measurements quantified the environment of the area. An oceanographic mooring located within 1 km of the acoustic recorders was deployed with temperature and salinity sensors. Temperature sensors were deployed at depths of 21, 25, 33, 38, 45, 50, 60, and 67 m. Salinity sensors were deployed at depths of 19, 29, and 55 m. Data were provided by NOAA PMEL. Sound speed was calculated using Equation 3-1 (Medwin, 1975).

\[
c = 1449.2 + 4.6T - 5.5 \times 10^{-2}T^2 + 2.9 \times 10^{-4}T^3
\]

\[
+ (1.34 - 10^{-2}T)(S - 35) + 1.6 \times 10^{-2}D
\]

**Knock Identification**

The data from the event detectors of each recorder consisted of extracted files that had already been determined to contain transient events. An automated walrus knock detector relying on the kurtosis of the acoustic signal was run on these extracted files to determine the presence of walrus knocks on the recordings. The kurtosis of a signal is a measure of the peakedness (Equation 3-2). Walrus knocks are well suited for detection using kurtosis due to their impulsive nature. The kurtosis was calculated for windows of 25 ms with 20% overlap. Detections within 12 ms of another detection were excluded. Detection occurred if the kurtosis for any sample exceeded a normalized value of 10. Window characteristics and detection threshold were selected empirically to produce a high detection rate with low computational time. Manual confirmation of the detections was conducted to confirm the presence of walrus knocks in these files and determine the usability of the walrus knocks for analysis (Figure 3-1).
\[ K(x) = \frac{\sum_{n=1}^{N} (x[n] - \mu)^4}{(N-1)\sigma^4} \]

Inclusion of walrus knocks for analysis was limited to recordings with at least 10 dB of signal-to-noise ratio. This cut-off was chosen based on what levels worked in sample analyses. When knocks were determined to be present and of sufficient signal to noise ratio, the Teager-Kaiser energy operator output for the time series was used to emphasize the knock. The Teager-Kaiser energy operator amplifies discontinuities in a signal and deemphasizes small transitions. For a discrete signal, the Teager-Kaiser energy operator for each data point is the square of the value minus the product of the data points immediately before and after the current data point (Equation 3-3). Initially, the period of time investigated containing the multipath arrivals was set to 0.125 seconds. The duration was refined to include up to the time at which point 99% of the cumulative Teager-Kaiser energy of the sequence was exceeded from the direct arrival peak identified using the kurtosis (Figure 3-2).

\[ TK[x(n)] = x^2(n) - x(n - 1) * x(n + 1) \]
Figure 3-1. Spectrogram, kurtosis, and pressure waveform of a sequence of knocks. Red circles identify kurtosis peaks above threshold of 10 and corresponding peaks in the waveform. Knocks were detected if the kurtosis of the time series was greater than 10. Knock detections were validated to insure that the signals were knocks and were not corrupted by other transient signals.
Figure 3-2. Pressure waveform, normalized Teager-Kaiser energy time series and cumulative normalized TK energy series for knock 26 from example sequence. The 99% level of the cumulative Teager-Kaiser energy was used to determine the length of the extracted knock signal used in the knock localization algorithm.
Source Localization

Assuming the propagation conditions are constant in time and space, and known, the distance and depth of the vocalizing individual can be estimated. Using the time difference of arrival of the direct, surface, and bottom reflected arrivals, the range \((r)\) and depth \((d)\) of the vocalizing animal can be determined by measuring the time delays and the use of Equations 3-4 & 3-5 (Aubauer et al., 2000).

\[
\begin{align*}
    r &= \left(\frac{c \cdot \tau_{1b}}{2}\right)^2 + b \cdot (a - b) - \left(\frac{c \cdot \tau_{1s}}{2}\right)^2 \cdot \left(1 - \frac{b}{a}\right) \\
    d &= \left(\frac{c \cdot \tau_{1b}}{2}\right)^2 + \left(\frac{c \cdot \tau_{1b}}{2}\right) \cdot r + b
\end{align*}
\]

Where \(c\) is the speed of sound, \(a\) is the hydrophone depth, \(b\) is the water depth, and \(\tau_{1b}\) and \(\tau_{1s}\) are the time delays of the bottom and surface reflected arrivals. In open water situations, the air-water interface introduces a phase reversal that permits the identification of first order surface reflected arrivals. The presence of ice prevents this classification; the reflection from the ice will not have this phase reversal as the ice has a higher impedance than water.

For example, consider a walrus vocalizing 32 m below the surface, at 800 m range from a receiver at 65 m depth. Assuming the speed of sound throughout the water column is 1450 m/s, the difference in path traveled for each of the first 9 arrivals is given in Table 3-1. An example of the propagation paths and image receivers is given in Figure 3-3. The series of unit amplitude, synthetic arrivals with infinitesimal duration for this situation is characterized by the peaks in Figure 3-4. The range and depth of the image receivers to the source are given by Equations 3-6 to 3-9. The relative time of arrivals for the multipaths were calculated for sources at any given range and distance with 1 m resolution from these equations for each day based on the average water column sound speed for that day.
Figure 3-3. Plot of multipath arrivals (solid lines) with isovelocity sound speed profile and identified image receivers (dashed lines). This is a cartoon of the situation documented in Figure 3-4, showing the longer propagation paths travelled by the higher order reflected paths.
Figure 3-4. Plot of idealized, synthetic peak arrivals from a source located 32 m deep and 800 m in range from receiver deployed to 65 m. Assuming an isovelocity environment with sound speed of 1450 m/s, each peak represents the time lag for an arrival relative to the direct path propagation (D). Arrivals are labeled with the reflections from the propagation path in the order they occur: B – bottom reflected; S – surface reflected; BS – bottom and surface reflected; SB – surface and bottom reflected.

\[ r_{ns} = \sqrt{r'^2 + h_{ns}^2} \]  \hfill (3-6)

\[ r_{nb} = \sqrt{r'^2 + h_{nb}^2} \]  \hfill (3-7)

\[ h_{ns} = \begin{cases} b \times (n - 1) + a + d, & n \text{ odd} \\ b \times n - a + d, & n \text{ even} \end{cases} \]  \hfill (3-8)

\[ h_{nb} = \begin{cases} b \times (n - 1) - a - d, & n \text{ odd} \\ b \times n + a - d, & n \text{ even} \end{cases} \]  \hfill (3-9)

Where \( a \) is the depth of the receiver, \( b \) is the depth of the water, \( r' \) is the horizontal range of the source to receiver, \( d \) is the depth of the source, \( n \) is the number of reflections for the given path.
Table 3-1. Range, depth, travel distance, and arrival lag for a synthetic vocalization. Calculation of distances and lags are based on a source 32 m below the surface 800 m in range from a receiver deployed to 65 m depth in 70 m of water. Water column is assumed uniform with sound speed of 1450 m/s. Time lag is the time in seconds between the arrival specified and the direct path arrival.

<table>
<thead>
<tr>
<th>Path</th>
<th>Range</th>
<th>Depth</th>
<th>Slant Range</th>
<th>Time Lag</th>
<th>Reflections</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>800</td>
<td>33</td>
<td>800.6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>800</td>
<td>47</td>
<td>801.4</td>
<td>0.00051</td>
<td>1</td>
</tr>
<tr>
<td>S</td>
<td>800</td>
<td>97</td>
<td>805.9</td>
<td>0.0036</td>
<td>1</td>
</tr>
<tr>
<td>BS</td>
<td>800</td>
<td>177</td>
<td>819.3</td>
<td>0.013</td>
<td>2</td>
</tr>
<tr>
<td>SB</td>
<td>800</td>
<td>111</td>
<td>807.7</td>
<td>0.0048</td>
<td>2</td>
</tr>
<tr>
<td>BSB</td>
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<td>191</td>
<td>822.5</td>
<td>0.015</td>
<td>3</td>
</tr>
<tr>
<td>SBS</td>
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<td>241</td>
<td>835.5</td>
<td>0.024</td>
<td>3</td>
</tr>
<tr>
<td>BSBS</td>
<td>800</td>
<td>321</td>
<td>862.0</td>
<td>0.042</td>
<td>4</td>
</tr>
<tr>
<td>SBSB</td>
<td>800</td>
<td>255</td>
<td>839.7</td>
<td>0.027</td>
<td>4</td>
</tr>
</tbody>
</table>

For each range and depth on each day, the relative multipath arrival lag from the direct path was computed for each of the 8 arrivals up to the fourth order multipath. A binary time-series, 1 or 0, with the same sampling rate as the detection, was created for the modeled environment representing whether the multipath arrival was present (1) or absent (0) for each time step for each range and depth pair. To compensate for uncertainties in the environment due to sound speed, location of the walrus and receiver, bathymetry, and ice coverage, a buffer of ±1 ms around each arrival was created in the binary matrix (buffer values equal to 1). A score, \( I \), representing the goodness of fit of the modeled relative arrival times with the Teager-Kaiser energy of the multipath arrivals was computed for each range and depth as

\[
I(r, d) = \frac{ms}{ms' M}
\]

where \( M \) is the number of multipaths included in the model for the duration including in the 99% of the cumulative energy, \( m \) is the normalized Teager-Kaiser energy, and \( s \) is the binary vector of multipath arrivals. \( s' \) is the logical complement (values are switched) to the binary vector and acts as a penalty for
mismatches. The range and location of the walrus was identified as the point with a maximum score I. This methodology was based upon Mouy et al. (2012). For a random selection of knocks from each recorder, the locations were validated through manual peak identification and solving of Equations 3-6 through 3-9.

**Data Validation**

The walrus localizations were plotted for comparison with the acoustic time series. The localizations from the knocks and time series were evaluated to determine whether they were all from the same walrus. If the knocks were determined to be from the same walrus, subjectively, then knocks that were localized incongruously with the rest of the sequence were flagged and excluded from source level estimation, but still included in timing analyses. If the knocks were determined to be from different walruses, they were excluded from all analyses. Sequences from different walruses had irregular or alternating patterns of amplitude and inter-knock-intervals. Knock sequences from different walruses that overlapped in time would corrupt analyses regarding timing, and the inconsistency in localizations would reduce confidence in source level estimates. The localizations of the sequence of knocks from Figure 3-1 were plotted in Figure 3-5. After listening to and visually inspecting the waveform and spectrogram, the knocks were determined to be from one walrus. The cluster of localizations at around 800 m in range at and 15 m depth are consistent, but the three localizations at less than 150 m in range are not (Figure 3-5). Knocks 7, 27 and 28 were excluded from the source level estimates. Examples of poor, average, and good multipath arrivals and the localization index maps associated with them are provided in Figure 3-6 through Figure 3-8.
Figure 3-5. Localizations of walrus knocks from example sequence (Figure 3-1) of walrus knocks from a 7 second sample. The localizations except those associated with the 7th, 27th, and 28th knocks were all at about 800 m range and 15 m depth, with a general downward trend. The incongruous knocks 7, 27, and 28 were excluded from source level estimation. The localized points at 800 m showed the walrus traveling away from the recorder and towards the surface.
Figure 3-6. Example of multipath knock arrivals, normalized TK energy, and localization index map for a poorly localized knock. There is no clear location that indicates where the vocalizing walrus was.
Figure 3-7. Example of multipath knock arrivals, normalized TK energy, and localization index map for an average knock localization. There are a couple locations, within a small range, where it was likely the vocalizing walrus was.
Figure 3-8. Example of multipath knock arrivals, normalized TK energy, and localization index map for a well localized knock. There is one clear location that indicates where the vocalizing walrus was.
**Reverse Propagation**

Using this approach, the location of the vocalizing walruses was obtained relative to the recorders. The effect of the propagation on the recorded signal can be accounted for by considering the physical effects on the signal due to propagation. The losses associated with the direct path are a result of an increasing ensonified area and absorption (Urick, 1983). The spreading loss, associated with the increasing ensonified area, can be accounted for with a spherical spreading model. The area ensonified by the direct path is just a sphere with radius equal to the range. The spherical spreading loss model is an acceptable model for the direct path as the short duration signal of the knocks yields peaks that are not affected by interaction with multipath arrivals. Therefore the spreading loss was accounted for using the \(20 \log_{10} R\) spherical spreading model, where \(R\) is the slant range from the localized walrus to the recorder. Absorption is related to the propagation range, the environmental parameters, and the frequency content of the signal.

The peak-peak amplitude was measured by finding the maximum and minimum of the time series from the 25 ms of data associated with the kurtosis sample that triggered detection. The 25 ms sample often included the first three to four arrivals in case interference between paths impacted the recorded amplitudes. The noise level estimates were calculated from periods immediately before and after the detected knocks without regard for other signals in the recording, except for other detected knocks. Samples from the time series were flagged as noise if they were not within any of the periods determined by the 99% cumulative Teager-Kaiser energy of the knock detections. Noise level was calculated from the mean-square of the calibrated pressure signal flagged as noise.

**Results**

A nearby oceanographic mooring was instrumented with temperature and salinity sensors at fixed depths. Sound speed was calculated with salinity values corresponding to the nearest temperature sensor.
Daily sound speed was calculated for the eight depths of the temperature sensors based on the mean temperature and salinity values from that date (Figure 3-9).

![Figure 3-9. Sound speed profile as a function of date from deployed temperature and salinity meters in the winter of 2009 at M5. After sea ice cover was present, the water column was relatively stable with isovelocity sound speed profile. Measurements were limited to below 19 m depth as instruments cannot be deployed safely above that depth due to possible ice keels.]

AURAL data were analyzed only from the year 2009. From the AURAL recordings, a total of 70,553 knocks were identified. Each knock contained anywhere from one to 9 multipath arrivals, with one arrival indicating that only one path, most likely the direct path, was detectable. After exclusion of sequences with overlapping knocks from multiple walrus, 58,836 knocks remained. From this total, 36,782 knocks were localized. Knocks from the PAL were analyzed from the years 2008-2013. In 2008, 293 knocks were localized from 38 files. In 2009, 84 individual knocks were detected in 13 files from the PAL. In 2010, 239 knocks were localized from 35 files. In 2011, a total of 159 knocks were localized from 17 files. In 2012, 110 knocks were localized from 13 files. In 2013, 80 knocks were localized from 13 files. The PAL data provides higher sampling rate data along with estimates from multiple years.
The sampling protocol of the PAL limited the number of knocks that were recorded. The maximum of 4.5 s of continuous recording prevented long sequences of knocks from being obtained. Knocks were identified in 129 PAL recordings from 2008 – 2013. The number of individual knocks identified on those 129 PAL recordings was 965, with a maximum of 21 knocks in one 4.5 s sample (Figure 3-10). The mean inter-knock interval measured from the PAL was 0.27 seconds (Figure 3-11). The sampling protocol of the PAL precluded the measurement of any sequence scale metrics.

Figure 3-10. Knock count per 4.5 s PAL file. The number of knock per file recorded by the PAL. Each file contained only a portion of a sequence ranging anywhere from 1 to 21 knocks.
Figure 3-11. Histogram of Inter-knock-interval for knocks detected on the PAL recorder. The majority of successive knocks had less than 0.5 seconds between them.

The mean source level calculated from the localized PAL knock detections for all years was 172 dB$_{pp}$ (re: 1 µPa @ 1 m) with a maximum source level of 197 dB$_{pp}$ (re: 1 µPa @ 1 m). The average spectrum measured from the PAL showed that the dominant energy of the knocks was contained below 10 kHz (Figure 3-12). The dB averaged signal-to-noise ratio calculated from 0 – 10 kHz on the PAL was 39 dB. As the distributions of source levels were not from a normal distribution, differences between mean ranks of the levels by year were compared in a non-parametric analysis using a Kruskal-Wallis test of variance. The mean rank of the source levels (Kruskal-Wallis: $\chi^2 = 41.1$, df = 1,046, p < 0.005) (Figure 3-13) and noise levels (Kruskal-Wallis: $\chi^2 = 78.8$, df = 1046, p < 0.005) were different between years. The SNR varied from year to year (Kruskal-Wallis: $\chi^2 = 83.3$, df = 1,046, p < 0.005).

The relatively high sampling rate of the PAL recorder permitted calculation of frequency content of the knocks. The knocks were broadband with an average bandwidth above the ambient spectrum from 100 Hz to 10,060 Hz. The average peak frequency of the knocks detected on the PAL was 1,074 Hz.
The dB averaged signal to noise ratio measured from the PAL recordings was 39 dB. Comparing the source level to the noise level, a relationship of 5.5 dB increase in source level for every 10 dB increase in noise level was observed. The linear fit of source level to noise level was significant ($R^2 = 0.11$, $F = 104.8$, $N = 966$, $p < 0.005$). To reduce the likelihood that a significant result was the result of a large sample size, the PAL SNR data were analyzed by year (Figure 3-15). All years, except 2009, had a positive relationship between source level and noise. The linear regressions of the source level to noise levels were significant and positive in all years except 2009 and 2013 (Table 3-2). Comparing the mean source levels and noise levels by year resulted in a similar 5 dB increase in source level for a 10 dB increase in noise level (Figure 3-16).

![Figure 3-12. Average spectrum from knocks recorded on the PAL. N = 966, FFT size 1024, 50% overlap, Hanning window. Frequency bins were averaged over the duration of each knock, and then the average of each knocks spectra was used to generate an overall average. Dominant energy was contained below 10 kHz.](image-url)
Figure 3-13. Source level versus year from the PAL. A Kruskal-Wallis test of source level and year showed significant differences in the mean ranks of source level by year. Some years were louder than others.

Table 3-2. Estimates of Lombard effect size by year, and for average yearly SNR with 95% confidence intervals. If the confidence interval does not include 0, an effect is present.

<table>
<thead>
<tr>
<th>Year</th>
<th>Estimate</th>
<th>95% confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>0.298</td>
<td>(0.14, 0.46)</td>
</tr>
<tr>
<td>2009</td>
<td>-0.832</td>
<td>(-1.45, -0.21)</td>
</tr>
<tr>
<td>2010</td>
<td>0.853</td>
<td>(0.63, 1.07)</td>
</tr>
<tr>
<td>2011</td>
<td>0.788</td>
<td>(0.61, 0.97)</td>
</tr>
<tr>
<td>2012</td>
<td>0.969</td>
<td>(0.47, 1.46)</td>
</tr>
<tr>
<td>2013</td>
<td>0.247</td>
<td>(-0.044, 0.54)</td>
</tr>
<tr>
<td>Yearly Average</td>
<td>0.550</td>
<td>(0.12, 0.98)</td>
</tr>
</tbody>
</table>
Figure 3-14. Plot of source level from PAL against noise level aggregated for all years. The increase in source level with a correlated increase in noise level is indicative of Lombard effect.
Figure 3-15. Source level versus noise level for each year of data from the PAL. All years except 2009 had a positive relationship between source level and noise level, and all years except 2009 and 2013 had significant regressions.
Figure 3-16. Average source level by year plotted as a function of average noise level associated with knocks for each year. A positive regression with similar effect size of 5 dB increase in source level per 10 dB increase in noise level was identified.
AURAL Source Level

The mean peak-peak source level estimated from detections made on the AURAL corrected for spherical spreading was 177 dB (re: 1 µPa @ 1 m) with 95% of the knocks between 163 dB and 189 dB. The maximum estimated peak-peak source level was 206 dB (re: 1 µPa @ 1 m) (Figure 3-17). There was a slight increase in the peak source level with increasing distance of 2.4 dB/km. This linear increase in level with distance was significant ($R^2 = 0.011$, $F = 421$, $N = 36781$, $p<0.005$). This was most likely due to a sampling bias. Quieter knocks at greater distances were received at the recorder at lower levels and were less likely to be detected. Exclusion of these knocks resulted in higher estimated source levels at greater ranges.

Figure 3-17. Calculated source level estimates from AURAL recordings. Source levels were calculated by correcting received levels for losses associated with spherical spreading over the propagation from the localized knocks from the multipath arrivals. A very slight increase in the source level with range was observed.
The calculated source level plotted against the date of the recording showed a weak linear trend of decreasing source level with date. The rate of the decrease was 3.1 dB per 100 days ($R^2 = 0.0099$ $F = 368$, $N = 36781$, $p<0.005$) (Figure 3-18). The knock detections did not occur uniformly over the sampling period. There were periods of relatively high numbers of detections interspersed with periods of lower numbers of detections. During a mid-winter ice retreat at the beginning of March 2009, the number of knock detections was reduced; however, other periods of reduced detection rate were not related to the ice. Ice conditions were fairly consistent through the middle of February 2009, which coincided with a period of limited knock detections.

Inspection of the walrus location depth with source level shows that most of the knocks were localized in the upper 50 m of the 70 m full depth of the water. There were three groupings of knock depth, one at the surface to 7 m, another from 10 m to 50 m and then one grouping at the sea floor. A linear relationship between the source level and the depth showed a decrease in source level with increasing depth, at a rate of 1.5 dB for every 10 m of depth ($R^2 = 0.035$ $F = 1337$, $N = 36781$, $p<0.005$) (Figure 3-19). There are a number of possible causes for this relationship including a reduction in source
level, increased ambient pressure affecting the source mechanism, and a change of behavior – the walrus changes direction, or directivity of the vocalization. Due to the localization process, none of these causes can be ruled out or confirmed. Most of the knocks were localized in the middle of the water column, including the loudest knocks detected.

![Figure 3-19. Calculated source level estimates by depth of walrus. The distribution of localizations by depth shows that most of the knocks were made by walruses in the top 50 m of the water.](image)

**AURAL Signal-to-Noise Ratio**

A linear regression of source level with noise level shows a positive linear effect for source level due to noise with an increase of 5.8 dB per 10 dB increase in noise (R² = 0.19, F = 13455, N = 58836, p < 0.005) (Figure 3-20). As the increase of peak amplitude with an increase in noise was less than unity, despite the increase in source level with noise, the SNR decreases with increasing noise at a rate of 4.2 dB per 10 dB increase in noise, the complement of the source level increase (R² = 0.11, F = 7030, N = 58,836, p < 0.005) (Figure 3-21).
The large number of samples included in this Lombard effect may artificially increase the significance of the test. To reduce the number of samples, analysis was limited to knocks that were localized to within 200 m of the receiver. In limiting the analysis to nearby walruses, it was more likely that low amplitude knocks would be included. Low source level knocks at greater range are attenuated due to distance and were more likely to be excluded with SNRs below threshold. This had the added
effect of further ensuring that the noise at the receiver was representative of the noise at the walrus. Analysis of the knocks within 200 m showed a much smaller effect of noise on source level, with an increase of only 0.2 dB increase in source level per 10 dB increase in noise, which is essentially a non-effect (Figure 3-22).

![Source level versus noise level for knocks localized to within 200 m range of the AURAL. Limited range results in lower source level knocks detected, and increases the likelihood that the noise at the receiver is similar to that at the walrus. The 95% confidence interval for the slope of the effect was (0.0041, 0.047).](image)

**AURAL Timing**

By a large margin, the most common interval between the knocks was less than 10 seconds (Figure 3-23). From analysis of walrus knocks recorded in captivity, the break in regimes between inter-knock-intervals occurred at approximately 2 seconds. Knocks were assigned to sequences if the inter-
knock-interval was less than 2 seconds. The inter-knock-interval for knocks within a sequence was likewise skewed with the greatest number of intervals less than 0.5 seconds (Figure 3-24).

![Histogram of inter-knock-intervals from any 9 minute sampling period. The time between the knocks was calculated and almost all of the knocks were within 100 seconds of a successive knock. Most knocks occur within a long sequence of knocks.](image)

**Figure 3-23.** Histogram of inter-knock-intervals from any 9 minute sampling period. The time between the knocks was calculated and almost all of the knocks were within 100 seconds of a successive knock. Most knocks occur within a long sequence of knocks.

![Histogram of counts for inter-knock-intervals less than 2 seconds. The highest proportion of the knocks actually had less than 2 seconds between successive knocks. This 2 second threshold was used as the cut-off for determining sequences of knocks.](image)

**Figure 3-24.** Histogram of counts for inter-knock-intervals less than 2 seconds. The highest proportion of the knocks actually had less than 2 seconds between successive knocks. This 2 second threshold was used as the cut-off for determining sequences of knocks.
Sjare et al. (2003) reported that Atlantic walrus breeding codas often ended with the knock rate increasing to a buzz. To determine whether this trend was apparent in the data collected in the Bering Sea, the inter-knock-interval as a function of sequence number was fit with a linear regression as well as with the logarithmic transform of the inter-knock-interval. The residuals from both regressions suggested that there was a bias in the fit with greater positive residuals occurring with lower sequence numbers.

The reduced inter-knock-interval with increasing sequence number was not due to the walrus increasing the rate of knocks with successive knocks, but rather due to shorter inter-knock-intervals associated with longer knock sequences. The null hypothesis, that the inter-knock-interval did not change from one knock to the next, could not be rejected (t-test: \( p = 0.22, N = 5204 \)) (Figure 3-26).

**Figure 3-25.** Scatter plot of inter-knock-interval versus sequence number from AURAL data.
Knocks were detected at all hours of the day (Figure 3-27). A waterfall plot of the probability distribution function for the time of knock detection for each day of detections on the AURAL suggest that there was no trend relating the hour of the day when the knocks were detected over the season (Figure 3-28).
Figure 3-27. Histogram of knock detections by hour from the AURAL in 2009. Knocks were detected at all hours of the day with peaks at 0500, 1300, and 2100 which is an 8 hour interval.

Figure 3-28. Probability distribution functions for the hour of the knock by date of detection. Each PDF represents the distribution in time of when the knocks were detected on the AURAL for a given day in 2009.
**Comparison between Recorders**

Within 2009, the source levels estimated from both recorders were similar 175 dB$_{pp}$ (re: 1 μPa @ 1 m) on the PAL and 177 dB$_{pp}$ (re: 1 μPa @ 1 m) from the AURAL. The mean ranks of source levels from both recorders in 2009 were different (Kruskal-Wallis: $\chi^2 = 22.5$, df = 36,864, p < 0.005). Localizations made from both recorders resulted in similar localizations for the same time periods. The average distance between localizations made with each recorder for similar time periods (within 6 minutes) was 21 m with the estimate from the AURAL slightly closer to the recorder. There was no significant difference between the localizations paired with temporally associated knocks (Paired t-test: $t = -2.9$, df = 83, p < 0.005). As the instruments were not time-synced pairing the estimates is tenuous, but the localizations were still expected to be close if they were from the same animals. Noise from the AURAL was compared with noise from the PAL to investigate the effect of the recorders on the estimated level. Spectra were computed over periods without an identifiable transient signal from recordings on each system that were within 60 seconds of a signal on the other system. The difference between the recorders was most noticeable in the low frequencies below 100 Hz, where the AURAL had much lower levels – most likely the result of system response (Figure 3-29).
Comparison with Captive Data

The mean source levels estimated from the captive data in Chapter 2 was 183 dB\text{\textsubscript{pp}} (re: 1 µPa @ 1 m). The source level estimated from both recorders in the wild was 177 dB\text{\textsubscript{pp}} (re: 1 µPa @ 1 m). The distributions of the source levels for each measure were not normal (AURAL: $\chi^2 = 1927$, df = 22, $p < 0.005$; SWSD: $\chi^2 = 155$, df = 21, $p < 0.005$). The mean ranks of source level estimates from the two data sets were different (Kruskal-Wallis: $\chi^2 = 2791$, df = 1.39261, $p < 0.005$). The middle 95% of source levels for the two datasets were between 163 dB and 189 dB (AURAL and PAL combined) and 168 dB and 195 dB. (SWSD).
The SNR calculated from both datasets had differences that were much greater than the difference between the calculated source levels. The mean SNR from the wild estimates was 45 dB from the AURAL and 39 dB from the PAL, while the mean estimate from the captive walrus was 23 dB. The mean noise level estimates from the wild recordings was 128 dB (re: 1 \( \mu \)Pa), whereas the mean noise level in captivity was 139 dB (re: 1 \( \mu \)Pa). Detections in the wild were localized at ranges of up to 2 km, while the captive male was limited to just over 15 m away maximum distance.
Figure 3-31. Source level versus noise level for both wild recorders and the captive recordings. All three datasets exhibited a positive relationship between source level and noise level of about 5 dB increase in source level for every 10 dB increase in noise level.
Discussion

The approximation of vocalization characteristics from wild recordings requires the acceptance of certain assumptions about the environment. Vocalizations recorded from remotely deployed recorders in the Bering Sea were not as loud as captive vocalizations but had similar source level distribution shapes. By localizing the vocalizations, the distance from the recorder was calculated and the effect of the propagation can be accounted for. The estimates of source level from the Bering Sea for the AURAL were 177 dB$_{pp}$ (re: 1 µPa @ 1 m) and for the PAL 175 dB$_{pp}$ (re: 1 µPa @ 1 m). Knocks were localized for sources up to 2 km away. There was an effect of noise level at the recorder on the source level calculated, indicating a noise induced vocal modification.

Source Level

Previous work estimating the source level from wild Pacific walruses by localizing and correcting for spherical spreading resulted in estimates of 177 dB$_{pp}$ (re: 1 µPa @ 1 m) (Mouy et al., 2012). This estimate was made from recorders deployed in the Chukchi Sea in the summer where few adult males are found. The work conducted from recordings made in the Bering Sea were collected during the Pacific walrus breeding season, during which the adult males perform stereotyped breeding codas hypothesized as either territorial displays or breeding condition. The mean source level estimated from these breeding periods was approximately the same as that estimated from the Chukchi Sea. The similarity in source level estimated suggests that the source level may not differ that much between these two age and sex groups. It should be noted that these estimates are based on detections from the recordings which may have limited the selection of lower amplitude knocks and therefore biasing the estimates on the high side. The maximum source level from the recorder in the Bering Sea was 206 dB$_{pp}$ (re: 1 µPa @ 1 m). There were 12 knocks out of over 36,000 recorded with source levels over 200 dB.
Signal-to-Noise Ratio

The mean SNR from the wild estimates was 45 dB from the AURAL and 39 dB from the PAL. With mean source levels of 177 dB it was not unexpected for there to be high SNR. An increase in source level was associated with an increase in noise level. The source walruses were all localized to within 2 km of the recorder. At this relatively short range, it can be expected that the walruses experienced noise conditions similar to the recorders. The Lombard effect has not been reported for any pinniped species. The estimates made here suggest that the source level for the walrus knocks increased 6 dB for every 10 dB increase in noise level. This rate of increase was similar to the increase measured in captivity of 5 dB for every 10 dB increase in noise level.

Timing

Due to variability in noise, the timing of knock production can be of interest for determining the audibility of signals. If noise in an environment varies due to the presence of transient signals from other animals or from the effects of weather and surface waves, producing knocks more often than the rate at which the noise varies will increase the likelihood that the knocks will arrive at their intended receiver during a period of relative quiet. The interval between knocks detected in the Bering Sea within a sequence was quite variable. There was no definitive break point for an interval between knocks within a sequence and the interval of a sequence, so the 2 second change point identified in the captive recordings was used for the wild. The intervals within a sequence spanned the range up to this two second cut-off. The interval was found to be fairly constant within a sequence, suggesting that the knock rate was static within a sequence and that the shorter intervals were associated with longer sequences. Knock detection methods excluded some lower SNR knocks, and may have introduced a bias the timing parameters.

Knocks were detected on the recordings during all hours of the day. The detections occurred from late January through March. Over this time period the amount of daylight the region receives
changes drastically, from approximately 6 to 12 hours. The environment during this period is usually
dominated by sea ice, although during the year of 2009, a short but dramatic retreat of the sea ice
occurred for 10 days at the end of February at the location of the recorder. This may have contributed to
the reduced number of knocks detected at the beginning of March (Figure 3-18).

**Persistent Localizations**

Plotting of the localizations for each one hour period revealed the presence of clusters of
localizations over time (Figure 3-32). The clusters of localizations indicate the presence of individual
walruses vocalizing at a fairly consistent location over the period of hours. This is similar to the findings
for Atlantic walrus that were observed to attend a group of females up to a few days before leaving the
area (Sjare et al., 2003). Localizations were not persistent throughout the time period, but would appear
at different intervals.

**PAL**

Lower numbers of detections on the PAL compared to the AURAL was expected. The duty-
cycle of the recorder, even in the higher sub-sampling rate, was far lower than the AURAL. The
detection algorithm of the PAL was not well suited for walrus knocks. Detections are based upon only 8
10.24 ms samples within each 4.5 s recording. The intermittent nature of the knocks reduces the
likelihood that signal would be detected. The PAL data did provide knock samples from multiple years
allowing the comparison of source levels and Lombard effect across years. Similar to the comparison
from wild to captive signals, the source levels appear similar but were determined to be from statistically
different sample sets (Figure 3-13). The maximum and minimum source levels from the PAL were not
similar across years and comparable to the AURAL, although the mean ranks were different in both
comparisons.
Figure 3-32. Plots of localizations from a 40 hour period with clusters of localizations. Red outlines highlight localization clusters that appear over multiple hours. Blue dots represent localizations from the first half hour, black dots represent localizations from the second half hour.
Conclusions

Estimation of source levels from wild walruses resulted in lower average source levels than those from a captive individual. The mean RMS noise level estimates from the AURAL recordings was 131 dB (re: 1 µPa), and the mean RMS noise level from captivity was 140 dB (re: 1 µPa). The increased noise level may have contributed to the difference in source level between wild and captive recordings. However, the estimates from the wild included maximum values that were greater than those from captivity. The effect of noise level on the source level of knocks was consistent with the findings from captivity. An increase in noise level resulted in an increase in source level. Prior to this, a Lombard effect has not been identified in any pinniped species. It was found that there were significant differences between the mean ranks of the captive and wild source level estimates as well as between years for wild source level estimates. The source levels of Pacific walrus knocks were variable, but a range of 163 – 189 dB dBpp (re: 1 µPa @ 1 m) included 95% of the samples. The mean estimate of 177 dBpp was used as an input to propagation models of the communication pathways of breeding herds of Pacific walrus and how changes in the environment will affect the detection of these signals examined in Chapter 5.
Chapter 4
Water-Ice-Air Propagation Measurements and Modeling

Introduction

Early investigations into air-ice-water acoustical systems were conducted in the 1950s. Multiple experiments studied the coupling of impulsive sources in all three media to the other media (Press and Ewing, 1951; Jardetzky and Press, 1952). The investigations focused mainly on flexural waves resulting from high amplitude impulsive sources from explosive charges. Since that time, most research in underwater acoustic propagation has been limited to propagation within the water column and the sediment. Recent work has shown how underwater impulsive sources can be localized from arrays of geophones mounted on sea-ice (Dosso et al., 2001; Dosso et al., 2002). More commonly, the upper boundary, whether it was an ice layer or air interface, was only considered of importance for the effects on a signal produced and transmitted underwater. From theory, the lower the angle of incidence for surface interacting rays, the greater the transmission of energy from one medium to another. However, at ranges of many kilometers from the source – the ranges often considered in underwater acoustics – waves with trajectories with near normal incidence at the surface wave will have been reflected many times and attenuated, due to transmission and scattering. The effects of a water-ice interface include scattering from the interface and coupling to shear waves which can have the potential for large losses with respect to the signal in the water column (Diachok, 1976; Duckworth et al., 2001). In all of these cases, the focus has been on propagation with ranges greater than 100 meters, and often over many miles related to the use of acoustic experiments for inversion techniques to assess environmental conditions (DiNapoli and Mellen, 1986; Duckworth et al., 2001; Gavrilov and Mikhailovsky, 2006).

There has been relatively little investigation of signals from underwater sources propagating to in-air receivers, as there are generally very few in-air receivers at the air-water interface. However, in animal communication, there are several situations where there would be an in-air receiver for an
underwater source. Both pinnipeds and sea birds spend a large amount of time at or just above the water-air interface. Some pinnipeds present a particularly interesting case as there are often individuals vocalizing underwater, while other individuals’ ears are out of the water. For polar and sub-polar species of pinnipeds, individuals receiving signals produced underwater are often hauled out on floating sea ice (Fay, 1982). Therefore signal propagation through air and water, including the coupling between media, is important.

The location of the source, the location of the receiver, the media through which the signal propagates, and the characteristics of the signal all affect the received signal. The highly dynamic environments of the polar and sub-polar regions have a complicated effect on the signal due to the seasonal changes in the environment. In an ice covered environment, the water column is relatively stable as there is limited influence from the atmosphere. However, a strong upward refracting velocity profile exists and causes surface ducting with increased interaction with the ice cover, and decreased interaction with the sea floor. As the effects of global climate change are expected to impact the polar and sub-polar regions disproportionately (Bernstein, 2007), the changes in ice conditions on the propagation of acoustic signals need to be considered to fully understand the effects of the changing climate on arctic pinnipeds. For highly vocal, aquatically mating arctic pinnipeds – including walrus, bearded and ribbon seals – the propagation effects due to climate change are compounded by the complicated conditions of the substrate on which the animals are hauled out, which vary naturally with time and location (Johannessen et al., 1999; Moore and Huntington, 2008). Throughout the course of the year, the animals may be hauled out on ice or beaches for rest during foraging, and rearing and raising young. The ice on which these animals are hauled out is in a constant state of flux. The thickness, layering, density, percent cover, and roughness, among other factors can change at temporal scales ranging from years to days.

While the purpose of the vocalizations for these species is not fully understood, they are often associated with mating (Ray and Watkins, 1975). If as hypothesized, the vocalizations are courtship displays, changing ice conditions could affect mate selection through changes in acoustic propagation. When considering the short-range signals received by hauled-out individuals, the impacts of the
environment on the signal propagation that need to be considered are different from those propagating over many kilometers to an in-water receiver, whether it is a conspecific (another walrus), or passive acoustic recorder. The signal from a male in water to a female on ice propagates through three different media – water, ice, and air. Any reduction in the extent, timing, and characteristics of sea ice could have impacts on the mate selection of pinnipeds that breed on or near sea ice (Tynan and DeMaster, 1997; Moore and Huntington, 2008). Pacific walrus breed during late winter through early spring in the Bering Sea. At that time females and males congregate after spending the summer separated. Female walrus return from their summer feeding grounds in the Arctic and male walrus from the western Alaskan coast. If conditions change such that the marginal ice zone, where the animals congregate, occurs over shallower water, or the ice thicknesses at these regions becomes thicker or thinner the received vocalizations could be affected. In shallower water, the males will be forced to vocalize at depths limited by the shallower bathymetry. By constraining the male walrus to shallower depths, the received vocalizations will be attenuated less due to the shorter propagation distance and could be at greater amplitude for longer durations, while the male is closer to the surface. Also, the range over which the vocalizations could be perceived might be impacted as there would be more interactions with the surface for similar horizontal ranges. If all that is required for mate selection is the perception of the vocalization, not the amplitude, less suitable mates might be chosen as they would be more audible at all depths.

The goal of this work was to measure the transmission loss from an underwater source, through ice and into air when the vertical and horizontal ranges separating the source and receiver are similar. Dosso et al. (2001) investigated the coupling of underwater acoustic sources to seismic waves in the sea-ice. Dosso et al. (2001), however, did not examine the acoustic signal in air as a result of coupling through the ice from the water. The result of this research provides quantification of the acoustic propagation effects over a short range. Comparison with an existing propagation model Ocean Acoustics and Seismic Exploration Synthesis (OASES) (Schmidt and Jensen, 1985) was done in order to determine if the model physics are adequate. If so, the model can be used to predict how changes in the environment may impact pinniped communication associated with breeding.
Methods

A propagation experiment was conducted near Barrow, Alaska on 12-13 March 2012. A controlled source/receiver was used to obtain in-situ transmission loss measurements. The transmission loss was measured between an in-water source and receivers in the 1) water, 2) mounted on the ice, and 3) in air over a two day period. Atmospheric environmental data were obtained from the Earth Sciences Research Laboratory’s Barrow Observatory, located 8 km east of the sampling station. One minute average temperatures, wind speed and direction, barometric pressure, and relative humidity were obtained. A 3 inch diameter ice core was collected at the research site to determine the density of the ice. Ice density was calculated for 5 sections of the ice core, each representing one fifth of the ice thickness. CTD casts were made before and after the experiment to measure the water temperature and salinity of the water to compute the sound velocity profile. From this data, the parameterization of the environment was obtained. Receivers were deployed in a line at 10 m, 20 m and 30 m horizontally from the location of the source along a straight line. At each range two hydrophones, a geophone and a microphone were deployed. All transducers were deployed on one ice floe without visible ridges (Figure 4-1). An underwater source was placed at two depths 10 m from the array, oriented endfire such that it was 10 m horizontally from the nearest receiver station and 30 m from the furthest. The shallow source placement was 3 meters below the air-ice interface and the deep source configuration had the source 9 meters below the air-ice interface. The field location was selected for its stability, accessibility, and lack of grounded ice. All depths are given relative to the air-ice interface.
Figure 4-1. Diagram of experimental design. Magenta triangles are geophones, red stars are microphones, black circles are hydrophones, and the black squares are the sources. The Compressional sound velocity profile is presented on the right, with a zoomed view of the measured profile in water to the extreme right.
Equipment

The output from the geophones, microphones, and hydrophones were recorded using a National Instruments NI-6062E multi-channel digital acquisition card connected to a NI BNC-2090 breakout, and a custom power supply and filter bank. The acquisition card recorded the 12 channels at 24 kHz sample rate. The system was controlled by a custom built Labview executable to write to binary data files. A 150 gallon insulated cooler was modified to serve as the housing for the acquisition system (Figure 4-2). Additional insulation and cable connections to connect transducers to the acquisition system were added. The acquisition system was powered by two 12V deep cycle marine batteries.

Figure 4-2. Picture of Recording equipment housing (insulated cooler) and deployed transducers at station 2. The geophones were housed in the black cases with the orange caps, and the microphones were mounted on an aluminum rod, 0.5 meters above the ice with a spherical windscreen. The hydrophones were deployed through a 10 inch borehole, to the left of surface transducers.
Two HTI-96-min and four HTI-94-SSQ hydrophones were used, both types of hydrophones have flat frequency responses of 2 Hz to 30 kHz (±4 dB). The geophones were Geospace Technologies GS-30CT in environmental shrouds with flat frequency responses between 10 Hz and 1 kHz (±5 dB). The geophone outputs were shunted with 1 kΩ resistors to reduce the resonance peak response. The environmental shrouds were Mark products model 10200. The microphones were GRAS 40AE, pre-polarized ½ inch free-field microphones, with flat (±2 dB) frequency response from 3 Hz to 20 kHz, with GRAS 26CA pre-amplifiers. All transducers were calibrated before and after deployment.

At each range a 10 inch diameter hole was drilled through the ice for hydrophone deployment (Figure 4-3). One hydrophone was deployed to 3 m below the air-ice interface, and the other was deployed 9 m below the air-ice interface. The geophone enclosure was frozen onto the ice surface with hot water. A section of ice was cleared of drift snow and leveled. Hot water was poured onto the flat area, and the geophone was placed onto this surface and subsequently frozen into place. The microphone was mounted 0.5 m above the ice on an aluminum rod frozen to the ice surface. A 3 inch diameter spherical windscreens were placed over each microphone. Rubber shims were placed between around the microphones and aluminum pole to reduce vibration. The air-ice interface was flat over the extent of the 30 meter range with no ridges or cracks visible. The ice thickness at the three receiver locations was 2 m, 1.4 m, and 1.6 m. The water depth at the three receiver stations was 11.3 m, 11.6 m, and 11.9 m, measured with a handheld fathometer and verified with CTD casts. The water depth at the source location was 10.4 m, with ice thickness of 1.3 m. An ice-core was taken from the ice to determine ice density at 0.87 g/cm³±.009. The density of the ice, measured from five 10 cm sections of the ice core, increased with depth from 0.866 g/cm³ to 0.880 g/cm³. The average density was used in the computational model as the sound speeds of the ice were not measured and increased confidence in the model would not be gained from greater depth resolution of the ice density.

The source signal used to measure the transmission loss was a broadband impulse (Figure 4-4). The impulses, inspired by walrus knocks, were broadcast as individual knocks every thirty seconds. The series of signals was broadcast for ten minutes and then the system recorded ambient noise until the
speaker was moved to the other location for the same broadcasts. The source signals were projected from a Lubell Labs LL9162T underwater acoustic transmitter, connected to the output signal with a solid-state Dual amplifier. The amplitude of the source signal files was adjusted so that the source level 1 meter from the speaker was approximately 155 dB (re: 1μPa<sub>pp</sub>) well below the estimated 186 dB (re: 1μPa<sub>pp</sub>) source level for walrus (Hughes et al, 2011). The beam pattern of the speaker was approximately omnidirectional (±1 dB) below 2 kHz. Up to 10 kHz, the projector has a main lobe wider than ±30° up to 5 dB, which keeps all of the hydrophones in the main lobe of the beam pattern. All of the microphones were in the main lobe when the speaker was 4 m below the air-ice interface. Only the microphone and geophone at station 1 were not in the main lobe of the speaker for the deep projection. After completion of the broadcast from each depth, the data were recovered, batteries were exchanged and the projector location adjusted.

Figure 4-3. Photo of field crew drilling borehole through the ice. Hydrophones and the source were deployed through the holes drilled by the 10 inch auger. Ice thickness was measured by determining the depth of the auger when water came up through the borehole.
Figure 4-4. Waveform and spectrogram of source signal used for experiment. Spectrogram level is in relative dB. The source signal was created by recording a hammer blow to a block of wood in a laboratory setting. The amplitude of the source signal was limited to below 160 dB to avoid additional permitting processes.

Figure 4-5. Sample waveforms and spectrograms from a microphone (L) and shallow hydrophone (R) for a broadcast with the source at the shallow depth. The impulsive nature of the signal resulted in a broadband signal with short duration. The amplitude of the in air signal was five orders of magnitude smaller than the underwater signal.
Signal Processing

Recorded signals were extracted, and all extractions were then plotted as waveforms and spectrograms (Figure 4-5). A Matlab function was used to automatically extract the signals. The beginning and end of the signal were selected manually. The extractions were graphically displayed, to ensure the presence of the signal. Before determining the beginning and end of the recorded signals, a background noise removal tool in Adobe Audition was implemented. The cleaned up audio signal was used for determining the start and end of the signal, as well as for figures. The original signal was used for calculation of the amplitudes. The envelope of the signal was calculated as the absolute value of the analytic signal, which is comprised of the signal and the Hilbert transform of the signal. To limit the influence of fluctuations in the background noise on the calculation of the signal duration, the amplitude envelope was smoothed with a moving average with a window of 1.25 ms duration. The onset of the envelope above the background noise by a factor of 2 was used to define the start of the signal on each channel. The end of the received signal was selected as the point at which the amplitude envelope re-approached the background noise within the same factor of 2 of the baseline amplitude envelope. The linear spectrum of the received signal was calculated over the period defined by the start and end of the signal for each sample. The spectra were intensity averaged over the 20 signals for each of the receivers.

For each receiver, the duration of the received signal was calculated as the difference between the start and end of the signal obtained from the amplitude envelope. The mean and standard deviation of the received signals were averaged for each channel.

Modeling

The Ocean Acoustic and Seismic Exploration Synthesis (OASES) range independent model was used to generate transfer functions to estimate the effect of the environment on the received signals for the environmental parameters and location of the source transducer (Schmidt, 2011). OASES is an
implementation of a wavenumber integration propagation model, sometimes referred to as a fast field program (FFP). The ability to calculate the acoustic field in elastic layers, such as sea ice, is a major benefit of this approach. OASES calculates the pressure field or particle velocity field for the environment. The hydrophones and microphones measured acoustic pressure and the geophone measured particle velocity. The ability to use the same model and compare the output for the two types of transducers was desired.

The propagation model was run twice, once with the normal stress (pressure) calculated, and once with the vertical component of velocity calculated. The resultant transfer functions were convolved with a calibrated recording of the source signal at 1 m range to estimate the received signal for this broadcast. The environment was parameterized with four ice configurations. The ice thickness was set to each of the four measured thicknesses from the source and receiver stations. For each of the four thicknesses, the ice was represented as either uniform density or as five layers with densities obtained from the ice core. The model had a temporal resolution of 50 μs, similar to the resolution of the recording system sample rate of 24 kHz. The model computed transfer functions utilizing complex contour integration of a full Hankel transform, designed for use in situations where the near field results are desired. Options and input parameters for the model are provided in Table 4-1.

Table 4-1. Input parameters for the OASES propagation model (OASP). J - Complex integration contour; N - normal stress; f - full Hankel transform; c_c - compressional speed (m/s); c_s - shear speed (m/s); a_c - compressional attenuation (dB/A); a_s - shear attenuation (dB/A); ρ - density (g/cm³); R - RMS roughness (m).

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<th>c_s</th>
<th>a_c</th>
<th>a_s</th>
<th>ρ</th>
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**Statistical Analysis**

To test the significance of the results, two different statistical tests were implemented. Comparisons of the measured linear amplitudes and durations within and between transducer types and locations or source depths were conducted using a 2-way ANOVA. To compare the modeled and measured levels and durations a Student’s t-test for location was used. For the t-test, the null hypotheses were that the means of the measured values at each transducer was the predicted value from the model at that transducer. A generalized linear model (GLM) was fit to the difference between the modeled and measured peak values to identify if any of the factors of range, transducer type, and source depth had significant effects upon the difference between amplitude measurements and estimations.
Results

Each recording was evaluated to ensure the signal was present in the recording. The results from the propagation followed a general trend across all three stations with some variability. Examples of waveforms recorded from one broadcast are provided in Figure 4-6. The time series represent the same time periods. No discernible difference could be seen resulting from waves that were incident on the ice directly below the geophones and microphones and waves that were incident at some horizontal range away from the sensors and propagated in the ice. Peaks related to the multipath arrivals of the broadcast signal can be seen in the hydrophone signals at 30 m from the speaker. The recordings were limited to 0.05 seconds of data around the peak arrival at each receiver. The reference values for pressure in water and air, and particle velocity of ice are all different, 1 μPa, 20 μPa, and 10^{-9} m/s respectively. This difference results in approximately 26 dB reductions for equal intensity signals from water to air. The hydrophones recorded similar levels to one another despite the difference in range. The linearly averaged levels of the transducers for the shallow and deep source are given in Table 4-3 and Table 4-4.

The GLM indicated that the transducer type and transducer range were significant predictors of the difference between the measured and modeled peak to peak levels. Source depth, however was not a significant predictor of the difference in values (Table 4-2). These results bolster the results of the t-test that showed that the hydrophones were best predicted by the model.

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<th>p-value</th>
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Figure 4-6. Example waveforms from one broadcast of the shallow source at the 12 receivers. First row has the microphones, second row has the geophone plots, third row has the shallow hydrophone, and fourth row has the deep hydrophone. X-axes are all the same, and referenced to the same time. Y-axes for the 2nd row of plots are in m/s; all others are in µPa. The red line represents the amplitude envelope used to calculate duration above background.
Figure 4-7. Modeled time series of source signal convolved with transfer functions for each of the transducers for the shallow broadcast. Amplitude envelopes in red. The underwater signals were peakier than signals recorded on microphones and geophones. The reduced peakiness may be due to attenuation of the higher frequencies for signals propagating through the ice.
Figure 4-8. Transmission loss as a function of frequency relative to the deep hydrophone located 10 m in range from the source. a) Transmission loss averaged over the 20 broadcasts for each signal with the source at the shallow deployment. b) Modeled transmission loss for the source at the shallow depth. c) Measured transmission loss averaged over the 20 broadcasts for the source at the deep deployment. d) Modeled transmission loss for the source at the deep depth.
Table 4-3. Average and standard deviation of levels for each transducer from the shallow and deep projections. Averages and standard deviations were computed in the linear domain.

<table>
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<tr>
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<th>M2</th>
<th>M3</th>
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Table 4-4. Peak and RMS modeled received levels at the transducers for the deep and shallow sources.

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Table 4-5. Student’s t-test statistic to determine if the measured value distribution varies from the modeled value. Green indicates the modeled values are not significantly different from the measured values.

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<td>12.4</td>
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<tr>
<td><strong>RMS</strong></td>
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</table>
Comparisons of the time domain signal of the transducers collecting measurements from the different media reveal that the signal duration generally decreased as the medium changed. That is, the hydrophones generally had the longest duration signal, the geophones were slightly shorter than the hydrophones and the microphones were slightly shorter than the geophones. The duration of the signal recorded by the hydrophones was 0.015 ±0.006 s (mean ± st. dev.), the duration of the signal recorded by the geophones was 0.012 ±0.004 s (mean ± st. dev.), and the duration of the signal at the microphones was 0.011 ± 0.004 s (mean ± st. dev.). For the deep broadcast, the average duration of the signal recorded by the hydrophones was 0.015 ±0.005 s (mean ± st. dev.), the duration of the signal recorded by the geophones was 0.014 ±0.003 s (mean ± st. dev.), and the duration of the signal at the microphones was 0.011 ± 0.0009 s (mean ± st. dev.).

Received signals were modeled by convolving the source signal with the modeled transfer function calculated by OASES. The propagation model utilized a sound velocity profile in the water from the CTD cast, ice density from the core, and sound speed in the air calculated from ambient temperature. The transmission loss estimated by the models with different ice thicknesses and density yielded estimates that varied by less than 1 dB at the receiver locations. Utilizing a range independent model inherently introduced errors as the environment varied over the range, if only slightly. The received signal estimated by the OASES (Figure 4-6) was similar to the experimentally obtained signals (Figure 4-4). The modeled received level displayed greater variability across frequencies compared to the averaged experimental values (Figure 4-8). It was expected that some of the variability would be removed due to the averaging of the experimental signals. Despite the variability, the modeled peak levels were comparable to the experimentally obtained values (Table 4-5). The amplitude envelopes of the modeled time series were calculated following the same process as in the recorded signal. To include the effects of noise on the modeled values, the onset of the signal was determined by finding the point where the amplitude envelope crossed the average threshold for the envelopes of the experimental data.

From the model with the shallow deployment the average duration of the modeled signals at the hydrophones was 0.017 ± 3e-4 s (mean ± st. dev.), the duration of the modeled signal at the geophones
was 0.017 ± 4e-4 s (mean ± st. dev.), and the duration of the modeled signal at the microphones was 0.016 ± 3e-4 s (mean ± st. dev.). From the model with the deep deployment the average duration of the modeled signals at the hydrophones was 0.017 ± 7e-4 s (mean ± st. dev.), the duration of the modeled signal at the geophones was 0.016 ± 2e-5 s (mean ± st. dev.), and the duration of the modeled signal at the microphones was 0.017 ± 3e-4 s (mean ± st. dev.).

A Student’s t-test was used to compare the durations of the recorded signals at each transducer to the duration of the modeled signals at the same transducers. For the shallow broadcast, there was no significant difference between the measured duration and the modeled duration (Table 4-6). For the deep broadcast, there was no significant difference between the measured and modeled durations except for the two nearer geophones (Table 4-7).

The received levels at the microphones were approximately 90 to 110 dB lower than the levels at the hydrophones. This behavior was apparent in both experimental data and the output from the OASES propagation model (Table 4-3 & 4-4). A one sample t-test was used to determine whether or not the measured levels were different from the value predicted by the model for each transducer. For the RMS levels, the t-test indicated that the measured levels at all transducers except for one microphone (Station 2) were similar to the modeled values. For the peak levels, the model predicted the measured hydrophone peaks well, but not the geophone or microphone peaks (Table 4-5).
Table 4-6. Student’s t-test results comparing modeled and measured durations at each transducer for the shallow broadcast. The t-statistic, $t$, is a ratio of the departure for the estimated parameter, here duration, from its notional value and standard error. The degrees of freedom, df, are the number of parameters that are free to vary. The standard deviation is given by sd. $P$ is the probability that the durations are actually the same but the results were obtained merely by randomness. $P$ values less than 0.05 were considered significant.

<table>
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<tr>
<th></th>
<th>M1</th>
<th>M2</th>
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</table>

Table 4-7. Student’s t-test results comparing modeled and measured durations at each transducer for the deep broadcast. The t-statistic, $t$, is a ratio of the departure for the estimated parameter, here duration, from its notional value and standard error. The degrees of freedom, df, are the number of parameters that are free to vary. The standard deviation is given by sd. $P$ is the probability that the durations are actually the same but the results were obtained merely by randomness. $P$ values less than 0.05 were considered significant.

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<th>M1</th>
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Discussion

The purpose of this work was to measure the impact of ice cover on in-air received acoustic levels from underwater sources. By propagating acoustic signals from two depths and measuring the received level at three ranges, in the water, on the ice, and in the air, the effect of the ice was compared with the horizontal range from the source and the depth of the source.

The levels received outside of the source medium seawater were attenuated relative to receivers in the water. The acoustic impedances of the water, ice, and air are all different; it was expected that the acoustic energy would not couple well from one medium into the others. At the interfaces of the media, some of the energy was transmitted into the adjacent medium, but a substantial portion was reflected. However, even for low amplitude sources, the signals were detectable above background by both geophones and microphones.

The peak-peak level of the in-air received signal relative to a hydrophone at the same horizontal range was measured to be 90 – 100 dB lower. The difference in level recorded between the microphones and hydrophones was attributable to two factors. First, the standard reference for the decibel is different between water and air. Traditionally, the reference pressure in air is 20 µPa and water is 1 µPa. This results in a 26 dB reduction in reported level for a signal of the same intensity in air compared to water. The larger impact, and what we were interested in, is related to transmission of energy from water, through ice and into air. The coupling of energy at both interfaces results in decreased energy in each subsequent media. In the ideal, plane wave case at the water-ice interface, a fraction of the energy is transmitted. At the ice – air interface an even smaller fraction of the energy couples into the air. To a smaller degree, loss of energy was also due to absorption. The RMS levels were similarly impacted by the environment.

The OASES transmission loss package (Jensen et al., 1994) utilized for this work produced estimates of cumulative root mean square transmission loss that were within 6 dB of measured
transmission loss. That error is not inconsequential, but the use of the model to estimate the impacts of a changing environment may be useful. The use of the range independent propagation model limited the amount of environmental detail which could be incorporated. Although, greater accuracy may be obtained with a range dependent model and higher resolution environmental data, it is unlikely that environments of interest will be precisely known as it is difficult to obtain ice conditions at the time and location that animals are present.

The differences between the measured and modeled levels at the geophones and microphones may be explained by the physics of acoustic propagation. Acoustic waves coupled to the ice surface from a source underwater excite both compressional and shear waves within the ice. The geophone mounted on the ice surface measured vertical velocity that may be due to compressional and shear waves, as well as surface waves, like Love waves. Although the ice was fairly uniform, and was modeled that way, there was no doubt some heterogeneity over the 30 meter range used in the experiment that was not incorporated into the range independent model and could have led to differences between the measured and modeled signal. The measured signal may also have been impacted by the mounting of the geophone to the ice surface. By freezing the geophone housings to the ice a strong bond was created, but it could have led to a variation in acoustic impedance causing a difference in level measured compared with the uniform model. The measured in-air acoustic levels may have suffered from reduced sensitivity of the microphones in the -10°C temperatures.

The limited sensitivity of model predictions to small perturbations in ice thickness is encouraging as knowledge of environmental parameters is often not known at high precision. To estimate the effect of changing environmental conditions on the propagation of walrus vocalizations, the ability to use a propagation model is desirable. The physics of the range independent OASES propagation model was determined to accurately predict the propagated signal in air for the metric of RMS level. Although the RMS level was accurately predicted, the peak level was under predicted by the OASES model. The under prediction of the peak level was up to 9 dB. As the peak values were under predicted, when considering whether or not a signal is detectable, the peak to peak levels will lead to conservative estimates – that is a
signal will be predicted to be undetectable even when it is detectable. The estimation of the time domain
signal using this model will allow inferences to be made for real world signals, such as walrus knocks.

The durations of the received signal above the ambient noise were affected by the media in which
the measurement was collected. The reduced duration coincided with reduced amplitude. The reduced
amplitude of the signal predictably leads to reduced time that the signal amplitude was in excess of the
background noise. The change in durations with media was apparent even though the noise reduction
methods were implemented to reduce the effect of the low signal to noise ratio in the air. Although the
durations of the detected signal were determined to be statistically different, it is likely that the difference
is not biologically significant. The temporal resolution of the hearing abilities of walrus have not been
investigated, but the difference of approximately 5 ms from hydrophones (longest duration) to
microphones (shortest duration) represents less than 30% of the total duration of the signal.

For most of the transducers the modeled durations were longer than the measured models.
Although the differences were statistically significant, the values were on the same order of magnitude.
When viewed in comparison to the durations of signals used to test hearing in walruses the modeled
values, as well as the measured values, are still quite a bit shorter than the half-second test signals
(Kastelein et al., 1996). Although the method for determining the duration relied upon the background
noise in the recorded signals, this could have caused a bias in the estimated durations.

*In situ* measurement of biotic signals on an ice floe is unlikely. Walrus are notoriously skittish,
flushing into the water from the scent of humans (Fay, 1982). Remote sensing of walrus vocalizations is
currently conducted using autonomous underwater passive acoustic monitors. Deployment of ice
mounted recorders, for ice borne and in-air signals, is possible, but the greatly reduced signal level in
these media relative to the underwater signals would require vocalizing walruses to be in the immediate
vicinity. Utilizing the strength of readily available computational models to estimate the transmission
loss of signals in a variety of environmental conditions will be advantageous to understanding the effects
of changing environmental conditions on communication. Under these circumstances, it is also possible
to consider changes to the source, including range and orientation to the receiver.
Chapter 5
Modeling of Detectability of Walrus Knocks

Introduction

Communication between two individuals requires that a signal be created by a caller, and that the signal is perceived by the receiver (Bradbury and Vehrencamp, 1998). In acoustic communication this means that the caller must produce a sound loud enough that an intended receiver can perceive the signal wherever they are. In the case of walrus breeding vocalizations, there are at least two possible groups of receivers that a male walrus is trying to communicate with. First, a male walrus producing a breeding vocalization in the proximity of female walruses hauled out on ice may be trying to communicate his fitness for breeding, and thus his offspring’s potential fitness with those females (Ray and Watkins, 1975). The second group that the male walrus may be trying to communicate with could be other walruses at greater ranges that are swimming in the water (Sjare and Stirling, 1996). A male might be trying to indicate to other males his dominance and defend his territory, the female walruses, with the breeding displays thus avoiding physical confrontation that is often costly. The male walruses may also be trying to communicate with other females to attract them to his position so that he may mate with them. In both cases – receivers on ice nearby and receivers in water – if the signal is not detectable by the receiver whether due to attenuation, masking by noise, or inattentiveness, the vocalizing male would be unsuccessful at communicating his message.

This work estimated the detectability of walrus signals by other walruses. Previous work in this dissertation has focused on determining the source level for walrus knocks and the applicability of propagation modeling for determining the effect of the environment on a signal propagating from water through ice and into air. This chapter will tie this previous work together along with propagation modeling entirely within the water column, and audiometric data for walruses to estimate the detectability of the walrus knocks as a function of the environment and source knock.
The lack of in-air recordings of underwater walrus knocks has limited the ability to determine the importance of these signals to walrus mate selection. The first step in determining whether the detection of these vocalizations is important would be to make acoustic recordings in situ. It is unrealistic to deploy acoustic recorders on ice floes near walrus breeding activities because the presence of humans in close proximity to areas of walrus breeding activities has caused walrus to flush into the water and change location (Fay, 1984). In addition, the highly dynamic environment of the Bering Sea in winter prevents deployment of in-air acoustic recorders on ice prior to the walrus congregating. The changes in ice are not predictable and could result in the recorder being located far away from the breeding displays or ending up in the water. As the in-air recordings of walrus breeding displays propagating through ice have not been made, acoustic propagation modeling can help to estimate the signal a female walrus would receive if she was hauled out on ice with a male walrus vocalizing in the water. By comparing the modeled received signal with the hearing capabilities of walruses we can determine whether or not the walruses can hear these signals and under what circumstances a signal becomes inaudible. The acoustic propagation algorithms require that the physical environment be quantified for use as inputs in the model.

**Bering Sea Ice**

The dominant feature of the Bering Sea in winter is sea ice. Sea ice characteristics are variable within and between years and the variability will continue even as the effects of climate change result in warmer summers with less ice in the Arctic (Stabeno *et al.*, 2012b). The latitudes at which Pacific walrus congregate to breed are expected to experience significant warming due to the effects of climate change during this century (Fay, 1982; Wang *et al.*, 2012). The local and seasonal effects of climate change are unknown. An increase in average temperature does not necessarily result in ice conditions similar to more southerly latitudes (Stabeno *et al.*, 2008a; Stabeno *et al.*, 2012a; Stabeno *et al.*, 2012b). The summer temperature may experience all of the effects of climate change while the winter temperatures remain similar to the historic ranges (Wang *et al.*, 2012). It is also possible that the extremes of both
summer and winter are exaggerated, resulting in a warmer summer, but also a colder winter with thicker ice and less open water (Stabeno et al., 2012a; Stabeno et al., 2012b; Wang et al., 2012). The variability of ice conditions from one year to the next is difficult to predict and the impacts on the communication of breeding Pacific walrus may be different each year.

Ice is classified as first year ice, or multi-year ice. First year ice is the ice that has formed in the current season; it has not survived a summer melt season. Multi-year ice has survived a summer melt season and is generally thicker, typically between two and four meters (NOAA Snow & Ice Data Center, 2014). Multi-year ice generally contains less brine and more pockets of air than first year ice. First year ice is less likely to contain pressure ridges than multi-year ice. The variable composition of multi-year sea ice, with varying brine concentration and air pockets leads to more complicated acoustical properties of multi-year sea ice compared to first year ice which tends to be more uniform and smoother (Press and Ewing, 1951; Ewing et al., 1957).

The Intergovernmental Panel on Climate Change (IPCC) has released five assessment reports since 1990. The most recent report was released in 2013. Based on analysis of outputs from 20C3M, SRES, and COMMIT climate models, reductions in summer Arctic sea ice extent have been predicted for the emission scenarios A2, A1B, and B1 of approximately 33% by 2080-2100 (Zhang and Walsh, 2006). These models and most of the media attention focus on summer ice conditions in the Arctic. The sub-Arctic Bering Sea, where Pacific walrus mate in winter, has historically been ice free in summer. Development of sea ice in the Bering Sea does not occur until after the Arctic freezes over each winter, however sea ice extent in the Bering Sea is not coupled to the previous summer’s Arctic ice extent (Figure 5-1 & Figure 5-2)(Stabeno et al., 2012a; Stabeno et al., 2012b). Models of Bering Sea ice extent predict, on average a decline in total extent for winter and spring months. By 2050, the averaged modeled sea ice extent varies from the Alaskan peninsula under the maximum case to St. Lawrence Island in the minimum case. Models of Bering Sea ice extent suggest that by the end of the century, ice extent for the months of February and April will be reduced by 50% (Wang et al., 2012).
Over the past 30 years for which the best data is available, there has been no clear multi-year pattern of ice cover in the Bering Sea (Figure 5-1). The area of the Bering Sea covered by ice is cyclical, ice is present in the winter and absent in the summer. The seasonal pattern of sea ice in the Bering Sea is predicted to continue despite the predicted increases in mean temperature. However, the changing climate is predicted to cause greater anomalies in the seasonal ice conditions (Zhang and Walsh, 2006). The area covered by ice each winter has been variable. In the early 2000s, the Bering Sea experienced a significant warming of approximately 3 °C which coincided with decreases in sea ice extent and concentration (Stabeno et al., 2007; Wang and Overland, 2009; Stabeno et al., 2010; Hunt et al., 2011). Since 2007, the Bering Sea has experienced a cooling period with greater sea ice extent and concentration. The winter of 2011 saw the greatest recorded extent of ice coverage in the Bering Sea (Stabeno et al., 2012b). Historical monthly sea-ice area anomaly measures show that while the Bering Sea has been experiencing increases in seasonal ice, the rest of the Arctic has experienced net decreases in the area covered by ice in the winter (Figure 5-1 & Figure 5-2). The complications continue when the dynamics within a given winter are considered. During the winter of 2009, a mid-season retreat of sea ice was observed in an area where Pacific walrus are known to breed (Fay et al., 1984; Miksis-Olds et al., 2013).
The Bering Sea is seasonally ice covered. In the winter the Bering Sea is covered by ice; in the summer the Bering Sea is ice free. In 2011, the ice coverage in the Bering Sea reached the greatest recorded extent.

In the years from 2008 to present, the Arctic experienced reduced sea ice coverage, while the Bering Sea saw increases in the ice extent.

Sea ice extent, the area that is at least partially covered by sea ice, is a common metric when discussing large scale phenomena related to sea ice. However, the effects of sea ice thickness and
concentration at local scales will most likely influence the activities of marine mammals like walrus, though these local metrics are difficult to measure and predict with confidence. Analysis of satellite telemetry data, shipboard, airborne, and land-based observations are combined for the National Weather Service’s Alaska Sea Ice Analysis (NOAA’s National Weather Service, 2014). The results of the analysis are produced every 2-3 days. This analysis produces spatial coverage of ice thickness and concentration in the form of geographic information system coverage files. The spatial resolution of the data is inherently limited. Satellite based ASMR-E ice concentration data has a spatial resolution of 12.5 km. Point and line transect observations may have higher resolution, but sacrifice coverage extent. In areas of the Bering Sea where walrus are known to gather for mating, the seasonal ice has predominantly been relatively thin, first-year ice (Wang et al., 2012). The sea ice conditions in the Bering Sea are variable on any given day and are highly dependent on geography (Figure 5-3). Islands, major land masses, and oceanographic conditions, among other factors contribute to the variability of sea ice conditions. In Figure 5-3 the regions to the south of St. Lawrence and St. Matthew Islands are darker than other regions directly surrounding the islands which correspond to lower ice concentrations.

Another method to measure ice thickness relies on the analysis of upward looking sonar systems deployed on sub-surface moorings (Moritz and Ivakin, 2012). The density and stiffness of ice result in a high acoustical contrast between ice and water permitting the estimation of sea ice thickness from active acoustic sensors. The strong reflectivity of the sea ice relative to the water results in a high echo level at the water-ice interface. This data results in higher temporal (and due to moving ice – spatial) resolution, but is limited in spatial coverage only providing results for the area in which the system is deployed.

**Walrus and Sea Ice**

In addition to the ice conditions that need to be incorporated into models for computing the acoustic propagation effects, walrus behavior and physiological limitations also influence the location of walrus breeding activities. The ice must permit the walruses to haul out and rest. Further constraining the
location of walrus breeding is the ability to forage. The few observations of breeding behavior of Pacific walrus suggest that these activities occur at open water leads, polynya, and water only partially covered with sea ice (Fay, 1982). During the breeding season walruses continue to forage (Sjare et al., 2003). Walrus are mostly dependent upon benthic invertebrates as a food source. Walrus are capable of deep diving up to 250 m, however most of their foraging dives are limited to water depths less than 80 m where their preferred food is more plentiful (Born et al., 2003). Most observations of walrus have been in water less than 100 m deep permitting access to the benthic invertebrates they prefer (Fay, 1982). The factors that influence the locations the walrus herds gather for breeding has not been studied. However, a recent study tracking walrus with divergent ice fields suggest that females and calves remain near the edge of the ice extent as it recedes north in the spring (Jay et al., 2010). Access to water from the sea ice limits the locations that walrus may be found. Access to open water, while seemingly preferred, is not required. Walrus have been observed to maintain breathing and access holes in ice up to 20 cm thick (Fay, 1982).

The effect of changing ice conditions on walrus has been observed for herds summering in the Arctic. Reduced summer sea ice extent may negatively impact walrus populations. Walrus will stampede into water when approached by polar bears or humans while hauled out on land. Young walrus may be trampled to death during these stampedes and reduced Arctic summer sea ice extent may increase this vulnerability. Furthermore, reduced sea ice extent may reduce access to foraging grounds resulting in increased energetic costs related to swimming to foraging grounds and greater concentration on shorelines that may increase their interactions with polar bears (Kelly, 2001). Native Alaskans have observed reduced body condition of walruses following summers with reduced sea ice extent compared to years with greater sea ice extent (Pungowiyi, 2000). Walrus increasingly hauling out on shorelines are at greater risk for disturbance from human activities and contamination (Metcalf and Robards, 2008). Recent news reports have anecdotally documented walrus deaths due to trampling from stampedes of walrus hauled out on shorelines in northern Alaska (Joling, 2011).
Observations of walrus during the breeding season suggest that the walrus congregate in pack ice near polynya so that individuals may still have access to the water. The polynya are features of the interplay of the sea-ice and the islands in the Bering Sea (Smith et al., 1990). The first year ice is driven away from the coastline into the pack ice leaving an open water region between the coastline and pack ice, generally south of these land masses (Figure 5-3). This basis of the polynya suggests that the locations are fairly static. The polynya that form near the island land masses in the Bering Sea are considered latent heat polynya, and form as a result of the prevailing winds pushing new ice away from the leeward coast of the islands (Smith et al., 1990). What will vary will be the ice conditions surrounding the polynya and the size and extent of the polynya. Furthermore, the highly dynamic ice conditions that have been observed (Miksis-Olds et al., 2013) suggest that if the walrus breeding herds remain with the ice edge or near polynya, the water depth in which the breeding activities occur will change.
Figure 5-3. NASA image by Rob Simmon based on data from Jeff Schmaltz, LANCE/EOSDIS MODIS Rapid Response Team at NASA GSFC. Ice in the Arctic is solid white indicating thicker, more contiguous ice. Ice in the Bering Sea has variable reflectivity indicating variable thinner ice and greater variability in percent coverage. The ice edge can be seen just below the location of the M2 mooring. Clouds and snow covered islands comprise the white regions below the ice edge.
Detectability

To determine the detectability of a signal the characteristics of the medium, source, and receiver are combined in the passive sonar equation (Urick, 1983). A form of the passive sonar equation was given in Equation 1-1. To estimate whether a signal was detectable, Equation 1-2 was evaluated for specific cases of interest. Chapters 2 & 3 estimated the source level of walrus knocks from captive and wild animals. The OASES propagation model described in Chapter 4 was used to estimate the transfer function representing the effects of the environment on the source signal. The source level and transmission loss were combined by convolving the source signal and transfer functions from the propagation model. Whether or not that signal is detectable depends on the sensitivity of the receivers.

Walrus Hearing

A behavioral in-air audiogram of a male captive pacific walrus was measured at a zoological facility in Denmark in the 1990s using a go/no-go testing paradigm (Kastelein et al., 1996). The researchers used headphones to deliver 500 ms shaped sine wave tones to the subject. The hearing sensitivity of each ear had a similar shape (Figure 1-2). As the threshold of hearing for each ear was tested individually, determining the sensitivity of walrus to binaural stimuli can only be approximated. Most of the research on the phenomenon of binaural loudness summation pertains to human subjects. No clear consensus on the magnitude of the effect exists, but equal loudness measures show increases of loudness of up to 10 dB for clearly audible signals (Moore and Glasberg, 2007). For signals near threshold, the effect of binaural stimulus decreases the threshold sensitivity by up to 2 dB of the more sensitive ear (Hellman and Zwislocki, 2005). A conservative approach for estimating binaural hearing sensitivity based on monaural data is to use the monaural thresholds. An underwater audiogram was obtained for the same subject for which the in-air audiogram was measured (Figure 1-3)(Kastelein et al., 2002).
The walrus knock is a broadband, impulsive signal. Determining audibility of this type of signal from an audiogram based on pure tone signals was not straightforward. The relationship between pure tone thresholds and threshold of hearing for impulsive sounds is poorly understood. Recent studies of harbor seals’ (*Phoca vitulina*) underwater hearing thresholds for pure tone signals and playbacks of pile driving recordings showed no clear relationship between the pure tone audiograms and the sound exposure detection threshold for the pile driving playbacks (Kastelein *et al.*, 2012; Kastelein *et al.*, 2013).

The practice of acoustic weighting provides a means to emphasize and de-emphasize different frequencies within an acoustic sample so that numerical analysis from a flat response system will resemble the perceived metrics by an individual whose hearing abilities are represented by the weighting function. In human hearing, the most common weighting curves are designated A – and C – weighting. These weighting curves have been designed to represent the effect of the physiological capabilities of humans on an acoustic signal for hearing. The sparse amount of data on detection thresholds and equal loudness curves for non-human animals has limited the development of similar curves for other species. There are current efforts to generate acoustic weighting curves for large categories of animals’ especially marine mammals that may be at an increased risk from the effects of anthropogenic noise (Southall *et al.*, 2007).

The detectability of individual walrus knocks was estimated by comparing modeled received signals to the hearing abilities of Pacific walrus. The OASES propagation model was used to estimate the effects of the environment on the propagated signal. A comparison between an open water propagation experiment and model results is presented to verify the adequacy of the model for this environment.

**Methods**

This work relied on propagation modeling to estimate the effect of a variety of environments on acoustic signals generated by male Pacific walrus underwater to conspecific receivers in air and water. Two different regimes were tested, a short range of less than 1 km; and a long range of up to 30 km. In
the short range regime, the model estimated the acoustic signal received 0.5 m above the ice at increasing range from a walrus vocalizing underwater at different depths for different ice conditions. For the long range regime, the model estimated the received signal from a walrus vocalizing underwater at different depths, with ice thickness and water depth varied, and receivers at different depths and ranges within the water.

For both regimes, estimation of the transmission loss from an underwater source to in air receivers above a layer of ice, and receivers within the water column, the OASES OASP package was used. Background and verification of this model’s physics for the short range regime was provided in Chapter 4. With inputs of environmental conditions, source characteristics of depth and frequency range, and receiver locations, this program outputs a transfer function related to the time-series effect due to the propagation through the environment. The output transfer function can then be convolved with a source signal in units of pressure to generate estimates of the received acoustic pressure time series signal at the receiver locations. To estimate the effect of the environment on the received signal for receivers in the water, the same propagation model was used. The adequacy of the model physics was validated by comparing the results of a propagation experiment of up to 1.2 km in range in water 70 m deep at the site of the receivers used for the recordings of wild vocalizations (Chapter 3).

**Open Water Propagation Experiment**

During the normal mooring operations associated with the recovery of the sub-surface oceanographic moorings maintained by PMEL, designated M2 and M5, along the 70 m isobath in the eastern Bering Sea, underwater propagation experiments were conducted. Immediately before recovery of the sub-surface moorings, an acoustic propagation experiment consisting of tonal and frequency modulated signals was undertaken. At approximately the same time, physical oceanographic characteristics were obtained from a conductivity, temperature, and depth (CTD) sensor cast from the
research vessel from which the deployment occurred. The CTD provided information to generate a sound velocity profile for the location.

The same recorders that were used to collect recordings of wild walrus vocalizations in Chapter 3 were used in this experiment. The AURAL was a commercially available, programmable passive acoustic recorder operating on a 30% duty cycle. The AURAL recorded with a sampling rate of 8192 Hz, continuously for 9 minutes every half hour. The Passive Aquatic Listener (PAL) was an adaptive sub-sampling passive recorder. The PAL recorded with a sampling rate of 100 kHz, for 4.5 s. The PAL had an on-board event detector that saved the digital acoustic recordings if an acoustic event was detected.

**Acoustic Source Equipment**

The experiment was conducted using a Lubell Labs Underwater speaker model LL9162T. The beam pattern of the projector was approximately omnidirectional (±1 dB) below 2 kHz. Up to 10 kHz, the projector has a main lobe wider than ±30° up to 5 dB. The projector was connected to a Dual solid state amplifier model XPA 2100 powered by a 12 V sealed lead acid battery. A cabled hydrophone, HTI-96-min was deployed 4 m astern from the projector to record the signal that was broadcast. Despite the best efforts of the officers and crew of the ship, the conditions of the Bering Sea prevailed and the ship experienced pitching during the broadcast which undoubtedly impacted the depth of the projector and cabled hydrophone, although both were deployed using elastic surgical tubing to attempt to limit the effects of the surface motion. The surface conditions also resulted in a changing location of the ship due to the current. The location and elevation of the ship were recorded from the shipboard GPS. The broadcast and local acoustic recording equipment were calibrated in the tank located in the basement of the Applied Science Building on the campus of Penn State before and after field work.
Propagation Model Parameters

The location of walrus breeding conditions is likely constrained by ice conditions and access to food. Due to the continuing foraging of walruses during breeding season, the location of breeding activities will most likely be limited to water shallower than 100 m. The 100 m isobath extends from Unimak Island, northwest to the northern edge of the Kamchatka peninsula (Figure 5.3). To adequately investigate possible bathymetric conditions at potential walrus breeding activity sites, acoustic propagation models were run for environments up to 100 m at resolutions of 5 m depth.

Ice Estimation

The M5 mooring containing the passive acoustic sensors on which the data from Chapter 3 were based also included a suite of active acoustic sensors. The sensors were deployed in an upward looking orientation. Data from these instruments was available from 2008 through 2013. The sea ice draft was identified in the backscatter sampled echogram by identifying the greatest backscatter volume difference between two range samples for each ping. The target strength for sea ice has been measured with values from -5 dB to -15 dB for acoustic frequencies of 100 kHz to 300 kHz (Stanton et al., 1986; Garrison et al., 1991). These target strengths are greater than those for other objects like plankton and ice algae that may be picked up by the sensor. The range from the transducer associated with the greatest change in backscatter volume was the location of the draft of the sea ice, how deep the ice protruded into the water, not the thickness of the ice (Moritz and Ivakin, 2012). The range from the face of the SONAR system to the ice draft can then be subtracted from the depth at which the system was deployed to determine the ice draft. The ice thickness can be estimated from the draft by multiplying by a constant from 1.1-1.2 for the density contrast of sea ice to sea water (Moritz and Ivakin, 2012). The mean value, 1.15, of the range of density contrasts was used. Active acoustic data were collected for a period of 5 minutes every half hour, at a rate of one ping per second. The frequency of the acoustic ping for the instrument was 125 kHz at
which sea ice is highly reflective. Estimates of ice thickness from the active acoustic data were compared with estimates from NWS Alaska Sea Ice Analysis.

The unknown impacts of climate change on the Bering Sea ice conditions requires modeling of the environment with variations in ice extent and thickness. The variable environment was modeled with different ice thickness, water depth, and vocalizing walrus depths. The ice thickness was modeled over ranges generated from analysis of sea ice data, with thickness resolution of 10 cm. Water depth was varied from 10 to 100 m in increments of 5 m. The water column was modeled with a uniform sound velocity profile with sound speed of 1435 m/s. This was the median value obtained from the measurements of sound speed from the data collected from the oceanographic mooring at M5 as described in Chapter 3. Substrate was modeled with sound speed and density of 1540 m/s and 1790 kg/m³ representing a coarse silt sea floor type (Urick, 1983; Grebmeier et al., 1988). The ice was modeled with compressional velocity of 3500 m/s and sheer speed of 1800 m/s and density of 910 kg/m³ (Kinsler et al., 2000). A temporal resolution of 42 µs was used which correlates to a 24 kHz sample rate (Table 5-1).

From analysis of wild recordings of walrus knocks and localization from these recordings, the majority of walrus knocks were produced from individuals at depths of 10-50 m below the surface. However, knocks were localized throughout the water column from the surface to the sea floor (Figure 3-19). For each environment modeled, the location of the source vocalization was varied through the water column at 5 m increments. This resulted in 2,470 simulations generating one transfer function for receivers located 0.5 m above the ice in 5 m range increments up to 1 km from the source. All depths in the model inputs were calculated relative to 1 m above the air-ice or air-water interface. For longer range propagation in which the receiver was also underwater, the same water depth ranges, ice estimate ranges, and source depth ranges were used. The sound speed parameters used for the underwater propagation were also the same as those for the multi-media propagation. The transfer functions were calculated at ranges up to 30 km in 100 m increments. The depths of the receiver walrus were varied with 5 m resolution up to the depth of the water being modeled.
Table 5-1. Input parameters for the OASES propagation model (OASP). J - Complex integration contour; N - normal stress; f - full Hankel transform; cc - compressional speed (m/s); cs - shear speed (m/s); ac - compressional attenuation (dB/Λ); as - shear attenuation.

<table>
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Source Knocks

To generate modeled received signals each transfer function was convolved with 20 calibrated knock recordings obtained from both captive and wild recordings. Knocks from both the PAL and AURAL autonomous recording systems were used, and chosen to cover a range of source levels. The calibrated knock recordings were resampled to 24 kHz sample rate as the majority of the walrus knock spectrum was below 12 kHz. The recordings from the AURAL were up sampled, and recordings from the PAL and captive recordings were down sampled after anti-alias filtering. The amplitudes of the source knock recordings were normalized to the mean estimate from wild recordings of 177 dBpp (re: 1 μPa).
Convolution of the OASES model transfer functions with the source recordings combined the source level and transmission loss into an estimated received signal. The effect of the environment on the signal, the transmission loss, was represented in this work as the transfer functions output from the propagation model. From this received signal two measures of received level were calculated for each in-air and underwater receiver location, a sound exposure level (dB re: \((20 \, \mu Pa)^2 \text{s} \, \text{air} / \text{dB re: } (1 \, \mu Pa)^2 \text{s} \, \text{water}) and a root-mean-square level (dB re: \(20 \, \mu Pa \, \text{air} / \text{dB re: } 1 \, \mu Pa \, \text{water})).

**Walrus Hearing**

The detectability of a signal by a receiver is dependent upon the hearing abilities of that receiver. The in-air audiogram of walrus was used to determine detectability in air (Kastelein et al., 1996). The underwater audiogram was used to determine underwater thresholds (Kastelein et al., 2002). The hearing capabilities of walrus were implemented in two ways. First, the root-mean-square pressures of the convolved signal for octave bands centered on the frequencies were computed for frequencies where pure tone hearing thresholds were tested. Second, a C-weighting filter was applied to the time-series signal and the sound exposure level was calculated and compared to a detection threshold estimated from the audiograms. The C-weighting curve was chosen over the pinniped hearing curve presented in Southall et al. (2007) as that curve was generalized for all pinnipeds, while the C-weighting curve more closely resembled the audiograms for Pacific walrus (Kastelein et al., 1996; Kastelein et al., 2002) (Figure 5-4). The C-weighting filter attenuates the frequencies below 400 Hz, with a flat response from 400 Hz to the Nyquist frequency of the modeled signal. The walrus hearing thresholds were effectively flat from 400 Hz to the highest frequency tested – 8 kHz. The modeled received signal was filtered by this weighting filter and the sound exposure levels were computed. The weighting filter was created using the filter design tool in Matlab with a bandwidth of 12 kHz.

The modeled received signal was filtered by one-third octave band pass filters centered at the frequencies for which pure tone thresholds are available. A Butterworth filter was created in the Matlab
functions *fdesign* & *design*. The stop band amplitudes were set to 60 dB with 0 dB pass band amplitude. The modeled time signal was much less than the 500 ms tone used to measure hearing. The band limited RMS values were calculated for each signal over the duration of the modeled signal.

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**Figure 5-4.** Pacific walrus audiograms (underwater – blue, in-air – red) and magnitude response of C-weighting filter used to approximate walrus hearing perception. The high and low frequency roll-offs in the walrus audiograms are similar to the roll-offs in the C-weighting filter. Decibel references are 1 µPa for underwater, 20 µPa for air, and 1 for frequency response.

**Detectability**

For both in-air and underwater receivers, detectability was estimated in the same manner, just with different thresholds. Detectability was measured differently for each implementation of walrus hearing. For the octave band filtered levels, the level was compared to the threshold of hearing as a function of frequency reported in the Kastelein *et al.* (1996) study. The relationship between pure tone hearing thresholds and perceptibility of impulsive signals is not well understood. The sound exposure level for the frequency of greatest sensitivity, 2 kHz, on the walrus audiogram was 53 dB (re: (20 µPa)^2s). A sound exposure level threshold of 71 dB (re: (20 µPa)^2s) for the detection of filtered knocks was used, as a conservative estimate 18 dB greater than the measured pure tone threshold. For octave band
thresholds and sound exposure thresholds, this produced a binary result that either the signal exceeded any of the thresholds or it did not. The sound exposure level for the frequency of greatest sensitivity underwater, 12 kHz, was 69 dB (re: 1 μPa²s). For a conservative estimate of detection threshold, a sound exposure level of 87 dB (re: 1 μPa²s) was used.

Statistics

Investigation of the effects of different parameters of range, source depth, ice thickness, water depth, and receiver depth was conducted using a generalized linear model (GLM). The GLM is a generalization of linear regression to permit the comparison of many input parameters on an output (Madsen and Thyregod, 2011). As the results of the detectability were binary in nature, either the signal was detectable or not, a binomial distribution is used. GLM tests require that a link function is used. The link function provides the relationship between the linear predictor variables and the distribution function. For binomial distributions, the logit function is the standard link function.

Results

Open Water Propagation Experiment

Both of the passive acoustic recorders deployed on the moorings were operating on a duty-cycle to extend battery and storage for longer deployments. Due to this reduced duration only a limited number of signals were recorded by either instrument. The limited number of acoustic signals recorded by the PAL each day prevented the recording of experimental acoustic signals as the daily quotas of saved files were already exceeded. The recordings from the AURAL on the dates of 18 May 2011 at M2 and 20 May 2011 at M5 provided the most useful data. Additional results from the PAL were obtained, but due
to the on-board processing, only spectral data were available, not the full acoustic record. Data from CTD casts were used to calculate the sound velocity profile at each site Figure 5-5.

![Figure 5-5. Sound velocity profiles measured at the sites of the propagation experiments for M2 (left) and M5 (right). The sound velocity profiles were calculated from the casts of the on-board SeaBird Electronics SeaCAT made at the same location as each of the broadcasts.](image)

On 20 May 2011, the signal was recorded on the AURAL at the M5 mooring. At the start of the broadcast, the ship was located at 59° 54’ 34”N and 171° 42’ 6”W. During the broadcast the ship drifted approximately 300 meters further from the mooring. The mooring location was 59° 54’ 40”N and 171° 42’ 26”W. This results in a range from the ship to the mooring of approximately 560 to 860 meters. On 18 May 2011, a propagation experiment at M2 was conducted with the ship located at 56° 52’ 52”N and 164° 3’ 26”W. The mooring was located at 56° 52’ 29”N and 164° 3’ 43”, for a starting range of 760 meters. During the 30 minute propagation, the ship drifted less than 50 m further from the mooring. Five signal types were recorded on the AURAL, CW tones at 1 kHz, 1.25 kHz, 2 kHz and 4 kHz, and a frequency modulated sweep from 500 Hz to 5 kHz (Figure 5-6, Figure 5-7, and Figure 5-8). The recorded frequency sweep was aliased above 4096 Hz due to the sample rate of the AURAL. The received level
for the CW tones calculated as the average of the band limited RMS pressure levels at those frequencies with 0.5 second time windows was 103 dB, 96 dB and 100 dB (re: 1 µPa) for 1.25 kHz, 2 kHz, and 4 kHz. The received level recorded on the AURAL at M2 was on 18 May 2011 was 105 dB, 104 dB, 102 dB, and 102 dB (re: 1 µPa) for tones with frequencies of 1 kHz, 1.25 kHz, 2 kHz, and 4 kHz. The levels were calculated in the same manner for the reference hydrophone at 4 m (Table 5-2) as they were for the acoustic record from the AURAL (Table 5-3). The source levels at 1 m for the experiment were calculated from the recording of the hydrophone located 4 m astern of the projector. During both experiments these locations were sea ice free.

Figure 5-6. Sequence of FM sweeps and CW tones recorded on AURAL at M5 on 20 May 2011. The Nyquist frequency of 4096 Hz resulted in the aliasing of the high frequency end of the linear FM sweep. This plot shows two FM sweeps and three CW tones at 1250 Hz, 2 kHz, and 4 kHz.
Figure 5-7. FM sweep recorded on AURAL at M5. This is a zoomed in view of the FM sweep up to the Nyquist frequency.

Figure 5-8. CW tone recorded on AURAL at M5. This is just the 2 kHz signal. The noise environment was consistent over the broadcast of the acoustic signals.
Using the OASES range independent propagation model, time domain transfer functions for the environments identified here were modeled. From this model, the transfer function was generated which can be used to determine the effects of the environment on the signal for a receiver at a specific location. The source signal was convolved with the transfer function to estimate the received level at the deployed recorders. Band limited RMS levels were computed from the resultant signal and compared to the recorded signal from the AURAL to verify the adequacy of the model physics for these environments. The model was run for frequency bandwidth of 8192 Hz for the AURAL. The measured and modeled transmission loss for each of the propagation experiments is given in Table 5-3. For the recorded signals, the average measured and modeled transmission losses were within 2 dB of each other for all frequencies. The sound velocity profiles represented by the blue lines in Figure 5-5 were used to define the water column in the propagation model. This region of the Bering Sea has a sediment composed mainly of fine and coarse sand (Grebmeier et al., 1988). The bottom properties for both sediment types were implemented in the model with a better fit resulting from the use of coarse sand. The bottom properties implemented were 1540 m/s and density of 1800 kg/m³ (Urick, 1983). Due to the drifting of the ship, the exact range of propagation was unknown. The model was run to compute the received level at ranges spanning the distance of the ship to the recorders and the results from the best fit were selected. This experiment validates the model physics for the OASES range independent propagation model for a signal that remains completely within the water column over greater ranges than were tested in the under ice experiment in Chapter 4.

### Table 5-2. Source level by frequency for signals recorded during propagation experiments from the ship.

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<tr>
<td>M5</td>
<td>20-May-11</td>
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</tbody>
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Table 5-3. Measured and modeled transmission loss for each location.

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<tr>
<td>M5</td>
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<td>43</td>
<td>48</td>
<td>47</td>
<td>44</td>
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</tr>
</tbody>
</table>

Figure 5-9. Source levels, and measured and modeled received levels for open water propagation experiments in the Bering Sea. Source levels are in blue and referenced to the right vertical axis. Received levels are in red and referenced to the left vertical axis. Modeled results have solid markers. M5 markers are triangles. M2 markers are squares.

Environment

Predictions of future sea-ice conditions are tenuous at best. To generate values of ice conditions in the Bering Sea, extremes of historical ice conditions were examined. Analysis of NOAA ice desk thickness maps indicate that the historical areas of Pacific walrus breeding activities, to the southwest of St. Lawrence and St. Matthew Islands, resulted in ice thickness estimates from 0 to over 1 meter thick (Figure 5-10). The upper limit of ice thickness reported in these analyses was “greater than 1.2 m”. From the analyses of upward looking sonar sensors deployed at the M5 mooring, maximum ice
thicknesses of 2.2 m were detected (Figure 5-10). Therefore, for the propagation model, ice thickness was modeled up to 2.5 meters thick at resolutions of 10 cm. Comparisons between the ice thickness metrics from NOAA and the results of analysis of active acoustic sensor data are confounded by the ice concentration. If the percent cover of the ice was less than 100%, part of the region did not have ice cover. Agreement between the two datasets can be seen during periods in which there was no sea ice, where both estimates drop to zero. Furthermore, while the calculated ice thickness from the active acoustic sensors results in continuous values, the ice thickness estimates from NOAA are limited to seven unique values.

![Figure 5-10](image.png)

**Figure 5-10.** Sea ice thickness (blue) and concentration (green) for the region around the M5 mooring from NOAA Sea Ice Desk. Solid lines are the mean values. Dashed and dotted lines are the minimum and maximum estimated values. NOAA published values approximately every 2 days. Sea ice thickness measured from an Acoustic Water Column Profiler (AWCP) (red line). AWCP estimates were made based on the average value calculated from 5 minutes of sampling every half hour.

**Modeled Received Level**

The output of the modeled transfer function was convolved with the calibrated source knocks to produce an unfiltered estimate of the received acoustic signal. From this estimated time-series, sound exposure and root-mean-square levels for receivers located 0.5 m above the ice and at depths within the
water column at 5 m increments were calculated. The received levels had a logarithmic relationship with range.

**Detectability**

Comparing the modeled received level to the hearing capabilities of walrus as specified by the in-air audiogram measured by Kastelein et al. (1996) yielded binary detectability measures for each model. Unweighted band limited root mean square levels for the modeled received knocks never exceeded the thresholds at ranges greater than 10 m from the source. Detection based on the C-weighted sound exposure levels compared to a threshold of 71 dB (re: (20 µPa)² s) yielded more variable results (Figure 5-11 & Figure 5-12). As expected the patterns of detectability changed with water depth, walrus depth, ice thickness, and range to receiver.

![Figure 5-11. Binary detectability of average received level 0.5 m above ice for walrus knocks for a walrus at 10 m depth in 100 m of water varying with range (x) and ice thickness (y). Knock is detectable for red cells.](image)
Figure 5-12. Binary detectability of average received level 0.5 m above ice for walrus knocks for a walrus at 70 m in 100 m of water varying with range (x) and ice thickness (y). Knock is detectable for red cells.

The detectability of the average received level of modeled walrus knocks as a function of vocalizing walrus depth and range of receiver for four ice thickness values – 20 cm, 80 cm, 140 cm, and 200 cm shows that the range and ice thickness have more effect than source depth on the detectability (Figure 5-13).

The binary detectability comparison of the modeled received level with detection threshold showed that knocks were detected through ice up to 1 m thick at ranges up to 1000 m (Figure 5-11 & Figure 5-12). The knocks were not always detectable for all water and walrus depths, but ice thickness above 1 m greatly reduced detectability at ranges greater than 200 m (Figure 5-13). Based on the ice thickness analysis from the NOAA Ice Desk, 1 m was often the upper limit of ice thickness near the M5 mooring when walrus knocks were recorded. With a threshold of 71 dB (re: (20 µPa)²s) an upper limit of 500 m on the effective range of audibility would be expected for these situations.
Figure 5-13. Detectability of walrus knocks in 100 m of water with four different ice thicknesses modeled a) 20 cm; b) 80 cm; c) 140 cm; d) 200 cm.
A generalized linear model (GLM) was used to examine the effect of predictor variables (water depth, walrus depth, ice thickness, source vocalization, and range) on detectability. For this test, the amplitude of the source signals were normalized to 177 dB<sub>pp</sub> (re: 1μPa) to remove source amplitude as a factor, which would clearly affect detectability. The results of the GLM indicate that all of the predictors are significant (Table 5-4). As they were inputs for the propagation model this was expected. Noise was excluded from this analysis as the hearing capabilities of walruses in noise has not been examined. With range, water depth, walrus depth, and ice thickness values all in units of meters, the absolute value of the coefficient estimates indicate the relative importance of the predictor on the output – detectability. The coefficient estimates can be thought of as the influence per meter of each predictor (except for source signal which were nominal data) on detectability. Ice thickness is the most influential factor per meter. The absolute value of the coefficient estimate was in line with the T-statistic values which are also used to estimate the influence of predictors.

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<td>0.00015</td>
<td>-7.78</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>WALRUS DEPTH</td>
<td>0.00099</td>
<td>0.00015</td>
<td>6.47</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ICE THICKNESS</td>
<td>-0.027</td>
<td>7.2e-05</td>
<td>-379.14</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SOURCE SIGNAL</td>
<td>0.28</td>
<td>0.0022</td>
<td>127.65</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RANGE</td>
<td>-0.0049</td>
<td>1.4e-05</td>
<td>-341.29</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Table 5-4. Results of a GLM comparing detectability by a walrus in air with water depth, walrus depth, ice thickness, source signal, and range. Source signal amplitudes were normalized to 177 dB<sub>pp</sub>
Estimates of received signals for receivers located within the water column were used similarly to the in-air estimates to determine a binary detectability of the impulsive knock signals. The modeled received signals within the water column were compared with a detection threshold of 87 dB (re: 1 $\mu$Pa·s). Binary detectability for a receiver in water was determined for each model with the same parameters as in the in-air model, plus receiver depth.

A GLM was used to examine the effect of the predictor variables of source depth, water depth, receiver depth, ice thickness, source file, and receiver range on detectability. This was similar to the model examining detectability in air with the added predictor of receiver depth. The GLM link and distribution parameters were the same as the in-air model: logit link and binomial distribution. The results of the GLM indicate that water depth, source walrus depth, ice thickness, and receiver range were all significant predictors of detectability (Table 5-5). Source signal and receiver range were not significant predictors. In this regime, the effect of ice thickness was less important than the other significant predictors of range, source depth, and water depth based on comparisons of the T-statistic values. The received acoustic signal would mainly be affected by the presence of ice due to reflection and not coupling from the water to the ice to the air, thus limiting the effect of thickness. For receivers that are in the water column, the most influential predictor was range between source and receiver. This was similar to what would be expected in more traditional underwater propagation environments.
Table 5-5. Results of a GLM comparing detectability by a walrus in water with water depth, source walrus depth, ice thickness, source signal, range, and receiver walrus depth. Source signal amplitudes were normalized to 186 dBpp.

<table>
<thead>
<tr>
<th></th>
<th>ESTIMATE</th>
<th>SE</th>
<th>T-STATISTIC</th>
<th>P-VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(INTERCEPT)</td>
<td>-3.55</td>
<td>0.030</td>
<td>-116.79</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>WATER DEPTH</td>
<td>0.047</td>
<td>0.00032</td>
<td>146.68</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>WALRUS DEPTH</td>
<td>-0.024</td>
<td>0.00024</td>
<td>-99.89</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ICE THICKNESS</td>
<td>-0.0012</td>
<td>6.9E-05</td>
<td>-69.06</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>SOURCE SIGNAL</td>
<td>-0.0025</td>
<td>0.0032</td>
<td>-0.77</td>
<td>0.44</td>
</tr>
<tr>
<td>RANGE</td>
<td>-3.81E-06</td>
<td>5.52E-08</td>
<td>-177.009</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RECEIVER DEPTH</td>
<td>0.00040</td>
<td>0.00016</td>
<td>2.4</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Discussion

Open Water Propagation Experiment

The OASES range independent propagation model adequately estimated the propagation in the environment. Using only one parameterization of the underwater environment for each location, the propagation model was able to estimate the levels of the received signal at the deployed underwater receivers. The relatively stable water column of the Bering Sea in winter, along with very gradual slope of the continental shelf encourages the use of the range independent model. The experimental propagation was limited to ranges of less than 1 km and was conducted with no sea ice cover. The model
worked adequately in the environment of the southeastern Bering Sea and has been used successfully to model underwater propagation over longer ranges with ice coverage (Goh et al., 1997).

Detectability

Range, ice thickness, water depth, and source depth contribute to the detectability of the walrus knock by conspecifics hauled out on ice. There was no clear cut off range after which the modeled knocks were not detectable; though range and ice thickness were the most important factors for determining detectability. The modeled signal level may be below detection threshold at a specific range, but then above threshold at a greater range with different ice conditions. The M-weighting curve (Southall et al., 2007) for pinnipeds was not used as higher frequencies were included with less attenuation than would be suggested by the underwater audiogram for Pacific walrus.

One caveat, for this analysis is that interpreting audiograms for signals other than those used during the testing process was not straightforward. Audiograms were measured by exposing a walrus to 500 ms (air) and 1500 ms (water) pure tone signals at specified frequencies in quiet environments. The predominant signal of walrus vocalizations is the knock, a broadband, impulsive signal with acoustic energy up to 12 kHz. Selection of detection thresholds based on this audiogram was inevitably problematic. Two methods for comparing the hearing ability of walrus with modeled received signals were used in this analysis: 1) The modeled signal was filtered by a weighting filter that matched the inverted shape of the audiogram, the C-weight filter used for human hearing; and 2) the band limited RMS amplitudes of the modeled signal were calculated for each of the frequency bands at which the audiograms were generated. These two methods produced vastly different results. Using band limited root-mean square values relies on the same metric that was used in measuring the pure tone detection thresholds, however, impulsive signals are different enough that the thresholds cannot be expected to be reliable. Sound exposure levels are the accepted metric for impulsive sounds, but sound exposure levels from pure tone signals, like those used to generate audiograms, do not translate to thresholds for impulses.
Furthermore, the in-air audiogram for walrus was obtained from one captive male. Wild adult females were the receivers of interest. There may be differences in auditory sensitivity based on life history, captive versus wild, and sex. Detection of signals near threshold is improved by repeated exposure. Underwater detection threshold of impulsive signals by harbor seals was improved when the signal was played more than once. It was as if the animal was unsure if they heard the sound, and on the second exposure the stimulus was confirmed (Kastelein et al., 2013). Walrus breeding codas contain many knocks arranged in sequences with consistent timing intervals which may increase the detectability of the sequences above any individual knock. As has been suggested by others and is currently underway (though not for walrus), more research effort should be focused on determining detection thresholds, as well as disturbance metrics, for non-pure tone signals (Southall et al., 2007; Kastelein et al., 2012; Kastelein et al., 2013). With most of the research efforts focused on the most critical or most available species of marine mammals a functional model for estimating detection thresholds of real-world signals from pure tone audiometric data would be extremely beneficial.

The great range at which walrus knocks appear to be detectable by underwater receivers is in no small part due to the relatively high source levels of these signals (Chapter 2 and Chapter 3). The variability of the source level will directly impact the range of detection for these signals. Furthermore, the detectability of the signal also depends on the attentiveness of the receiver. An individual focused on migrating or foraging may not be able to detect signals that an attentive individual would. Furthermore, simply because a signal is detectable, the ability to garner information from the signal may be limited, especially near the limits of detection.

**Noise Level**

Detectability was determined for model results without consideration for noise. Published values of in-air noise near hauled out walruses are available for an Atlantic herd hauled out on a gravel beach in Svalbard (Table 5-6) (Kastelein et al., 1993). These noise values are well below the published hearing
thresholds of Pacific walrus. Furthermore, the hearing thresholds were determined under idealized conditions in which the noise was limited. Therefore, noise was not included in determining the detectability of walrus knocks. For most of the predictions, the signal excess was small, less than 10 dB and therefore would likely be affected by the presence of noise 10 dB greater than hearing thresholds. For the frequencies of greatest sensitivity with thresholds around 60 dB, band limited noise levels of 70 dB would be conceivable due to non-breeding vocalizations of hauled out walruses, wind and other weather related noise, and ice noise. For a receiver underwater, we have a better understanding of the noise that would be experienced, however, the lack of understanding of the effect of noise on the detection of impulsive signals prevents concrete interpretation of the effects of noise. Sound exposure levels computed C-weighted noise samples from the Bering Sea for durations of the knocks resulted in values below the thresholds used in the model. This was most likely the case because of the short duration and the dominant energy in the noise was low frequency and attenuated by the weighting function.

Table 5-6. Reported octave band levels from a herd of Atlantic walrus hauled out on a gravel beach (Kastelein et al., 1993).

<table>
<thead>
<tr>
<th>Hz</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>dBA</th>
<th>dBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>dB</td>
<td>35</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>35</td>
<td>45</td>
<td>50</td>
</tr>
</tbody>
</table>

The effects of water depth on the in-air detectability of walrus knocks was less than ice thickness and range. If the location of the polynya shifts to shallower water, the main effects will still be due to ice thickness and range to receiver. What may be of concern is the effect that the shallow water would have behaviorally. In shallower water, will the males make mostly vertical or horizontal dives? Will the dives result in the male walrus swimming away from the females during the display, thus negatively impacting the detectability of his knocks? The short range over which the knocks are detectable regardless of water depth suggest that the local water depth does not play a role in the detectability of knocks by females hauled out in the vicinity of a vocalizing male.
Walrus that are hauled out on ice within tens of meters of an underwater vocalizing male are likely to be able to hear the knocks of the breeding displays even on ice over 2 m thick. Prediction of walrus knock detectability at ranges and ice thicknesses resulting in barely detectable received levels are specious. It would be difficult to assume that the walrus are listening intently and that ambient noise and other social sounds would not negatively impact detectability.

Conclusions

The overall extent of ice conditions in the Bering Sea and specific conditions at any given time and location are highly dynamic and could influence the timing and location of breeding herds of walrus at a local scale. Suitable conditions will most likely continue to be available, though not necessarily in the historical locations. In the regions where walrus breeding activity have taken place, the ice is generally young ice with limited thickness. These ice conditions are predicted to continue as the reduction in summer ice extent in the Arctic will limit any multiyear ice in the Bering Sea during the winter. The expansive Bering Sea shelf provides a large area over which permissive ice conditions could exist with water depths still within foraging limitations, such that walrus breeding activities can occur. The effect of changing ice conditions on the breeding interactions of Pacific walrus will manifest in timing and location, which already occurs. For water depths up to 100 m it is likely that a walrus knock from an underwater male could be heard by a walrus hauled out on ice overhead and within tens of meters in range regardless of reasonable sea ice thickness (less than 3 m). The main factors that influence the likelihood of detection in-air are ice thickness and range from vocalizing individual. For conditions of ice for recent years for which there is thickness data, the ice has generally been limited to less than 1 m, under such conditions a knock could be detected up to a couple hundred meters in range from the vocalizing individual.
Acoustic waves propagate through water more efficiently than electromagnetic waves, including light. Due to this, many species of marine mammals have developed communication and foraging systems that are highly dependent on acoustic signals. Investigations of these animals’ acoustic communication systems are often limited to a single medium. Conspecific communication between dolphins is not dependent on how much acoustic energy would be received above the water surface – a dolphin is rarely out of the water. Pinnipeds – seals, sea lions, and walruses – are often just as likely to be out of the water as they are to be in the water. With the possibility of these animals being outside of water, there may be some benefit for communication between an individual in water and an individual in air.

The work described in this dissertation attempted to generate and compile information in order to determine the feasibility of communication from an underwater caller to receivers in-air and under water under a variety of conditions. The Pacific walrus is an interesting case as the male walruses vocalize underwater in the proximity of potential female mates hauled out on nearby sea ice. These displays have been hypothesized as advertisements of fitness as well as defense of territory. Source level and transmission loss estimates were compared to detection thresholds to determine the detectability of individual vocalizations.

To determine the detectability of underwater walrus vocalizations by other walruses both in and out of the water a number of acoustic parameters were needed. Synthesis of source level, transmission loss, and detection threshold parameters for the propagation of walrus vocalizations permitted the estimation of detectability under a variety of environmental conditions. These parameters were combined to reduce a complex physical problem into simple mathematical inequalities (1-2). Values for the constituent variables were determined individually and then combined. Source level estimates were
generated from recordings of both captive and wild walruses. Environmental effects on the propagation of these signals were obtained through the use of computational propagation models. The adequacy of the propagation model was validated for this problem in two propagation experiments. Transmission loss and source level were compared to detection thresholds obtained from walruses to estimate detectability of these signals.

Summary of Chapters

The ability to concurrently collect acoustic and visual records of adult male Pacific walrus performing acoustic displays in the wild is improbable. The behavior of walruses and remote, dynamic, and harsh conditions of the Bering Sea in winter prevent the collection of these data with direct human observation. With the collaboration of SeaWorld San Diego a hydrophone was deployed in the walrus enclosure while the adult male walrus was in rut. Concurrent collection of audio and video recordings permitted the estimation of source levels of walrus knocks from this individual. Chapter 2 details the collection and analysis of recordings of walrus knocks from this animal. It was found that the mean source level of the knocks was 183 dB$_{pp}$ (re: 1 µPa). There was variability in the level of the knocks. Two factors that were found to significantly affect the source level of the knocks were the ambient noise level immediately before the knock, and whether the walrus was resting underneath an overhang. Of course, the captive environment was quite different from the wild environment. The range between the walrus and the receiver was limited; there were walls and floor made of cement; most of the surface was a water/air interface.

The change in source level with respect to the walrus resting under the overhang suggests that, at least for this individual, getting louder could occur simply by using an environmental feature to maintain position. Walruses in the wild could similarly rest under the sea ice. All things being equal, creating louder knocks will increase the range over which an individual can be heard. By resting under an
overhang, and by inference under the sea ice, a male walrus can increase his effective communication range. For an individual trying to defend his territory (nearby females), encourage females to enter the water to mate, or attract females from other areas this may be a strategy that accomplishes this with reduced energetic costs. Another hypothesis for this behavior is that the male voluntarily increases the source level of the knocks while in contact with the overhang to attempt to couple more energy to the ice above him. This relationship may also be a means to more effectively couple the knocks to the ice and have more energy reach receivers on the other side of the ice.

Increases in the noise level recorded on the hydrophone deployed in the walrus exhibit pool were accompanied by increases in source level of knocks. The Lombard effect may be involuntary and suggests that increases in the ambient noise, whether due to natural or anthropogenic causes, could increase energetic costs of these displays. Furthermore, as the slope of the relationship between source level and noise level was less than unity (Figure 2-13), increases in noise may reduce the detectable range of the knocks.

In Chapter 3, source levels were calculated for walrus knocks recorded on instruments deployed in the Bering Sea. By comparing the relative multipath arrival times of the knocks, the source location could be estimated and the propagation distance can be accounted for in the estimates of source level. From this analysis the average source level from the wild walruses was determined to be 177 dB_{pp} (re: 1 μPa). Localizations from the walruses showed that while knocks were recorded from walruses localized throughout the water column, a majority of the knocks came from walruses 10 m to 50 m deep (Figure 3-19). Reported depths of walrus knocks from Mouy et al. (2012) indicated that most of the knocks were localized to source depths in the top 20 m of the water column. Clearly, the difference in water depth at these two locations influenced the depth of the vocalizations, but this suggests that the function of these vocalizations may indeed be different.

The Lombard effect identified in the recordings of the captive walrus vocalizations (Chapter 2) was corroborated in the analyses of the wild recordings (Figure 3-20). The size of the effect was similar between the two datasets, wild and captive, at about 5 dB increase per 10 dB increase in noise level. The
datasets used to generate the estimates of source level from wild walruses were made from two different recorders collecting data over two different periods. The median source level over multiple years varied. The multiyear dataset was limited in the number of knocks detected each year. While the median source level values were different each year, the size of the difference was limited, with all of the median values within 6 dB of one another. While changes of the level would be cause for concern, the inconsistent direction of the change in level may mean that this is just a normal variation from year to year and does not represent a marked increase or decrease of knock source level.

A comparison of the source level of knocks from one captive male walrus and estimates made from localizations obtained from autonomous recorders of wild individuals suggests that the source levels for these two groups were not the same. There are many factors that could result in this disparity. They could in fact be different. The between animal variability may be large enough that the estimates from the captive animal were natural outliers that would naturally arise from any population. This disparity may also result from the fact that the captive individual was not exposed to other animals and did not alter his knock source levels in response to the knocks of other animals. While the captive subject was in rut, he was kept separated from the other walrus that was also housed in the same exhibit. If knock vocalizations are used to elicit mates, he was continuously unsuccessful at garnering a mate. Perhaps he was vocalizing at higher amplitudes in an attempt to attract females at greater ranges.

For both the wild and captive estimates, a relationship between source level and noise level was identified. The noise in the captive environment was consistently louder which may help to explain the fact that the captive individual was, on average, louder than the population of wild walruses. This work is the first demonstration of a noise-induced vocal modification identified for any pinniped. While a variety of modifications have been identified in a number of species including humans, terrestrial mammals, birds, and whales, it has not been identified for pinnipeds. Estimates from both captive and wild recordings resulted in an apparent Lombard effect. Significant, positive correlations between noise level and source level were identified in both datasets.
While the data from the captive walrus provide estimates from direct observations where the location, identity, and life history of the individual vocalizing was obtained, the estimates were based on recordings from only the single individual. In contrast, the recordings from the wild walruses were from an indeterminate number of walruses with no life history information, and the assumption that the vocalizing individuals were male. The difference in source level reported by one study of wild pacific walrus and one study of a captive pacific walrus was 10 dB (Hughes et al., 2011; Mouy et al., 2012). The recordings of the captive walrus indicated that the mean source level was greater than those described in a paper discussing source levels from recordings of female and juvenile walruses summering in the Arctic (Mouy et al., 2012).

Chapter 4 detailed an experiment to measure the propagation of sound from water, through ice, and into air with sediment and ice composition similar to those found in the Bering Sea. The experiment was conducted near Barrow, Alaska on first year shore fast ice that was less than 2 m thick. Environmental metrics of the experimental site were parameterized and input into the OASES acoustic propagation model. The resulting estimates derived from the propagation model were similar enough to the measured values to give confidence that the model can be used to adequately represent the effect of acoustic signals propagating in complex environments where received signals in air, ice, and water are of interest.

A compilation of the results of the preceding chapters combined with inferences from audiometric data of Pacific walrus examined the detectability of walrus knocks by other walruses in a variety of environments with different ice thicknesses; water, source, and receiver depths; and ranges. In Chapter 5 it was shown that even using a conservative detection threshold estimate, walrus knocks are likely to be heard by female walruses hauled out on sea ice within a few hundred meters of a vocalizing male. Furthermore, other walruses should be able to hear these displays when they are swimming at ranges of up to 20 km depending on the environment and source level of the vocalization.
Biological Significance

The vocalization displays associated with breeding activity of adult male Pacific walrus are most likely audible to females hauled out on ice nearby. Both the underwater and surface vocalizations may influence the females’ mate selection process. A number of different factors can influence how the females perceive the signal from a male vocalizing below the ice platform on which they are resting. For a given environment, the source level of the produced signal will be the main difference between two knocks received by a female. If walrus congregate in different regions, with different bathymetries due to the changing ice conditions, there may be other influences on the received signal. Shallower water may force the walrus to vocalize at shallower depths. Females hauled out on thicker ice floes will experience lower received levels compared to those hauled out on thinner ice floes with everything else the same. If these vocalizations play a role in the mate selection process, the various factors that influence the received acoustic signal may affect the fitness of these animals. While this study did not investigate the relationship between fitness and knock characteristics, one may exist. Hypothetically, a more vigorous male may be able to produce louder knocks than a less fit competitor. However, if the competitor is attending females on thinner ice floes, the females may perceive him to be just as fit as a male in a different region, as the received levels of their knocks were similar. Should females select less fit males, their offspring may experience the negative effects of poorer genetic makeup, thus reducing the overall health of the herd.

General Discussion

The wide variability of source and environmental characteristics mean that there will not be a definitive answer as to what the limits of detectability of these signals are. The research conducted here relied on a range independent propagation model to estimate the effect of the environment on a received signal. The resolution of environmental characteristics measured during this data was less than the range
over which the signals of interest were propagating. If the inputs of the model are not well known, inferences from the results of the computational model must include the caveats that they are the result of under-represented environmental data. These results may still be useful, but the limitations of the computational model should not be ignored.

Further research is required to more fully answer the question of how well these animals are able to hear these signals. Animal mounted sensors, like tags equipped with acoustic recording packages, could be used to help determine the received signal of knocks for females during the breeding season. Creating a walrus-proof device that can withstand the harsh environment in and out of the Bering Sea and still record in-air acoustic signals would be challenging and is a leading reason that this has not been done. However, the wealth of information and the wide array of applications for other large pinnipeds could make such a device extremely valuable to understanding the relationship of these animals to their environment and each other. Accelerometers could also be used to measure the behavior of the animal and correlate them to the acoustic records to help determine whether the signals are influential in the mating process.

The detection thresholds used in this analysis were derived from pure tone audiograms. The signals of interest in this research were impulsive. To more accurately determine the audibility of these signals, detection thresholds for similar impulsive signals should be measured directly. Furthermore, the relationship between received level, repetition rate, and detectability needs to be examined. In addition to providing information on the identity (Stirling et al., 1987) and possibly fitness (Fay, 1982) of the vocalizing male, the repeating signals within the breeding coda may also increase detectability, similar to harbor porpoises improved detection of repeated pile driving signals (Kastelein et al., 2013). If repeated knocks are more detectable than individual knocks of the same amplitude, as would be expected, an interesting follow up question would be at what repetition rate does the increase in detectability diminish? In the research presented here, knocks were considered to be part of one sequence if they were separated by no more than two seconds. These two factors may be related to one another.
As climate change increasingly changes the habitat that these animals inhabit, especially in the summer, the overall fitness of the animals may be negatively impacted. It will be even more advantageous than it is now for female walruses to select the fittest mates, and do so while expending as little energy as possible. Attracting as many mates and avoiding physical confrontations with other males will become even more important to breeding males.

An additional complexity due to sources and receivers being sentient is that there is an inherent lack of consistency in the factors directly dependent upon the animals. The source level of a vocalization can vary wildly within and between individuals. Depending on the context a caller may be inclined to produce vocalizations with different amplitude, shifted frequency content, or altered timing characteristics. Additionally, the characteristics may be modified subconsciously by the caller in response to environmental stimuli. Vocalizations made to attract mates during the breeding season may be different than social vocalizations used the rest of the year. Conspecific competition – a shouting match – might result in louder vocalizations than if only one animal was vocalizing. Noise induced vocalization modifications can result in instinctive source characteristic modifications.

In addition to the source characteristics being different, individual animal receivers have different hearing abilities, and the information we have on all but a very few species is extremely limited. For Pacific walruses, both the in-air and underwater audiograms come from the same captive male. The behavioral state of the individual can also impact detection of acoustic signals. Detection thresholds for attentive listeners are more sensitive than for inattentive listeners. Without knowing the behavioral state of the animal, predicting the detectability of a signal relies on the assumption that the animals are in one state or another, attentive or inattentive. However, it is more likely that the true state lies somewhere in between.

The amphibious nature of walrus and the environment in which breeding activities occur creates a further complexity that needs to be addressed to determine whether signals are detectable. The reflection coefficient at the water – air interface is so high, usually just assumed to be one for mathematical simplicity, that most of the acoustic energy is reflected back into the water. This assumption, while
adequate in most situations, is just an assumption and not strictly true. A relatively small fraction of the acoustic energy is transmitted into a propagating wave from water to air, and only for a small range of angles.

If the vocalizations of the male walrus breeding coda are intended as sexual advertisements to the females hauled out on the ice above them, acoustic propagation models must include acoustic parameters of the ice and air, in addition to the water. There are two main pathways that the signal could propagate from an underwater source to a receiver on ice: 1) from the water, through the ice, and into the air; and 2) from the water directly into the air. Propagation path 2) relies on diffraction of the signal in air, coupled from the water, over the ice to the receiver hauled out on the ice. Condition 1) results from coupling through a layer of ice that does not couple efficiently from either the source aqueous medium or the destination gaseous medium. In both situations, large attenuation from the underwater signal to the in-air receiver would be expected. The use of propagation modeling to estimate the effect of the environment on a signal provides insight in this situation.

One method of sensing of acoustic signals that was not examined in this research was mechanical vibrations in the ice. The acoustic waves from the water couple with the ice creating mechanical waves that can couple into the air as sound. The level of the in-air acoustic waves was compared with detection thresholds for Pacific walruses. Sensation of mechanical vibrations by walruses was not investigated as there is no data on the sensitivity of these animals to vibration. The detectability of these signals is most likely variable depending on the positioning of the walrus. Walrus’s vibrissae are individually innervated and are sensitive to tactile stimulation. Walruses depend on their vibrissae for finding prey in the soft sediment of their foraging grounds. If the vibrissae are in contact with the ice an individual may be able to detect lower amplitude vibrations than if the vibrissae are not in contact with the ice.

The results of this research suggest that hauled out female walrus are able to hear the underwater portions of the breeding displays of nearby male walruses. The ability to hear these signals suggests that in addition to the surface portion of the breeding displays, the underwater portion of the displays may play a role in the mate selection process.
References


NOAA Snow & Ice Data Center (2014). "All about sea ice."


Appendix A

Animal Use Permits and Application

INVESTIGATOR: Samuel Daines

AFFILIATION: Pennsylvania State University

ADDRESS: The Pennsylvania State University

Applied Research Laboratory

PO Box 30

CITY: State College

STATE: PA

COUNTRY: USA

POSTCODE: 16804

PHONE: 555-344-4362

FAX: 555-344-4363

EMAIL: sld888@psu.edu

TITLE OF PROJECT: Synthesis of SONAR Equation Parameters for Walrus Vocalizations

SEAWORLD/BUSCH GARDENS COLLABORATOR: Dr. Judy St. Leger

IS THE PROPOSED WORK SUPPORTED BY A RESEARCH GRANT OR CONTRACT? No

WILL YOU PAY FOR SPECIAL SUPPLIES, CONTAINERS AND SHIPPING COSTS AS NECESSARY? Yes

WHAT DATES, OR TIME FRAME (e.g. 1 July – 1 Dec; 3 months) ARE REQUESTED? Two week time windows during male walrus rut at SWO & SWSD. Up to six days of 2 to 4 hours of deployment of recorder in walrus exhibit pool. One four hour calibration period in the exhibit pool at each location.

WILL YOU, OR A MEMBER OF YOUR STAFF, BE ON THE PREMISES DURING THE RESEARCH? Yes

PROVIDE A SYNOPSIS OF WHAT IS BEING REQUESTED OF THE PARTICIPATING PARK(S).

1) Access to walrus enclosure for recording of vocalizations associated with breeding display of male Pacific walrus.

PARKS INVOLVED: ☑ SWSD ☑ SWSA ☑ SWO ☑ BGT ☑ BGW ☑ DC

ATTACH A RESEARCH PROPOSAL AND PROVIDE IACUC INFORMATION (see page 2).

The investigator agrees to acknowledge the appropriate SeaWorld/Busch Gardens park(s) and staff in any publication, contract report or other document in which the specimens/data are used, to provide the appropriate park(s) with a pre-publication copy of relevant manuscripts, and to provide the appropriate park(s) with ten (10) copies of all published manuscripts or reports. The investigator agrees to provide notice of any press releases or other media contacts initiated by the investigator other than media inquiries reviewed by the investigator that concern the research work conducted at the SeaWorld or Busch Gardens parks or involving data/specimens provided by the SeaWorld or Busch Gardens parks. The investigator agrees to provide the SeaWorld parks or Busch Gardens with advance notice of publication of relevant research results on the internet.

The investigator agrees to submit an annual Program Report in January of each year.

The investigator agrees not to transfer specimens or parts thereof to other investigators without written permission from SeaWorld and/or Busch Gardens Tampa.

NOTE: If the investigator is a student, this form must be co-signed by his/her faculty supervisor.

RETURN TO:

SeaWorld

Corporate Zoological Operations

todd.andrews@seaworld.com

407-226-5181, fax 407-226-5189

Please allow 60 DAYS for processing.
RETURN TO:
Brad Andrews
Corporate Zoological Operations
brad.andrews@seaworld.com
407-226-5181; fax 407-226-5189

Please allow 60 DAYS for processing.
General Instructions and IACUC Certification

The request form and all appended documents must be typed. Handwritten documents will be returned for typing and processing will be delayed.

The investigator must attach a research proposal that includes a discussion of relevant background information, objectives, methodology, anticipated results and anticipated duration of the project. When specimens are requested, it is important to demonstrate that the proposed work is not unduly duplicative of previous studies.

The investigator must attach a copy of his/her curriculum vitae and copies of the vitae of co-investigators.

A given request may take 60 days for processing due to the number of people in the review process.

The following Institutional Animal Care and Use Committee Certification (IACUC) must be completed:

Does your institution have an IACUC? ☑ YES ☐ NO

If yes, has your proposed research been reviewed and approved? ☑ YES ☐ NO

If 'yes', please submit a copy of the approval letter.

If 'no', when is the review expected?

Is your institution registered as a research facility with the USDA? ☑ YES ☐ NO

If yes, please give registration number. 23-R-0021

Does your institution have a current Animal Welfare Assurance Letter on file with the U.S. Public Health Service (NIH/OPPR)? ☑ YES ☐ NO

If yes, please give Assurance Number. A3141-01

Please indicate the plans for presentation and publication of this information: . Data will be included as part of a dissertation required for a doctorate in Acoustics from the Pennsylvania State University to be completed December 2013. Presentations will be made at the Acoustical Society of America conferences and, possibly, the Society for Marine Mammalology conference in 2013. Manuscripts for publication of the results in peer reviewed journals will be submitted during the 2013 and 2014 calendar years.

RETURN TO:
Brad Andrews
Corporate Zoological Operations
brad.anthony@seaworld.com
407-228-5161, fax 407-228-5189

Please allow 60 DAYS for processing.

(rev 12 Feb 2010)
Date: May 10, 2011

From: William G. Greer, Assistant Director, Animal Care, Biosafety and Radiation Programs

To: Jennifer L. Mikus-Olds

Subject: Results of IACUC Protocol Review – New Protocol (IACUC# 37002)

Approval Expiration Date: May 9, 2012

“Synthesis of sonar equation parameters for the propagation of walrus vocalizations”

The Institutional Animal Care and Use Committee (IACUC) has reviewed and approved your protocol for the use of animals in your research. This approval has been granted for a one-year period.

Approval for the use of animals in this research project is given for a period covering one year from the date of this memo. If your study extends beyond this approval period, you must contact this office to request an annual review of this research.

This Institution has an Animal Welfare Assurance on file with the Office for Laboratory Animal Welfare. The Assurance number is A 3141-01. The Pennsylvania State University is also registered with the US Department of Agriculture (Certificate No. 23-R-0021). As of February 13, 2001, The Pennsylvania State University was awarded Full Accreditation by the Association for Assessment and Accreditation of Laboratory Animal Care International (AAALAC).

The IACUC does not require the principal investigator to provide copies of permits (e.g., PA Game Commission, Bird Banding, US Fish and Wildlife Service) prior to approval. However, if your research mandates a permit requirement, it is your responsibility to acquire such permits prior to conducting the research described in your IACUC protocol.

By accepting this decision, you agree to notify the Office for Research Protections of (1) any additions or procedural changes and (2) any unanticipated study results that impact the animals. Prior approval must be obtained for any planned changes to the approved protocol. Any unanticipated pain or distress, morbidity or mortality must be reported to the attending veterinarian and the IACUC.

On behalf of the IACUC and the University, I thank you for your efforts to conduct your research in compliance with the federal regulations that have been established for the protection of animals.

If you are interested in subscribing or being removed from ORP listerv, send an email to L-ORP-Research-L-subscribe-request@lists.psu.edu to subscribe or L-ORP-Research-L-unsubscribe-request@lists.psu.edu to unsubscribe. There is no need to add any text in the subject line or in the message body of the email.

WGG/mpp

Attachment

cc: Samuel L. Denes
To the Investigator:

Please forward the enclosed original approval letter to your funding agency, if applicable. This approval is effective for one year. During this time, you should notify this office of any changes in the protocol that will affect the care and use of the approved animals or that will result in the use of additional animals.

In a continuing effort to comply with federal regulations, this office reviews IACUC approvals on an annual basis. On the anniversary of this approval, you should expect to receive a letter soliciting your request for an “annual review” by the IACUC. It is my hope that this process aids researchers in maintaining active IACUC approvals and avoids the use of animals without the proper approval.

Also, in order for records of your animal usage at ARP and ORP to remain current, please review the information below. If you feel there is any discrepancy between this information and your request, please contact our office (ORP) immediately at 865-1775. Thank you.

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<td>Jennifer L. Miksis-Olds</td>
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An Equal Opportunity University
Synthesis of SONAR Equation Parameters for the Propagation of Walrus Vocalizations

Summary of proposed activities:
The proposed research will address the following objective:

To characterize the acoustic characteristics of vocalizations of male Pacific walrus.
To achieve these objectives the following requests of time and access are being requested.

- Walrus exhibit pool calibration
  - 4 hours with animals out of pool
- Authorization to deploy passive acoustic transducer in walrus exhibit pool.
  - Deployment of equipment for 2 to 4 hours per day during daylight for up to 6 days during male’s breeding display time period for both SeaWorld San Diego and SeaWorld Orlando.
- Access to video monitoring system

All work will be conducted in collaboration with Dr. Ann E. Bowles, with oversight by SeaWorld Wild Arctic staff in San Diego and Orlando.

Timeline:

1. Vocalization recordings
Test deployment of hydrophones and calibration will be conducted upon approval of research request and at the convenience of Wild Arctic animal care staff in San Diego and Orlando.

Collection of recordings will begin with the onset of breeding vocalizations (2012). Recording of stereotyped vocalizations over the 6 day period will permit collection many samples from individuals in San Diego and Orlando. Comparison of acoustic characteristics will be made with recordings from autonomous recording units deployed in the Bering Sea.

Initial results will be presented at a conference in 2013.

Data collected at SeaWorld will be included as part of a dissertation required for a doctorate in Acoustics from the Pennsylvania State University to be completed December 2013.

A manuscript for publication of the results in a peer reviewed journal will be submitted during 2013.
Denes Research Request

Background

Walruses are regarded as a keystone species in the Arctic. Being an upper trophic level animal, walruses may be disproportionately affected by environmental changes that affect Arctic food webs [1]. The expected impact of climate change on the species’ environment has led to listing Pacific walrus as “warranted but precluded” as a threatened species by the US Fish and Wildlife Service [2, 3]. The remote and extreme nature of the walrus’ habitat increases the needs for studies of captive individuals. A better understanding of acoustic characteristics of walrus vocalizations will aid in the estimation of populations using passive acoustic monitoring (PAM), currently a very active area of research [4]. Current research efforts of the investigators include PAM recorders deployed along the 70m isobath of the eastern Bering Sea.

Walruses are a vocal species, producing underwater sounds year round. Walruses make at least four types of underwater sounds: knocks, rasps, grunts and bells. The mechanisms by which walruses create these sounds are unknown. This work will focus on the knock, which are loud, impulsive, broadband sounds with most of their acoustic energy below 2 kHz [5-7]. In the breeding season from January through March, male walruses produce energetically expensive acoustic displays while tending to a group of females. The exact function of the display remains unknown, but the timing and location of these displays suggest a role in breeding [8]. The male vocal displays are comprised of impulsive and tonal sounds [9]. There are two distinct portions of these displays – surface and underwater. These displays have been identified in both captivity and the wild, as well as for both Pacific and Atlantic walruses [5, 6, 8]. The propagation characteristics of the calls and ability of female walruses to perceive different call modalities (acoustical vs. vibrational) are unknown. Developing a greater understanding of this species’ communication processes in the captive environment will provide information that cannot be collected in the extreme and dangerous environment in which these breeding displays occur.

Vibrations in sea ice resulting from underwater acoustic sources have been studied for the past 50 years [10]. Recently, it has been shown that the direction to an underwater source can be determined from acoustic and vibrational signals received on the ice surface [11]. Most of the research regarding vibrations in ice use impulsive sources, much like the walrus knock. This transmission mode provides a mechanism by which these signals may be received by female walrus hauled out on ice. The perception of vibrational signals by various species of animals is an active area of research. Species studied include snakes, seals, manatees, and elephants [12-14].

Incorporating source, propagation media, and receiver characteristics is required to determine whether a signal can be detected. The SONAR equations are used to reduce the complexity involved in the determination of detectability of acoustic signals. The equation converts the logarithmic relationships of amplitude, distance and perception to arithmetic relationships [15].

\[ SL - TL > NL - DI + DT \]

SL is source level in intensity 1 meter from the source. TL is transmission loss due to the propagation media due to spreading loss, absorption and attenuation. NL is the ambient noise level of media. DI is the combined directivity indices of the source and receiver. DT is the detection threshold, the level the signal must exceed the ambient to be detected. If the left hand side of the equation is greater than the right hand side, the signal is detected by the receiver. The overarching goal of this research is to
synthesize values for parameters of the passive sonar equation so that acoustic propagation models can be developed to estimate the effective range of walrus vocalizations in different acoustic environments. This research will provide a predictive capability for determining how changes in the environment will impact walrus communication and detection. Each step of this project will result in improved estimation of the input values for the sonar equation to determine detectability of walrus vocalizations by conspecifics and remotely deployed passive acoustic monitoring systems. The project will be multifaceted with four integrated but independent objectives, the first of which requires the collaboration of a captive facility that houses male walruses.

**Objectives of the thesis project:**

1. To characterize vocalizations of male Pacific walrus.
   - Q: Are source levels of captive Pacific walrus vocalizations representative of wild vocalizations?
     - a. Measure vocalization source levels from captive Pacific walrus.
     - b. Estimate source level from inverse propagation and localization of detected vocalizations in the Bering Sea.

An important gap in the walrus vocalization literature is an estimate of source levels. The first objective will be to obtain source level measurements of different vocalizations from a captive individual and compare to source levels estimated from wild animals. Obtaining direct measurements of source levels from wild individuals is difficult because visually determining the exact location of the vocalizing individual relative to a receiver is impractical and unsafe given the extreme conditions. However, it is possible to determine approximate source levels from wild animals using localization and propagation models to obtain an estimate of source level for comparison with captive individuals [16]. Estimates of source levels from wild individuals will be made from walrus vocalizations recorded on passive acoustic recorders deployed in the Bering Sea. To determine the source level of captive walrus, a self-contained recording unit with a calibrated hydrophone will be deployed in a walrus enclosure (SeaWorld San Diego and SeaWorld Orlando) along with video recording equipment so that the distance of the vocalizing individual from the hydrophone can be estimated. Vocalizations will be recorded opportunistically from displays during the breeding season. Source levels for as many call types as possible will be determined. The reverberant nature of the enclosure will be compensated for using the results of the calibration procedures. A finite element model will be implemented to estimate the impact of multi-path acoustic propagation on the received level.

To minimize the impact of the recording equipment on the animals and visitor experience, self contained recording units will be used. Deployment and servicing of the devices will be at the discretion of the animal care staff. Prior to deployment, animal care and veterinary staff will be asked to provide comments and suggestions to ensure that they are safe.

Collection of the acoustic recordings will occur during the period that the male walruses are emitting vocalizations as part of their breeding display which in the wild occurs during the late winter (end of January through March) but can vary in captivity, occurring in late spring. Following collection, the recordings will be analyzed for source characteristics.

Initial data will be presented at a conference in 2013. Data will be included as part of a dissertation required for a doctorate in Acoustics from the Pennsylvania State University to be
Denes Research Request

completed December 2013. A manuscript for publication of the results in a peer reviewed journal will be submitted during the 2013 calendar year.

References

Appendix B

CDR Carl Allen Hager, USN, Ph.D.
United States Naval Academy
Department of Oceanography
572C Holloway Road
Annapolis, Maryland 21402

Mr. Samuel Denes
The Pennsylvania State University
201 Applied Sciences Building
University Park, Pennsylvania 16802

Dear Dr. Hager and Mr. Denes:

The National Marine Fisheries Service (NMFS) has reviewed your (the applicant) request for a Letter of Concurrence (LOC) documenting that the taking of marine mammals is not likely to occur incidental to the short range acoustic propagation loss experiment in the Arctic Ocean within 20 miles of Barrow, Alaska.

Output from a multi-element geophone, microphone and hydrophone array will be recorded using a multi-channel digital acquisition system. A project will broadcast multiple low-energy, impulsive signals (source levels not exceeding 160 dB re: 1 µPa at 1 m) at different depths and orientations relative to the receiving array, which will consist of 7 hydrophones, 3 geophones, and 3 microphones. The source, a Lubell Labs 9162 underwater speaker will generate the impulsive signals with dominant energy between 250 Hz and 10 kHz. The geophones, microphones and six of the hydrophones will be deployed in three sets consisting of two hydrophones, one microphone and one geophone arranged in a line spaced twenty meters apart. The source will be deployed both end fire and broadside to the line array of receivers. The seventh hydrophone will be deployed within 3 meters from the source to verify source level. All transducers will be cabled to an equipment rack containing signal conditioning and acquisition hardware. All equipment, including a heating element for the equipment rack, will be powered by 12 V sealed lead acid batteries. The experiment will consist of at least 4 configurations, differing with the location of the source. From each of two positions relative to the receiving array, broadside and end fire, the source will produce signals from different depths – one near the bottom of the ice, and a second near the sea floor. To facilitate quicker data acquisition, two underwater speakers can be deployed one at each depth for each of the two configurations relative to the receiving array. Each experimental configuration will require no longer than 6 hours.

Wave propagation parameters through the ice will be attained from sledge hammer blows incident upon a wooden four by four frozen into the ice. Repeatable source levels will be
Letter of Concurrence Arctic Experiment
generated by utilizing an apparatus allowing the hammer to swing from a constant angle. Accurate source timing will be triggered by a geophone mounted directly to the four by four.

Set-up of the experiment will consist of fixing the geophones to the ice surface by pouring warm water around the base of the instrument. Deployment of hydrophones and speaker will require drilling through ice. The required time for deployment will depend on the thickness of the ice, and the speed with which the drill can penetrate the ice. Microphone tripods will be anchored to the ice using guy lines and stakes. This deployment should take no more than 4 hours of active work time. Additional time will be required to install the four by four posts. Servicing of recording equipment and redeployment of underwater speakers into the second configuration will require 2 hours. Final recovery of equipment will require 3 hours.

The experiment will occur within 20 miles of Point Barrow in the Arctic Ocean covered by land-fast ice. The water in this coastal area is approximately 30 meters deep. The exact date of the activity will depend on weather conditions. The experiment will be limited to one 24-hour period during the week of 10-16 March 2012.

Based on the description of the action provided, NMFS concurs with your determination that an Incidental Harassment Authorization (IHA) is not necessary pursuant to the Marine Mammal Protection Act (MMPA), for the short range acoustic propagation loss experiment you planned in the Arctic Ocean.

A number of marine mammal species are expected in the vicinity of the proposed project area. A brief description of each species, along with the likelihood of occurrence in the project area, is provided in the LOC application.

NMFS has established received level threshold criteria to estimate the onset of Level B harassment for multiple sound sources. For impulsive sounds, such as those from a mini-sparker, the Level B harassment threshold is 160 dB re: 1µPa (rms). To receive NMFS' concurrence that take is not likely to occur, the applicant must avoid exposing marine mammals to sound levels at or above this threshold. The LOC application stated that the source level of the low-energy impulsive sound source will not exceed 160 dB re: 1 µPap @ 1 m. Therefore, based on NMFS' established received level threshold criteria for marine mammals, NMFS does not consider that there will be take of marine mammals as a result of the proposed short range acoustic propagation loss experiment.

Because the proposed acoustic propagation loss experiment will occur in Arctic waters, the applicant must ensure that the activity will not have an unmitigable adverse impact on the availability of marine mammal species or stocks for taking for subsistence uses. Subsistence remains the basis for Alaska Native culture and community. The main species that are hunted include bowhead and beluga whales, ringed, spotted, and bearded seals, walruses, and polar bears. The importance of each of these species varies among the communities and is largely based on availability. The community closest to the proposed short range acoustic propagation loss experiment is Barrow. Barrow conducts a
spring bowhead hunt in April and May and a fall hunt in September and October. Because the proposed acoustic propagation loss experiment will be conducted in March for only one day, there will be no interference with bowhead hunts. There has been minimal harvest of beluga whales in Beaufort Sea villages in recent years. Additionally, if belugas are harvested, it is usually in conjunction with the fall bowhead harvest. Therefore, the proposed acoustic propagation loss experiment will not interfere with any potential beluga hunts.

Bearded seals are primarily hunted during July in the Beaufort Sea; however, in 2007, bearded seals were harvested in the months of August and September at the mouth of the Colville River Delta. An annual bearded seal harvest occurs in the vicinity of Thetis Island in July through August. Approximately 20 bearded seals are harvested annually through this hunt. Spotted seals are harvested by some of the villages in the summer months. Although ringed seals are available to subsistence users in the Beaufort Sea year-round, and they are primarily hunted in the winter or spring (October-June) due to the rich availability of other mammals in the summer, the low level acoustic signals used for this work is not expected to have any impact on the availability of the species or stocks for subsistence uses.

NMFS believes that due to the low levels of acoustic source (source levels not exceeding 160 dB re: 1 \mu Pa at 1 m) and the short duration of the proposed experiment (limited to one 24-hour period during the week of 10-16 March 2012), takes of marine mammals are not likely to occur, and an IHA is not necessary pursuant to the MMPA. If for any reason that the applicant plans to change the proposed experiment by deploying more powerful acoustic sources and or significantly extending the experiment duration, then our concurrence with the applicant’s determination does not apply, and NMFS would recommend that the applicant apply for an IHA under section 101(a)(5)(D) of the MMPA. The same recommendation would apply if the applicant subsequently obtains information during the acoustic propagation loss experiment that indicates that marine mammals have been disturbed by the proposed activities. Although NMFS has concurred that take is not likely to occur, the applicant remains liable for any unauthorized takes of marine mammals resulting from the use of the low-energy sound sources. For additional information on this action, please contact Shane Guan at 301-427-8401 or Shane.Guan@noaa.gov.

Sincerely,

James H. Lecky, Director
Office of Protected Resources
Vita

Samuel L. Denes

Sam grew up in suburban Los Angeles, California, developing a love for the outdoors from an early age. He attended the University of California, at San Diego earning a bachelor’s of science degree in bioengineering in 2004. During his tenure at UCSD, Sam was a four year letter winner as a member of the Triton Track and Field team, and was captain for his junior and senior seasons. Following graduation, Sam accepted a position as the bioacoustics engineer at the Hubbs-SeaWorld Research Institute (HSWRI) in San Diego. It was here that he discovered the field of bioacoustics and realized the joy from combining engineering and wildlife research through acoustics. After four years at HSWRI, Sam enrolled in the Graduate Program in Acoustics at the Pennsylvania State University in August of 2008. He was lucky enough to marry his best friend in 2010. In his free time, Sam can often be found mountain biking with his dog Ellie and anyone else who is willing to join.