WAVEGUIDE PROPAGATION ALLOWS RANGE ESTIMATES FOR NORTH PACIFIC RIGHT WHALES IN THE BERING SEA

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ABSTRACT

The shallow and uniform water depth of the eastern Bering Sea shelf results in an acoustic waveguide. Propagation within this waveguide produces waveform dispersion which is dependent upon range. We present a means for using dispersed waveforms to determine range to calling whales from a single autonomous acoustic recording instrument. The predominant North Pacific right whale (*Eubalaena japonica*) call is frequency upswept from about 90 Hz to around 160 Hz and lasts approximately 1 s. The regional bathymetry of the eastern Bering Sea middle shelf is relatively uniform and shallow (~ 70 meters deep). This geometry provides a plane-layered waveguide in which right whale upswept calls can be detected at ranges over 50 km and have multiple modal arrivals that become dispersed, displaying different propagation velocities for different frequencies. Dispersion characteristics of modal arrivals are dependent on the calling whale's depth, the receiver's depth, the water depth, the range from caller to receiver, and various environmental parameters including water and sediment density and sound velocity. A model of sound propagation for the eastern Bering Sea middle shelf is developed from right whale call dispersion recorded on sonobuoys and seafloor acoustic recording packages, using individual calls recorded at multiple instruments. After development of the model, waveform dispersion allows estimation of caller range based on single instrument recordings. Estimating range between instrument and calling whales provides a means to estimate minimum abundance for the endangered North Pacific right whale.

RÉSUMÉ

L'eau peu profonde et uniforme de la rive Est de la mer de Béring produit un excellent guide d'ondes acoustiques. Dans ce guide de propagation, la dispersion des ondes sonores est dépendante de la distance. Nous présentons ici un moyen pour utiliser la dispersion des ondes sonores pour déterminer la portée de sons émis par des baleines à partir d'un unique instrument d'enregistrement du signal acoustique. La vocalisation prédominante de la baleine franche du Pacifique Nord (*Eubalaena japonica*) est une modulation ascendante d'environ 90 à 160 Hz et d'une durée approximative de 1 s. La bathymétrie régionale de la rive Est de la mer de Béring est relativement uniforme et peu profonde (~70 m de profondeur). Cette géométrie fournit un guide d'ondes à couches horizontales ou les vocalisations modulées de baleines franches peuvent être détectées à des distances supérieures à 50 km et ont de multiples arrivées modales qui deviennent dispersées, démontrant différente vitesse de propagation à différentes fréquences. Les caractéristiques de dispersion des arrivées modales sont dépendantes de la profondeur de la baleine, la profondeur du récepteur, la profondeur de l'eau, la distance de l'émetteur et du récepteur et une variété de paramètres environnementaux incluant la densité de l'eau et des sédiments, et la vitesse du son dans ces deux media. Un modèle de la propagation du son pour la rive Est de la mer de Béring est développé à partir de la dispersion des vocalisations des baleines franches enregistrées à partir de bouées acoustiques et de systèmes acoustiques ancrés sur le fond marin, en utilisant les vocalisations individuelles enregistrées à partir de multiples instruments. Après le développement du modèle, la dispersion de l'onde sonore permet l'estimation de la distance de la vocalisation basée sur l'enregistrement d'un seul instrument. Estimer la distance entre l'instrument et les vocalisations de baleines permet d'estimer l'abondance minimale de la baleine franche menacée d'extinction dans le Pacifique Nord.

1. INTRODUCTION

The North Pacific right whale (*Eubalaena japonica*) is a critically endangered baleen whale. There is no reliable estimate for the eastern population, but it probably numbers less than 50 individuals (Clapham *et al*., 1999). Efforts to study these whales in the eastern Bering Sea have provided visual observations of them since 1996 (Fig. 1) (Goddard and Rugh, 1998); (Moore *et al.,* 2000); (LeDuc *et al.,* 2001); (Tynan *et al.,* 2001). To complement these visual surveys, shipboard acoustic surveys have recorded North Pacific right whale calls in the eastern Bering Sea since 1999 (McDonald and Moore, 2002). In addition to providing the first descriptions of North Pacific right whale calls, the shipboard acoustic surveys provided the baseline acoustics needed to use long-term, autonomous acoustic recorders for passive monitoring of these endangered whales.

Long-term autonomous acoustic recording provides a means for monitoring whale calling activity in poor weather conditions and during periods when ship-based visual and acoustic techniques are either impossible or cost prohibitive (Wiggins, 2003). By recording sound continuously for periods of more than one year, whale seasonal occurrence and minimum population estimates can be made. To do this requires an understanding of the relationship between calls recorded and total number of whales present within a given region. Knowledge of call detection range is critical. How far a call can be detected with an acoustic instrument depends on the characteristics of the call and the acoustic environment. Environmental noise from ships, storms or other calling whales may reduce the call detection range. In addition, acoustic propagation depends upon environmental factors such as water temperature profile and bathymetry. These factors can effectively enhance or decrease call detection range, and may distort call characteristics.

Calls may be distorted by the environment in a range dependent way such that the distorted calls contain information about the caller's location. For example, multi-path arrivals are common in environments where the distance from caller to receiver is less than a few times the water depth. The first arrival of the call at the receiver is from the direct path wave. The next few arrivals are from surface and bottom reflected waves and may interfere with the first and other arrivals. The call will appear at the receiver to be a summation of these arrivals, however, knowledge of the acoustic propagation may allow for the original call to be extracted from the distorted signal. If the sound speed profile, the water depth, and the receiver location are known, then range to and depth of the caller can be calculated.

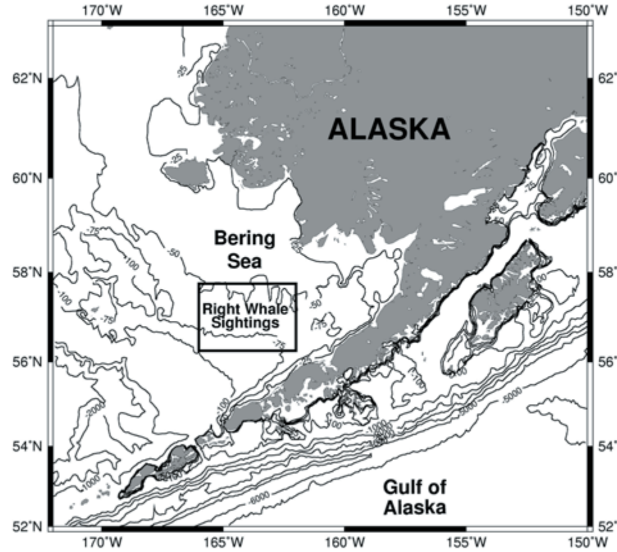

Fig. 1. Eastern Bering Sea. Bathymetric contours are every 25 m for the first 100 m, then every 1000 m. The box outlines where North Pacific right whales have been visually observed each summer since 1996, and acoustically observed since 1999. Bathymetry data from Smith and Sandwell (1997).

In shallow-water waveguides, calls that are more than several water depths in range away may become distorted due to multimode dispersion. Analysis of this distortion can provide an estimate of the distance to the caller. Normal-mode waveguide modeling helps to describe the observed waveform distortions. As the range between caller and receiver is increased, the original call will become increasingly distorted. The relatively shallow and flat continental shelf of the eastern Bering Sea provides an acoustic waveguide environment. In waveguides, the call or source waveform reflects off the seafloor and sea surface and these reflections will constructively and destructively interfere to create multiple mode arrivals and waveform dispersion, where different frequencies of the waveform travel at different velocities. The variation of velocity with frequency allows range estimates between source and receiver to be made for calls that sweep through a band of frequencies. The majority of North Pacific right whale calls upsweep in frequency and will become noticeably dispersed in shallow water after a few kilometers (McDonald and Moore, 2002). Another example showing shallow-water mode dispersion for right whale upswept calls was presented in a sonobuoy localization study in the Bay of Fundy where North Atlantic right whales (*Eubalaena glacialis*) were studied (Laurinolli *et al.,* 2003).

During 2000 to 2002 autonomous acoustic recording packages were deployed in the eastern Bering Sea to investigate the seasonal presence and population of North Pacific right whales. While some individual right whale calls were recorded on multiple instruments allowing for time-difference hyperbolic localization techniques to be used, many calls were recorded only on one instrument. Normal-mode modeling allows for estimating ranges to these callers and provides information on their calling depth.

2. METHODS

2.1 Acoustic Data

During July 1999 sonobuoys were deployed in the eastern Bering Sea to provide acoustic data in conjunction with a right whale visual survey (McDonald and Moore, 2002). Sonobuoys provide real-time acoustic data using radio telemetry to a support ship where they can be recorded and analyzed with computer software. The DIFAR (DIrectional Frequency Analysis and Recording) sonobuoys used during this survey were configured with the hydrophone sensor at 28 m below the sea surface and provided bearing data in the band from 10 Hz to about 4 kHz. These sonobuoys were often deployed in array configurations at known GPS (global positioning system) coordinates and drift rates were calculated from bearings to the research ship so that caller locations could be calculated using multiple bearings and correlated with visual sightings. Concurrent visual and acoustic observations provided species identification of the caller.

McDonald and Moore (2002) analyzed over 500 North Pacific right whale calls and reported the predominant call type to be an upswept call which has similar characteristics to those reported by Clark (1982) for southern right whales (*Eubalaena australis*). From these sonobuoy data, typical 'up' calls sweep from about 90 Hz to 150 Hz in 0.7s and have sweep rates ranging from 35 to 150 Hz/s, although some of the variability reported in these calls may be caused by waveguide distortions. The acoustic waveform data are transformed into the frequency domain using Fourier transforms and viewed as spectrograms. Spectrograms allow narrow-band signals (such as right whale calls) to be detected above broad-band ocean noise. A single right whale call recorded on four different sonobuoys is shown as spectrograms in Fig. 2. Notice that the call becomes progressively distorted and extended in time with increasing range. These changes in the signal are a result of the waveguide propagation and associated dispersion.

In October 2000, four autonomous acoustic recording packages (ARPs) (Wiggins, 2003) were deployed in the eastern Bering Sea to monitor North Pacific right whales. The ARPs were configured to record continuously with a hydrophone sensor tethered approximately 10 m above the seafloor and with a bandwidth from 5 to 250 Hz. These instruments were deployed in the area where right whales have been observed since 1996, and were placed 60 to 80 km apart in about 70 m water depth (Fig. 3). The array was not configured to provide good localization geometry; however, because propagation in this environment was better than anticipated, there are many cases of multiple instruments recording the same call. Using GPS instrument deployment locations, individual calls recorded with multiple ARPs were localized with time-difference hyperbolic localization software (Mellinger, 2002). In addition to providing call detection ranges for minimum population estimates, these localizations are used to evaluate the normal-mode range-estimate modeling.

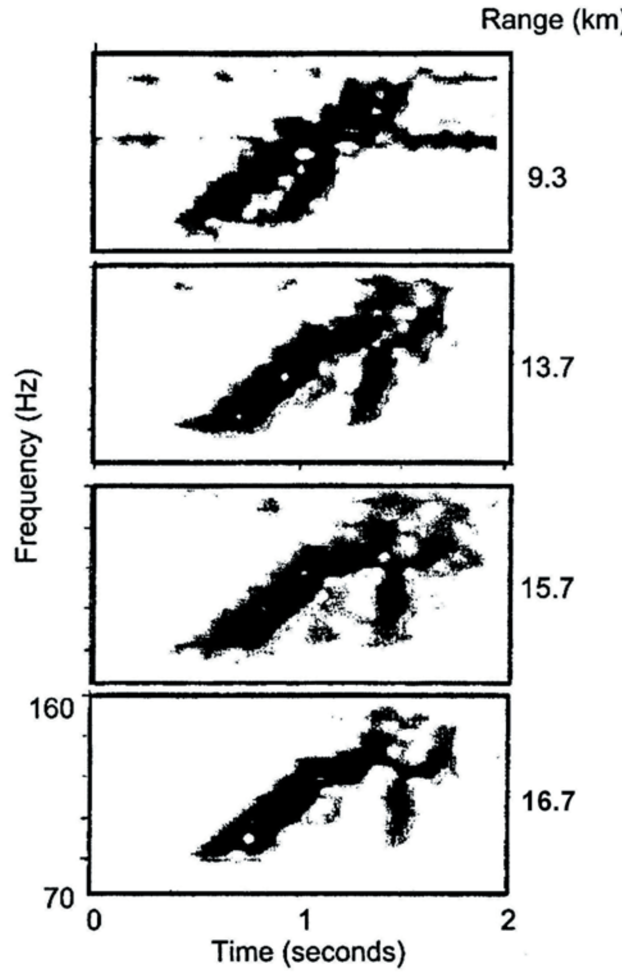

Fig. 2. An example spectrogram of a North Pacific right whale call recorded with four sonobuoys in the eastern Bering Sea. Notice that the call becomes spread-out in time, especially at lower frequencies, for the most distant sonobuoys. The spectral parameters used are 0.5 second FFT length with 87.5% overlap. See Fig. 3 for sonobuoy and whale locations during recordings. (Figure 7 from McDonald and Moore, 2002.)

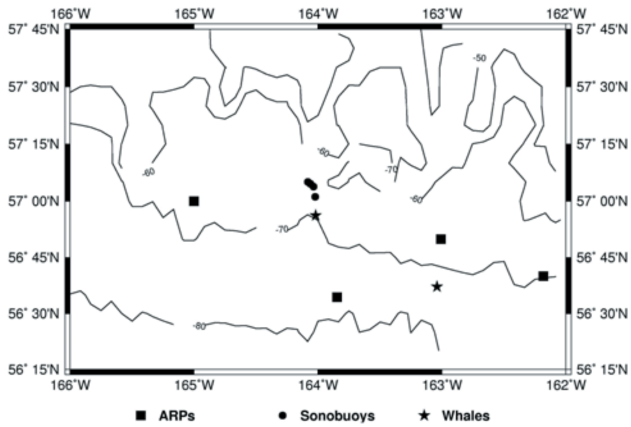

Fig. 3. Bathymetry and instrument locations of 'Right Whale Sighting' box from Figure 1. Autonomous acoustic recording packages (ARPs) are squares, sonobuoy locations during recording spectrograms in Figure 2 are circles, stars are locations of whales for example calls. Bathymetry data from Smith and Sandwell (1997).

2.2 Normal-Mode Modeling

To model sound transmission in shallow water environments, the normal-mode approach is often preferred over the ray-path method because the normal-mode approach provides better computational efficiency at long ranges (>10 times the water depth) and moderate to low frequencies (<500 Hz) (Officer, 1958); (Medwin and Clay, 1998). Shallow water environments can be described as waveguides in which ray paths of plane waves are trapped between two reflecting surfaces (Fig. 4). Normal-mode methods for a simple two-layer ocean model were first developed by Pekeris (1948) and have been used widely to investigate acoustic propagation in shallow water (e.g., Jensen *et al.,* 2000). The normal-mode solution considers all waveguide-trapped ray paths and their combined interference effects.

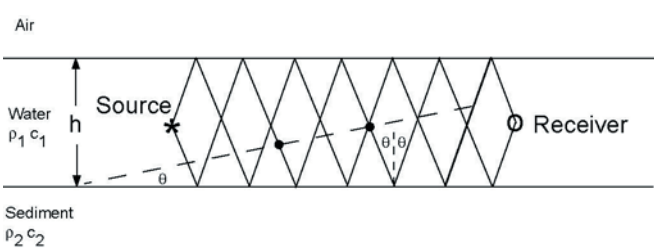

Fig. 4. Schematic of sound transmission in a shallow-water waveguide. Waves will reflect off the sea surface and seafloor boundaries and incur phase changes based on environmental physical properties.

Interference between up going and down going reflecting waves in a waveguide depends on their frequency. At frequencies where the phase difference between the interfering waves is an integer number of 2π, the waves constructively interfere. At all other frequencies the waves interfere out of phase and have negligible contribution at long ranges. For each angle of incidence, θ, of up going and down going waves, there is a set of discrete frequencies that constructively interfere. Each frequency corresponds to a mode and travels at a different velocity along the waveguide. These velocities are the group velocities. For angles of incidence, θ, more grazing than the critical angle ($\theta_c = \sin^{-1}(c_1/c_2)$ where c_1 is the sound speed of the water and c_2 is the sound speed of the sediment), a set of frequencies and group velocities can be calculated for each mode. A plot of these frequencies versus group velocity for each mode are dispersion curves and provide a means of estimating range to dispersed calls.

From Medwin and Clay (1998), the group velocity of the *m*th mode is

$$u_m = \frac{d\omega}{dk_m} \qquad (1)$$

where, the angular frequency, ω, and horizontal wave number, k_m, are expressed as

$$\omega = \frac{\gamma_m c_1}{\cos(\theta)} \qquad (2)$$

and

$$k_m = \left[\left(\frac{\omega}{c_1}\right)^2 - {\gamma_m}^2\right]^{1/2}. \qquad (3)$$

The vertical wave number, γ_m, derived from the mode equation is

$$\gamma_m = \left(\pi(m-1) + \frac{\pi}{2} + \phi\right)\frac{1}{h} \qquad (4)$$

and the phase shift at the seafloor, ϕ, is

$$\phi = \tan^{-1}\left(\frac{\rho_1 c_1 g_2}{\rho_2 c_2 \cos(\theta)}\right) \qquad (5)$$

with g_2, the imaginary part of Snell's Law cosine at the seafloor for $\theta > \theta_c$, expressed as

$$g_2 = \left[\left(\frac{c_2}{c_1}\right)^2 \sin^2(\theta) - 1\right]^{1/2}. \qquad (6)$$

The dispersion curves are calculated by numerically differentiating Equation (1) after substituting in Equations (2-6) and using a set of incident angles $\theta_c \le \theta \le \pi/2$. The waveguide parameters are water sound speed, c_1, sediment sound speed, c_2, water density, ρ_1, sediment density, ρ_2, and water depth, h.

Which frequencies constructively interfere to produce a dispersion curve is dependent upon the physical parameters of the waveguide. For up going waves, a phase change of π occurs at the sea surface. For down going waves, the phase change at the seafloor boundary (Equation 5) depends on water and seafloor sound speeds and densities, and on the angle of incidence. The depth or thickness of the waveguide also affects what frequencies constructively interfere because it defines the geometry in which the waves reflect and where phase changes take place.

The water depth of the study area is approximately 70 m (Fig. 3). The sound velocity (1470 m/s) and density (1026 kg/m^3) were obtained from Generalized Digital Environmental Model (GDEM) which is based on the US Navy's Master Oceanographic Observation Data Set (MOODS) (Teague *et al.,* 1990). The sound speed and density do not vary much with depth nor season probably because these waters are relatively well mixed, and are considered homogeneous for our purposes. The sediment velocity (1675 m/s) and density (1500 kg/m^3) are based on Deep Sea Drilling Project (DSDP) results from seismic reflection data and core samples in the Bering Sea, albeit off the shelf (Shipboard Scientific Party, 1971).

Using these physical parameters for a simple two layer lossless Pekeris waveguide (homogeneous water layer over a homogeneous half-space of sediment), dispersion curves for the first four modes were calculated and plotted (Fig. 5). For each mode at its cutoff frequency (frequency below which waves are not trapped in the waveguide and attenuate rapidly with distance), the group velocity is the sediment velocity. Above the cutoff frequency, the steep decrease in group velocity with increasing frequency occurs for seismic ground waves. At frequencies above the lowest velocity (Airy frequency or inflection point) of the dispersion curve, a more gentle increase in group velocity with increasing frequency occurs for water waves in the waveguide, and the group velocity approaches the water sound speed at high frequencies. Dispersion for water waves is greatest near the Airy frequency which leads to the greatest distortion in the received call. Also, the group velocities decrease as the mode number increases at a given frequency. This causes higher modes to arrive after lower modes, and the time difference between mode arrivals can be used to estimate the range to the source.

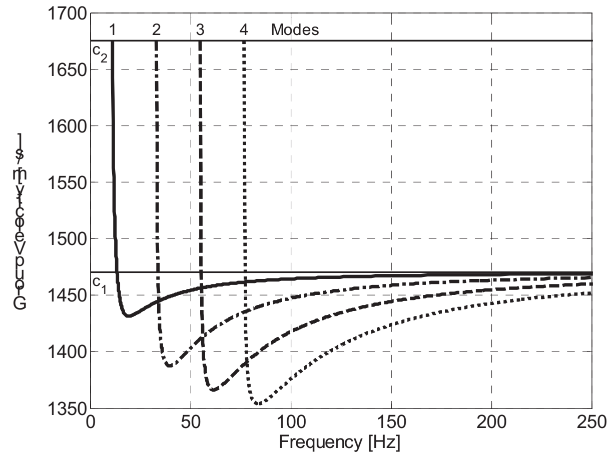

Fig. 5. Dispersion curves calculated from normal-mode modeling for first four modes. At high frequencies, as the frequency increases, the group velocity approaches the water sound speed (1470 m/s). At low frequencies, as the frequency decreases near the cutoff, the group velocity increases rapidly toward the sediment velocity (1675 m/s) and most of the energy is trapped in the sea floor as seismic ground waves.

Waveguide distorted calls can be modeled by applying the dispersion curve to an undistorted synthetic call at a given range. Estimates of modal arrival times from source to receiver are made simply by dividing the range by the velocity (dispersion) curve for each mode at the different frequencies and adding the result to the original synthetic call. If the call sweeps through a band of frequencies, then dispersion will distort the call with the low frequencies traveling slower than the higher frequencies (Figs. 2 and 5). The distortion becomes more pronounced at greater ranges because the energy at each frequency has had more time to travel at a different velocity. Also, higher modes are more dispersed leading to more distortion and increasing modal separation with increased range.

Sensitivity of the group velocity model can be evaluated by changing each environmental parameter independently and comparing the results to the unchanged model. The model is most sensitive to parameter change near the cutoff frequency of each mode, but model change decreases rapidly with increasing frequency. Based on environmental and bathymetric data for the Bering Sea, two extreme values for each parameter are tested: water sound speed, c_1, (1450 and 1490 m/s), sediment sound speed, c_2, (1550 and 1800 m/s), water density, ρ_1, (1025.5 and 1025.5 kg/m^3), sediment density, ρ_2, (1300 and 1700 kg/m^3), and water depth, h, (65 and 75 m) (Teague *et al.,* 1990); (Shipboard Scientific Party, 1971); (Smith and Sandwell, 1997). The change in group velocity models for the first four modes using these parameters are less than 1.5% (c_1), 0.5% (c_2), 0.01% (ρ_1), 0.1% (ρ_2), and 0.5% (h) for frequencies above the Airy frequency.

The interference effects in a waveguide also define how modes will be excited with depth. The depth dependence of the mode excitation is expressed as

$$Z_m(z) = \sin(\gamma_m z) \qquad (7)$$

where z is depth. As above, Equations (4-6) are substituted into Equation (7) and a set of incident angles $\theta_c \le \theta \le \pi/2$ are used to solve for various angles and frequencies. As an example, using a 100 Hz source, the normalized sound pressure as a function of depth is calculated from Equation (7) and plotted using the same environmental parameters for the dispersion curves (Fig. 6). A mode zero crossing (node) indicates the depth at which a mode is not excited. For example, a source at 20 m deep will not excite the fourth mode but will fully excite the second mode, however, if the receiver is at 40 m deep, neither the second nor the fourth mode will be received. No modes are excited at the pressure release boundary sea surface. Since the depths of the receivers are known for this study, the relative amplitude of excited modes provides information on the source (calling whale) depth.

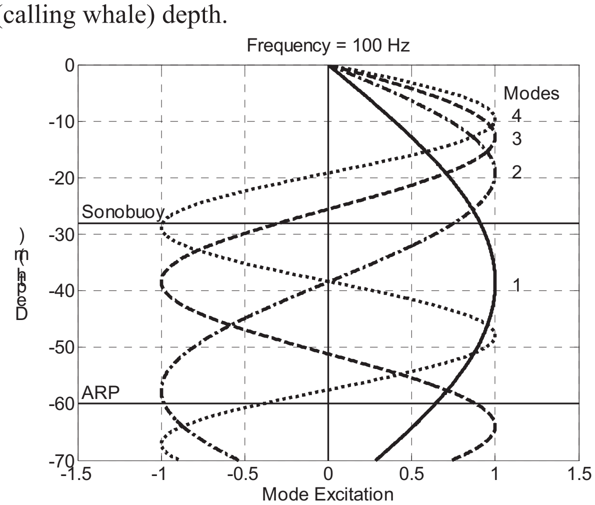

Fig 6. Normalized sound pressure versus depth from normal-mode modeling for first four modes at 100 Hz. No modes are excited at the sea surface which is a pressure release boundary.

3. RESULTS

3.1 Sonobuoy recordings and modeling

Upswept North Pacific right whale calls propagate long ranges as dispersed modes in the shallow and relatively flat waveguide of the eastern Bering Sea. The effects of modal dispersion of a right whale call recorded by four sonobuoys concurrently with shipboard visual observations of the calling whale are shown in Figure 2 (McDonald and Moore, 2002) with the sonobuoy and whale positions plotted in Figure 3. For the closest recording (9.3 km), separation of modes is evident by the gap in power of the spectrogram near 0.7 s at low frequencies. At greater ranges, further separation of modes is apparent and the highest propagating mode of the farthest recording (16.7 km) has distorted so much that the original gentle upsweep appears near vertical.

To investigate how normal-mode modeling fits the sonobuoy right whale data, an initial synthetic three-part upswept call was used to best fit the first mode of the closest recording. The synthetic received call was calculated using the modal dispersion curves, the known range, and the initial synthetic call. Synthetic received calls are overlaid as thin black lines on spectrograms of the recorded calls for the close and far sonobuoys recordings (Fig. 7). The match between the modeled calls and the recorded calls for both the closest and farthest sonobuoy is good. However, notice in the recorded data, the third mode appears minimally excited compared to modes one, two and four.

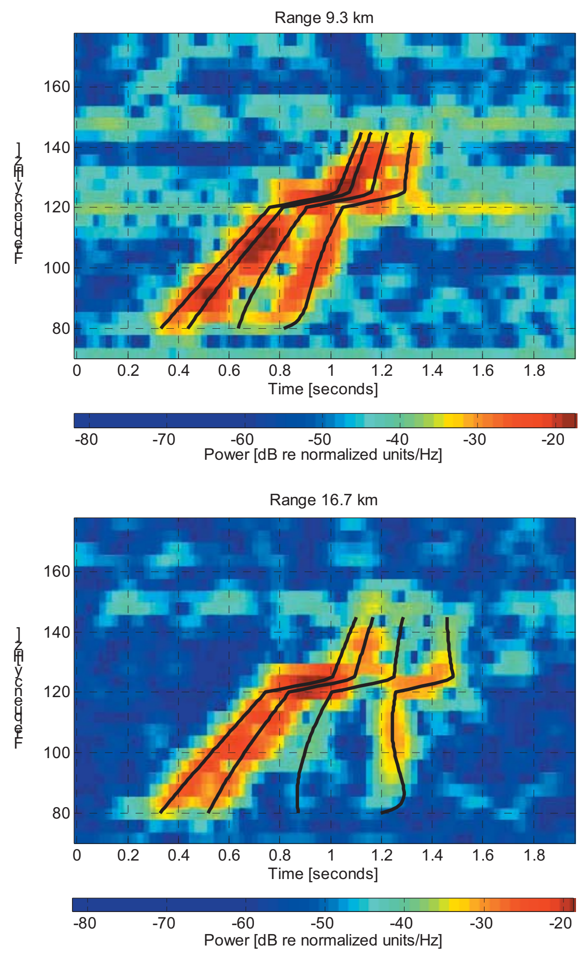

Fig. 7. Spectrograms of closest and farthest sonobuoy right whale recordings (from Fig. 2) overlaid with normal-mode modeling synthetic received call. Note the good match between the model and the data, and that the third mode is minimally excited in the recorded data.

The lack of third mode excitation in the sonobuoy example can be attributed to source and/or receiver depth. The depth of the calling whale is unknown, but the sonobuoy hydrophone is suspended from a sea surface float at approximately 28 m. This depth is near a node for the third mode on the excitation plot (Fig. 6). For this waveguide model and for sources around 100 Hz, the third mode will be minimally excited for receivers and sources near 25 m deep. A synthetic spectrogram illustrating this point is shown in Figure 8. The relative received power has been combined with the synthetic received call by choosing a source and a receiver depth and evaluating the contributions from the modal excitations at these depths over the frequencies of the call. The power for the synthetic spectrogram is simply the product of the absolute values of the modal excitations at the source and receiver depths. For example, if the source and receiver were placed at 40 m depth, then for a source at 100 Hz the first and third modes would have powers near one (0 dB), whereas the second and fourth modes would have powers near zero (large negative dB) (Fig. 6). In this example, the source was chosen to be at 25 m and the receiver at 28 m. From the synthetic spectrogram it is apparent that the third mode is minimally excited compared to the other three modes by comparing their relative power (Fig. 8), similar to the recorded data.

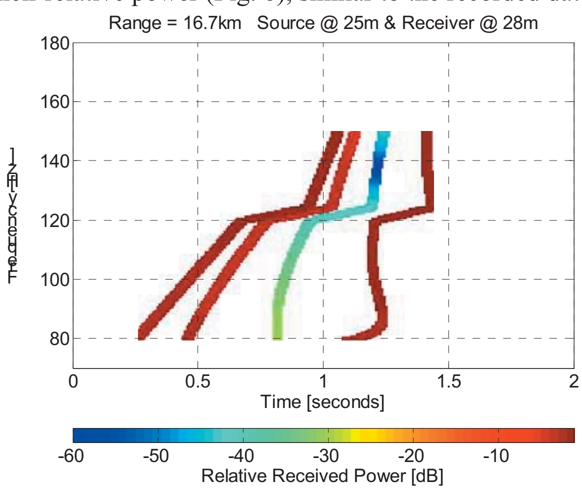

Fig. 8. Synthetic spectrogram for farthest sonobuoy example (16.7 km range). The synthetic received call from Figure 7 is combined with the relative received power calculated as the product of the absolute values of the modal excitation over the call frequency range and for source depth at 25 m and receiver depth at 28 m. The third mode is minimally excited compared to modes one, two and four, which is consistent with the sonobuoy recordings.

3.2 ARP recordings and modeling

The seafloor ARPs also recorded North Pacific right whale calls and can be modeled in a similar fashion to the sonobuoy recordings to verify the normal-mode modeling. An individual call recorded on three or more instruments (to allow localization) is required to compare the modeling results to the recorded calls. Once the model has been verified, it can be used to estimate range to calling whales recorded on single instruments.

An example right whale call is overlaid with synthetic received calls for the two most eastern ARPs (23 km and 56 km ranges) in Fig 9. The ranges were calculated using a hyperbolic localization technique, 1470 m/s water sound speed, and arrival times at 150 Hz. The initial synthetic call is an upsweep from 95 Hz to 170 Hz with a sweep rate of 120 Hz/s. This is a simplification of the actual call, but incorporates the range-dependent varying section of the upsweep. The mostly-constant tonal at the beginning of the call below 100 Hz does not add much range information and is omitted. The modal arrival times are calculated using the same sound speed, density and waveguide thickness parameters that were used for the sonobuoy modeling. The model fits the data well for both ranges including modes five and six on the closest ARP recording (23 km range).

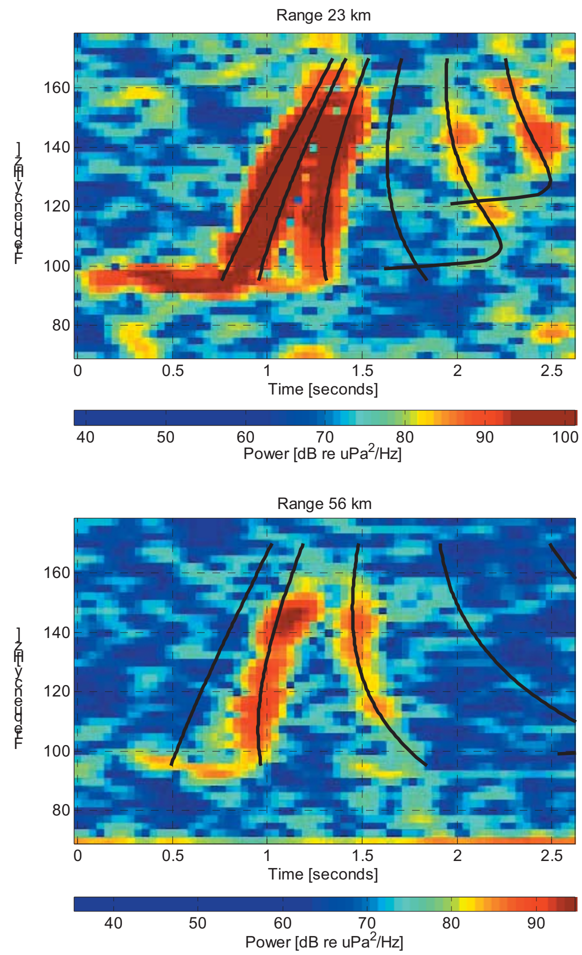

Fig 9. Spectrograms of right whale recordings from seafloor ARPs overlaid with synthetic received calls from normal-mode modeling. The model fits the data well for both ranges including modes five and six on the closest ARP (23 km range). Note mode four is not excited in both spectrograms and only modes two and three are above the background noise at the most distant ARP (56 km range).

On both the closest and farthest ARP recordings, the fourth mode is not excited above the background noise. The receiver hydrophone for the ARP is about 10 m off of the seafloor or at about 60 m depth which is near a zero-crossing node for the fourth mode, but still some excitation should be present. Perhaps for this call, the whale is near the 20 m deep node for mode four, so the combined modal excitation contribution is negligible (Fig. 6). This explanation of source depth is also valid for why mode two is more strongly excited than mode three and why mode one is not observed at 56 km range (Fig 9). A synthetic spectrogram of the farthest ARP recording was produced similarly to the sonobuoy synthetic spectrogram, but with a source depth of 18 m and receiver depth of 60 m (Fig. 10). The synthetic spectrogram agrees with relative power of the recorded data where modes two and three are the strongest and mode one is weaker.

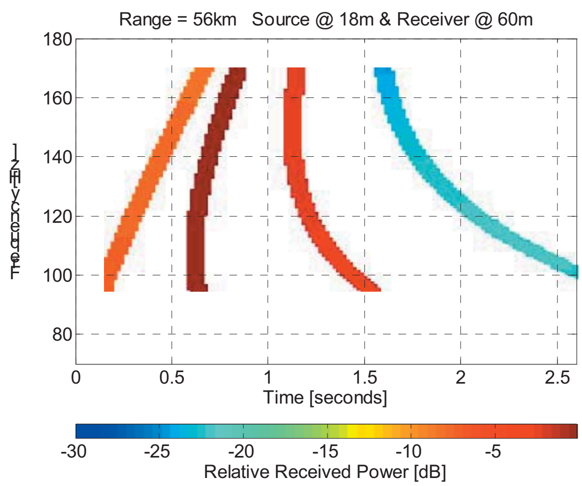

Fig 10. Synthetic spectrogram for the most distant ARP example (56 km range). The synthetic received call from Figure 9 is combined with the relative received power calculated as per Figure 8, but with the source at 18 m and the receiver at 60 m depth. The strongest arrival is mode two followed by mode three then mode one, which is not visible above the noise in the ARP recording.

4. DISCUSSION

Examples of North Pacific right whale calls distorting into dispersed modes with increasing range in the shallow-water waveguide eastern Bering Sea have been shown to contain source-receiver range and source calling depth information. With normal-mode modeling, estimating range to calling whales from single instruments is possible and can add to hyperbolic localizations from multiple instrument arrays. By understanding the detection range, whale abundance estimates for long term acoustic recordings can be improved (Buckland *et al.,* 1993).

The group velocity dispersion model presented has been qualitatively and successfully fit (forward modeled) to recorded data for different right whale calls, different types of instruments, and during different time periods. Preliminary work with downswept minke (*Balaenoptera acutorostrata*) and fin (*Balaenoptera physalus*) whale calls recorded on the ARPs also has shown that this model fits well for these localized calls. However, minke and fin whale calls sweep through lower frequencies (80 to 50 Hz, and 35 to 15 Hz, respectively) than right whales, and only excite the first few modes because these frequencies are below the cutoff frequencies of higher modes.

How well these simple models fit the recorded calls depends upon the environmental parameters used in the models. The bathymetry of the eastern Bering Sea shelf changes only a few meters over the propagation path (10's of km) from caller to receiver (Fig. 3) (Marlow *et al.,* 1999). This amount of change has minimal impact on group velocities at frequencies above the Airy frequency, and provides consistent results between the recordings at various ranges. The sediment sound speed had the greatest uncertainty, but was adjusted from 1600 m/s to 1675 m/s to best fit the observed data for modes four and above. This adjustment had minimal effect on lower modes and on shorter range (<20 km) modeled calls. Uncertainties in water sound speed have the greatest impact on group velocity, however, the sound speed is almost constant with depth (+/- 5 m/s) during the late summer and early fall when the calls were recorded (Teague *et al.,* 1990). Low variability in the model parameters allows the same model to be used for the sonobuoy and ARP data.

While qualitative curve fitting to the data works well, a method more capable of automation could be developed for large data sets. One approach would be to choose one frequency of a right whale call and measure the time difference between modes at that frequency and estimate range from caller to receiver by using the modeled group velocities for those modes. For example,

$$R = \frac{u_i u_j}{\left|u_i - u_j\right|}\left|t_i - t_j\right| \quad (8)$$

where R is range, u and t are respectively the group velocities and arrival times for modes i and j. It is best to choose a low frequency, close to the Airy frequency of the dispersion curve, because group velocities are slowest and the time difference will be greatest there. With large time differences, arrival time picking errors can be minimized. Also, because higher order modes are more dispersed, choosing these modes would minimize arrival time picking and range estimate errors. However, if only one frequency is used, then it is essential to know which modes are being excited and recorded. For example, if the time difference at 100 Hz between modes two and three for the ARP recorded call at 56 km range (Fig. 9) was presumed to be for modes one and two or for modes three and four, then the range would have been incorrectly estimated to be 95 km or 37 km, respectively. To prevent such gross errors, it would be best to analyze the full-sweep spectrogram because it requires that the dispersed modes fit for all frequencies in the call band. Match field processing or inverse modeling techniques then could be applied to a set of mode time-frequency data to solve for range and statistical error estimates.

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