

## **Development and application of a three-dimensional seismo-acoustic coupled-mode model**

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Award Number: N00014-14-1-0222

### **LONG-TERM GOALS**

The overall goal of this research is the development of an accurate and reliable propagation model applicable to environments which exhibit strong range dependence in all three spatial dimensions.

### **OBJECTIVES**

The objective of this work is to gain an understanding the physics of propagation in continental shelf areas, specifically horizontal refraction and mode coupling induced by three-dimensional (3D) inhomogeneities in the waveguide.

### **APPROACH**

Normal-mode approaches, including both adiabatic- and coupled-mode techniques, were used to understand propagation in a variety of range-dependent environments that produce out-of-plane propagation effects. First, a 3D propagation model with stepwise coupled-modes [Ballard (2014)] was applied to calculate propagation in set of submarine canyons. The model is formulated in a cylindrical coordinate system, and the solution is obtained from a separation of variables. The depth-separated Helmholtz equation is solved using a gradient half-space approach, and leaky modes are included in the solution to account for a wide vertical angle. Modal amplitudes are calculated from the horizontally separated part of the Helmholtz equation with a hybrid technique in which a parabolic solution provides the description of horizontal refraction in the azimuthal direction and a stepwise coupled-mode technique accounts for mode-coupling in the radial direction.

Next, a method to estimate source range in continental shelf environments based on a hybrid modeling approach using vertical modes and horizontal rays was applied [Ballard (2013)]. The technique exploits measurements recorded on a horizontal line array of a direct path arrival and a refracted path arrival. According to vertical modes/horizontal rays approach, rays are traced in the horizontal plane with refraction determined by the modal phase speed. Invoking reciprocity, the rays originate from the center of the array and have launch angles equal to the estimated bearing angles of the direct and refracted

paths. The location of the source in the horizontal plane is estimated from the point where the rays intersect.

Finally, a hybrid propagation model based on adiabatic modes was applied to model time series data from a scale model experiment. The modeled time series are generated by applying an inverse Fourier transform to the frequency domain solutions. In the hybrid model, ORCA [Westwood and Koch (1999)] is used to solve the depth separated normal-mode equation and a parabolic equation [Collins (1994)] (PE) in Cartesian coordinates is applied to solve the horizontal refraction equation. Although the adiabatic-mode model does not fully capture all the physics of the measured data, it is used as a starting point to understand key aspects of the experimental apparatus before applying more computationally intensive approaches.

## **WORK COMPLETED**

The main accomplishments of 2013 include: (1) application of the 3D coupled-mode model to calculate acoustic propagation in a set of canyon environments, (2) evaluation of the effects of environmental uncertainty on source range estimates obtained using measurements of horizontal multipath, and (3) modeling acoustic data recorded in a scale model experiment.

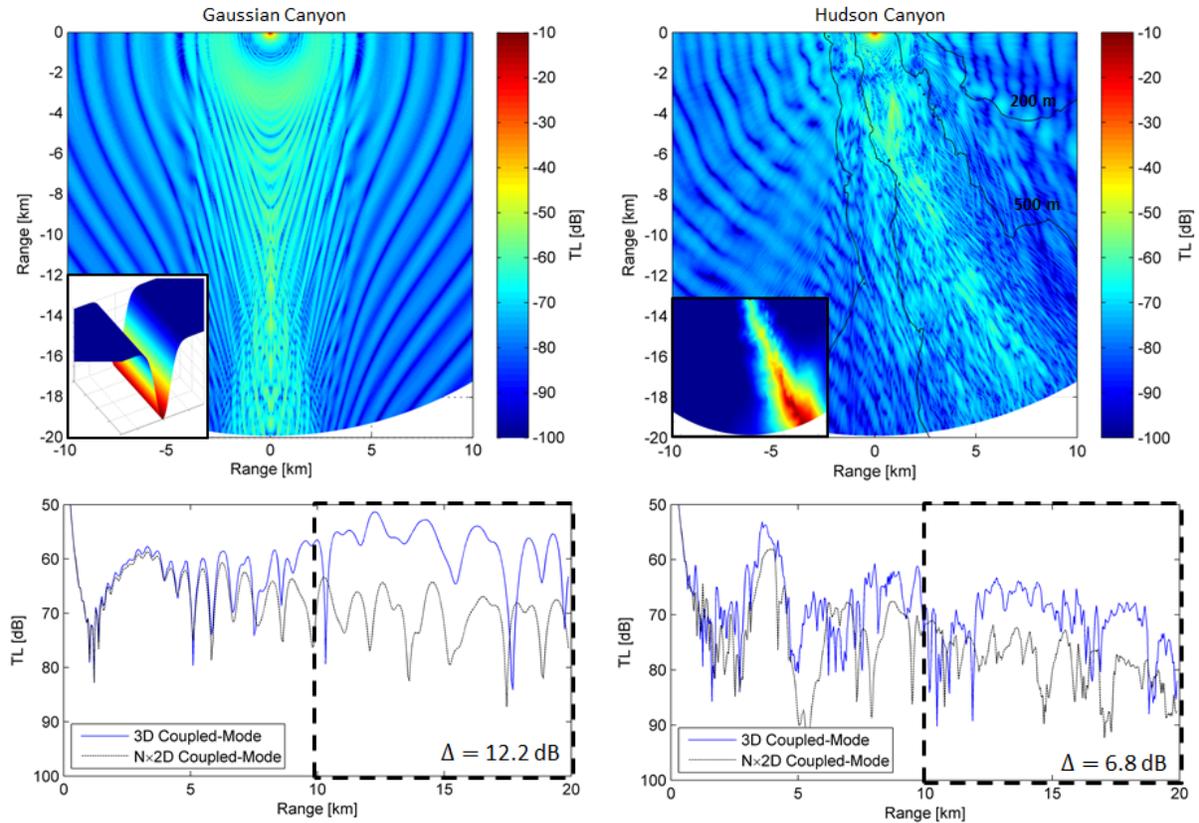
## **RESULTS**

### *Application of the 3D coupled-mode model to the canyon environment*

The 3D coupled-mode model was applied to model propagation in two canyon environments. First, a Gaussian canyon described by a smooth analytic shape with variations in depth independent of one horizontal dimension was considered [Tolstoy et al. (2001)]. The propagation environment was described by an isovelocity water column sound speed profile over an acoustic half space so that the only range dependence enters the problem through the bathymetry. The solution calculated with the 3D coupled-mode model showed good agreement with a published result [Arvelo and Rosenberg (2001)]. Transmission loss at a depth of 35 m is shown in the top left panel of Fig. 1, with an image of the bathymetry inset in the figure. The lower left panel shows a comparison of the 3D and  $N \times 2D$  solutions along the canyon axis. For ranges between 10 km and 20 km, focusing of sound into the canyon caused an average decrease in TL of 12.2 dB.

An example based on measured bathymetry of the Hudson Canyon was considered next. The environment for the Hudson Canyon used the same geoacoustic properties as the Gaussian canyon to allow for ease of comparison between the solutions. The calculated TL is shown in the right panel of Fig. 1, with the 200 m and 500 m isobaths. The lower right panel shows a comparison of the 3D and  $N \times 2D$  solutions along the canyon axis. For ranges between 10 km and 20 km, focusing of sound into the canyon caused an average decrease in the TL of 6.8 dB.

This work considered two canyon environments with similar features: they both had concave shape that extended in a single direction and they both had approximately the same depth extent. However, compared to the Gaussian canyon, the bathymetry in the Hudson Canyon varied in the along-shelf direction as well as in the in cross-shelf direction. Additionally, the bathymetry in the Hudson Canyon environment was generally characterized by greater variability which induced increased forward scattering of the acoustic energy. This difference in the environments resulted in higher loss for both the



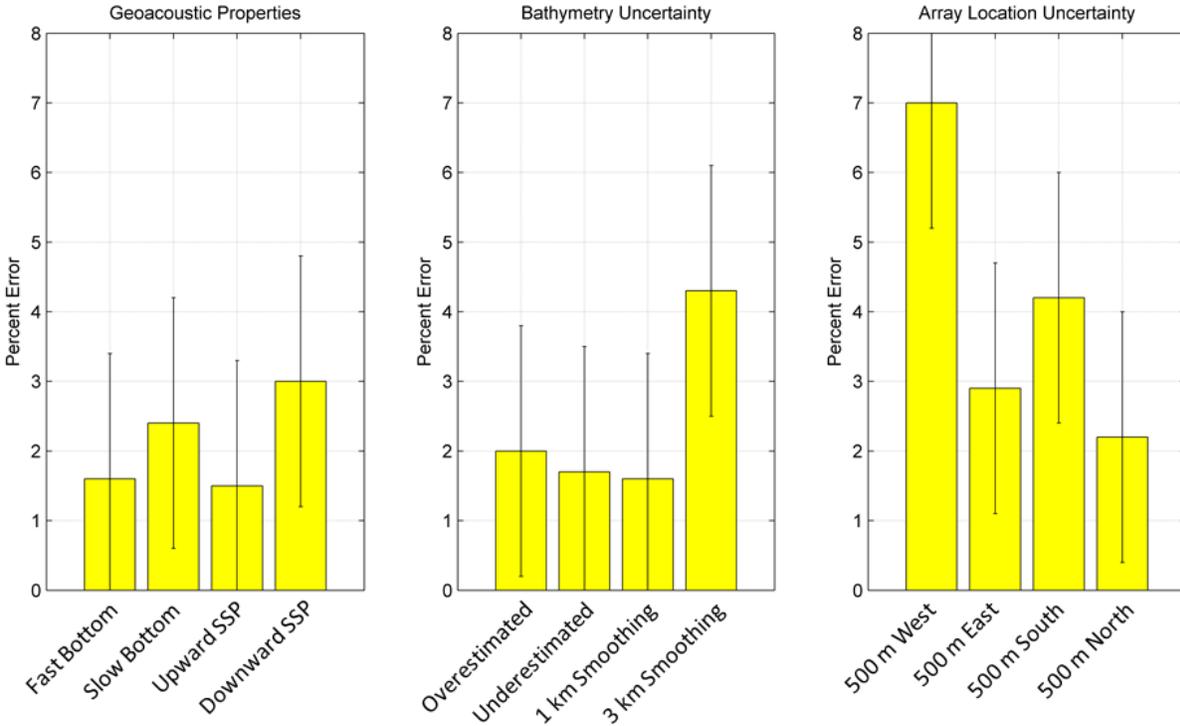
**Figure 1: Comparison of TL in two canyon environments. The left panel shows TL calculated in a Gaussian-shaped canyon, and the right panel shows TL in the Hudson Canyon. For both panels, the top plots are TL in the horizontal plane with an inset image depicting the range-dependent bathymetry, and the bottom plots are TL along the canyon axis showing a comparison between 3D and  $N \times 2D$  solutions.**

3D and  $N \times 2D$  solutions. An additional consequence was the decreased horizontal focusing of sound along the canyon axis. Simplified environments that can be described analytically are often used for the development and testing of acoustic propagation models. This comparison shows the increased complexity of 3D acoustic propagation over real ocean bathymetries, and how simplified environments may result in greater enhancements due to 3D propagation effects.

### ***Effect of environmental uncertainty on source range estimates using horizontal multipath***

In previous work, the horizontal multipath ranging technique was applied to acoustic data recorded on an HLA located 12 km east of the southern coast of Florida [Ballard (2013)]. During the experiment, a source was towed parallel to the Florida coastline. Using a simplified representation of the environment which neglected details of the geoaoustic properties of the seabed as well as range- and depth-dependence of the water column sound speed profile, the location of the source was tracked with average error of 3.7% compared to the GPS range. The majority of the error was attributed to inaccuracies in the estimated arrival angles due to low SNR.

In this year's work, the effects of unknown environmental parameters, including the sediment properties

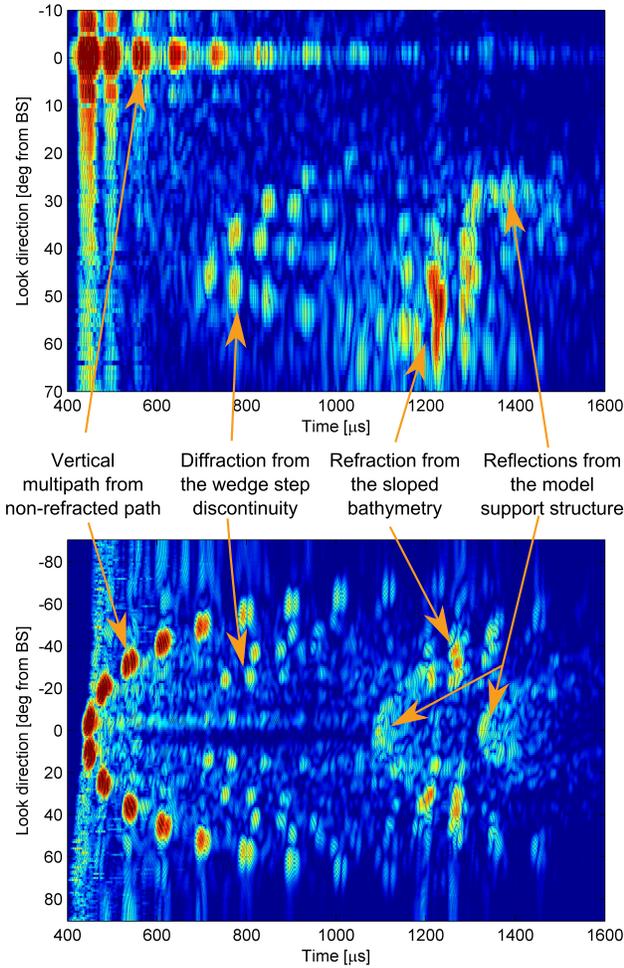


**Figure 2: Effects of environmental uncertainty, including uncertainty in the geoacoustic parameters of the seabed and water column sound speed profile, uncertainty in the bathymetry, and uncertainty in the array location, on source range estimates from horizontal multipath. The error bars were determined from the error in the unperturbed ranging estimate.**

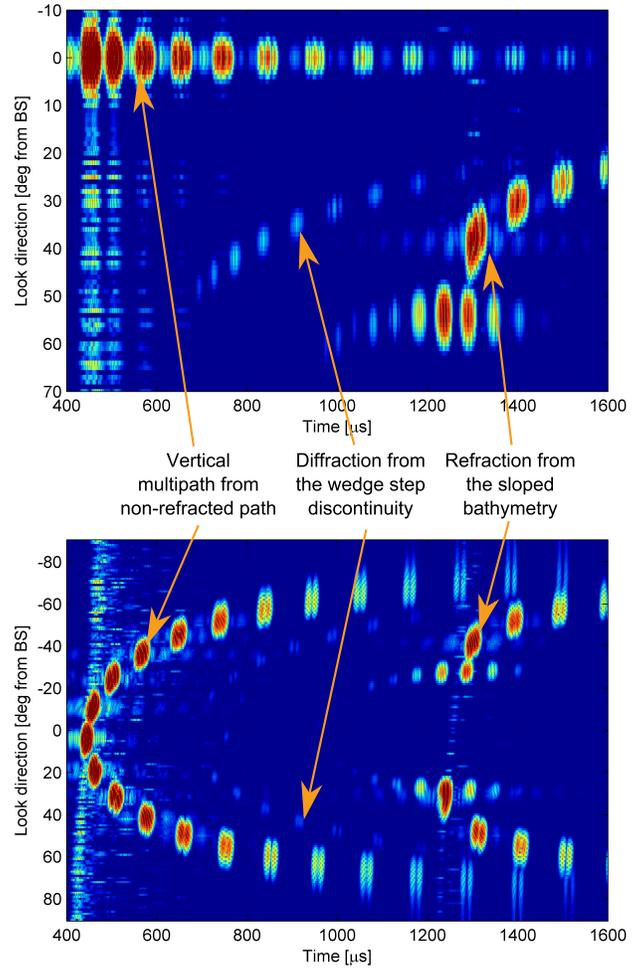
and the water-column sound-speed profile, on the source range estimate were assessed. Error resulting from uncertainty in the measured bathymetry and location of the receiver array was also quantified. A study was carried out using synthetic data representative of the Florida shelf environment. The results of this study are summarized in Fig. 2. For each case shown in the figure, the horizontal launch angles were estimated for an isovelocity water column over an acoustic half space. The effect of a single parameter on the ranging estimate was determined by perturbing the environment used to calculate the horizontal ray trace. The results of the study are (1) an accurate estimate of source range can be obtained without detailed knowledge of the water column sound speed profile or geoacoustic properties of the seabed, (2) it is necessary to know the bathymetry [but low resolution, O(1km) maybe sufficient], and (3) it is necessary to know the location of the HLA [error in the array location on the O(500 m) degraded results].

### ***Modeling acoustic data recorded in a scale model experiment***

Initial modeling of data recorded in a 1:7500 scale laboratory tank was conducted. The laboratory measurements were made by Jason D. Sagers, and more information about the design of the tank and details of the measurements system can be found in Sagers (2013, 2014). For the measurements considered in this work, the bathymetry was configured with a range-independent region having a nominal water depth of 3.5", with a wedge having a 10° slope that extended from the 3.5" water depth to a depth of 1.75". There is a 0.040" step discontinuity in the bathymetry at boundary between the



**Figure 3: Measured data: beamformed using an HLA (top panel) and VLA (bottom panel). Arrivals resulting from vertical and horizontal multipath are labeled.**



**Figure 4: Calculated data: beamformed using an HLA (top panel) and VLA (bottom panel). Arrivals resulting from vertical and horizontal multipath are labeled.**

range-independent region and the edge of the slope. The bathymetry was fabricated from a closed-cell polyurethane, whose ultrasonic reflection coefficient nearly approximates a pressure release boundary [Sagers et al. (2013)]. An acoustic source broadcasting an LFM chirp was positioned in the range-independent region, 18” away from the edge of the slope. The signal was recorded by two synthetic aperture arrays having vertical and horizontal apertures, with their centers located 26” away from the source in the along shelf direction. The HLA was orientated with a broadside look at the source. The measured data were filtered in the frequency domain, cross-correlated with the input waveform, and beamformed. The processed data are shown in Fig. 3.

Although a relatively simplistic adiabatic-mode model was used to calculate time series for comparison with the measured data, considerable steps were taken to account for details in the experimental apparatus. For example, the frequency-dependent transmitting and receiving sensitivity and vertical directionality of both hydrophones were included. In addition, inversion techniques were applied to resolve uncertainty in geometric parameters, including water depth and source and receiver positions.

An additional loss mechanism, possibly caused by scattering from the interface, was modeled by adding a fixed value to the ultrasonic reflection coefficient. The frequency domain solution was calculated over a 600 kHz band centered at 600 kHz. The modeled waveforms were processed using the same procedure as the measured data. The results are shown in Fig. 4.

The calculated waveforms from this initial modeling effort agree favorably with the measured data. For both data sets, three distinct sets of arrivals are observed: (1) a set of vertical path arrivals observed at the bearing of the source, (2) a set of out-of-plane arrivals that result from diffraction from the step discontinuity at the edge of the wedge, and (3) a set of horizontally refracted arrivals that result from horizontal refraction due to the sloped bathymetry. Nevertheless, significant differences between the measured and calculated data can be observed. Specifically, the measured data show more complexity in the out-of-plane arrivals, which exhibit additional horizontal and vertical arrivals compared to the calculated data. These arrivals result likely from mode coupling, an effect that was not included in this initial modeling result.

## **IMPACT/APPLICATIONS**

The impact of this work is an increased understanding of acoustic propagation through complicated coastal environments for which the bathymetry, seabed properties, and oceanography can vary in three dimensions.

## **TRANSITIONS**

The primary transition for this project is an accurate and reliable model for acoustic propagation in environments with strong three-dimensional range dependence. Because coupled-mode approaches are computationally intensive, they have historically been used to benchmark faster techniques which approximate the solution to the wave equation.

## **RELATED PROJECTS**

### ***Geoacoustic inversion in three-dimensional environments***

The goal of this project is to estimate water column sound speed in a 3D volume using modal travel time measurements from multiple source-receiver pairs. A thorough understanding of the forward problem, including the effects of horizontal refraction and mode coupling, is necessary to successfully estimate environmental parameters in regions with 3D inhomogeneities.

### ***Acoustic propagation modeling for diver detection sonar systems***

The purpose of this work is to characterize waveforms at virtual receiver distances on the order of a 1000 meters away from active diver detection sonar systems installed at fixed locations within operational sites of interest. The 3D coupled-mode model is applied for this purpose.

### ***Laboratory and field measurements of compressional and shear wave speed***

Under this project laboratory measurements of the compressional and shear wave speeds and attenuations in coarse and fine grained sediments have been obtained. One highlight of this work is the measurement of the shear wave speed in muds with comparison to a recently developed card-house

theory [Pierce and Carey (2008)]. Additionally, a system to obtain *in situ* measurements of the seismo-acoustic properties of marine sediments is under development.

### ***Acoustic propagation modeling for habitat-associated sound as a settlement cue***

At the time of settlement, the larvae of coral reef fish need to locate a reef, and sound emanating from reefs may act as a cue to guide them. Using acoustic data collected from Bahia Almirante on the north coast of Panama, this study examines the distances from potential settlement sites for which reef sounds can be detected by reef fish larvae. Maps of signal excess are created using source levels measured at the reef, transmission loss calculated with range-dependent acoustic propagation models, and hearing thresholds for the larvae.

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## **PUBLICATIONS**

### ***Refereed Journal Articles***

Christopher M. Bender, Megan S. Ballard, and Preston S. Wilson, “The effects of environmental variability and spatial sampling on the solution of the three-dimensional linearized inversion problem for ocean sound speed,” *J. Acoust. Soc. Am.*, **135**(6), pp. 3295–3304, 2014.

Megan S. Ballard, George V. Frisk, and Kyle M. Becker, “Estimates of the temporal and spatial variability of ocean sound speed on New Jersey shelf,” *J. Acoust. Soc. Am.*, **135**(6), pp. 3316–3326, 2014.

Jason D. Sagers, Megan S. Ballard, “Observation of three-dimensional acoustic propagation in the Catoche Tongue,” *J. Acoust. Soc. Am.*. [accepted for publication]

George V. Frisk, Kyle M. Becker, Subramaniam D. Rajan, Cynthia J. Sellers, Chad M. Smith, and Megan S. Ballard, “Modal Mapping Experiment Using Sonobuoys,” *IEEE JOE*. [accepted for publication]

Megan S. Ballard, Benjamin M. Goldsberry, and Marcia J. Isakson, “A three-dimensional propagation model with stepwise coupled modes,” *J. Comp. Acoust.*. [in review]

Megan S. Ballard, Kevin M. Lee, and Thomas G. Muir “Laboratory P- and S-wave measurements of a reconstituted muddy sediment with comparison to card-house theory,” *J. Acoust. Soc. Am.*. [in review]

### ***Conference Proceedings***

Megan S. Ballard, Kevin M. Lee, and Thomas G. Muir “Laboratory measurements of shear wave speed in muddy sediments with comparison to card-house theory,” *POMA*, **21**, 055007, 2014.

### ***Presentations***

Megan S. Ballard, Jason D. Sagers, and David P. Knobles, “Explanation of an extended arrival structure measured in the Catoche Tongue using a three-dimensional propagation model,” 167<sup>th</sup> Meeting of the Acoustical Society of America, Providence, Rhode Island, May, 2014.

Megan S. Ballard, Kevin M. Lee, and Thomas G. Muir, “Laboratory measurements of compressional and shear wave speed and attenuation in muddy sediments,” 167<sup>th</sup> Meeting of the Acoustical Society of America, Providence, Rhode Island, May, 2014.

Megan S. Ballard, Jason D. Sagers, and David P. Knobles, “Three-dimensional modeling of acoustic propagation in the Gulf of Mexico,” 11<sup>th</sup> International Conference on Theoretical and Computational Acoustics, College Station, Texas, March, 2014.

Megan S. Ballard, “Three-dimensional propagation over a Gaussian-shaped canyon: A coupled-mode solution,” 11<sup>th</sup> International Conference on Theoretical and Computational Acoustics, College Station, Texas, March, 2014.

Megan S. Ballard, Benjamin M. Goldsberry, and Marcia J. Isakson, “Three-dimensional propagation: comparison of finite element and coupled-mode solutions,” 166<sup>th</sup> Meeting of the Acoustical Society of America, San Francisco, California, December, 2013.

Sumedh Joshi, Megan S. Ballard, and Peter J. Diamessis, “Modeling sound propagation through internal waves using a spectral element method,” 166<sup>th</sup> Meeting of the Acoustical Society of America, San Francisco, California, December, 2013.

Kevin M. Lee, Megan S. Ballard, Sanjai Bashyam, and Thomas G. Muir, “Laboratory measurements of shear wave properties in marine sediments using bender element transducers,” 166<sup>th</sup> Meeting of the Acoustical Society of America, San Francisco, California, December, 2013.

Megan S. Ballard, “Estimates of source range using horizontal multipath in continental shelf

environments,” 166<sup>th</sup> Meeting of the Acoustical Society of America, San Francisco, California, December, 2013.