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

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LONG-TERM GOALS

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

OBJECTIVES

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

APPROACH

Normal-mode approaches, including both 2D and 3D techniques, were applied to calculate acoustic propagation in environments with fluid and elastic bottoms. First, a 3D propagation model based on adiabatic modes was applied to model time series data from a scale model experiment. A horizontal ray trace was used to identify three distinct sets of arrivals, which were observed in both the measured and modeled beamformed time series. A manuscript describing these results has been submitted.

A robust normal-mode code for calculating the eigenvalues and eigenfunctions in environments with elastic bottoms has been completed. The model reliably locates all the eigenvalues within a specified contour with a known accuracy. This is a necessary step towards the development of a 3D seismo-acoustic coupled-mode model. The performance of the algorithm is evaluated through comparison with other mode finding techniques and propagation codes. It is also used to calculate modeled time series for comparison with the measured interface wave arrivals.

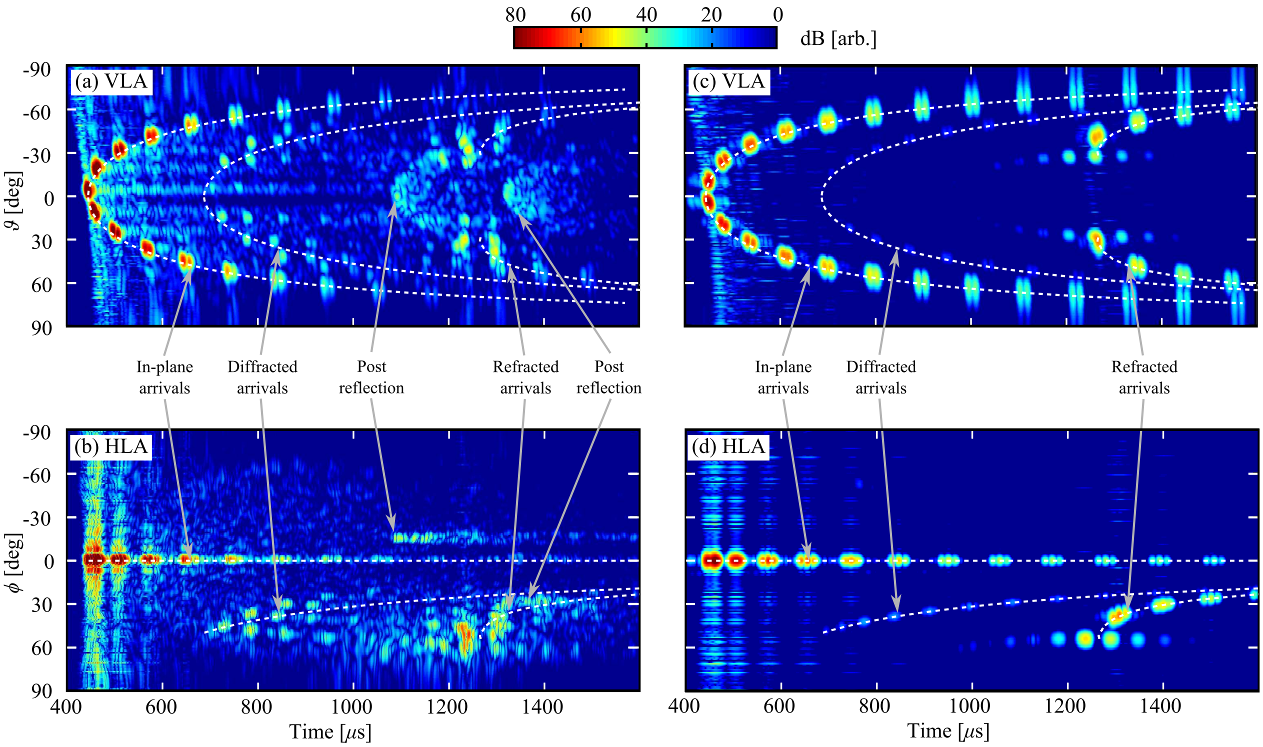

Figure 1: Comparison of measured (left column) and calculated (right column) data: beamformed data from an VLA (top row) and HLA (bottom row).

WORK COMPLETED

The main accomplishments of 2015 include: (1) 3D propagation modeling out-of-plane arrivals from a scale model experiment, (2) development of a robust mode finding algorithm for environments with elastic bottoms, (3) and propagation modeling of interface waves with comparison to measured data.

RESULTS

Modeling acoustic data recorded in a scale model experiment

Three-dimensional 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 (2015). 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^{o} 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 range-independent region and the edge of the slope. 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 the left column of Fig. 1.

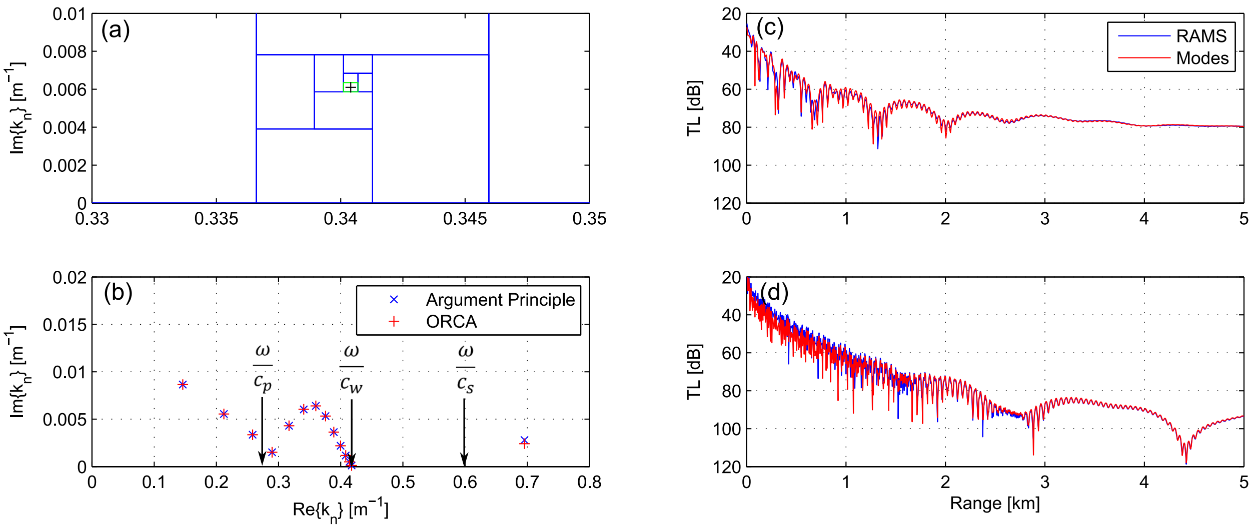

Figure 2: (a) Illustration of argument principle for mode 8, (b) comparison to modes found using ORCA, (c,d) comparison of transmission loss calculated with modes and RAMS.

The vertical mode/horizontal ray analogy [Weinberg and Burridge (1974)] was applied to identify the features responsible for the arrivals observed in the measured data. In this analysis, the refraction of the horizontal rays is determined by the modal phase speed, and the travel time along each ray path is determined by its modal group speed. In addition to providing an estimate of modal travel time, the vertical and horizontal arrival angles for each mode are predicted. These predictions are overlaid by the white dashed lines on the beamformed time series in Fig. 1. The horizontal ray trace was instrumental in identifying three distinct sets of arrivals: (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.

To further corroborate the measurements, an adiabatic-mode model was applied to compute the acoustic field in 3D, and the time domain signals were beamformed for comparison with the measured data. 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)] in Cartesian coordinates is applied to solve the horizontal refraction equation. The modeled waveforms were processed using to the same procedure as the measured data. The calculated beamformed time series are shown in the right column of Fig. 1. The calculated data show excellent agreement with the arrival time and angles predicted by the horizontal ray trace. 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 these modeling results.

Development of a robust mode finding algorithm for environments with elastic bottoms

A robust normal mode code for calculating the eigenvalues and eigenfunctions in environments with elastic bottoms has been developed. A brief description of the algorithm is provided here. The shear ψ

and compressional ϕ potentials satisfy

$$\nabla^2\phi = \frac{1}{c_p^2}\frac{\partial^2\phi}{\partial t^2},\ \nabla^2\psi = \frac{1}{c_s^2}\frac{\partial^2\psi}{\partial t^2}$$

where c_p is the compressional wave speed and c_s is the shear wave speed. The displacements and stresses can be written in terms of the potentials as

$$u(r,z) = \frac{\partial\phi}{\partial r} + \frac{\partial^2\psi}{\partial r\partial z}, \qquad w(r,z) = \frac{\partial\phi}{\partial z} - \frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial\psi}{\partial r},$$

$$\sigma_{zz}(r,z) = (\lambda+2\mu)\frac{\partial w}{\partial z} + \lambda\frac{1}{r}\frac{\partial(ru)}{\partial r}, \qquad \sigma_{rz}(r,z) = \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial r}\right),$$

$$\sigma_{rr}(r,z) = \lambda\left(\frac{1}{r}\frac{\partial}{\partial r}(ru) + \frac{\partial w}{\partial z}\right) + 2\mu\frac{\partial u}{\partial r}, \qquad \sigma_{\phi\phi}(r,z) = \lambda\left(\frac{1}{r}\frac{\partial}{\partial r}(ru) + \frac{\partial w}{\partial z}\right) + 2\mu\frac{u}{r}$$

where λ and μ are the Lamé constants.

Applying the boundary conditions for the Pekeris elastic waveguide (i.e., pressure release at the sea surface, and continuity of vertical displacement, normal stress, and tangential stress at the bottom interface) results in the characteristic equation [Ewing et al. (1957)]. The roots of the characteristic equation are the horizontal wavenumbers. Root finding in the complex plane is accomplished using a hybrid method, based on a procedure described by McCollom and Collis (2014). The algorithm has been implemented in Matlab with an emphasis on creating a robust mode finder. First, the roots are isolated in the complex plane using the argument principle. In this step, the contour is divided into increasing small regions until the size of each contour reaches a threshold and each contour contains only a single root. Then Newton's method is applied to find the root, using the center of the contour as the initial value.

The technique described above was applied to find the eigenvalues for a frequency of 100 Hz in a waveguide 100 m deep with a chalk bottom. The application of the argument principle is illustrated for mode 8 in Fig. 2(a). The blue lines represent the contours, which are increasing divided into smaller contours until the root is isolated and its location is fairly well-known, i.e., within the green contour. In Fig. 2(b), the modes found using the argument principle are compared to modes found using ORCA [Westwood and Koch (1999)]. With the exception of the zero mode, there is excellent agreement. As a second test, transmission loss for a source located a 0.5 m above the bottom was calculated using the modes found with the argument principle. The result is compared to transmission loss calculated with RAMS [Collins (1991)] in Fig. 2(c) and (d) for a receiver in the middle of the water column and near the sea floor, respectively. The agreement in the calculated transmission loss curves is very good.

Propagation modeling of interface waves

A study of acoustic propagation in very shallow water was conducted in October 2014 in Currituck Sound, North Carolina. Signals from the Combustive Sound Source (CSS) were recorded on five geophones located 50 m to 200 m away. Fig. 3(a) shows the bathymetry of Currituck Sound with locations of the CSS shot and geophones. A spectrogram of the CSS shot recorded on the vertical component of geophone SN110 is shown in Fig. 3(b). In the plot, the time is relative to the onset of the CSS signal arrival. The compressional wave arrival is contained within the first 0.4 s, and is made up

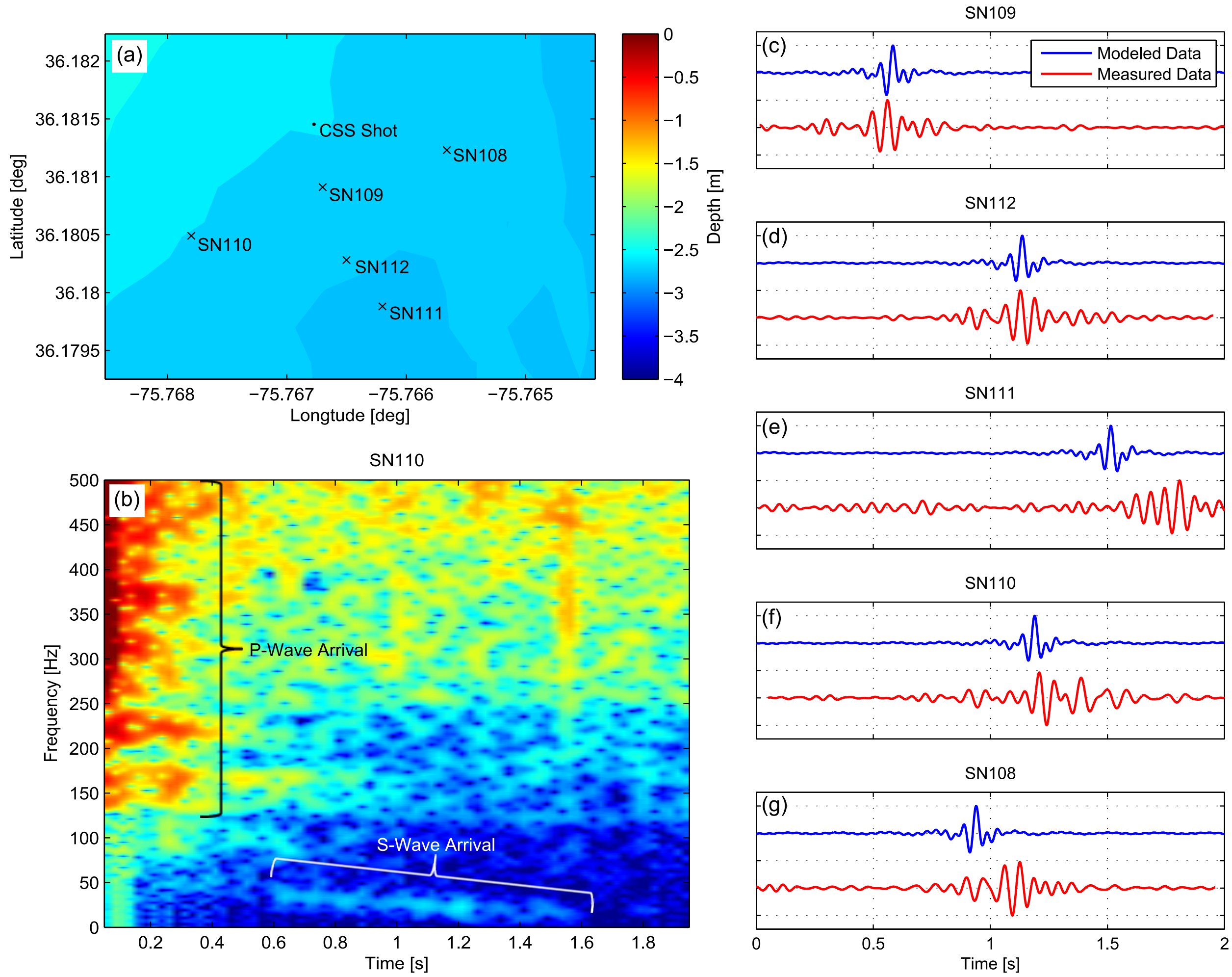

Figure 3: (a) Bathymetry of Currituck Sound with locations of CSS shot and geophones, (b) spectrogram of data recorded on the vertical component of geophone SN110, and (c-g) comparison of measured and modeled interface wave arrivals in the 5 Hz to 20 Hz frequency band.

primary of frequencies above 140 Hz, which is the cut-off frequency for this waveguide. The arrival of the interface wave extends from 0.6 s to 1.6 s and has frequency content below 50 Hz. The signal from the interface arrival is a weak compared to the compressional wave arrival, and it can be observed in the data because the two arrivals have different frequency content.

The mode finding algorithm described above was applied to calculate the received signals on the geophones in the 5 Hz to 20 Hz frequency band. The environment was modeled as an isovelocity waveguide ($c_w = 1490$ m/s, $\rho_w = 0.998$ g/cm^3) with a depth of 2.63 m over an elastic half space ($c_p = 1700$ m/s, $c_s = 150$ m/s, $\rho_b = 1.5$ g/cm^3, $\alpha_p = 0.1$ dB/λ, $\alpha_s = 0.1$ dB/λ). The modeled time series were calculated from a Fourier transform of the frequency domain solutions. The model-data comparison is shown in Fig. 3(c-g). In the figure, both the measured and modeled time series are aligned relative to the onset of the compressional wave arrival. To increase the signal-to-noise ratio of the measured data, the received signals from two CSS shots originating from the same location were averaged together. The measured data were also filtered in the 5 Hz to 20 Hz frequency band. Qualitatively, there is fairly good agreement between the measured and modeled time series. Some differences are due to the simple environmental model, which fails to produce the frequency dispersion of the measured interface wave arrival. Direct measurements of the sediment acoustic indicate significantly slower compressional and shear wave speeds near the sea floor [Ballard et al. (2015)]. Future modeling efforts will account for the depth dependence of the seabed properties.

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

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 an laboratory measurements 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.

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Megan S. Ballard and Jason D. Sagers, "Numerical analysis of three-dimensional acoustic propagation in the Catoche Tongue," *JASA Express Letters*, accepted for publication.

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Megan S. Ballard, "Coupled mode analysis of three-dimensional propagation over a cosine shaped hill," 169^{th} Meeting of the Acoustical Society of America, Pittsburgh, Pennsylvania, May, 2015.

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Megan S. Ballard, "Effects of environmental uncertainty on source range estimates from horizontal multipath," 168^{th} Meeting of the Acoustical Society of America, Indianapolis, Indiana, October, 2014.

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HONORS/AWARDS/PRIZES

Underwater Acoustics Technical Committee Chair, Acoustical Society of America (2015 – 2018)