Simulation of Bottom-interacting Ocean Acoustics: Transition into New Applications

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LONG-TERM GOALS

The ability to accurately and efficiently model the sound field in the water column when there exists significant acoustic interaction with the seafloor is critical in a variety of ocean-acoustic applications. Simulation methods with detailed fundamental treatments of the effect of acoustic energy on an elastic solid are often insufficiently robust when the environment is complicated or when long ranges are desired. The goal of this research is the creation of stable and computationally inexpensive acoustic modeling methods that can accommodate range dependence in both the water column and the bathymetry, accurately portray bottom reflection even when it is substantially impacted by support for elastic shear conversion, and still reliably develop predictions at ranges as long as the basin scale.

OBJECTIVES

The objectives of the reported research can be summarized as follows:

- Examination of the performance of complex-density, equivalent-fluid methods in predicting acoustic characteristics of the data in the Basin Acoustic Seamount Scattering EXperiment (BASSEX)
- Application of these methods to computationally efficient, simplified geoacoustic inversions to provide estimates of bottom parameters
- Application of these methods to simulations of propagation in the horizontal direction from sources designed for geoacoustic exploration

APPROACH

Objectives of this research can be addressed through the use of "equivalent fluids" to represent the acoustic effects of the solid seafloor. Equivalent-fluid models are based on using effective parameters to mimic the reflection characteristics of an actual elastic solid. Simulations using equivalent fluids are more robust and computationally efficient than models that incorporate a thorough treatment of shear; they are useful when the sound field in the water is the quantity of interest. Prior uses of equivalent

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14. ABSTRACT

The ability to accurately and efficiently model the sound field in the water column when there exists significant acoustic interaction with the seafloor is critical in a variety of ocean-acoustic applications. Simulation methods with detailed fundamental treatments of the effect of acoustic energy on an elastic solid are often insufficiently robust when the environment is complicated or when long ranges are desired. The goal of this research is the creation of stable and computationally inexpensive acoustic modeling methods that can accommodate range dependence in both the water column and the bathymetry, accurately portray bottom reflection even when it is substantially impacted by support for elastic shear conversion, and still reliably develop predictions at ranges as long as the basin scale.

15. SUBJECT TERMS

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fluids were based on a calculation of an effective complex density to portray the impact of the seafloor (Zhang and Tindle, 1995) for low shear speed and grazing angle. In order to extend the validity to larger shear speeds and higher grazing angles, all of the parameters of the equivalent fluid are treated as free parameters in an attempt to accurately depict the elastic reflection coefficient.

The degrees of freedom represented by the selection of an effective compressional (sound) speed and complex density enable a "fit" to an elastic reflection coefficient resulting from parameters that are known *a priori*. Equivalent-fluid representations of the bottom can also be used in a procedure to estimate elastic parameters that are treated as unknown. Since models using an equivalent-fluid bottom are computationally straightforward, simulated acoustic fields using a range of parameters for the effective compressional speed and complex density can be executed practically for a variety of ranges of potential interest. Then, these model results can be compared to an experimental reception and the equivalent fluid that best represents the experimental effect of the elastic seafloor can be determined. Finally, the best equivalent-fluid simulation can be used to estimate the actual parameters of the seafloor solid based upon the degree of correspondence between the reflection coefficients of the given equivalent fluid and a set of elastic parameters.

This method of inverting for geoacoustic parameters by employing equivalent-fluid representations of the solid can be applied to data from the BASSEX experiment. During the BASSEX experiment, the NPAL Kauai source (Worcester and Spindel, 2005) was recorded on ONR's Five-Octave Research Array. Because of the portability of the receiver, receptions were recorded at a variety of azimuthal directions and relatively short ranges from a few to a few hundred kilometers. The accuracy of the equivalent-fluid representation can then be examined at ranges other than the one used to identify the complex-density parameters. Processed data for these purposes has been supplied by Dr. Kevin Heaney of Ocean Acoustical Services and Information Systems.

These modeling methods can be adapted to different types of experiments. A scenario of particular interest involves airgun array sources. These experiments are designed to provide highly accurate, detailed characterizations of the seafloor based on the direct return. However, significant amounts of acoustic energy can propagate in the horizontal direction out to long ranges. Simulations using an equivalent fluid could depict this energy effectively; the need to model the propagation on a fine grid of azimuthal directions could be addressed efficiently and reliably with these techniques. These efforts would represent a substantial improvement to current models, typically with only a single *2D* environmental slice, no treatment of shear in the bottom, and a simplified treatment of the source output (DeRuiter *et al.*, 2006). Collaborative discussions are underway with Dr. James Stephens, also of the University of Southern Mississippi, on the acoustic output of airgun arrays and deployments in the Gulf of Mexico. A systematic modeling effort to determine the far field of such sources in all horizontal directions would be valuable in, for example, quantifying and examining possible concerns over marine mammal exposure.

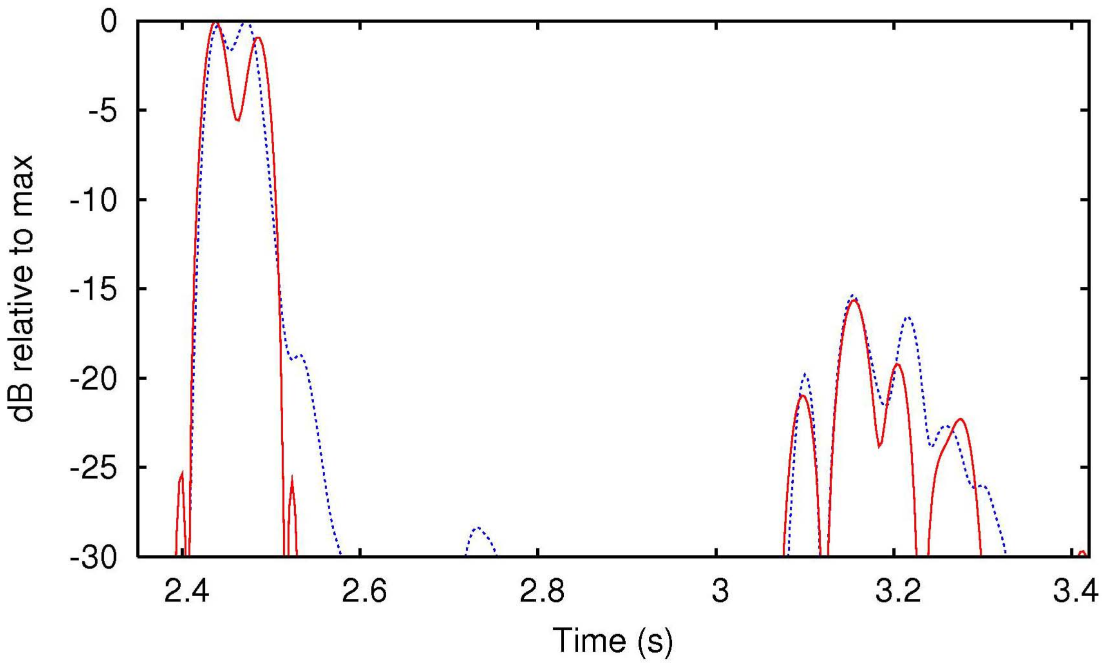

Figure 1: The received level data from a BASSEX reception at a range of 3.59 km is shown as a blue line. The set of equivalent-fluid parameters that were found to correspond most closely to the data yielded the simulated level shown as a red line.

WORK COMPLETED

Comparisons to combined elastic-acoustic computations and to experimental data have shown that equivalent fluids can be an effective proxy for elastic media, even with substantial shear effects. To expand on these prior efforts, the investigation turned toward the use of the technique in an approximate geoacoustic inversion. A reception at a range of 3.59 km was selected from the BASSEX data and used as the basis for determining an equivalent fluid that successfully replicated the influence of the actual seafloor. Bottom parameters tested included 20 values of the compressional speed (from 1000 to 4800 m/s), and 14 values each for the real and imaginary parts of the effective density (from 200 to 2800 kg/m^3) for a total of 3920 cases. The data and the best equivalent fluid simulation result (with a compressional speed of 4200 m/s and a density of 400+1200i kg/m^3) are depicted in Figure 1.

The best equivalent-fluid simulation can then be used to estimate the actual elastic parameters of the seafloor solid. Ray calculations were performed in order to examine the relevant interval of grazing angle over which the equivalent fluid and the elastic solid should have similar reflection coefficients; these calculations were also used to show that the energy between 2.4 and 2.6 s consists of both direct arrivals and near-source reflections. Bottom-reflected rays with travel times from 3.0 to 3.4 s were treated as corresponding to the reflected arrival. Based on these results, the relevant grazing-angle interval in the comparison between the reflection coefficient of the equivalent fluid and the elastic solid was identified. This process can be seen as the inverse of the generation of an equivalent fluid from a known elastic medium; in this case, a set of elastic parameters are identified that correspond closely to the bottom loss of the equivalent fluid. Since that equivalent fluid was found to be an effective representation of the bottom by corresponding closely to the experimental data, its bottom loss should, over the relevant grazing angles, be similar to the actual elastic media. Therefore, by identifying the elastic media with the same bottom loss characteristics as the equivalent-fluid media that reproduced the data, the actual parameters of the elastic solid can be approximated.

Experiments in the Gulf of Mexico are impacted by a very different type of seafloor material than the shear-dominated volcanic basalt of Kauai. Simulations were developed in a model environment motivated by experiments in the Gulf of Mexico, such as the LADC project (Tashmukhambetov *et al.*, 2008). A model elastic material with only a small influence due to shear was developed, with a density of 1700 kg/m^3, a compressional speed of 1800 m/s and a shear speed of 600 m/s. This value is likely representative of relatively high shear speeds for this environment. Based on these parameters, a preliminary equivalent fluid was developed based on a wide range of angles. The bottom losses resulting from the model shear medium, from a fluid that simply neglects the shear parameter, and from a preliminary equivalent fluid are shown in Figure 2.

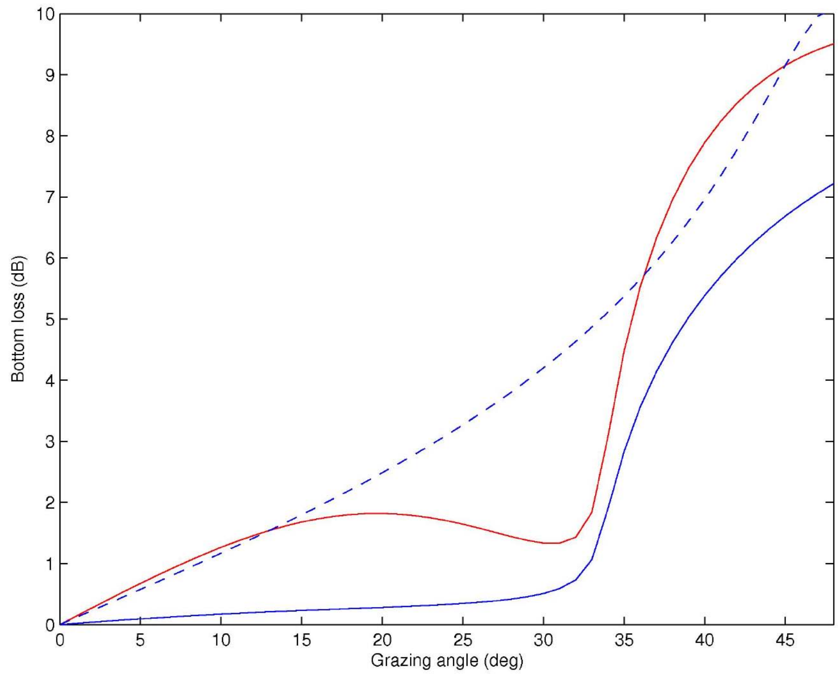

Figure 2: The bottom loss for a shear medium with a compressional speed of 1800 m/s and a shear speed of 600 m/s is shown as a red line. The dashed blue line is the bottom loss for an equivalent fluid based on the entire depicted angular interval. The solid blue line results from simply neglecting the shear speed.

These experiments are also likely to involve higher frequencies than the tomographic implementations of previous efforts. Therefore, the selected model case involves a single-frequency 1-kHz source at a depth of 10 m. Though, ultimately, the utility of equivalent-fluid methods will involve long ranges, initial efforts involved ranges of only a few kilometers. The model environment had a water depth of 990 m. A preliminary simulation performed for this test case indicates that substantial numerical issues remain to be addressed. Nevertheless, the result also supports the feasibility of using equivalent-fluid methods to represent the effect of elastic shear. Improvements in the computational approach, as well as a more systematic investigation into the grazing angles that most affect a reception at a particular range, can be expected to improve these results. Ultimately, of course, an equivalent-fluid approach that treats all parameters as free in an attempt to best replicate a reflection coefficient can only improve the performance of a non-elastic simulation intended to depict an environment where shear is an influence.

RESULTS

This project has demonstrated the utility of equivalent fluids in inverting for geoacoustic properties that are treated as unknown. The elastic parameters that corresponded most closely to the successful equivalent fluid depicted in Figure 1 are a compressional speed of 2500 m/s and a shear speed of 1500 m/s. The bottom loss of the equivalent fluid can be regarded as a reasonable approximation to that of the elastic solid for those grazing-angle intervals that most affect the reception. This solid is roughly comparable to an initial estimate made for the elastic parameters in this area (a compressional speed of 2200 m/s and a shear speed of 1100 m/s).(Vera *et al.*, 2005) The ability of these simulations to portray the experimental propagation indicates the utility of equivalent-fluid techniques and, with the relatively large shear-speed estimates resulting from the process, the need to consider elastic shear in explaining the loss observed in reflected arrivals. The central role played by elastic shear in determining the acoustic losses also suggests that the shear speed is the parameter best approximated in this procedure.

Another reception from the BASSEX data selected for analysis is shown in Figure 3; for both the simulation and the data, the levels are given relative to the peak of the 3.59 km reception. The elastic parameters determined above are taken as given and an equivalent fluid is generated to mimic the elastic bottom loss for the different grazing angles relevant to this case with a range of 21 km. Ray analysis indicates that, at this range, the direct path is several hundred meters below the receiver. Of primary interest is the comparison of arrival times and levels of these arrivals, which are entirely bottom-interacting. Despite the complexity and sensitivity of these arrivals, the times and levels generated by the simulation are reasonable. The correspondence in this difficult case supports the utility of equivalent-fluid methods and the estimate of the local shear speed.

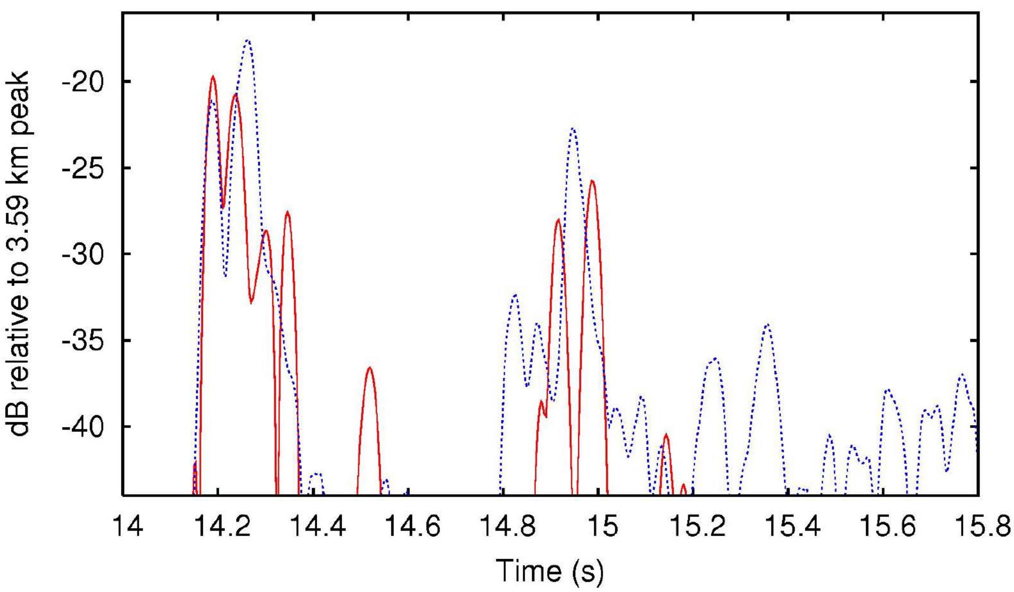

Figure 3: BASSEX data (blue) and an equivalent-fluid simulation that represents the elastic parameters resulting from the inversion at 3.59 km (red) are shown at a range of 21 km. The levels are shown relative to the peak value at 3.59 km for both cases.

IMPACT/APPLICATIONS

The ability to accurately simulate acoustic interaction with the seafloor is necessary in several different types of propagation scenarios. Support in the bottom material for shear waves can impact (or even dominate) the losses incurred upon reflection. Modeling the conversion of acoustic energy into elastic modes based on fundamental principles using combined elastic-acoustic algorithms is computationally demanding and can be numerically unstable, particularly for highly range-dependent, long-range transmissions. Since the loss due to shear is incorporated into the properties of a complex-density fluid, simulations using equivalent fluids are computationally inexpensive and stable.

This numerical performance was critical in successfully simulating basin-scale transmissions from the Kauai source in the NPAL experiment (Vera *et al*., 2005). These models were required to accommodate a broadband source mounted upon shear-supporting volcanic basalt and portray propagation for several thousand kilometers. Though the resulting simulations enabled an unambiguous identification of the data receptions, the accuracy of the method was not known precisely at that time. The present results indicate that equivalent fluids can be used to effectively represent the sound reflected back into the water column, even for strongly shear-supporting materials, a broad range of frequencies and/or very long ranges. These methods can be successfully employed whenever the sound field in the water column is the quantity of interest and the effect of the seafloor can be represented in terms of reflection. The efficiency and accuracy of the method for a broad range of bottom materials suggests that continuing applications in modeling lateral propagation from airgun arrays are likely to be successful.

RELATED PROJECTS

Dr. Arthur Baggeroer and Dr. Kevin Heaney have made it possible to use data from the BASSEX experiment and are supported by ONR Code 321OA.

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Heaney, K.D., M.D. Vera and A.B. Baggeroer (2009). "Geoacoustic inversion for a volcanic seafloor using equivalent fluids," *J. Comp. Acoust.* [refereed]