Mid-Frequency Bottom Scattering Model Development and Validation

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LONG-TERM GOALS

The propagation of mid-frequency (1-10 kHz) acoustic waves in shallow water regions (depths of 100-200 m) is strongly influenced by the characteristics of the ocean bottom. While there has been much progress in developing and validating bottom scattering models, much of the focus has been in the high frequency regime with comparatively less focus in the mid-frequency. This is an important topic, since in the mid-frequency regime the acoustic field can penetrate the rough interface into the sediment and undergo multiple scattering from sediment stratification and volume inhomogeneities. In this work, the long-term goal is to develop an understanding of the spatial and temporal characteristics of the acoustic field through a rigorous modeling and measurement effort. In addition, the feasibility of using tools such as a chirp sonar for bottom characterization will be considered and assessed.

OBJECTIVES

The objective of this research is to examine the acoustic scattering physics in the mid-frequency regime to isolate and characterize the scattering contributions due to bottom roughness, sediment stratification, and embedded volume scatterers. A further objective is to evaluate the use of a chirp sonar system for characterization of the ocean bottom. This will provide a means for accurately quantifying parameters such as reflection losses and bottom penetration over a broad frequency range in support of Navy sonar applications.

APPROACH

The technical approach for this work is as follows. First, current models for ocean acoustics and models in use in the electromagnetics community were surveyed and considered in terms of the ability to handle combined layer and volume scattering but with a simple enough structure to potentially allow for inversion. The result of this process identified the Radiative Transfer (RT) formulation as a promising framework – particularly for plane parallel geometries – that had extensive use in the remote sensing and seismic communities (see, for example, [1-3]), but had not yet been applied to ocean acoustics. In tandem with the development of a new ocean bottom RT, analysis of data from the Shallow Water 2006 experiment (SW06) was ongoing, providing knowledge of bottom structure and potential for model validation. The data from SW06 includes chirp sonar returns that provide information on the bottom substructure, and which were obtained in conjunction with careful characterization of bottom roughness and sediment layers. The chirp sonar was operated by Dr. Altan Turgut (NRL) and the mid-frequency bottom characterization was performed by Dr. DJ Tang (APL/UW). A Portland State University PhD student, Jorge Quijano, participated in SW06 and assisted with the measurements. Jorge is working on his PhD thesis in the area of acoustic scattering

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14. ABSTRACT
The propagation of mid-frequency (1-10 kHz) acoustic waves in shallow water regions (depths of 100200 m) is strongly influenced by the characteristics of the ocean bottom. While there has been much progress in developing and validating bottom scattering models, much of the focus has been in the high frequency regime with comparatively less focus in the mid-frequency. This is an important topic, since in the mid-frequency regime the acoustic field can penetrate the rough interface into the sediment and undergo multiple scattering from sediment stratification and volume inhomogeneities. In this work, the long-term goal is to develop an understanding of the spatial and temporal characteristics of the acoustic field through a rigorous modeling and measurement effort. In addition, the feasibility of using tools such as a chirp sonar for bottom characterization will be considered and assessed.

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models for ocean bottom characterization, and is supported by this ONR grant. Dr. Dan Rouseff (APL/UW) is on Jorge's committee, and is providing additional technical guidance.

WORK COMPLETED

The work completed during second year of effort is as follows:

- An initial version of a RT model for ocean acoustic bottom scattering was developed and implemented. This model calculates the acoustic intensity from either a half-space or finite layer (future versions will allow cascading of layers) containing spherical scatterers. The model accounts for both shear and longitudinal waves in the ocean sediments. Scattering from individual particles is computed using Mie theory, and the combined scattering is computed using an independent scattering assumption (densely packed scatterers which can result in multiple scattering can be handled via a variation of the RT formulation, the Dense Media Radiative Transfer equations). The model was compared with results from an ultrasound RT formulation [4] and initial results for ocean bottom parameters have been produced.

- Extensions to the above model have been identified and will be made during the next year of the effort. These may include the incorporation of rough interfaces via Kirchhoff scattering [5] and incorporation of time domain information via the transient RT formulation [6].

- Data from SW06 was analyzed. The data results show an absence of strong layer structure from the top (1-5 meters) of the sediment, possibly due to strong distributed scatterers.

- Initial plans for a water tank measurement system were prepared. The water tank can be used as a general educational tool (for example, for students to observe ocean waveguide propagation) but may also provide a controlled environment for RT model validation.

RESULTS

As described above, a Radiative Transfer (RT) formulation was developed and implemented for the ocean bottom sediment problem. The RT framework provides an extensible method of handling layer and volume scattering in terms of the acoustic intensity, *I*. The scalar RT equation in three dimensions can be written as

$$\nabla . pI(r,t,p)dp + \frac{\partial I(r,t,p)}{\partial t} = \eta\varepsilon(r,t,p)dp - \eta\sigma I(r,t,p)dp$$

where p is a unit vector in the direction of propagation, r is a position vector, η is the number of scatterers per unit volume, σ is an extinction coefficient, and ε is an emission coefficient. The equation is a differential equation that accounts for the loss of energy due to extinction (scattering and absorption) and the gain due to scattering from other directions into the direction of interest, and is shown pictorally in Figure 1. The emission coefficient can also be written as an integral equation, so that (1) is a first-order integro-partial differential equation in space, time, and propagation direction, and its solutions are in general non-trivial. Both σ and ε can be determined in closed form by Mie theory for regular shaped scatterers.

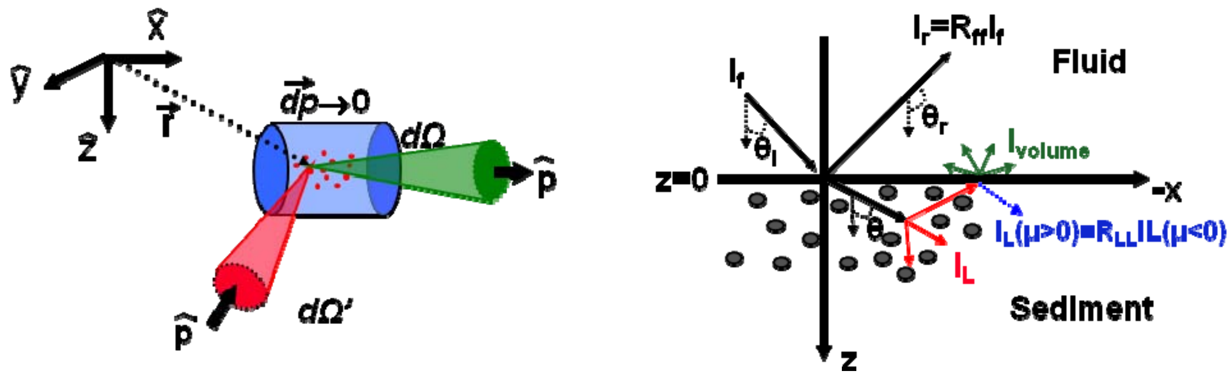

Figure 1. Diagram on left-hand side shows the acoustic intensity described by (1) through a differential volume into direction p. Right-hand side shows the water-sediment boundary with reflection coefficients that are used in boundary conditions.

A vector RT equation may be derived by considering a Stokes vector which contains five components: the longitudinal, shear vertical and shear horizontal waves, plus two terms representing the coherent inteference between shear waves [4]. For a plane parallel case, the RT equation may be solved numerically by applying Gaussian quadrature on the elevation angle θ (i.e., discrete ordinate method) and a Fourier transform on azimuth angle ϕ. This results in a matrix eigenvalue equation that may be solved numerically.

One of the main advantages of the RT formulation is that it allows an easy interpretation of the results, since each term of the differential equation is related to a physycal scattering phenomena. The propagation of acoustic energy in the elastic media can be independently analized to evaluate the importance of the contribution of shear and longitudinal components, which might be of importance to distinguish between the scattering from sand and more consolidated sediments.

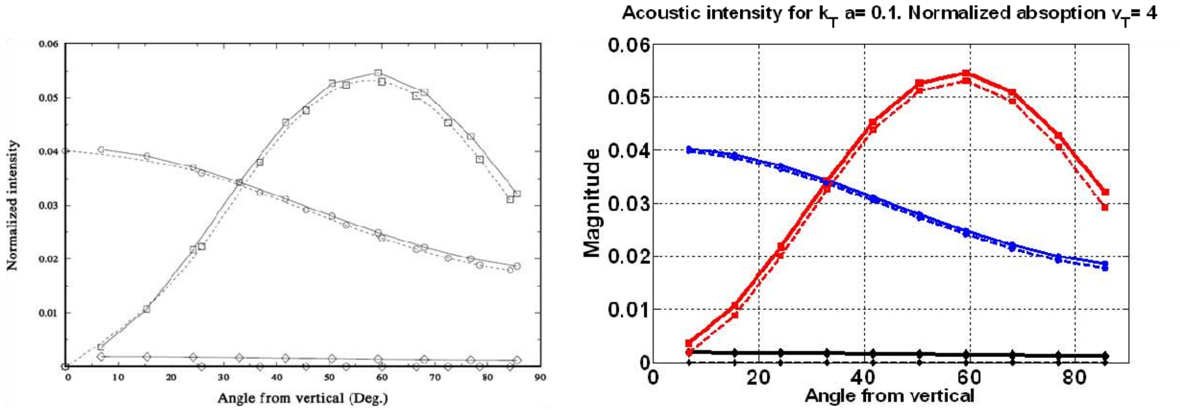

Figure 2. Acoustic intensity for a half-space of scatterers with $_{T}a=0.1$, with sphere radius a=50 µm, and normalized absorption cross section $v_T=4$. Left-hand plot is from [4], right-hand plot is the computation performed for the same geometry with NEAR-Lab code. Red line is vertical shear, black is horizontal shear and blue line is longitudinal

The NEAR-Lab implementation of RT was verified by reproducing results for an ultrasound RT published in [4]. Figure 2 shows the acoustic intensity as a function of scattering angle for a half-space of scatterers. Results for a sandy ocean bottom sediment with embedded spherical cavities were produced and presented in [7]. For this case, the intensity in the water column is derived by enforcing boundary conditions at the sediment-water interface. The boundary conditions are represented by the angle-dependent Fresnel reflection and transmission coefficients that exist for both the shear and longitudinal waves and are computed using the background sediment properties (for large concentrations of particles, an effective media calculation could be used to characterize the sediment-scatterer mixture). The total intensity in the water column due to a source in the water column is then the reflected wave from the interface plus the intensity resulting from volume scattering in the sediment (that is transmitted across the boundary). The intensity at the sediment interface can be written as

$$I_L(z=0,\mu>0,\phi) = R_{LL} I_L(z=0,\mu<0,\phi) + R_{xL} I_x(z=0,\mu<0,\phi) + R_{yL} I_y(z=0,\mu<0,\phi)$$

where R_{iL} is the reflection coefficient (i=L for longitudinal-to-longitudinal, i=x horizontal-to-longitudinal, i=y horizontal-to-longitudinal) and $\mu=\cos\theta$.

The RT code developed as described above provides a framework for incorporating mixed layer and volume scattering in ocean bottom scattering. Although widely used in other plane parallel problems, the current implementation is the first for ocean bottom applications. It provides a intuitive but powerful method for understanding and interpreting chirp data for more general sediment materials.

IMPACT/APPLICATIONS

Many Navy sonar systems operate in the mid-frequency (1-10 kHz) band (for example, surface ship active ASW, SQS 53). In shallow water regions (depths of 100-200 m) the performance of these systems is strongly influenced by the presence of environmental variability. The impact of this work is to provide an understanding of the spatial and temporal characteristics of the acoustic field in the mid-frequencies in order to optimize sonar performance.

RELATED PROJECTS

Physics-Based Processing for Sonar Mapping of Coral Reefs; (FY07, sponsored by the Nature Conservancy)

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PUBLICATIONS

J.E.Quijano and L.M. Zurk, Application of Radiative Transfer Theory to Acoustic Propagation in the Ocean Bottom, IEEE Oceans Conference, Vancouver BC, Canada, September 2007.