

A Radiative Transfer Model for Acoustic Propagation in Ocean Sediment Layers

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Award Number: N000140910331

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 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:

- 1) Identification of a mathematical model for ocean bottom scattering: The Radiative Transfer (RT) formulation was identified as a promising framework to study random media scattering, due to its ability to handle combined layer and volume scattering¹⁻³. The RT formulation has been successfully applied in electromagnetics remote sensing, in geometries similar to the ocean bottom sublayers (i.e. discrete scatterers within parallel-plane layers). It has also been suggested in the acoustics community⁴ for seismics⁵ and material analysis⁶, but had not yet been applied to ocean acoustics.

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2012		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE A Radiative Transfer Model for Acoustic Propagation in Ocean Sediment Layers				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) PO Box 751-ECE Portland State University Portland, OR 97201				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

- 2) Comparison of the RT model with a classic scattering model: since the RT equation can be derived from fundamental principles of wave propagation, its results can be compared to classic models. The RT model for ocean bottom scattering will be compared to the integral equation method using weak scatterers (Born approximation). The RT formulation has the advantage that it is not restricted to the assumption of small perturbations.
- 3) Implementation of the Transient RT formulation: The time-domain solution of the RT equation is the most recent research effort in transport theory in the electromagnetics⁷ and the acoustics community⁶. The appeal of the transient solution is that it allows computation of scattering levels due to broadband finite pulses, giving a representation of the scattered intensity as a time series.
- 4) Tank experiments to validate the model: Scaled tank experiments⁸ were conducted at ultrasound frequencies using well characterized random media such as a substrate slab with embedded glass beads and aluminum scatterers distributed in fine sand. The measured scattering cross sections were compared to the scattering levels predicted from the RT simulator.

WORK COMPLETED

- The approach for Ultrasound Radiative Transfer presented by Turner and Weaver⁴ has been adapted to Ocean Acoustics, and implemented in Matlab for a three-layer environment that consists on a half space water column on top, a finite layer of sediment with discrete spherical scatterers in the middle and an infinite half space at the bottom. The RT model assumes flat boundaries and uses elastic plane wave reflection and transmission coefficients to account for the coupling of acoustic energy between layers. The solution given by this model corresponds to steady-state excitations. The RT formulation for ocean bottom scattering and demonstration of the conservation of power in lossless media are explained in detail in Quijano et al⁹⁻¹⁰.
- Implementation of the Transient RT equation: Time domain solutions of the specific intensity were implemented in Matlab following the approach by Turner et al⁶. Accuracy of the time domain solutions were verified¹⁰ by comparing to published results of scattering from polycrystalline iron and by comparison to analytical solutions of the wave equation under the assumption of single scattering.
- Tank experiments were conducted at the NEAR-Lab measurement facility using several combinations of background materials and scatterers⁸, in the frequency band 200 kHz-500 kHz. The experiments allowed testing the proposed RT model by varying experimental parameters such as the frequency range, attenuation of the background media, concentration of scatterers and its size relative to the wavelength of the excitation signal.
- The RT model was further validated by comparing to field measurements of angle-dependent backscattering from sediments containing trapped gas bubbles¹⁰.

DESCRIPTION OF THE RT MODEL

Details of the theory and implementation of the RT equation for steady state excitations are explained in a published paper⁹. In summary, the RT equation gives a solution to the general problem depicted in Fig.1, where the incident longitudinal wave in the water column can excite multiple streams of longitudinal($S_1^{L\downarrow}$) and shear (not shown) energy in the sediment containing random scatterers.

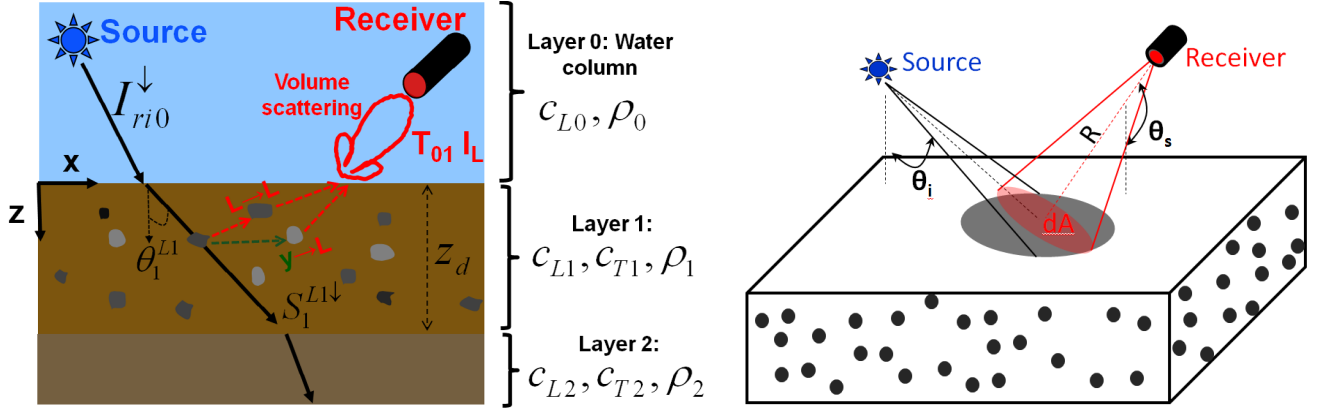


Figure 1: (a) The incident intensity in the water column $I_{ri0}^{\downarrow}$ interacts with the water-sediment interface, giving rise to a coherent stream of intensity $S_1^{L\downarrow}$ transmitted into layer 1. This intensity becomes a “source” of diffuse intensity in the RT equation, and is used to compute the total amount of volume scattering $T_{01}I_L$, where T_{01} is the transmission coefficient at the sediment-water interface.

Each elastic layer is characterized by the mass density ρ_n , and the longitudinal and shear sound speeds, c_{Ln} and c_{Tn} . **(b)** From the RT model, the received power is found as⁸ $P_r = \int_{\Delta\Omega} T_{01}I_L d\Omega$, where $\Delta\Omega$ is the solid angle that subtends the area dA .

The RT equation that describes figure 1 is^{4,10}:

$$\cos\theta \frac{\partial I_L}{\partial z} + \frac{1}{c_L} \frac{\partial I_L}{\partial t} = -\eta\sigma_L I_L + \frac{\eta}{4\pi} \int \int_{\phi', \theta'} [P_{LL}I_L + P_{xL}I_x + P_{yL}I_y] \sin\theta' d\theta' d\phi' + S_1^{L\downarrow} \exp\left[-\frac{\eta\sigma_L z}{\cos\theta_1^{L_1}}\right] \delta\left(t - \frac{z}{\cos\theta_1^{L_1}c}\right) \quad (1)$$

where $I_L \equiv I_L(\theta, \phi, z, t)$ is the longitudinal diffuse specific intensity, θ and ϕ are the elevation and azimuth angles, respectively, η is the number of scatterers per volume in the random media, t is the time, σ_L is the scattering cross section of a single scatterer due to an incident longitudinal wave, and P_{LL} , P_{xL} , and P_{yL} are the cross polarizations from longitudinal, shear horizontal and shear vertical energy into longitudinal energy, respectively. The term $S_1^{L\downarrow}$ represents the coherent (longitudinal) energy that

propagates into the sediment, and it can be seen as a “source” term of the diffuse intensity in (1). Similar terms can be added to account for multiple bounces of this coherent intensity between the boundaries of the layer.

Solution of (1) can be obtained for steady-state excitations (i.e. by making $\partial I_L / \partial t = 0$) or for transient sources (mathematical details discussed elsewhere^{9,10}). When comparing the RT model to results from experimental data, the received power is found as:

$$P_r = \int_{\Delta\Omega} T_{01} I_L(\theta, \phi, z = 0) d\Omega \quad (2),$$

where the integration is performed over the solid angle $\Delta\Omega$ that subtends the area dA illustrated in Fig.1(b).

RESULTS

RT model compared to scaled experiments: Tank experiments^{8,10} were conducted at the NEAR-Lab Measurement facility to measure angle- and frequency-dependent acoustic scattering from well characterized random media in the frequency band 250 kHz to 500 kHz. Experimental parameters such as elastic properties of the media, concentration and size of the scatterers, and geometry of the measurement apparatus were input to the RT model, which was able to match the details of the measured scattering levels. The experiments were conducted in a water tank of dimensions 5x7x3 feet, using a directional transducer (Panametrics A391S) to generate broadband pulses to probe the random media, and an omnidirectional hydrophone (TC4038) to measure the scattered waveforms. The recording system was a data acquisition board (PCI-6110) with sampling rate of 5 MS/s. As a preliminary step to verify system calibration, scattering from an aluminum plate and a tungsten-carbide sphere was measured and compared to analytical solutions. Table 1 summarizes the parameters for the validation experiments. Comparison of the measured vs modeled scattering cross section was presented in previous reports and publications^{8,10}. These experiments show that the RT model is able to support a variety of experimental conditions:

- a. Random media with scatterers in the Mie and geometrical optic regimes.
- b. Reflective elastic boundary conditions.
- c. Different concentrations of scatterers, with fractional volumes ranging from 0.9% to 10%
- d. The effect of frequency-dependent background attenuation.

Table 1: Summary of tank experiments conducted for validation of the RT model. Experiments 1 and 2 are on the geometric optics scattering regime, while experiment 3 is on the Mie regime.

Experiment	Scatterers	Background	Fractional volume	Results
1	Aluminum, 2.4 mm radius	Water	0.9% to 2.7%	See ref.8
2	Aluminum, 2.4 mm radius	Sand, grain size ~300 μ m	5%	See ref.10
3	Glass, 0.5 mm radius	Polyurethane slab	10%	See ref.8

Comparison of the model to field experimental data: the RT formulation was compared to measurements from an experiment¹¹ conducted in 1993. The experiment can be summarized as follows: a 5 m tall tower was placed on the seabed, in a region where the sediment is known to have a layer containing trapped gas bubbles, as shown in Fig.2(a). The tower supported a transmitter and receivers, and narrow band pulses of frequency $f=40$ kHz were transmitted to be incident upon the sediment. Due to the spherical pattern of the transmitted waveform, the energy hits the sediment at angles ranging from 20° to 5° . The scattered echo from the sediment was recorded in two hydrophones on top of the tower. The time of flight of the transmitted pulse was utilized to separate the amount of scattering from different patches of ground, each one associated with a corresponding incidence angle. For this experiment, sediment density, sound speed and attenuation are available from the literature¹¹. Other quantities required by the RT model such as bubble size distribution, fractional volume and layer thickness were used as free parameters to match the measured backscattering levels, with results shown in Fig.2(b). The best fit was found for a layer of thickness 8 cm containing bubbles with radius $a=3.5$ mm, with a density of $\eta=112500$ scatterers/ m^3 , and gas fractional volume of 1.2%. These values are in agreement to core samples extracted in this area¹². In addition, the best fit found with the RT model is in agreement with a previous single scattering model used by Guoliang et al.¹¹, based on the assumption of a thin layer of scatterers (Fig.2 (b), blue curve).

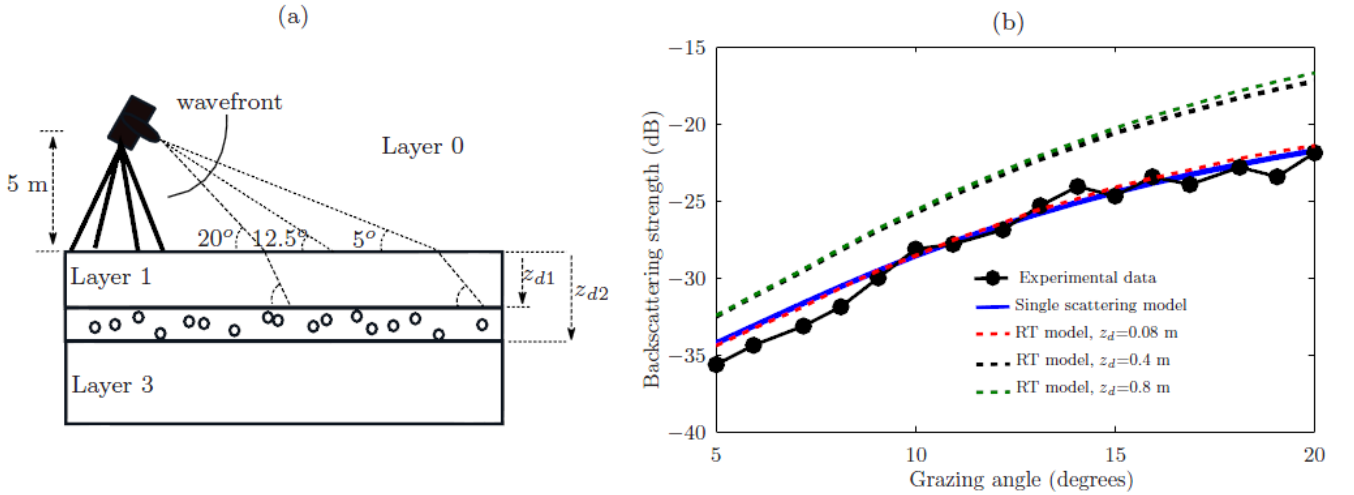


Figure 2: (a) Side view of the Experimental setup for the Eckernförde Bay experiment¹¹ to measure acoustic scattering from sediment containing gas bubbles; (b) Comparison of the RT model to the experimental data and to a single scattering model (Guoliang et al.¹¹). The best fit of the RT model to the experimental data was achieved for bubbles of 3.5 mm radius, $\eta=112500$ scatterers/ m^3 , and $z_{d2}-z_{d1}=8$ cm, all of them in agreement with data from core samples¹².

Transient RT model: solution of (1) with $\partial I_L / \partial t \neq 0$ allows to compute the specific intensity as a function of time for the case in which the source of acoustic energy is a finite-length pulse¹⁰. A simulation with the setup shown in Fig.3(a) illustrates the application of the transient RT model. The media consists of a layer of scatterers randomly distributed in a layer of 2 m thickness. In this simulation, the scatterers are spherical air bubbles of 2.1 mm radius suspended in water. The concentration of bubbles is 8636 scatterers/ m^3 . Fig.3(b) shows the backscattering intensity predicted by the transient RT model for two cases: the full solution of (1), and the single scattering solution (i.e.

assuming that the double integral in (1) is zero). The sharp transition at $t = 2.73$ ms is caused by the thickness of the layer, and corresponds to the two-way travel time of the energy that enters the slab. As expected, the full solution curve has heavier tails due to the acoustic energy temporary “trapped” in the random media while it undergoes multiple scattering. As an additional test of the accuracy of this simulation, Fig.3 (b) also shows the analytical solution for the backscattered intensity assuming single scattering as presented by Ishimaru³, which is in agreement with the single scattering RT transient model. Given that the RT model relies on the principle of conservation of energy, the normal power flux incident to a slab of random media must equal the sum all the outgoing power fluxes. This conservation is studied in Fig.4, which shows the incident flux $F_{rio}^\downarrow$ at $z=0$, the diffuse fluxes $F_{d1}^{L1\uparrow}$ and $F_{d1}^{L1\downarrow}$ at $z=0$ and $z=2$ m, respectively, and the outgoing reduced flux $F_{rio}^\downarrow$ at $z=2$ m. For lossless media¹⁰,

$$F_{rio}^\downarrow|_{z=0} = F_{rio}^\downarrow|_{z=2} + F_{d1}^{L1\downarrow}|_{z=2} + F_{d1}^{L1\uparrow}|_{z=0} \quad (3).$$

This relation is not met in the case of the single scattering solution shown in Fig. 4(a), indicating significant contribution from multiple scattering. The results corresponding to the full solution in Fig. 4(b) show an increase in the upward and downward diffuse fluxes, giving a solution that accurately accounts for the conservation of the power fluxes in (3).

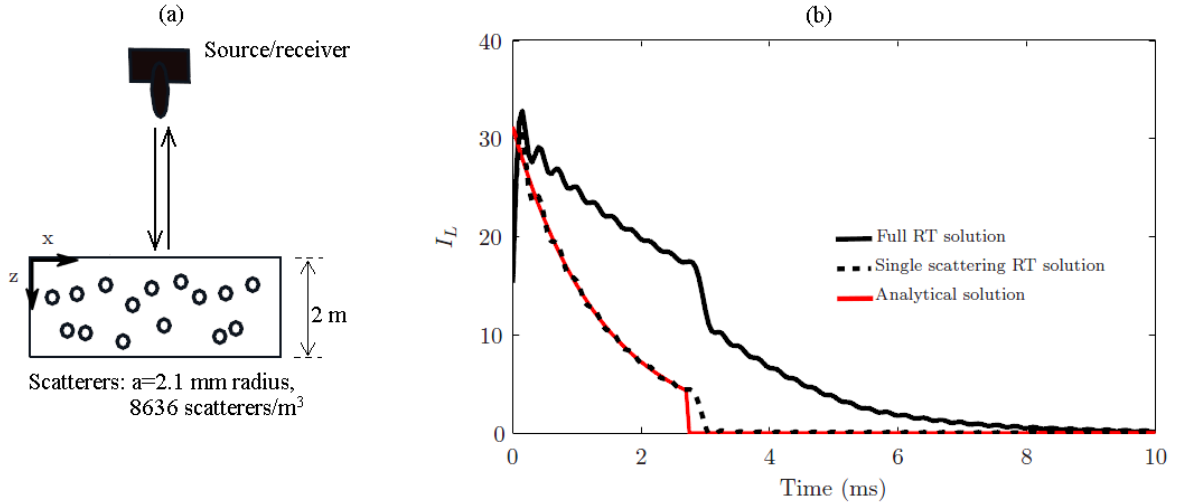


Figure 3: (a) Simulated environment used to study the time dependence of the backscattered intensity; (b) Solution of the transient RT equation (full and single scattering approximation) and comparison to the analytical solution for single scattering.

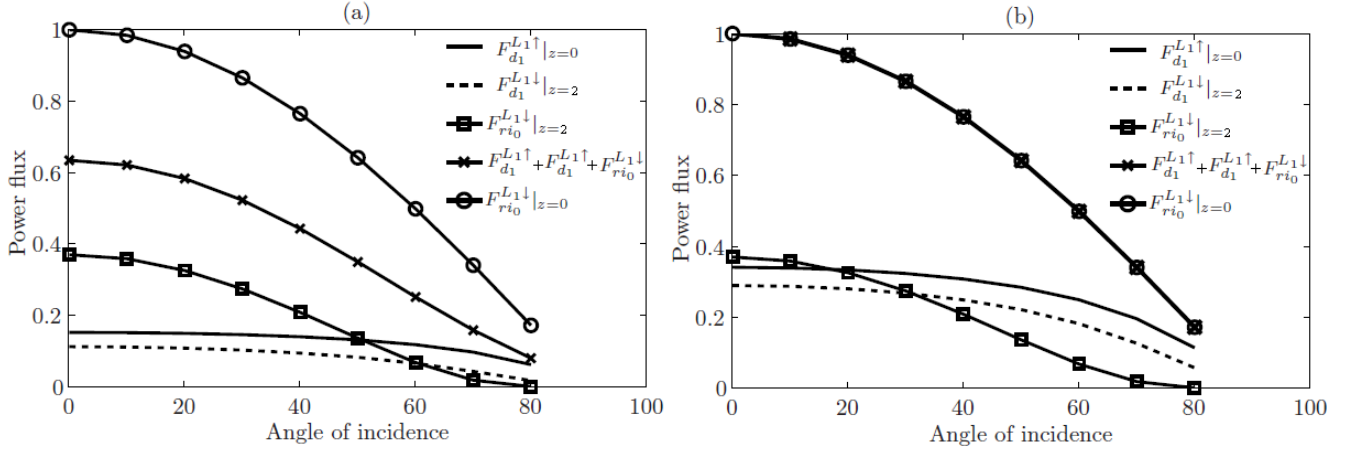


Figure 4: Coherent and diffuse normal power fluxes at $z = 0$ and $z = 2$ m for the simulated environment in Fig.3: (a) The single scattering solution of the transient RT equation and (b) The full solution.

IMPACT/APPLICATIONS

Many Navy sonar systems operate in the mid-frequency (1-10 kHz) band. 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. The RT model is characterized by its flexibility to adapt to a broad range of experimental conditions of interest for seabed acoustics in this frequency band. The model is not subject to some of the assumptions typically required by traditional models, such as small scatterers, small perturbation or high frequency of operation. Tank measurements showed that the RT model can be applied to experiments involving volume scattering in the Mie and the geometric optics regimes. The results of these experiments at frequencies ~ 350 kHz with scatterers of size 1 mm to 4.8 mm can be extrapolated to sonar mid-frequencies (i.e. 12 kHz to 40 kHz) with scaled scatterers in the size range of small pebbles and shells (i.e. 2.9 cm to 4.2 cm, respectively). Due to the requirement of energy conservation, the RT model has a natural way to incorporate all the polarizations supported by elastic scattering media, and energy re-distribution from one polarization into another at the layer boundaries or at the surface of the scatterers is implicit in the model.

RELATED PROJECTS

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

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HONORS/AWARDS/PRIZES

Jorge Quijano, PhD student at Portland State University working on developing the RT model, was awarded the Best Student Paper Award (1st place) in Underwater Acoustics at the 159th Meeting of the Acoustical Society of America, Baltimore, MD, 2010. Jorge gave a talk entitled "Tank experiments for validation of volume scattering models".