Transport Theory for Propagation and Reverberation

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LONG-TERM GOALS

Development of computationally efficient modeling methods for shallow water propagation and reverberation that can account for the effects of multiple forward scattering from waveguide boundary roughness and volume heterogeneity such as internal waves.

OBJECTIVES

Our objective in FY10 was to improve the generality of our previously developed shallow water propagation model based on transport theory to include range dependent bottom depth. Transport theory, as we have developed it, can account for the effects of multiple forward scattering from boundary roughness. The emphasis of this work is on the mid-frequency range (1-10 kHz) where effects of forward scattering can be important.

APPROACH

Accurate propagation and reverberation modeling is important for many prediction methods that are important for Navy applications and for underwater acoustics systems development. While acoustic propagation and reverberation modeling has been extensively developed for many years, significant limitations still exist on current capability, particularly in the area of computation speed. In addition, the modeling problem increases in complexity as the frequency is raised from the low frequency region (< 1 kHz) to the mid frequency region (1–10 kHz). At mid frequencies (and higher) the effect of forward scattering from the sea surface and bottom has a greater effect on propagation and reverberation than in the low frequency region, especially in shallow water environments.

The available options for modeling forward scattering in propagation are very limited, and are largely confined to computationally intensive methods that can yield benchmark solutions for certain simplified problems. When PE is used for practical propagation modeling, only large-scale bathymetry variations are included with small-scale boundary roughness ignored, and internal waves are also generally ignored. Even the simple expedient of using a loss at the boundary to approximately account for boundary roughness is not conveniently included in PE propagation simulations. Similarly, normal mode methods generally ignore mode coupling due to boundary roughness in forward propagation, and in reverberation simulations only a single scattering (the backscattering) is included. In order to include the stochastic effects of boundary forward scattering and internal wave forward scattering in

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**
4. TITLE AND SUBTITLE **Transport Theory for Propagation and Reverberation**		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) **University of Washington,Applied Physics Laboratory,1013 NE 40th St,Seattle,WA,98105**		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

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

propagation simulations, investigators have typically applied a full-wave method, such as PE, and performed propagation simulations using many realizations of the fluctuating environment in a "Monte Carlo" approach. Averaging the results over the set of realizations can then give accurate results for averages (or moments) of the field, and by using a sufficient number of realizations even pdfs of field amplitudes or intensities can be obtained. In the case of boundary roughness scattering, simulations using the finite element method have also been used. The computational demands for full-wave Monte Carlo simulations for propagation and particularly for reverberation are severe.

Instead of doing time consuming Monte Carlo simulations, much faster solutions for field moments can be obtained if equations governing the evolution of the moments themselves can be obtained and solved. Any method that works with evolution equations for the moments of the propagating quantities can be described as a "transport theory," though not always referred to as such. While transport methods have been applied to propagation through internal waves, there has been no related extension to propagation in the presence of rough boundaries (except for work by our APL-UW group) or to reverberation for either case. The historical emphasis on internal waves may be due to their importance even at low frequencies where boundary scattering is less important. For mid frequencies forward scattering from both internal waves and boundary roughness are of importance.

Therefore, the need exists for much faster computational approaches for obtaining moments of the field for propagation and reverberation at mid frequencies that can account for boundary and internal wave scattering. Past work has been restricted to the range independent case. In the current project this is being extended to range dependent propagation and full reverberation scenarios. Our approach is based on expanding the acoustic field in modes, and therefore would most readily apply at mid-frequencies and below, and in relatively shallow water environments such as on the continental shelf.

We have focused on the case where forward scattering is due to scattering from sea surface roughness. Evolution equations are obtained for the first and second moments of the mode amplitudes, accounting for mode coupling due to scattering from a rough sea surface using first-order perturbation theory [1]. Comparisons with rough surface PE simulations [2] are used to verify the accuracy of the transport theory method.

WORK COMPLETED

Previous work [1] had assumed a range independent environment, aside from the rough sea surface. For practical applications it would be important to account for the range dependence of the environment. Thus, we have generalized our transport theory method to account for slowly varying range dependence in the bottom depth. For a slowly varying depth, we can expect that the adiabatic mode approximation would be useful. Therefore, the accuracy of the adiabatic approximation was examined for the case of a linear depth change with range. In particular, the depth was varied linearly from 50 m at the start to 45 m at range R_0. To examine the adiabatic approximation, PE runs were made with a flat sea surface and the linearly varying bottom depth at a frequency of 3 kHz. Mode projections of the PE fields (using range varying mode sets) show little mode coupling unless R_0 is reduced to about 1 km. For R_0 several times greater than 1 km, the adiabatic approximation is found to be very good, i.e., there is very little mode coupling. Therefore, transport theory has been modified to use adiabatic modes with linear interpolation to account for changes in mode horizontal wave numbers and in the mode functions. Even for $R_0 = 1$ km, the mode coupling is only significant to nearest neighbor modes. Therefore, to go beyond the adiabatic approximation in future work, it may be sufficient in many cases to only consider nearest-neighbor mode coupling.

RESULTS

The problem considered is CW propagation at 3 kHz in two space dimensions with a source at mid depth. A rough sea surface is described by a 1-D Pierson-Moskowitz roughness spectrum for a wind speed of 7.7 m/s (15 knots). The waveguide depth varies linearly from 50 m to 45 m at a range of 12 km in the first example. The sea floor sediment has sound attenuation of 0.5 dB/wavelength. The sound speeds are 1500 m/s in the water and 1600 m/s in the sediment. The computational region extends 50 m into the sediment, and continuum modes are represented as closely spaced discrete modes. For a 50 m depth there are 74 trapped modes, but 200 modes have been used to display the field penetrating into the sediment above the critical angle.

The propagated intensity will be displayed in three forms: the total intensity $\langle|p|^2\rangle$, the coherent intensity $|\langle p\rangle|^2$, and the incoherent intensity $\langle|p|^2\rangle-|\langle p\rangle|^2$, which is the forward scattered component. In these expressions $\langle\ \rangle$ denotes an average over an ensemble of rough sea surface realizations. For the transport theory result (bottom panel in each case), the averaging has been formally done. For the rough surface PE simulation result (top panel), the averaging has been done numerically using the results for 50 surface realizations.

For the transport theory results, the Dozier-Tappert approximation (see [1]) has been made. This is a neglect of cross-mode coherences in the incoherent intensity. Comparisons with the rough surface PE simulations have shown that there is very little loss in accuracy in making this approximation.

Figure 1 shows a comparison between PE and transport theory results for the total intensity. Note the change in depth from 50 m at the start to 45 m at 12 km range. The periodic focus points at mid depth are shifted to slightly shorter ranges than for a constant depth of 50 m. In particular the constant depth focus at a 10 km range has been shifted to a range of about 9.3 km. The adiabatic mode result matches fairly well the focus locations and other detailed features of the PE result. However, one important aspect of the PE result is the field that is shown penetrating into the sediment, and that aspect is largely missing in the transport theory result, though is present in range independent examples [1]. This deficiency appears to be related to interpolation problems encountered because of the presence of leaky modes interspersed among the continuum modes. It appears that this deficiency can be readily dealt with in ongoing work.

Figures 2 and 3 show the corresponding comparisons for the coherent intensity, and the incoherent intensity, respectively. The coherent intensity comparison is excellent, while the transport theory incoherent intensity shows the same lack of intensity penetrating the sediment mentioned above. Again, this deficiency should be readily corrected in ongoing work. Note that in Figure 3 the PE result shows some structure in the water column in the first few hundred meters that is not captured by transport theory. The source used is a Gaussian tapered point source with a full width of 20 deg and with the beam axis at an elevation angle of 10 deg. The main structure shown by the PE simulation at short range is the forward scattered field leaving the surface while still showing some remnant of the source beam pattern. The use of the Dozier-Tappert approximation with transport theory washes out such structure from the incoherent intensity. But as additional surface scattering occurs with increasing range, this structure is rapidly lost from the PE result, with the consequence that the Dozier-Tappert approximation is quite accurate except at very short range.

It should be kept in mind that transport theory is much faster than full wave approaches that use a Monte Carlo method with many rough surface realizations. Also, any number of forward scattering interactions can accounted for as the field propagates along the waveguide.

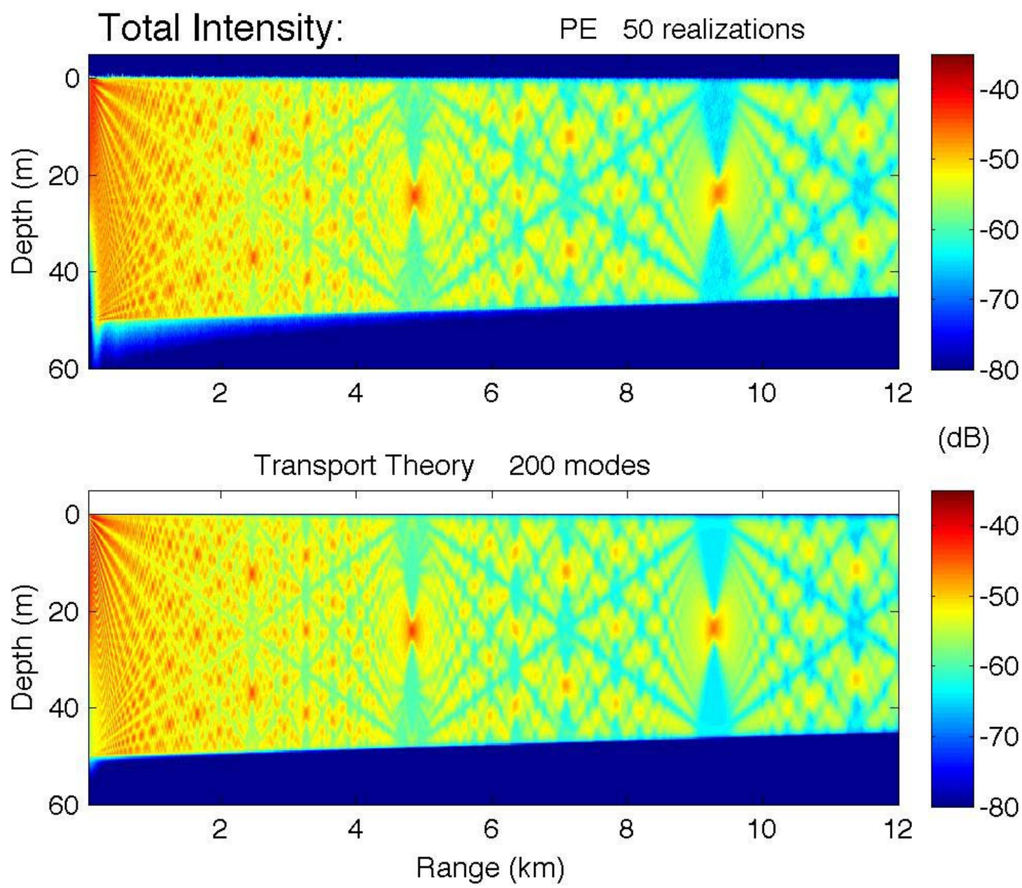

Figure 1. The total intensity for PE averaged over 50 surface realizations (top), and for transport theory (bottom).

IMPACT/APPLICATIONS

Work in transport theory propagation and reverberation modeling should lead to improved simulation capability for shallow water propagation and reverberation in which multiple scattering from rough boundaries is properly taken into account. This capability should be particularly important in the mid-frequency range where multiple scattering effects can be important, yet where a modal description can be used. Transport theory propagation and reverberation modeling has the potential to be even faster than ray tracing, yet be able to account for scattering effects outside the scope of other efficient modeling methods.

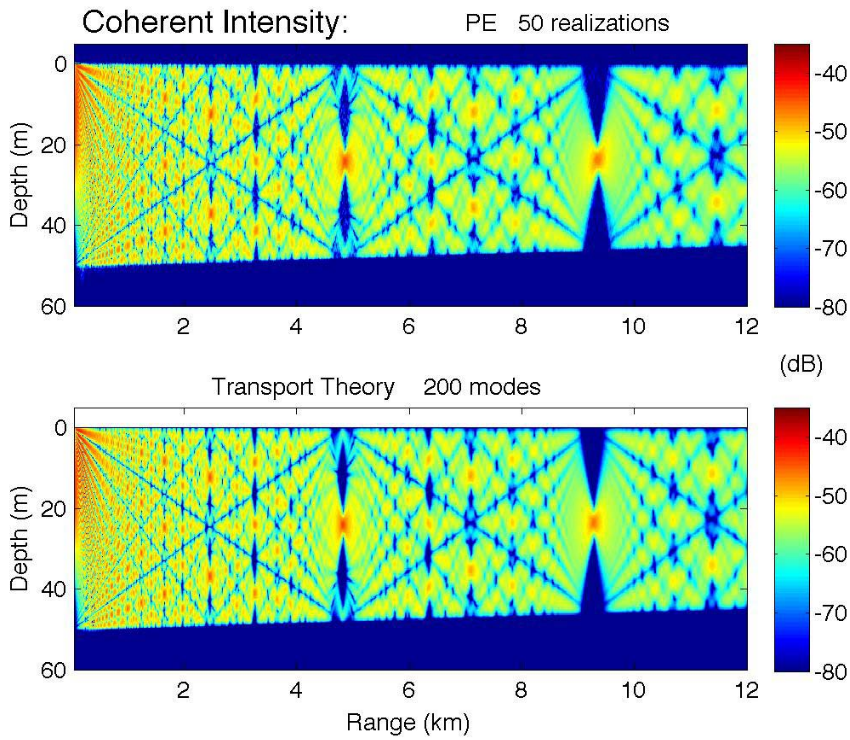

Figure 2. The coherent intensity for PE averaged over 50 surface realizations (top), and for transport theory (bottom).

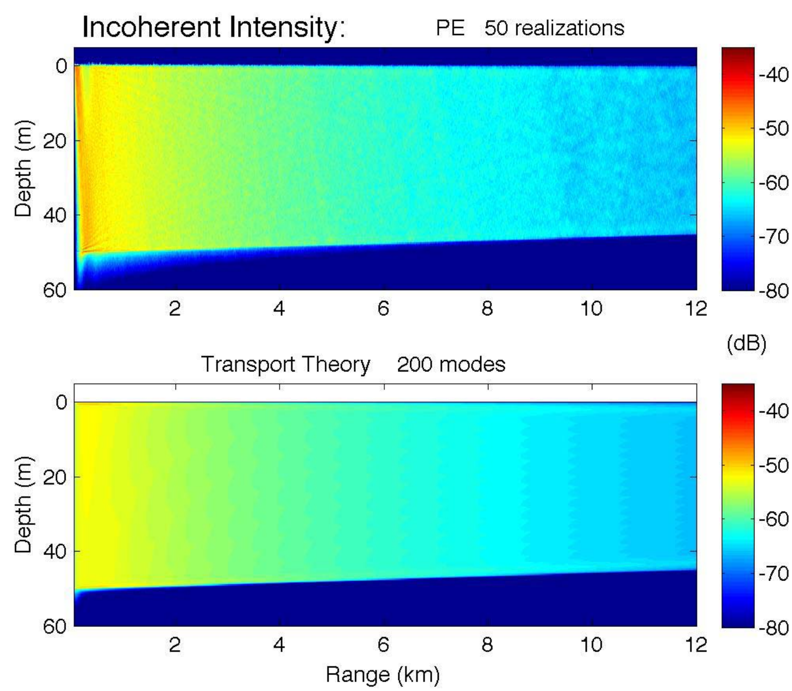

Figure 3. The incoherent intensity for PE averaged over 50 surface realizations (top), and for transport theory (bottom). This is the forward scattered component.

RELATED PROJECTS

1. Reverberation Modeling Workshops, Eric Thorsos and John Perkins co-chairs. This effort has developed a set of well-define reverberation problems with consensus solutions. This will be important for testing the accuracy of transport theory when it is extended to reverberation problems in FY11 work.

2. ONR (John Tague) has been supporting work on extending the Sonar Simulation Toolset (SST, development under the direction of Bob Goddard, APL-UW) to lower frequencies. A PE based reverberation model is presently being proposed for SST for the low frequency extension.
A future possibility of utilizing transport theory propagation has been discussed in this context, with the proviso that it first requires additional development.

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[2] A. P. Rosenberg, "A new rough surface parabolic equation program for computing low-frequency acoustic forward scattering from the ocean surface," *J. Acoust. Soc. Am.* **105**, 144-153 (1999).

PUBLICATIONS

E. I. Thorsos, F. S. Henyey, W. T. Elam, B. T. Hefner, S. A. Reynolds, and J. Yang, "Transport theory for shallow water propagation with rough boundaries," *Shallow-Water Acoustics*, Proceedings of the Second International Shallow-Water Acoustics Conference, Shanghai, China, September 16-20, 2009, AIP Conference Proceedings 1272, pp. 99-105.