Modeling of Mid-Frequency Reverberation in Very Shallow Water

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LONG-TERM GOALS

The long-term goal of this research is development of computationally efficient physics-based methods for modeling of propagation, scattering, and reverberation in shallow waters with complicated spatial and temporal variability of environmental parameters.

OBJECTIVES

Scientific objective of this project is to develop a model of mid frequency reverberation for very shallow water environments. The model is to be relevant to specific conditions (1 – 10 kHz, ~20 m water depth, ~ 5 km range) of the ONR Target and Reverberation experiment [1] performed during the spring of 2013 (TREX13). This will result in developing codes for computer simulations to be used in TREX13 data analysis based on environmental inputs measured or/and typical for the chosen location.

The research is to contribute to involving non-traditional approaches to better understand shallow water propagation and reverberation. This would support the idea expressed in the white paper [1], that a new area of investigation for WPRM (Wave Propagation in Random Media) should be suggested, to be relevant to TREX13 conditions. Particularly, for the chosen mid frequency range and very shallow waters, joint effects of the relatively large bottom penetration and 3D variability of the sediment properties, along with related effects of propagation, 3D refraction, and scattering within the seafloor, should be taken into account. Therefore, an approach is needed that treats heterogeneous stratified sediments as a critical part of the propagation channel (in addition to heterogeneous water column with rough boundaries).

APPROACH

Generally, the physics of reverberation in highly heterogeneous shallow water environment involves two major processes. These critical processes are (1) two-way propagation, i.e., propagation from source to scattering area and then from this area to receiver, and (2) local scattering from this area in corresponding directions (e.g., for monostatic reverberation, backward and near backward directions). The monostatic (or quasi-monostatic) situation is most complicated case here, because forward (outgoing) and backward (incoming) propagating waves can be mutually correlated and interacting. There is an approach to this problem developed by De Wolf [2] and then successfully used for description of electromagnetic propagation and multiple scattering in a turbulent atmosphere.

Particularly, the approach is applicable to description of the so-called backscattering enhancement effect, known also as "weak localization" and "coherent backscatter" effects. This approach is well recognized in WPRM community, and called the MFSB-approximation (Multiple-Forward-Single-Backward-scatter). While similar terminology appears frequently in the underwater acoustics literature, such approach for conditions of shallow water reverberation has not yet been adequately developed (although experimental observations exist [3]).

For description of multiple-scattering effects in acoustics of heterogeneous marine sediments, the MFSB-approach was used in [4,5], however only the case of a non-stratified sediment was considered. Recently it was reformulated for the case of long-range reverberation in a shallow-water waveguide [6]. The main complication in this case (in comparison with previous work) appears because of the multi-path conditions for propagation in a waveguide. Another complication appears in describing a local scattering in stratified (layered) environments. The problem of local scattering can be handled, but only with certain limitations (to neglect non-local interaction effects), in terms of an "effective scattering surface" approach originally developed for the case of scattering in arbitrarily stratified sediments with random volume fluctuations of the density and compressibility [7]. This approach is well-known now and used as a theoretical foundation in most advanced codes for mid-frequency geoacoustic bottom interaction (such as GABIM, see [8] and Refs therein). Its expansion on the case of discrete scatterers, arbitrarily shaped and sized, in a stratified environment is given in [9].

An alternative approach outlined recently in [10,11] suggests omitting the "effective scattering surface" step, i.e. it is not required to calculate "effective bottom scattering strength" (or to measure it locally, which may be difficult) as an intermediate step in evaluation of shallow water reverberation (which is a necessary step in standard models, such as CASS-GRAB). The approach exploits a new integral expression obtained in [10,11] for the scattering intensity which has a factorized integrand comprised of two kernels, the double propagator and local volume scattering coefficient. The propagator describes the local intensity of the forward propagation field and can be calculated using available models, such as PE, normal modes, or ray approximations. The scattering kernel can be specified using available volume scattering models for continuous or discrete heterogeneity of sea-water column and seabed caused by spatial fluctuations of compressibility and density, or randomly distributed discrete targets, such as bubbles, fish, shells, and others.

The reverberation intensity results from a spatial integration of the two kernels product and appears as a smoothed range dependent function averaged over a certain volume (which is, in a sense, a range-depth-resolution cell for the problem). The size of this cell can be defined accordingly to specific parameters of the problem, pulse duration, frequency bandwidth, source-receiver directivity, etc. Considering a reasonably small size of this cell and the integration within this elementary volume of the waveguide provides a correspondingly small uncertainty in the double propagation range-time relationship, which then can be used to plot the reverberation intensity (averaged over chosen time-resolution scale) as a desired function of double propagation time. Another output of this approach results from integration over the waveguide depth and provides predictions for a sonar "scatterer map", i.e. a 2D (azimuth angle – range, or angle-time) distribution of the local scattering strength.

In this research, the approach outlined in [6,10,11] will be developed further, treating heterogeneous sediment as a critical part of the propagation channel, that would then allow including all three mechanisms of scattering in the shallow-water environment: rough water surface, heterogeneous water column, and a stratified rough heterogeneous seabed, into consideration of reverberation.

WORK COMPLETED

This report is for the first-year work of a two-year project. For this year, two main tasks were suggested, corresponding to the TREX13 timeline. *First task* was to perform *pre-test* computer simulations, helping with planning the acoustic experiment and environmental ground truth measurements. The focus was on analysis of bottom scattering mechanisms, with environmental inputs typical for the chosen location (assumed to be the same as for a 2012 test in this area), to predict their impact and relative contributions. Such analysis has been performed, and, in particular, the impact of large shells on reverberation was found substantial at reasonable (for TREX13 environment) assumptions. Therefore more effort was suggested for collecting such shells during field experiments to provide sufficient ground truth for model/data comparisons.

Second task of the first year work was to develop an initial version of a physics-based model for reverberation in a very shallow water environment relevant to TREX13 data analysis. Such a model has been developed based on an alternative approach to volume scattering described in [10,11] which significantly simplifies accounting for the effect of stratification and presence of interfaces. The approach also allows considering all relevant volume scattering mechanisms (including heterogeneity of sediments and water column) in a unified model. Initial computer simulations using parameters typical for the TREX13 conditions have been performed to demonstrate computational capabilities of this approach to significantly faster yet reasonably accurately estimate volume reverberation in complex very shallow water environments. A discussion of the modeling approach and initial results are submitted to the coming Fall 2013 ASA meeting [12].

RESULTS

Initial numerical simulations to demonstrate capabilities of this simplified modeling approach for fast yet reasonably accurate estimations of shallow water reverberation were performed and results are presented in Figures 1,2, to show two critical steps in the algorithm of these estimations. The first step is to evaluate the propagator kernel in the waveguide of interest. An example of PE-based calculations of the propagation field's magnitude in very shallow water with parameters typical for TREX13 environment is given in Figure 1.

The double propagator, which in the case of monostatic reverberation corresponds to fourth power of the field's magnitude (being a function of range and depth specified for given shallow water waveguide), then can be used as an input to calculate the reverberation intensity as a function of the double propagation time, generally, for an arbitrary distribution of scatterers defined by their volume scattering strength, or the scattering cross section per unit volume. This new modeling approach is therefore more general than, and can be used for verification of, existing reverberation models. For instance, the new model provides estimations of bottom reverberation without calculations of the equivalent surface scattering strength (although may include it as a particular case).

To demonstrate computational capabilities of this approach, particularly if fast yet reasonably accurate estimations of volume reverberation are needed in the case of complex very shallow water environments, computer simulations using parameters typical for the TREX13 conditions have been performed. The results are illustrated in Figure 2, that shows potential contributions of different mechanisms of scattering using comparison of relative contributions of scatterers with the same scattering strengths but located at different depths in water column or in the sediment.
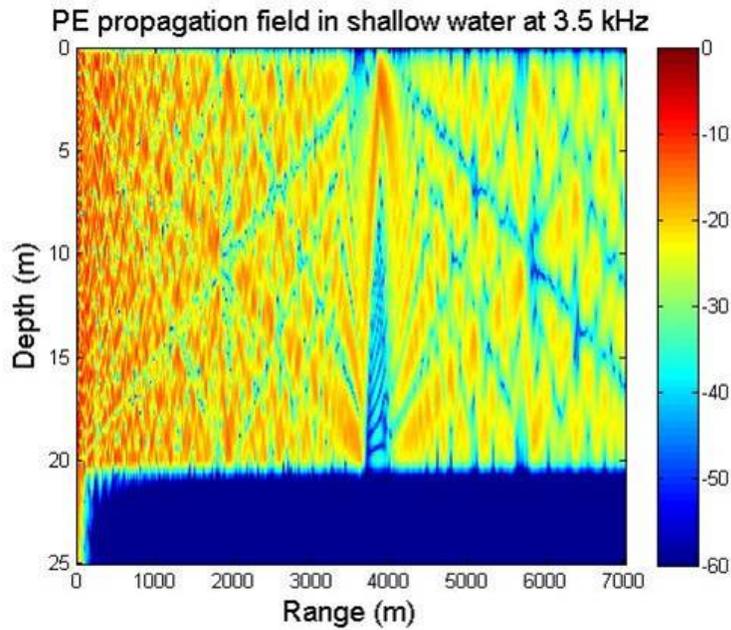
Figure 1. PE propagation field's magnitude in a very shallow water (having 20m depth) at 3.5 kHz, for a source located at a distance 1m above a sandy half-space (non-stratified), calculated using a PE code [13]. These calculations are used then as inputs (through a double propagator) to a simple model of monostatic volume reverberation illustrated in Figure 2.
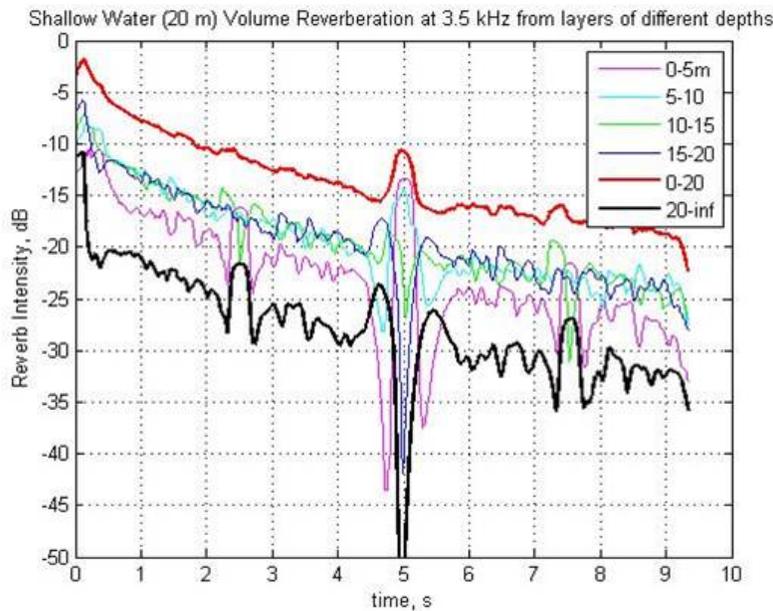

Figure 2. Normalized monostatic reverberation intensity from scattering layers located at different depths (0-5, 5-10, 10-15, and 15-20 m) in water column (having 20m depth) and in a sandy sediment half-space (20-inf) bottom. "Normalized" means "per unit volume scattering strength", i.e. reverberation intensity calculated assuming the same volume scattering strengths for all scattering mechanisms. This allows then a fast estimation of potential contributions of different mechanisms of scattering with arbitrary strengths and locations.

IMPACT/APPLICATIONS

This research is to contribute to further development of shallow water reverberation models and codes. The results of this research will allow testing currently used bottom reverberation codes and their applicability to very shallow water environments at mid frequencies. Particularly, this concerns using CASS/GRAB codes with inputs of GABIM, Geophysical Acoustic Bottom Interaction Model. These models and codes have been widely used in the applied research and development community for predicting and analysis of bottom reverberation at mid frequencies for a wide variety of sea bed types. In particular, they are primary tools used in the Ocean Bottom Characterization Initiative (OBCI).

RELATED PROJECTS

This plan is built on results of previous projects funded by ONR-OA [5,6,8-10] and other work [4,7,11] on shallow water reverberation and scattering from heterogeneous marine environments. This research assumes a close collaboration with TREX PIs, Drs. Todd Hefner, DJ Tang, Kevin Williams, and other TREX investigators and researchers working in this field. This research is also closely related to Todd Hefner's effort on theory of high frequency acoustic propagation and scattering in heterogeneous sediments.

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