Broadband Scattering from Sand and Sand/Mud Sediments with Extensive Environmental Characterization

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LONG-TERM GOALS

To model the effects of volume heterogeneities, both discrete and continuous, in scattering from sand and mud sediments. A better understanding of the role of heterogeneities in seabed scattering could lead to improvements in sediment characterization using remote sensing techniques and a greater understanding of the mechanisms that affect mid-frequency reverberation.

OBJECTIVES

The goal of this research is to further develop and test models of volume scattering by utilizing the existing suite of instrumentation previously developed at APL-UW for the study of high-frequency acoustics. These models include perturbation models applied to scattering from the seafloor due to heterogeneities in the sediment properties and models developed by Dr. Ivakin[1] for scattering from inclusions in the sediment. To accomplish this goal, we have focused on three experimental efforts:

1. High-frequency scattering measurements conducted in the NSWC-PCD test pond in 2010.
2. Mid- to high-frequency scattering measurements made in the Gulf of Mexico as part of the Target and Reverberation Experiment in 2013 (TREX13).
3. Mid- to high-frequency scattering measurements made in St. Andrew's Bay as part of the Bay Experiment in 2014 (BayEx14).

The first of these experiments was conducted as part of a previously funded ONR effort to connect attenuation within the sediment to scattering from volume heterogeneities. Following that experiment, problems with the NRL-Stennis CT imager prevented us from measuring the volume heterogeneity within the sediment, severely limiting the data/model comparisons possible at the time. This characterization deficit has been recently overcome through the use of conductivity probe measurements made in the test pond in 2006. Data/model comparisons are now possible with this historic environmental characterization to provide insight into both the dominant seafloor scattering mechanism for a "pure" sand seabed and the possible connection to a scattering loss model for attenuation developed during the previous effort [2]. Both the measurements made during TREX13 and BayEx14 were conducted in conjunction with synthetic aperture sonar (SAS) measurements of target scattering. These SAS measurements were conducted using the APL-UW rail system and the work conducted under the project reported here leveraged the rail deployment by mounting both a high-frequency and mid-frequency array on the rail tower.

APPROACH

To collect the acoustic scattering data, this work utilizes the APL-UW rail and tower that was deployed during both TREX13 and the BayEx14. The tower was originally developed for the Sediment Acoustics Experiment 2004 (SAX04) and includes a high frequency array of sources and receivers as well as a piston source and receiver combination (EA33 and EA41) [3]. Since SAX04, the tower has been modified on several occasions, but the capability to operate with these legacy sonars remains intact. The high frequency array has since been reincorporated into the tower design and has been successfully deployed with the tower in both the NSWC-PC test pond and in the Gulf of Mexico. For TREX13, the piston source and receiver was reincorporated into the tower design for TREX13 and BayEx14. With these two systems backscatter data can be collected from 200-500 kHz (source and receiver array) and from 20-150 kHz (piston source and receiver) along the APL-UW rail and collocated with the SAS target field.

During both experiments, data was collected at multiple grazing angles and frequencies at 25-50 positions along the APL-UW rail system. These multiple locations provide different realizations of the sediment in order to provide a clear picture of the scattering statistics. The area of the seafloor where the acoustic data was collected was 5 m in range and 4 m in cross-range. In an effort to preserve the natural seabed, divers were prevented from working in this area until after the measurements were completed.

In preparation for TREX13, APL-UW developed the Bottom Sonar System (BSS). This system consists of an ITC-1007 source and a separate receiver in a small mount that can be deployed from a ship or boat. The BSS is suspended above the seafloor and transmits and receives pulses in the 2-20 kHz range. This system is designed to drift along a track collecting data at multiple locations. The frequency range of this system is such that it can measure both scattering from the seafloor and from subbottom layers. This system complements the measurements made by both the chirp sonar and the NSWC-PC BOSS at the TREX13 site. Between these three systems, backscatter can be measured from 2-500 kHz capturing both mid and high-frequency scattering mechanisms. Due to the shallow water depth at the BayEx14 site, the BSS was not deployed.

In order to make the accurate data/model comparisons, extensive environmental characterization accompanied each of these experiments. This includes roughness measurements using the Laser-Line Scanner (LLS), conductivity probe measurements using the In-situ Measurement of Porosity (IMP2), sound speed and attenuation measurements, the collection of diver cores, and excavation of sediment volumes for shell size distributions. During TREX13 this environmental characterization was performed at both the target scattering site and along the main reverberation track. This data is being compiled and will be made available to the TREX13 participants and included in the environmental data set to be distributed as part of the TREX13 reverberation data set. The results of the St. Andrew’s Bay environmental characterization have also been made available to all of the BayEx14 participants.

WORK COMPLETED

As discussed below, the IMP2 has been used extensively during TREX13 and BayEx14 to measure the porosity in both sand and mud sediments. Analysis of this recent data inspired a reexamination of previous data sets, particularly from deployments in the NSWC-PCD test pond. During these deployments, the system was primarily used to measure one-dimensional roughness profiles and collected conductivity probe data along a 5 cm deep region just below the interface. Figure 1 shows an example from 2006 where the system measured the elevation of a ripple scraped into the sediment by divers. In 2010, backscatter data was collected in the NSWC-PCD test pond and the sediment for these measurements was scraped smooth in an effort to reduce rough surface scattering. Using diver cores collected during the 2010 experiment and assuming that the preparation techniques were sufficiently similar in 2006 and 2010, a porosity fluctuation spectrum was extracted from the conductivity probe data. This was the final piece of environmental data needed to constrain fluid and effective density fluid models (EDFM) of volume scattering from the seafloor. The data/model comparisons for both roughness and volume scattering are discussed in the next section.

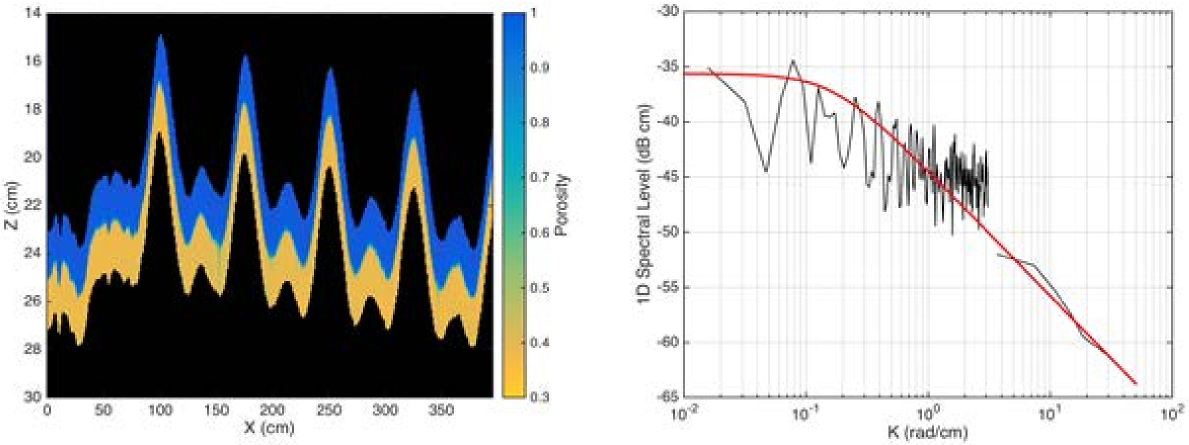

Figure 1: Porosity measured by the IMP2 conductivity probe in the NSWC-PCD test pond in 2006 (Left panel) and the 1D porosity fluctuation power spectra in the vertical and horizontal directions extracted from that measurement (right panel). The red line is a fit to the power spectra by a 1D von Karman power spectrum.

Work has also continued on the analysis of the TREX13 datasets. Of particular focus has been the preparation of manuscripts for the special collection to be published in the IEEE Journal of Oceanic Engineering. Since this collection is about the reverberation portion of the experiment, analysis of the sediment roughness and seabed property data has received the greatest amount of attention with manuscripts scheduled for submission in November. All of the roughness data collected throughout the site by APL-UW has been analyzed for both mid-frequency and high-frequency scattering models, providing spatial dependent roughness power spectra with their associated uncertainties. This analysis has utilized additional measurements made at the TREX13 site such as the multibeam sonar survey conducted by Drs. Chris DeMoustier and Barbara Kraft. An example of this analysis is discussed in the next section.

The analysis of the BayEx14 data has continued with both the processing of the scattering data and further analysis of the environmental characterization. Original analysis of the BayEx14 environmental measurements indicated that the site was composed of a mud layer over a sand bottom. More careful analysis has found that the underlying sand may actually be a sand/mud mixture and that there is a gradual transition from the mud/water interface into the sand/mud mixture. This has significant implications for both scattering from the sediment and for the response of mine-like targets embedded in the mud layer.

RESULTS

NSWC-PCD Test Pond

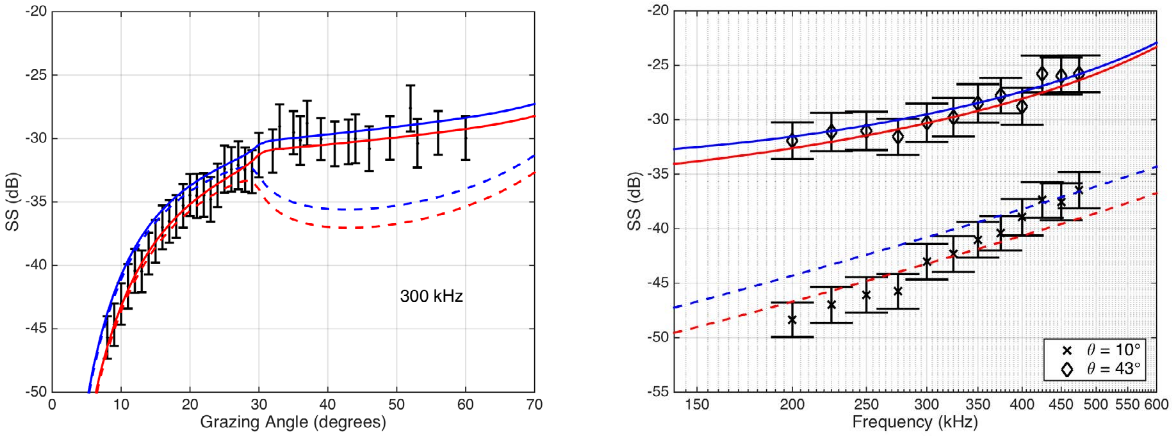

Figure 2: Comparisons of small perturbation theory to the backscatter strength measured in the NSWC-PCD test pond. In both panels, either the EDFM (red lines) or fluid model (blue lines) is used. The dashed lines are the predictions of small perturbation theory for rough surface scattering and the solid lines are the combined scattering strength for both volume and rough surface scattering.

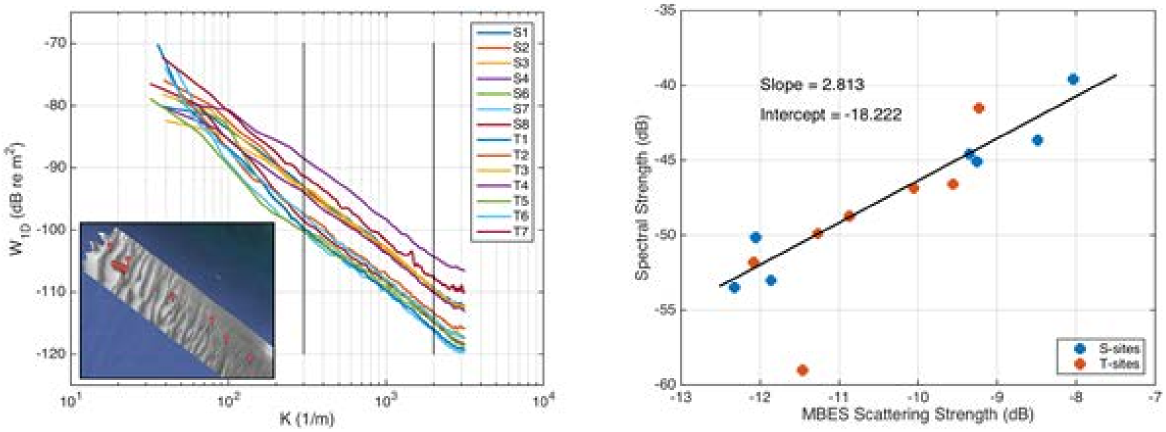

Figure 3: The high wavenumber components of the spectra measured at the TREX13 site using the APL-UW seafloor laser-line scanner (SLS) (Left panel). The inset shows the locations of the SLS measurements relative to the map of 400 kHz multibeam backscatter measured by Drs. Chris DeMoustier and Barbara Kraft. The spectral strengths of these high-wavenumber spectra are linearly correlated to the multibeam sonar backscatter strengths (right panel).

Using the porosity fluctuation spectrum shown in Figure 1 and additional sediment parameters such as sound speed, attenuation, and the roughness power spectrum, the predictions of small perturbation rough surface and volume scattering theories could be tested. This was done for both the fluid model and EDFM and the data/model comparisons are shown in Figure 2. The data/model comparisons indicate that there are two dominant scattering mechanisms for a pure sand in the absence of shells, shell fragments, and any burrowing organisms. Below the critical grazing angle, scattering from the sediment interface roughness dominates while above the critical angle, sound is scattered by fluctuations in the porosity of the sediment. This pure sand sediment provides a baseline for scattering and the strength of any additional scattering mechanisms such as shells or animal burrows need to exceed these base mechanisms in order to be significant. This experiment also serves as a rigorous test of small perturbation theory since the model parameters are so tightly constrained by measurements. *TREX13*

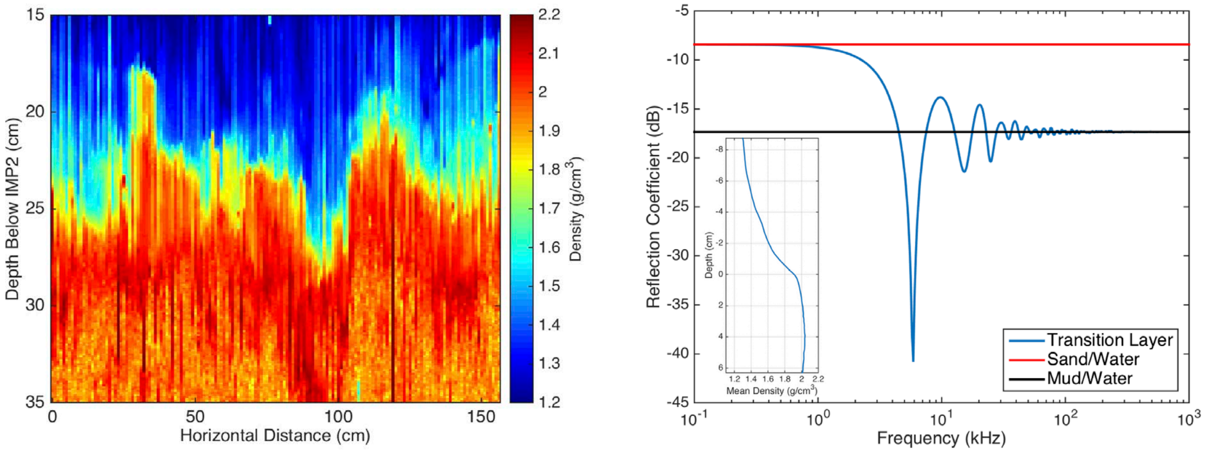

Figure 4: Density at the mud/sand transition in the BayEx14 sediment measured using the IMP2 conductivity probe (left panel). The normal incidence reflection coefficient accounting for the density changes across mud/sand transition as a function of frequency (right panel). The inset shows the mean density across the transition.

While the low wavenumber roughness power spectra measured throughout the TREX13 site appear to be approximately equal, the high wavenumber power spectra appear to be well described by a single spectral exponent ($\gamma = 1.93$) but varying spectral strengths (Figure 3). The spectral strengths are linearly related to the 400 kHz backscatter strength measured using a multibeam sonar at the TREX13 site. Using this linear relationship, it is possible to estimate the high wavenumber spectra throughout the TREX13 site. Above the critical angle, scattering measurements made using the arrays on the rail tower indicate that volume scattering from shells and shell fragments is the dominant, high frequency scattering mechanism for portions of the TREX13 sediment. This should also be true for the multibeam sonar scattering. The results in Figure 3 indicate that the shells exposed on the sediment surface are largely responsible for the measured roughness. Efforts are underway to correlate the shell content with the surface roughness making it possible to generate a map of the shell content across the TREX13 site. This shell content map could be used as a proxy to eventually understand the distribution of mid-frequency volume scattering mechanisms.

BayEx14

By assuming that the BayEx14 sand sediment is a mixture of sand and mud, it was possible to invert the conductivity probe data for the density through the transition from mud to muddy sand (Figure 4). The inverted data show that the transition is not defined by a single jump in density as one descends into the muddy sand, but rather a gradual increase in density through the transition. This has a significant effect on sound scattering from and penetration into the sediment[4]. To illustrate this, the normal incidence reflection coefficient was calculated using the mean density across the boundary.

At low frequencies, the reflection coefficient corresponds to that of a sand/water interface. As the frequency increases and the wavelength approaches the thickness of the layer, the reflection coefficient decreases and reaches a strong minimum value when the thickness is approximately a quarter wavelength. Beyond this, the reflection coefficient approaches the mud/water value at high frequencies. This occurs since the density is changing at scales much larger than a wavelength and as a result the wave passes smoothly through the boundary. The only reflection therefore occurs at the top of the layer. A similar effect should also be seen for the shallow grazing angle reflection coefficient and should have a pronounced effect on scattering from the sediment and targets within the sediment.

IMPACT/APPLICATIONS

The sediments considering in this project represent a transition from a simple sand sediment to a much more complicated mix of the mud and sand. By considering sediments with increasing complexity it is possible determine when and how a particular scattering mechanism becomes dominant and what the best modeling approach should be to capture the physics. This improved understanding of the role of heterogeneities in scattering and their effect on forward propagation and reverberation in the ocean waveguide could lead to improvements in sediment characterization using remote sensing techniques. It will also contribute to our understanding of the effect of these heterogeneities on the statistics of target detection.

RELATED PROJECTS

1. "Acoustic Color of mines and mine-like objects: Finite Element modeling (FEM), developing Automatic Target Recognition (ATR) strategies, and at-sea experimental validation." P.I. Kevin L. Williams funded by ONR.

2. “Mid-frequency reverberation measurements with full companion environmental support” P.I. Dajun Tang funded by ONR.

REFERENCES

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