The Effects of Sand Sediment Volume Heterogeneities on Sound Propagation and Scattering

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Award Number: N00014-10-1-0089
http://oa.apl.washington.edu

LONG-TERM GOALS

To model the effects of volume heterogeneities in 1) scattering from sand sediments and 2) in sound propagation within those sediments. A better understanding of the role of heterogeneities in both scattering and propagation could lead to improvements in sediment characterization using remote sensing techniques as well as in high-frequency detection of mine and mine-like targets resting on or buried within the seafloor.

OBJECTIVES

The goal of this work 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, recently developed models by Dr. Ivakin [1], which model scattering from inclusions in the sediment such as shells and coarse grains, models which account for the transition layer observed during SAX99 which could have a strong effect on volume scattering at high frequencies, and perturbation theory for sound propagation through a varying poroelastic sediment.

APPROACH

In order to test models of volume scattering, experiments have been performed in both the NSWC PC test pond and in the Gulf of Mexico. Each of these experiments leveraged the deployment of the APL-UW SAS rail system to perform high-frequency scattering measurements using an array that was previously developed for the Sediment Acoustics Experiment in 2004 (SAX04). The high-frequency scattering data was collected immediately in front of the rail and sampled a region of the sediment that extended out to 5 meters. The configuration of the array allowed data to be collected at grazing angles from 8° to 60° and from 200 to 500 kHz. In order to perform the data/model comparisons, extensive environmental measurements were also being made during each of these experiments. These included roughness measurements using the Laser-Line Scanner (LLS), sound speed and attenuation measurements, and the collection of diver cores. These diver cores are being analyzed for both grain size and porosity distributions.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **2012**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **The Effects of Sand Sediment Volume Heterogeneities on Sound Propagation and Scattering**	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) **Applied Physics Laboratory, University of Washington 1013 NE 40th Street 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

The original document contains color images.

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**	**SAR**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

In addition to the scattering measurements, model development has focused on connecting the attenuation in the sediment to the scattering from the sediment interface due to volume heterogeneities. This continues previous work developing propagation models that used perturbation theory to model scattering loss for propagation through heterogeneous Biot media. This previous work focused on media in which there were heterogeneities in the frame bulk modulus [2]. The current work has focused on the simpler Effective Density Fluid Model (EDFM) [3] and the role of porosity heterogeneities in this media [4]. Significant research has been done to examine the role of porosity fluctuations, or alternatively the associated density and compressibility fluctuations [5], in the scattering of sound from a sand sediment and the present work seeks to determine if these fluctuations can also lead to scattering loss within the sediment. The approach taken here has been to develop a scattering theory of propagation that can model the observed linear attenuation in sand sediments. Once this theory has been shown to fit the linear attenuation, the parameters used in the fit can be applied to models of scattering *from* the sediment to then compare to the measured scattering data.

WORK COMPLETED

In the spring of 2012, an engineering test in preparation for the upcoming Target and Reverberation Experiment in 2013 (TREX13) was conducted in the Gulf of Mexico off of Panama City Beach, FL. This test was a joint effort between APL-UW, ARL-Penn State, and NWSC PC and both the APL-UW SAS rail system and the Five Octave Research Array (FORA) were deployed. During this experiment, the rail system was used to measure high-frequency scattering from the sediment as described above. Collocated with these scattering measurements, were measurements of the sediment roughness collected using the LLS as well as sound speed and attenuation. Volume samples of upper 20 cm of the sediment were collected and sieved to determine the distribution of shells with diameters greater than 1.6 mm. Diver cores were also collected for both shell and grain size analysis.

These measurements were also performed to support planning and preliminary modeling for TREX13. The LLS is one of several systems that will be used to measure roughness during that experiment and the measurements collected during the engineering test are being used to support modeling of the reverberation measured during the engineering test on both an APL-UW horizontal array and the FORA. The LLS is part of the In-situ Measurement of Porosity (IMP2), a system that was developed for the Sediment Acoustics Experiment in 1999 and has since seen extensive deployment in SAX04, the Shallow Water 2006 (SW06) experiment, and in both the NSWC PC test pond and St. Andrew’s Bay. In preparation for TREX13 and an upcoming ONR-supported experiment in St. Andrew’s Bay, an extensive rebuild of the IMP2 is underway to ensure that the system will be able to accurately and reliably measure both roughness using the laser line system and porosity fluctuations using the conductivity probe. This is a valuable and unique system for environmental characterization and the repairs should significantly extend the system’s operating life.

Theory development has focused on determining what form the covariance or power spectra for the porosity fluctuations should take in order to produce the observed linear attenuation in sand sediments. To construct the required covariance, the covariance was expressed as a sum of exponentials, each of which provides an analytic solution to the integrals involved in the scattering theory. A fit to measured attenuation and sound speed thus provides the weighting of the constituent exponentials. Simplifications to the perturbation theory have also been explored in order to produce an accurate yet computationally efficient expression for the sound speed and attenuation.

RESULTS

Scattering strength measurements collected at the TREX13 site indicate that below the critical grazing angle, interface roughness scattering is the dominant mechanism. These measurements, however, were collected in the SAS target field towards the end of the engineering test when large schools of fish had congregated around the rail tower. These fish fed in the target field and significantly affected the sediment roughness as can be seen in the measured power spectra (left panel of Figure 1). At low wavenumbers the roughness is similar to that observed during SAX04 and is likely due to sediment transport induced by wave motion and currents [6]. At high wavenumbers there is a significant increase in the spectral slope due to the pock marks on the interface due to feeding fish. The scattering levels predicted by perturbation theory using the spectral slope in this high wavenumber region compare very well to the measured scattering strengths which indicates that the fish significantly influenced the scattering. During the previous engineering test in 2011, the roughness spectra had a spectral slope that was continuous across the entire measured range. Thus the 2012 measurements likely do not reflect that scattering strengths that would be observed outside of the target field.

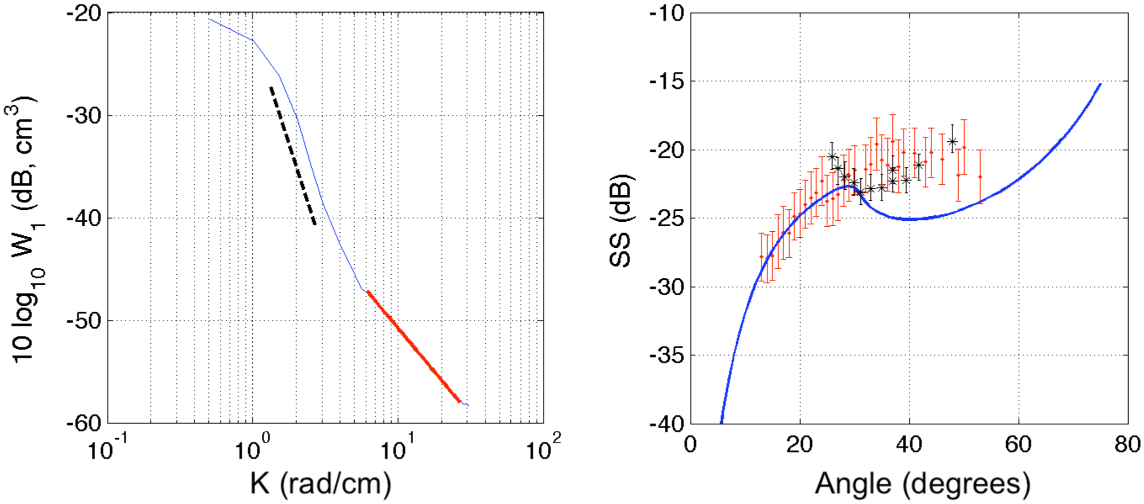

Figure 1: (Left) Power spectrum measured in the target field of the APL-UW SAS rail system during the Spring 2012 engineering test compared to the spectrum measured during SAX04 (black dashed line). (Right) Scattering strength at 350 kHz measured during the Spring 2012 engineering test (red dots) compared to the measured values from SAX04 (black points). The blue line is the prediction of perturbation theory using the fit to the roughness spectra shown by the red line in the left plot.

Although the fish significantly affected the sediment roughness, perturbation theory underpredicts the scattering strengths above the critical angle. This was also observed at SAX04 although the roughness spectra measured during that experiment did not extend to the high wavenumbers needed to properly model the data. For mid-frequencies, where the spectral strengths were available, the roughness was found not to play a significant role both above and below the critical angle. This indicates that it may be reasonable to extrapolate the spectrum and conclude that roughness did not play a role for the higher frequencies as well. For the SAX04 high frequency scattering, there seemed to be a different mechanism than that observed at the lower frequencies (Figure 2). The scattering mechanism at the low frequencies was likely volume scattering with the heterogeneities being associated with mud layers and inclusions.

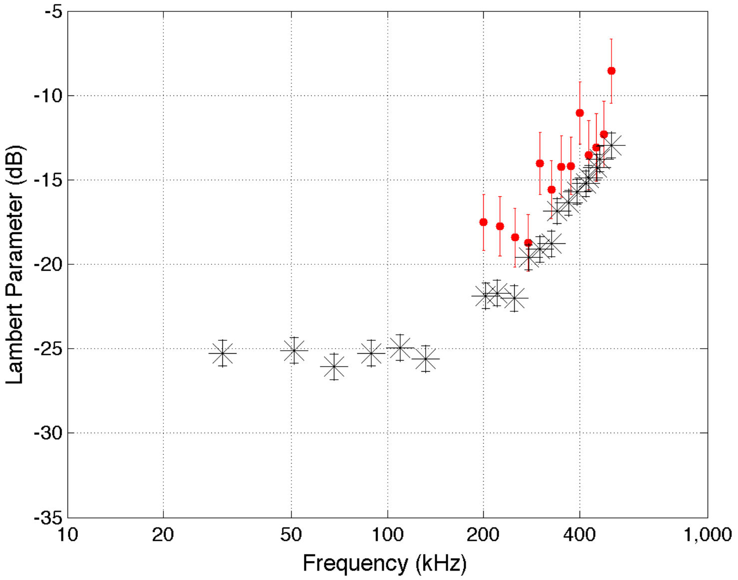

Figure 2: Lambert parameter as a function of frequency for the Spring 2012 engineering test (red) compared to the values measured during SAX04 (black). Both sets of measurements are for a grazing angle of 30°.

Scattering from discrete inclusions such as shells and shell hash was proposed as a possible mechanism for the scattering levels observed at the high frequencies. During SAX04, sediment samples were collected and seived to determine the shell size distribution (Figure 3). For the SAX04 experiment, the total shell content was less than 1% by volume. Similar sediment samples were collected from the 2012 site and seiving has shown that the total shell content is closer to 3% by volume. If shells are similarly responsible for the scattering observed at the 2012 site, the scattering scattering strengths should be larger and this is observed in the data (Figure 2). Work is currently underway to model scattering due to these shell size distributions.

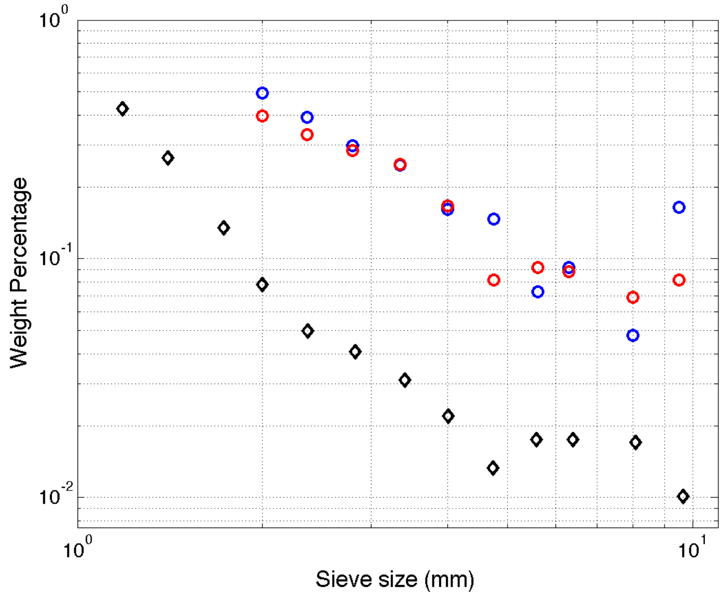

Figure 3: Shell size distribution histograms from the Spring 2012 engineering test (blue and red) compared to the SAX04 shell size distribution.

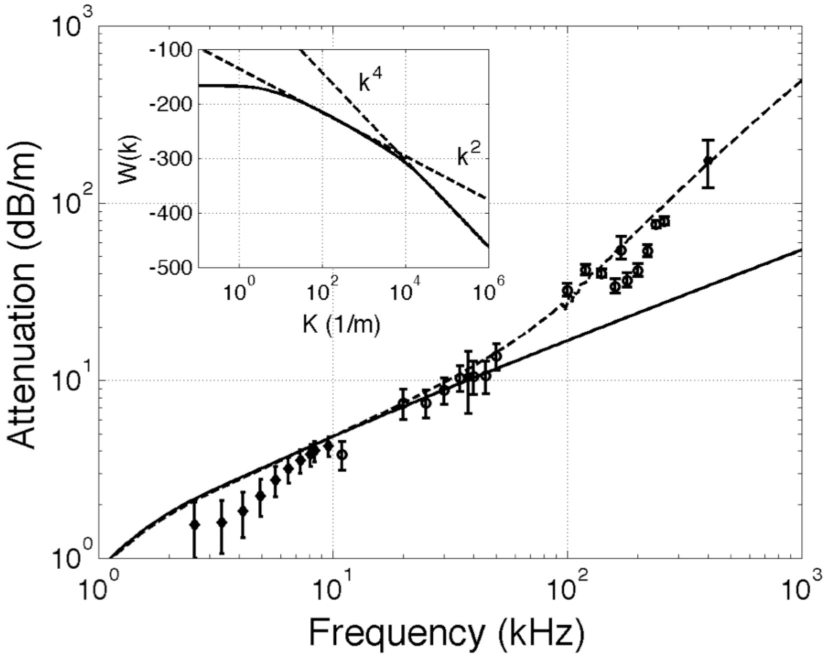

Figure 4: Fit to the SAX99 attenuation measurements using perturbation theory applied to the EDFM assuming fluctuations in the porosity (dashed line). Also shown is the unperturbed EDFM prediction (black solid line). The inset shows the power spectrum for the porosity fluctuations that was used to the fit the SAX99 data.

To test scattering from porosity fluctuations as a possible loss mechanism in propagation through a sand sediment, two well-known covariance functions were examined. The first was the exponential covariance which was found at low frequencies to produce an attenuation that goes as the square of the frequency and at high frequencies to produce a constant attenuation. The von Karman covariance followed the same frequency law at low frequencies but at best could produce an attenuation at high frequencies that followed a square root frequency dependence. To create an arbitrary covariance function, the covariance was expressed as a weighted sum of exponential covariances. The weighting could be modified to produce a fit of the SAX99 data (Figure 4) and the corresponding porosity fluctuation power spectrum was found to have a dual power law behavior. At low wavenumbers, the spectrum is flat and at high wavenumbers the spectra follows a k^{-4} dependence. For the mid wavenumbers, the spectra follows a k^{-2} dependence.

This is consistent with the progression observed for the exponential and von Karman spectra which goes from a constant attenuation when the spectra is k^{-4} to an $f^{1/2}$ attenuation when the spectra approaches at k^{-3}. It would seem reasonable that the spectra require to fit a linear attenuation would need to go as k^{-2} for all wavenumbers, however this would be unphysical and would lead to an infinite variance for the medium. It's necessary for the spectra to fall off faster then f^{3} in order to remain physical and the spectra shown in the inset of Figure 4 satisfies this criteria.

IMPACT/APPLICATIONS

The results of the measurements and ongoing analysis should help understand the role of continous and discrete volume scattering in the acoustic characterization of the sediment. Knowledge of these scattering mechanisms is valuable for the detection of mines both in determining the sediment properties required to model the target response and in determining the background scattering levels that may mask 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.

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PUBLICATIONS

1. B. T. Hefner and D. R. Jackson, “Power-law attenuation due to scattering from porosity heterogeneities in sandy sediments,” in the Proceeding of the European Conference on Underwater Acoustics 2012.