High-Frequency Sound Interaction with Ocean Sediments and with Objects in the Vicinity of the Water/Sediment Interface
&
Mid-Frequency Shallow Water Propagation and Scattering

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Award Number: N00014-06-1-0225

http://www.apl.washington.edu/projects/SAX04/summary.html

LONG-TERM GOALS

1. Development of accurate models for acoustic scattering from, penetration into, and propagation within shallow water ocean sediments.

2. Development of reliable methods for modeling acoustic detection of buried objects at subcritical grazing angles.

3. Improving our understanding and modeling of shallow water propagation.

Our work will contribute to the objectives of improving the Navy's ability to detect and classify buried mines in shallow water and of improving sonar performance in shallow water in general.

OBJECTIVES

Relative to the first two long-term goals our specific objective for FY07 was to document both the results from the Sediment Acoustics Experiment in 2004 (SAX04) and the associated analysis and modeling techniques that were developed. Those results include (1) measurement of backscattering levels from buried objects at subcritical grazing angles using synthetic aperture sonar (SAS) measurements in order to test buried-object-detection modeling accuracy; (2) identification of the dominant high-frequency backscattering and subcritical penetration mechanisms, including a demonstration that these acoustic processes can be quantitatively modeled based on measured sediment properties; and (3) measurement of sediment attenuation and sound speed over a wide range of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **High-Frequency Sound Interaction With Ocean Sediments And With Objects In The Vicinity Of the Water/Sediment Interface And Mid-Frequency Shallow Water 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) **University of Washington,Applied Physics Laboratory,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
code 1 only

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)**	**7**	

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

frequencies and the use these results, combined with measured sediment properties, to test the validity of sediment acoustic models, and in particular the poroelastic (Biot) model. Addressing these as well as several ancillary issues has led to the preparation of 9 articles for submission to a Special Issue of the IEEE Journal of Oceanic Engineering on Sediments Acoustic Processes scheduled for publication in 2008. Short summaries of some of these articles are given below.

Our objective in FY07 relative to modeling shallow water propagation was to improve the accuracy of our previously developed shallow water propagation model based on transport theory to eliminate modest differences between PE simulation and transport theory results for propagation in a waveguide with a rough sea surface.

APPROACH

Our objectives related to sediment acoustics are being addressed using measurements from a major field experiment (SAX04) combined with modeling and simulations based on detailed environmental characterization. Our objectives related to shallow water propagation are being addressed using a rough surface and rough bottom PE code to provide ground truth for development of a computationally fast shallow water simulation method based on transport theory.

WORK COMPLETED

Nine papers are in various stages of preparation for the IEEE-JOE special issue on Sediments Acoustic Processes with APL-UW first authorship. The titles, authors, and status are as follows:

1. “Acoustic Observation of the Time Dependence of the Roughness of Sandy Seafloors,” D. R. Jackson, M. D. Richardson, K. L. Williams, A. P. Lyons C. D. Jones, K. B. Briggs, and D. Tang (Submitted).

2. “Acoustic Backscattering from a Sand and a Sand/Mud Environment: Experiments and Data/Model Comparisons,” K. L. Williams, E. I. Thorsos, D. Tang, D. R. Jackson, and K. B. Briggs (Submitted).

3. “Forward Scattering from a Rippled Sand/Water Interface: Modeling, Measurements and Determination of the Plane Wave, Flat Surface Reflection Coefficient,” K. L. Williams (Submitted).

4. “Inversion of Sandy Sediment Ripple Fields from High-Frequency Backscatter,” D. Tang, K. L. Williams, and E. I. Thorsos (Submitted).

5. “Mid- to High-Frequency Acoustic Penetration and Propagation Measurements in a Sandy Sediment,” B. T. Hefner, D. R. Jackson, K. L. Williams, E. I. Thorsos (Under internal review).

6. “Synthetic Aperture Sonar Imaging of Simple Finite Targets during SAX04,” S. G. Kargl, K. L. Williams, and E. I. Thorsos (In preparation).

7. “Characterization of Bottom Roughness Following a Significant Storm Event off Fort Walton Beach, Florida,” D. Tang, B. T. Hefner, A. P. Lyons, and K. L. Briggs (In preparation).

8. “Numerical Time-Domain Simulation of First-Order Scattering from a Rough Sea Bottom,” D. Tang and E. I. Thorsos (In preparation).

9. “Generating Realistic-Looking Sediment Ripple Fields,” D. Tang, F. S. Henyey, and B. T. Hefner (In preparation).

In addition there will be an overview paper of SAX04 acoustics and environmental measurements, written by special issue editors Eric Thorsos and Mike Richardson.

Regarding shallow water propagation modeling, the modest PE/transport theory differences can be noted by comparing the ranges of the mid-waveguide focus positions in Figs. 1 and 2 in [1]. The reason for these differences was identified and completely resolved with no increase in computation time. Further details are given in the section on results.

RESULTS

High-Frequency Sound Interaction

In the following subsections we summarize some of the IEEE-JOE special issue papers authored by APL-UW investigators and give examples of results presented.

Acoustic observation of the time dependence of the roughness of sandy seafloors

A statistical model has been developed for the time evolution of seafloor roughness created by biological activity. This model may find Navy application in predicting the rate of growth of biological roughness features and in predicting the rate of decay of storm-generated ripples. Scientifically, it can be inverted to determine levels of benthic biological activity using sonar data. In this model, the function describing small-scale seafloor topography obeys a time-evolution equation with a random forcing term that creates roughness and a diffusion term that degrades roughness. As described in the next subsection, modeling results have shown that backscattering during SAX04 at frequencies above 30 kHz was dominated by scattering from near-interface volume heterogeneity rather than from interface roughness. However, biological activity that would lead to a decorrelation in near-interface volume heterogeneity should lead to a similar decorrelation in interface roughness. Therefore, we have used temporal changes in backscattering to infer the temporal scale for changes in interface roughness.

The model provides expressions for the growth and decay of roughness spectra and scattering strength. In the case of natural roughness that may be evolving but without change in the spectrum, this evolution can be characterized in terms of the cross-correlation of echoes from successive pings. The cross-correlation of complex backscatter pressures obtained from pings transmitted at times t_1 and t_2 is proportional to $\exp[-D_b K_b^2 (t_2 - t_1)]$, where D_b is the diffusivity, and K_b is the Bragg wavenumber. As an example of the application of this result, Fig. 1 shows fits of the model to ping-to-ping cross-correlation data taken at 40 kHz during SAX04 and during the earlier Coastal Benthic Boundary Layer (CBBL) experiment.

The model gives a prediction for the frequency dependence of growth and decay rates. Considering the two frequencies used in the SAX04 decorrelation measurements, ping-to-ping correlation should decay 56 times faster at 300 kHz than at 40 kHz. It was not possible to test this prediction precisely in SAX04, as the 40 kHz and 300 kHz data were taken at different times and sites, but the 300 kHz decay rates were larger than the 40 kHz rates by factors between 20 and 150, with the highest rates at sites of strong fish feeding activity.

The application of the model to SAX04 data has given plausible results and suggests further experiments in which ground-truth measurements of diffusivity are made using standard methods for comparison.

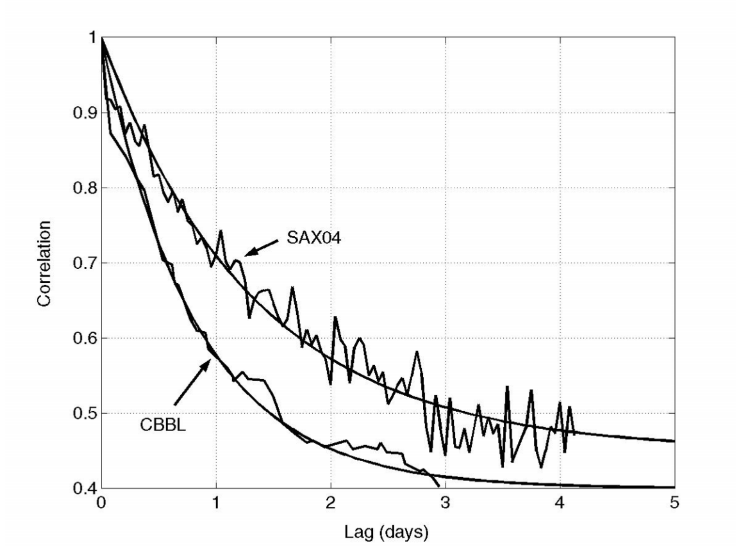

Figure 1. Comparison of measured and modeled ping-to-ping correlation at 40 kHz for two sandy sites off the Florida Panhandle: CBBL and SAX04. The smooth curves are model results for CBBL (D_b = 1.3x10^{-10} m^2 s^{-1}) and SAX04 (D_b = 9x10^{-11} m^2 s^{-1}).

Acoustic Backscattering from a Sand and a Sand/Mud Environment: Experiments and Data/Model Comparisons

SAX04 experimental results for backscattering as a function of grazing angle are shown in Fig. 2 as points with error bars based on statistical and calibration uncertainties. The three colors indicate data acquired with the center grazing angle of the transmitter/receiver set to different values (cyan: 36^o, red: 28^o, black: 20^o). Transmission problems at 50 kHz for two of the center grazing angles prevented data from being acquired; thus, there are only red data points.

Modeling based on measured interface roughness indicated that interface scattering played essentially no role above 30 kHz for the conditions of SAX04. The modeling results shown in Fig. 2 incorporate a thin mud layer over a sand half space, with volume scattering due to heterogeneities within both the mud layer and the sand. The heterogeneity within the sand was measured but that within the mud was not. Without the mud layer the model captured the rapid drop in scattering seen in the data at frequencies of 70 kHz and higher as the grazing angle drops just below the sand critical angle (30^o). However, volume scattering from the sand was unable to explain the increase in scattering around 20^o. These observations motivated the inclusion in the modeling of a layer above the sand composed of a mud/sand mixture. This is also experimentally justified by the fact that diver observations indicated that such a layer did exist in the region of the backscattering experiments. The mud heterogeneity values used to reproduce the behavior of the data in the vicinity of 20^o were similar to the values found in the sand,

Mid- to High-Frequency Acoustic Penetration and Propagation Measurements in a Sandy Sediment

During SAX04, a buried array was deployed to measure acoustic penetration into the sediment. This data set was processed to measure both the levels of subcritical acoustic penetration into the sediment and the sound speed and attenuation within the sediment. Both of these measurements were performed over the 4 to 50 kHz range. During SAX99, the dominant mechanism for subcritical acoustic penetration at high frequencies was diffraction due to sand ripples. In order to study this mechanism during SAX04, due to the absence of ripples at the buried array site, it was necessary to create artificial ripples with 50-cm and 70-cm wavelengths on the sediment interface. For these artificial ripple fields, the penetration was consistent with simulations modeled using the small-roughness perturbation approximation. At frequencies below 10 kHz, the penetrating field was dominated by the evanescent wave as seen in both speed-angle ambiguity plots of the penetrating field as well as data/model comparisons of the penetration loss into the sediment.

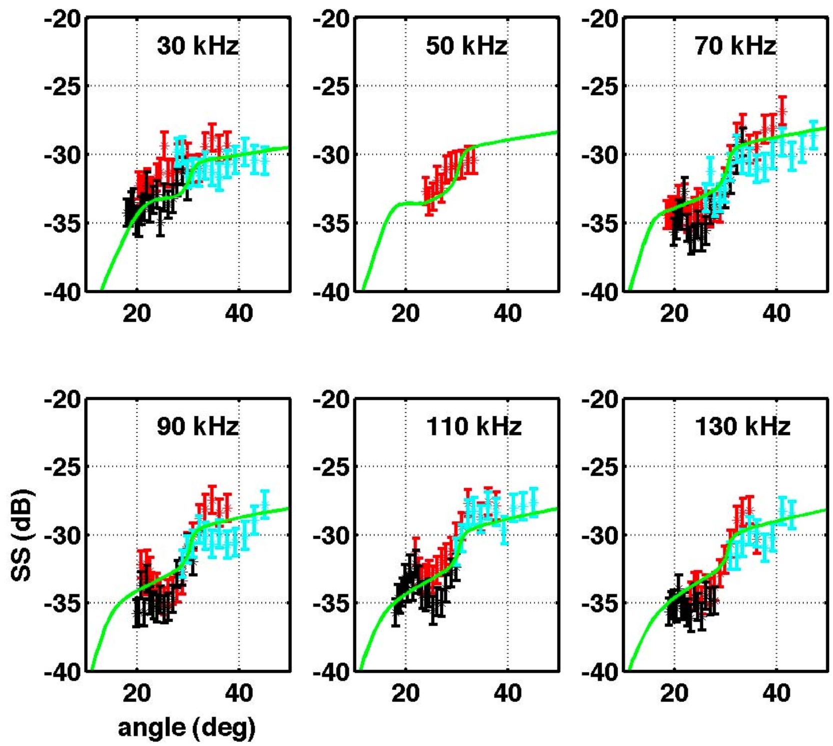

Figure 2. Experimental results for backscattering as a function of grazing angle (points with error bars) and model comparison (green curves). Model incorporates a thin (mean thickness of 4 cm) mud layer over a sand half space (consistent with diver observations), with volume scattering due to heterogeneities within each layer.

For relatively steep grazing angles, the data from the buried array were processed to determine the sound speed and attenuation within the sediment. In addition to the buried array, a small diver-deployed transducer array was also deployed to make measurements of sound speed and attenuation at higher frequencies and the combined data set covers the 4 to 260 kHz frequency range. The data set was compared to the predictions of Biot theory, which were calculated using the parameters of the sediment measured during SAX04 as shown in Fig. 3. While the theory captures the dispersion shown by the data, the theory over-predicts the sound speed by roughly 1 % over the entire frequency range. The Biot theory results also over-predict the attenuation for frequencies below 20 kHz and under-predict the attenuation for frequencies above 180 kHz. These comparisons, however, are preliminary and a full comparison with data sets collected by all of the systems deployed at the SAX04 site remains to be performed.

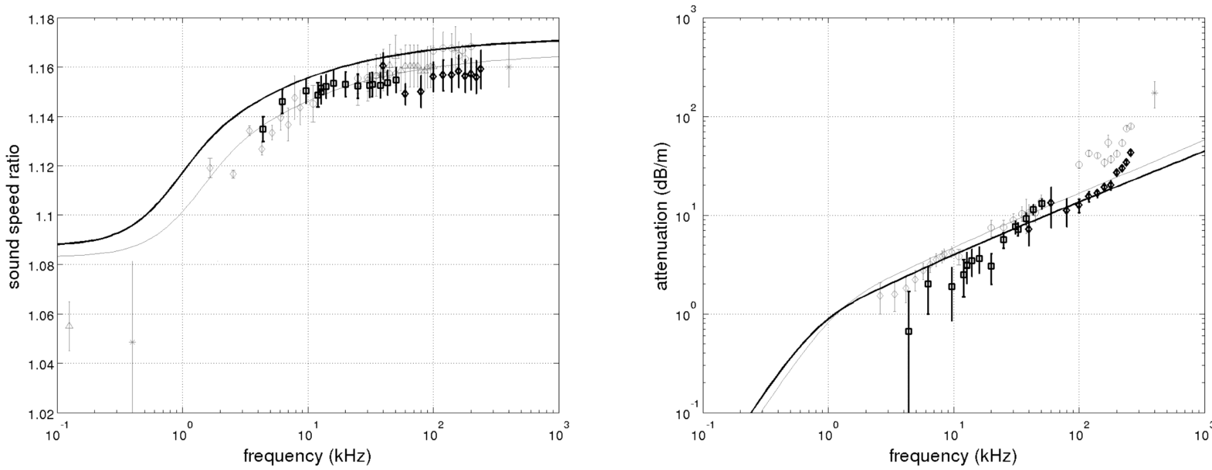

Figure 3. Sound-speed and attenuation predictions using Biot Theory are compared to the sound-speed and attenuation data collected by the buried array (black squares) and the attenuation array (black diamonds). The solid black line uses the values for the sediment parameters measured at the SAX04 site. Also shown in light gray are the sound-speed results from SAX99 and the best fit for Biot theory using the parameters measured during SAX99.

Mid-Frequency Shallow Water Propagation and Scattering

Our transport theory propagation model [1] is based on a modal description of the field. Its advantage is that it can account for all orders of multiple scattering in propagation simulations. Our initial work has been at a frequency of 3 kHz, where effects of multiple forward scattering can be important. The modest discrepancies between transport theory and PE results in [1] were first found to be removed when the vertical partition used in the modal description was sufficiently reduced in magnitude. However, this solution increases the time required to compute the mode functions, which could be detrimental in range dependent environments (not considered here) where new mode sets may need to be recomputed often. The finer vertical zoning was required to obtain accurate mode solutions because of the sudden change in medium properties across the water-sediment interface. To avoid this potential problem, a new procedure was developed to obtain the modes in which the boundary conditions at the water-sediment boundary were explicitly invoked. This was first done with a tri-diagonal description of the discrete version of the governing mode equation, and this was later generalized to an even more accurate penta-diagonal description. The net result is that the transport theory and PE propagation solutions have completely converged for the cases studied, and the vertical partition no finer than originally used.

IMPACT/APPLICATIONS

High-Frequency Sound Interaction

Work in this area should lead to improved high-frequency models for acoustic scattering from sediments, for penetration into sediments, for propagation within sediments, and for modeling the detection and classification of buried objects. A corollary to acoustic model refinement should be a better understanding of the essential parameters that are needed for practical models.

Mid-Frequency Shallow Water Propagation and Scattering

Work in transport theory propagation modeling should lead to improved simulation capability for shallow water propagation 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 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.

RELATED PROJECTS

1. Title: Acoustic scattering from heterogeneous rough seabeds, Grant # N00014-01-1-0087, A. N. Ivakin, PI. This project is focused on improving understanding of scattering from seabed roughness and volume heterogeneity, central elements of SAX99 and SAX04 measurements. In particular, scattering from shell fragments and other discrete inclusions is being modeled under this program, and the results will likely have important applications in SAX04 analysis.

2. Title: Laboratory Investigations and Numerical Modeling of Loss Mechanisms in Sound Propagation in Sandy Sediments. Grant # N00014-05-1-0225, B. T. Hefner, PI. The scientific objectives of this grant include quantifying the relative importance of scattering and frictional losses in the attenuation of sound in sand sediments.

3. Title: APL-UW component: Target Scattering Measurements and Modeling for MCM Applications, ONR BOA # N00014-01-G-0460, K. L. Williams, PI. The objective of this collaborative APL-UW, NSWC-PC effort is to obtain backscattering and bistatic target scattering data under controlled conditions in the NSWC-PC test pond.

REFERENCES

[1] E. I. Thorsos, F. S. Henyey, W. T. Elam, S. A. Reynolds, and K. L. Williams, “Modeling shallow water propagation with scattering from rough boundaries,” Proceedings of High-Frequency Ocean Acoustics Conference, La Jolla, California, March 1-5, 2004, AIP Conference Proceedings 728, pp. 132-140.

PUBLICATIONS

Publications are summarized in the section on work completed.