

High Frequency Acoustic Reflection and Transmission in Ocean Sediments

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LONG-TERM GOALS

Development of a physical model of high-frequency acoustic interaction with the ocean floor, including penetration through and reflection from smooth and rough water/sediment interfaces, scattering from the interface and volume roughness and propagation within the sediment. The model will aid in the detection and classification of buried mines and improve SONAR performance in shallow water.

OBJECTIVES

Using the results of the SAX99 and SAX04 experiments and additional laboratory measurements in the ARL:UT sand tank, an improved model of sediment acoustics will be developed that is consistent with all values of geophysical and acoustic measurements over a broad frequency range.

APPROACH

Our approach to this problem has three distinct areas of concentration:

- 1) Development of a broadband theoretical model to describe the acoustic interaction with the ocean floor in littoral environments,
- 2) Measurements for model verification and
- 3) The development of a database for bottom interaction measurements.

Each task is discussed below.

Task 1: In this effort, we developed a model of acoustic wave interaction with sand grains that included partitioning of wave energy into the rotational degrees of freedom of the sand grain. This model provides a physical explanation of the low frequency sound speeds measured at SAX99 and SAX04 which were found to be significantly below the Wood's equation prediction. This effort was led by Nicholas Chotiros and Marcia Isakson (ARL:UT).

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Task 2: Although the measurements for dispersion and attenuation at SAX99 spanned a large frequency range, the reflection measurements were taken only at normal incidence and over a limited frequency range. Therefore, our second approach is to measure and analyze reflection coefficient data over a broad frequency and angle range to provide a third complete data set for model development both in situ at SAX04 and in the laboratory. These reflection coefficient measurements will not only aid in model development, they will also provide verification of dispersion results since the critical angle is closely related to the wave speed in the sediment. These data can also be used for the inversion of sediment parameters for remote sensing of the ocean bottom. The reflection coefficient measurement effort was led by Marcia Isakson (ARL:UT). Also, it has been noted in the literature that the bulk density gradient can severely influence the value of the reflection coefficient at high frequencies. [Kimura, 2002.] Therefore, a diver deployed system to measure the bulk density gradient in situ using x-ray attenuation has been developed. This effort was led by Marcia Isakson (ARL:UT).

Task 3: Over the past 50 years, in the 10 kHz to 1 MHz range, a large number of bottom scattering measurements have been made at an enormous accumulated cost. While each measurement is valuable individually, the total collection is far more valuable as a whole. Therefore, ARL:UT has proposed to assemble a database of all the published measurements to fully comprehend the scope of the problem. This database could be used to verify the validity of such models as HFEVA. Thus, the database not only guides the development of basic research in modeling of acoustic scattering from the seabed but it also guides sonar application decisions. This effort was led by Nicholas Chotiros (ARL:UT)

WORK COMPLETED

The main achievements of 2005 and their associated tasks include:
(Task 2)

- 1) Analysis of SAX04 reflection coefficient data which revealed effects of rough interface scattering, bulk property variations and layering. (Task 2)
- 2) Development of a grain rolling theory to account for the low frequency sound speeds as measured in SAX99 and SAX04. (Task 1)
- 3) Laser light sheet improvements and calibration data collection at NWSC-PC. (Task 2)
- 4) Further development of an x-ray device to measure the density of the transition layer. (Task 2)
- 5) Assembly and analysis of bottom scattering measurements. (Task 3)
- 6) The inversion of laboratory reflection data using current acoustic models and verification through inversion of simulated data. (Task 2)

Analysis of laboratory data to confirm analytic models of spherical wave effects and quantify the effects of bulk property variations.

Reflection coefficient measurements were taken in the laboratory to confirm analytic models of spherical wave effects. The measurements were taken on smoothed water/sand interface. Therefore,

interface scattering effects are expected to be minimal. The raw data were analyzed to provide the amplitude and phase of the reflection coefficient. These data were compared to plane wave and spherical wave models using several models of acoustic interaction. [Camin and Isakson, submitted.]

Analysis of SAX04 reflection coefficient data which revealed effects of rough interface scattering and layering.

Reflection coefficient measurements were taken *in situ* at SAX04 to confirm models of the interaction of acoustic waves with sandy sediments. A data set of over 5000 pings was taken which spanned a frequency range of 4.5 to 50 kHz and a grazing angle range of 10 to 89 degrees. The conditions at SAX04 were less than ideal and precluded the measurement of the interface roughness using the laser light scan method.

Development of a grain rolling and sliding theory to account for the decrease in sound speed at low frequencies.

In SAX99, low frequency sound speed measurements indicated sound speeds which were less than the Wood's equation, the theoretical lower limit of sound speed in unconsolidated sediments. These measurements were confirmed in SAX04 by Hines, Osler and Lyons. [Hines, 2005.] A theory has been advanced suggesting that this could be caused to a reduction in the fluid bulk modulus due to benthic activity. [Stoll, 2002.] In our theory, the low sound speeds are accounted for by including an additional terms in the kinetic energy term due to grain rolling and sliding. This theory has been developed for unconsolidated sediments with air as the interstitial fluid and sound speed reductions on the order of those measured at SAX99 and SAX04 have been obtained. This year, the grain rolling theory was extended to included slippage at the grain contacts. With the slippage extension, the theory challenges the traditional method of determining Poisson's ratio for an unconsolidated frame. We will be advancing the theory to water saturated sediments in the future.

Laser Light Sheet Improvements and calibration data collection at NWSC-PC

In order to quantify the effects of rough interface scattering, the profile of the interface must be obtained. We have improved the laser light sheet method of profiling the water/sand interface that works well *in situ*. The entire system is mounted on the ROV. This year we have researched methods of tracking the ROV position using the correlation of the images obtained. This method has been shown to track the ROV motion with greater than centimeter accuracy.

ROV-mounted laser light sheet data were collected at NWSC-PC for comparison with other interface roughness measurements. A full set of calibration data were taken including data from the ARL-UT test piece, the simulated ocean bottom from APL-UW and IUT, Taiwan as well as data from a rippled surface in the NSWC-PC test pond.

Development of an x-ray device to measure the density of the transition layer.

An accurate *in situ* measurement of the bulk density of the transition layer is critical to the interpretation of the data. Previously, bulk density measurements were either taken from scans of cores which disrupted the natural grain assembly or conductivity probes in which the density is measured indirectly. Therefore, a novel means of determining the density gradient *in situ* using x-ray attenuation was developed. The x-ray attenuation device was tested with several liquids and the attenuation was found to vary with molecular composition. Also, significant x-ray hardening was measured and a new detector was designed and installed to account for this effect. A scheme to account for the variation was developed and applied successfully to modeled data.

Assembly and analysis of bottom scattering measurements

Work has commenced on the gathering of acoustic scattering data. The sediment acoustics conference in Bath was particularly useful in establishing collaborative links and developing new data sources. The SAX04 experiment is also a rich source of data, and the upcoming Shallow Water Experiment is also expected to provide more data. The objective is to build upon a small database that has already been assembled with data up to 1995, to produce a larger update data base that will be a definitive collection of the published sources to date. The analysis will be expanded to include a range of grazing angles (instead of just one) and correlations between backscattering statistics and geographical locations and water depth will be attempted. The results will impact Navy high frequency scattering models.

The inversion of laboratory reflection data using current acoustic models and verification through inversion of simulated data.

Laboratory data were inverted for sediment parameters using three sediment representations: fluid, vico-elastic and poro-elastic. For the poro-elastic representation, it was hypothesized that the sensitivity of the inversion may be frequency dependent for certain parameters. This was verified using simulated data.

RESULTS

Analysis of laboratory data to confirm analytic models of spherical wave effects and quantify effects of bulk property variations.

The laboratory reflection coefficient measurements confirmed the spherical wave models. (See Figure 1.) However, the measurements also exhibited a large variance. The variation in the data as measured by the scintillation index had a large frequency and angle dependence (See Figure 2.) It is unlikely that the variation is caused by the interface scattering since the interface had less than a 0.5 mm RMS height variation. The large data variance also cannot be explained from bulk sediment variations using traditional models. Using traditional models, the data variance implies a 230% change in the local impedances, indicating unphysical sound speeds or densities of 1200 to 3200 m/s or 0.9 to 5.4 g/cm³ respectively. New models of the acoustic sediment interaction such as the BICSQS model may be able to account for these variations. (Chotiros and Isakson, 2005.) However, more work is required in this area to understand the physical nature of the variation and the implications to long range propagation in shallow waters.

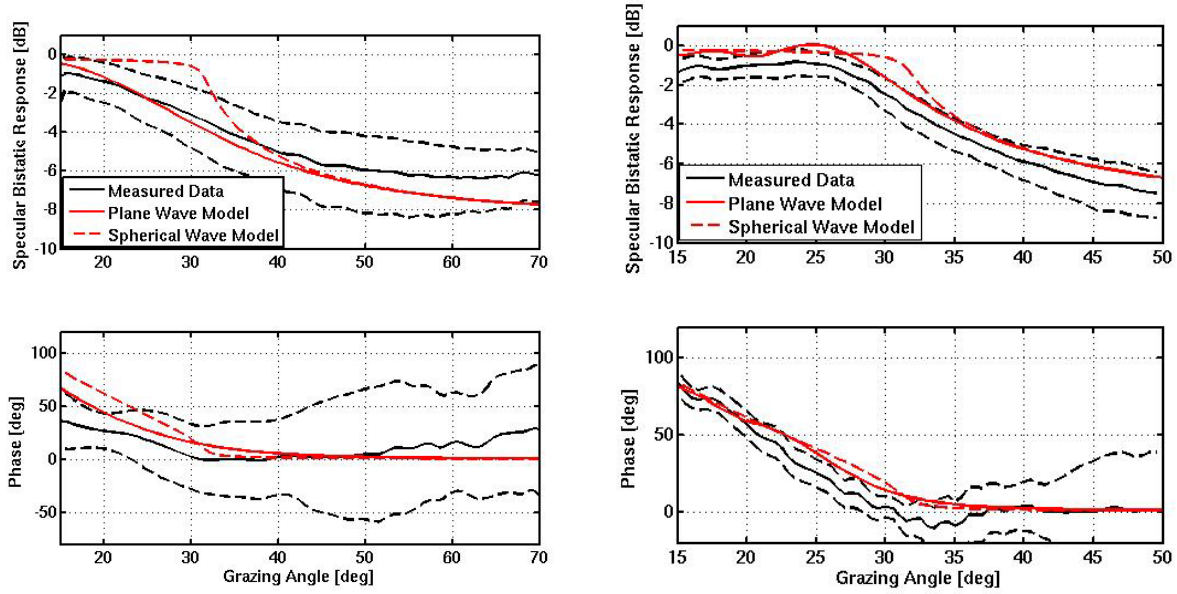


Figure 1: Specular bistatic response as a function of grazing angle at 54 kHz for a range of 0.25 m and 1.27 m. The closer range exhibits severe spherical wave effects including a large decrease of the apparent critical angle. The spherical model is calculated using plane wave decomposition.

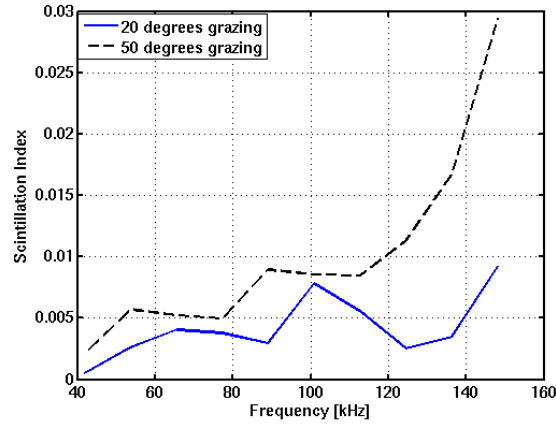


Figure 2: The scintillation index as a function of frequency at two different values of the grazing angle. The variation in the data is much larger than expected for the interface conditions.

Analysis of SAX04 reflection coefficient data which revealed effects of rough interface scattering and layering.

The reflection coefficient measurements from SAX04 exhibited evidence of layering and high variance. The layering was evident in the analysis of the time of arrival of the reflected pulse as shown in Figure 3. The interface scattering could contribute to the large variance in the data as represented by the scintillation indices in Figure 4. Although the interface scattering likely played a large role in producing the data variance, the scintillation indices measured are not consistent with rough interface scattering. The expected scintillation index for the SAX04 interface conditions was calculated using the Bottom Response from Inhomogeneities and Surface using Small Slope Approximation (BoRIS-

SSA) code developed at the NATO Underseas Research Center. It exhibits a large frequency dependence. Yet the SAX04 data scintillation index does not. This may be related to the large variance found in the laboratory measurements. Research into the origin of this data variance will be investigated in the upcoming year.

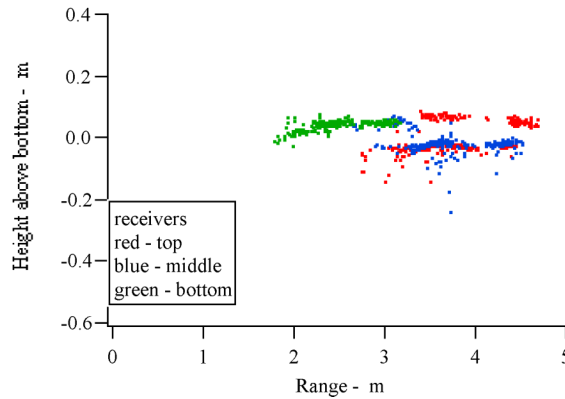


Figure 3: Time of return for the high frequency chirp from SAX04 data. The two different return times imply a ~10 cm layer is present.

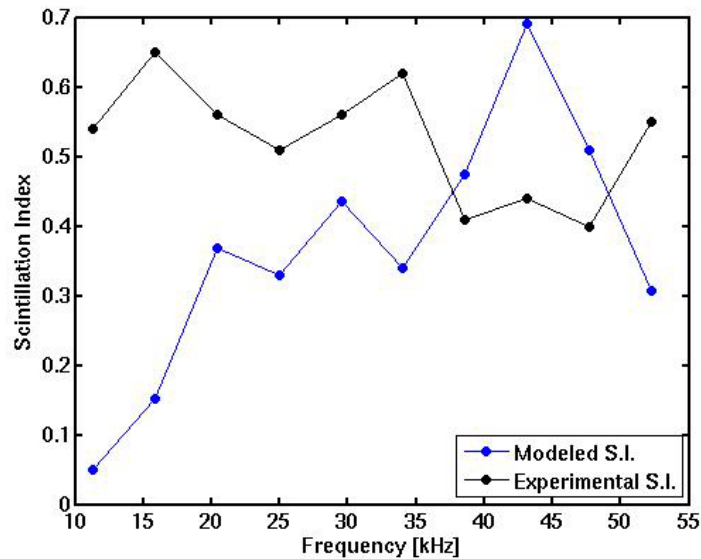


Figure 4: The scintillation index from the reflection coefficient measurements as compared with the expected scintillation index. The SAX04 data have significantly higher variation in the low frequencies.

Laser Light Sheet Improvements and calibration data collection at NWSC-PC

Successive images were analyzed from the ROV mounted laser light sheet apparatus. These images were correlated to provide a measurement of the ROV motion. (See Figure 5.) This correlation tracked the motion of the ROV with greater than centimeter accuracy. This method will be used to analyze the data taken at the NSWC-PC test pond.

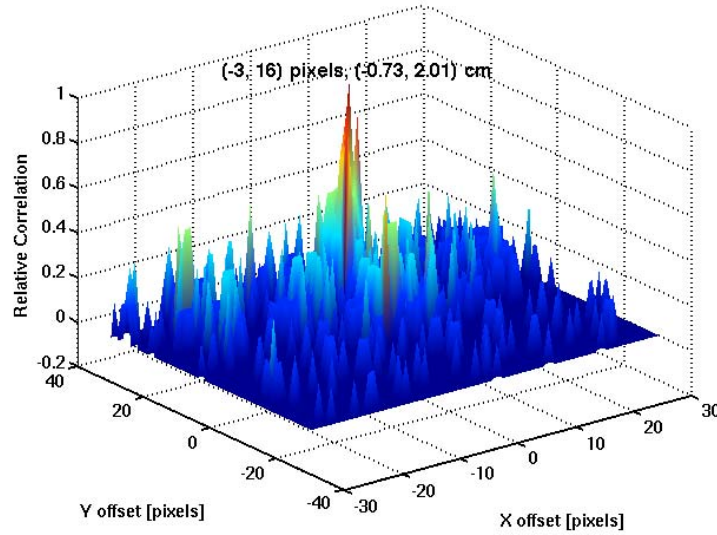


Figure 5: The correlation of two successive images of the ROV mounted laser line scan system. The correlation indicates an ROV motion of 0.73 cm South and 2.01 cm East.

Measurement of Sediment Density as a Function of Depth

The XRAM system was used to measure the bulk density of water, methanol and castor oil. A significant effect due to molecular composition was found. It was determined that this dependence on molecular composition is due to the photo-electric effect. Data were also taken on a water/saturated glass bead interface. (See Figure 6.) The data were successfully modeled using the known attenuation curves including the photo-electric effect. Using this knowledge, the modeled data were inverted for sediment density as a function of depth. (See Figure 7.) Due to variations in the source spectra, experimental data has not yet been inverted but we expect experimental inversions for density gradient by December 2005.

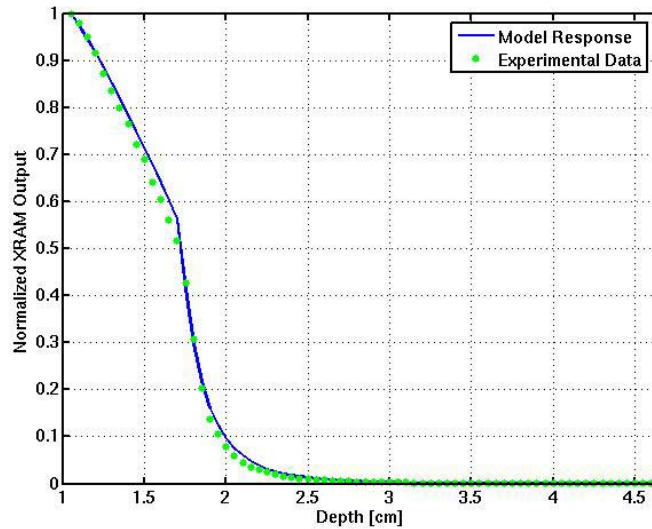


Figure 6: The measured x-ray attenuation vs depth for the water/saturated glass bead interface. The model response is also shown and accurately predicts the data.

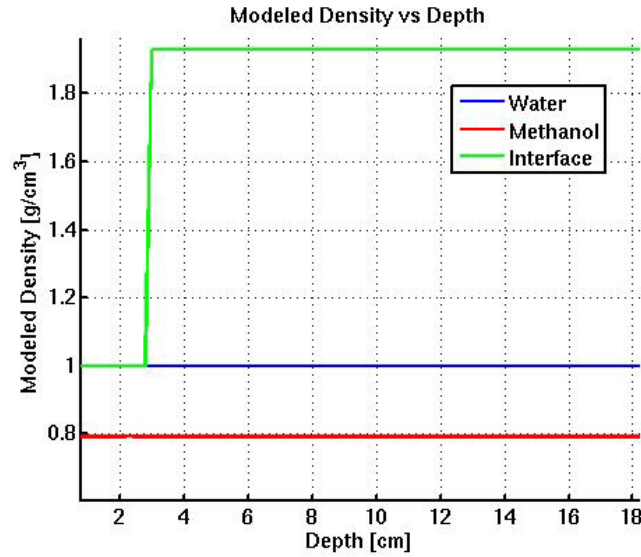


Figure 7: The modeled x-ray attenuation data inverted for depth dependent density.

Development of a grain rolling and sliding theory to account for the decrease in sound speed at low frequencies.

The extension of the grain rolling theory to include slippage has important implications for the values obtained for Poisson's ratio for an unconsolidated frame. Shown in Figure 8 are values for Poisson's ratio from traditional analysis (a) and for the grain rolling theory (b) with and without slippage. From the figures, one can see that including grain rolling and slippage can significantly alter the value for Poisson's ratio. This work has been submitted to the Journal of the Acoustical Society of America for consideration. [Chotiros and Isakson, submitted.]

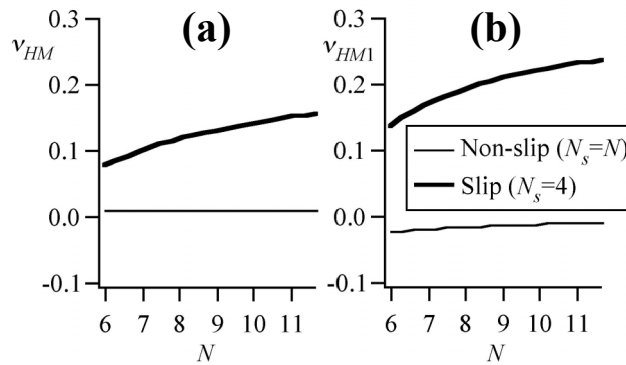


Figure 8: The value of Poisson's ratio as calculated using traditional analysis from measurements (a) and grain rolling theory (b) with and without slippage.

The inversion of laboratory reflection data using current acoustic models and verification through inversion of simulated data.

The inversion of laboratory reflection data produced unphysical parameters when the sediment was represented by a fluid or visco-elastic model. The poro-elastic parameters were within physical bounds, and the permeability, tortuosity and porosity were determined with greater than 15% accuracy.

This is consistent with results from simulated data in the same frequency range which suggested that only permeability, porosity, fluid bulk modulus and the frame moduli were most sensitive in this frequency band. Tortuosity was also found to be sensitive but in a lesser degree. No known values for the frame moduli were available to confirm the accuracy of the frame parameter inversion.

IMPACT/APPLICATIONS

All of the current standard acoustic propagation and scattering models that have been accepted and certified by the Navy's Ocean Acoustic Mathematical Library (OAML) approximate the ocean sediment as a visco-elastic medium. This study has identified deficiencies with that approximation and an improved model has been developed. The model developed by this study predicts significant reflection loss at sub-critical angles which impacts long-range propagation models in ASW applications, particularly in littoral environments where the propagation loss is largely controlled by bottom reflection loss. Lastly, the grain rolling theory questions the validity of the current method of determining sound speed at low frequencies and the Poisson's ratio of unconsolidated sediment.

RELATED PROJECTS

This project is closely related to other projects under the ONR "High Frequency Sediment Acoustics" thrust since the environmental inputs required for analysis are dependent on other projects within the thrust. We collaborate with the NATO Undersea Research Center to use the SSA algorithm to calculate the contribution from scattering in the measured pressure of our experiment. The inversion technique used was developed under the Environmentally Adaptive Shallow Water Signal Processing project. Similarly, the results of this project have led to a more accurate model of bottom reverberation to aid in locating and identifying shallow water targets under that program.

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