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 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: development of a broadband the oretical model to describe the acoustic interaction with the ocean floor in littoral environments, measurements for model verification and the application of new inversion techniques for model verification. For broadband model development, we not only concentrated on capturing the salient features of the dispersion, attenuation and reflection measurements from SAX99 (Williams. 2002), but also other available data sets from Hamilton (Hamilton, 1980), Nolle, Hoyer, Mifsud, Runyan, and Ward (Nolle, 1963), Thomas and Pace (Thomas, 1980), Simpson and Houston (Simpson, 2000), and Turgut and Yamamoto (Turgut, 1990). This effort was led by Marcia Isakson (ARL:UT).
Although the measurements for dispersion and attenuation at SAX99 spanned a large frequency range, the reflection measurements were only taken at normal incidence and over a limited frequency range. Therefore, our second approach is to develop a method of measuring reflection coefficients over a broad frequency and angle range to provide a third complete data set for model development. 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. Through literature research and laboratory testing, it was determined that reflection measurements can be severely influenced by interface scattering, effects resulting from using spherical transducers and transition layer effects. Therefore, an effort has been made to quantify these effects. The reflection coefficient measurement effort was led by Marcia Isakson (ARL:UT).
Finally, the reflection data set is suitable for inversion since reflection coefficient measurements have a high number of unique measurements, one for each frequency and angle measured. (In the laboratory, there are typically 900 unique measurements for 60 angles at 15 different resolvable frequencies with

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14. ABSTRACT

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current data analysis techniques. At sea, the frequency range will be much larger.) Therefore, an effort has been made to improve the accuracy and speed of reflection coefficient inversions for model testing and verification. This effort was led by Marcia Isakson (ARL:UT) and Trancianne Neilsen (ARL:UT).

WORK COMPLETED

The main achievements of 2003 include:
1) Broad band acoustic modeling.
2) A faster inversion process.
3) Laser light sheet improvements.
4) Quantization of effects due to using spherical transducers. Achievements 1 and 2 significantly improve our ability to model the acoustics of ocean sediments. Achievements 3 and 4 are expected to give us new capabilities in the upcoming SAX04 experiment.

Broadband Acoustic Modeling

The dispersion was explained in terms of the Biot-squirt flow (BISQ) model of Nur and Dvorkin. (Dvorkin, 1993.) By expanding the BISQ model to include the effects of viscous drag on the shear modulus (BISQS), the observed diverse behavior of the attenuation was also correctly modeled. The effects of the presence of microscopic gas bubbles were included as suggested by Stoll. (Stoll, 2002.) Also incorporated in the model was a departure from the constant flow value for permeability since the permeability in high frequency acoustics may be very different than constant flow.(Chotiros, submitted.)

Inversion

It was determined that the current inversion scheme was extremely inefficient for two reasons. First, the algorithm relied on writing out and reading in files for every iteration. Second, the search algorithm was less efficient than current available algorithms. We have developed a method of accessing the components of OASES in a more efficient manner and are working on calculating the reflection coefficients within the inversion code to eliminate the need of using OASES. Second, we have incorporated rotated coordinates to our simulated annealing algorithm to improve the efficiency of the search algorithm.

Rough Interface Scattering Effects

In order to quantify the effects of rough interface scattering, the profile of the interface must be obtained. We have improved and calibrated a laser light sheet method of profiling the water/sand interface that works well in the laboratory. A calibration piece was constructed to cover the spatial frequencies of 0.1 to 1 cycles/cm. The system may also be mounted on our ROV for field applications as it was for SAX99. The system has now been incorporated with the data acquisition system for real time bottom profiling.

Preliminary calculations were performed to determine the effects of interface scattering on laboratory measurements. An effort was made to extend the equations developed by Chotiros (Chotiros, 1994) for normal incidence over the entire angle range. The results were compared with reflection coefficient measurements taken in the ARL:UT laboratory.

Spherical Wave Effects

Calculations were made to estimate the contribution of spherical wave effects in our reflection coefficient measurements for a number of different frequencies and experimental geometries. The calculations were performed using plane wave decomposition. It has been determined that the predominate effect is due to interference with the head wave. Since spherical wave effects are highly dependent on the phase of the reflection coefficient, these effects may be exploited to obtain information about the phase of the reflection coefficient. Calculations for fluid and visco-elastic models of the ocean floor have been completed. A Biot-Stoll model is being constructed. Laboratory tests are being initiated to verify the results.

RESULTS

Broadband Modeling Results

The results of the BISQS model for the SAX99 data set are shown in Figure 1. Also shown in the figure is the Biot-Stoll poro-ealstic model using the parameter set from Williams, 2002. The Biot-Stoll model does not predict the low wave speeds at low frequencies or the high attenuation at high frequency. Previously, the low wave speeds have been explained by a decrease in the fluid bulk modulus due to the presence of gas bubbles produced by benthic activity. (Stoll, 2002.) This is a plausible explanation and the concentration of gas required is below that which could have been measured at SAX99. This idea of a lower fluid bulk modulus has been incorporated into the BISQS model. The high attenuation at high frequencies has been previously explained by scattering. This is unlikely for two reasons. First, Rayleigh scattering indicates an f^4 dependence. The observed attenuation does not go as f^4. Second, if the attenuation was due to scattering from grains, it should increase with increasing grain size. The opposite has been observed experimentally. (Thomas, 1980 and Nolle, 1963.) Lastly, if the observed loss is due to scattering from large volume inhomogenieties, this would be a forward scattering phenomenon and there would be no net loss of energy. Therefore, on average the attenuation would not be affected. Therefore, there must be another mechanism for the loss. The viscous drag on the shear modulus as provided for within the BISQS framework offers a plausible solution.

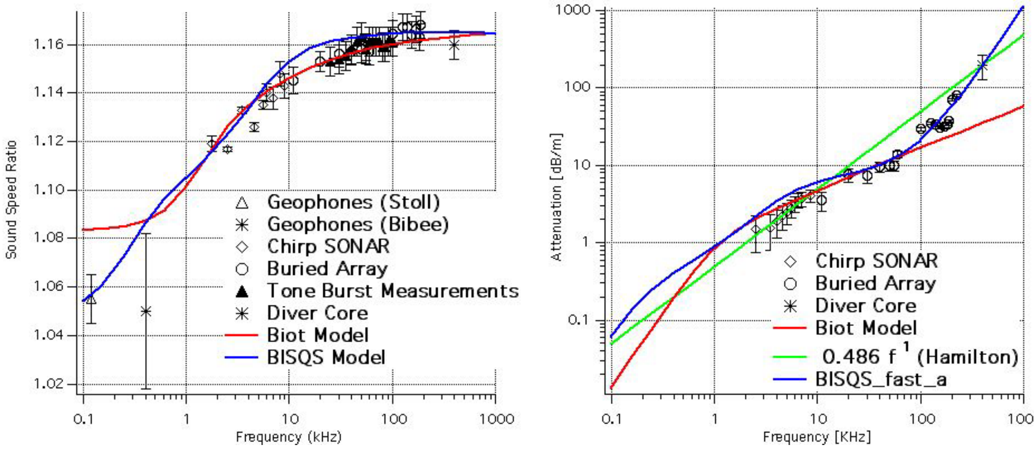

Figure 1: Dispersion and attenuation data from SAX99 modeled with the Biot model with the Williams parameter set (Williams,2002) and the BISQS model (Chotiros, submitted). Also plotted is Hamilton's empirical model for attenuation (Hamilton, 1980).

Inversion Results

The inversion code is currently being verified. Therefore, we do not yet have inversion results.

Laser Light Sheet Calibration Results

The laser light sheet method of determining the profile of the sand/water interface was calibrated using a calibration piece specially designed to capture the spatial frequencies between 0.1 and 0.8 cycles/cm. The piece was specially machined from aluminum and then anodized so as to have approximately the same reflectivity as the ocean floor. The profile of the calibration piece is shown in red in Figure 2. The data obtained by the laser light sheet method is shown in blue. As one can clearly see in the figure, the laser light sheet method correctly measures the peak heights to within about 1 mm for spatial frequencies up to 70 cycles/m. This method will allow us to profile the bottom *in situ* to obtain relief statistics for scattering calculations.

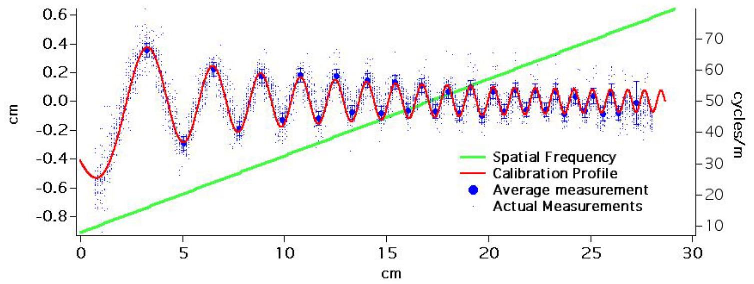

Figure 2: Calibration of the Laser Light Sheet Method of Bottom Profiling

Scattering Calculation Results

We have extended the scattering calculations from Chotiros, 1997 over the entire angle range. When compared to laboratory data taken on a smoothed water sand interface, we obtained comparable results. (See Figure 3.) The next step is to measure the reflection coefficient from a roughened surface and compare with our model. We plan to extend our model by using the small slope approximation (SSA) algorithm developed at SACLANTCEN.

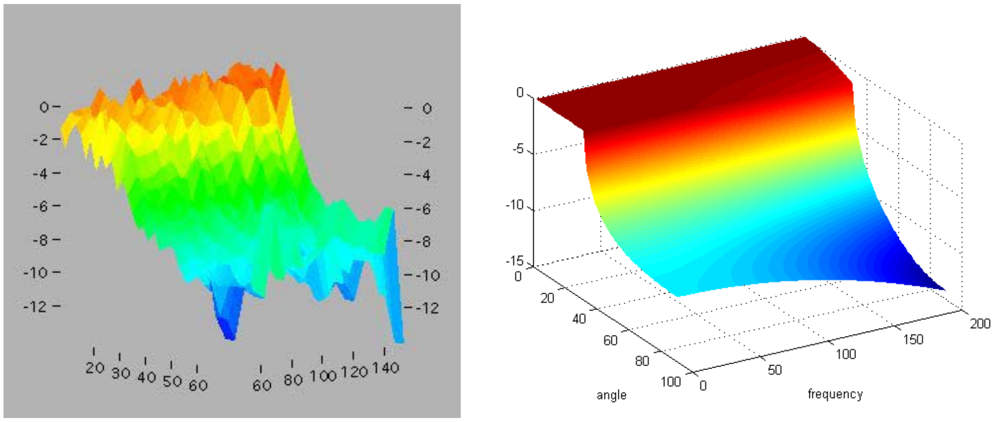

Figure 3 : (R) Lab data taken from the ARL:UT sand tank on a smoothed water/sediment surface. (L) A calculation of the contribution from scattering for a roughness of 0.09 cm and a correlation length of 10 cm using the second moment of the scattering integral

Spherical Wave Effect Calculation Results

We have calculated the contribution of error in our reflection coefficient measurements from spherical wave effects. The dependence on experimental geometry and frequency are quite severe. In Figure 4, the pressure measured (normalized for spherical spreading) is shown alongside the actual reflection coefficient for a visco-elastic model. In the absence of spherical wave effects, the pressure measured would be the same as the reflection coefficient. As one can see for a low frequency such as 4 kHz and a small separation distance of 1m, the spherical wave effects are quite severe. This should be measurable. As the distance between the transducers and the frequency increase, the pressure measured approximates the plane wave reflection coefficient. Therefore, we can both measure the true reflection coefficient by ensuring the transducers are far enough apart for the frequency being tested and at closer distances we may be able to use the spherical wave effect to obtain information about the phase of the reflection coefficient.

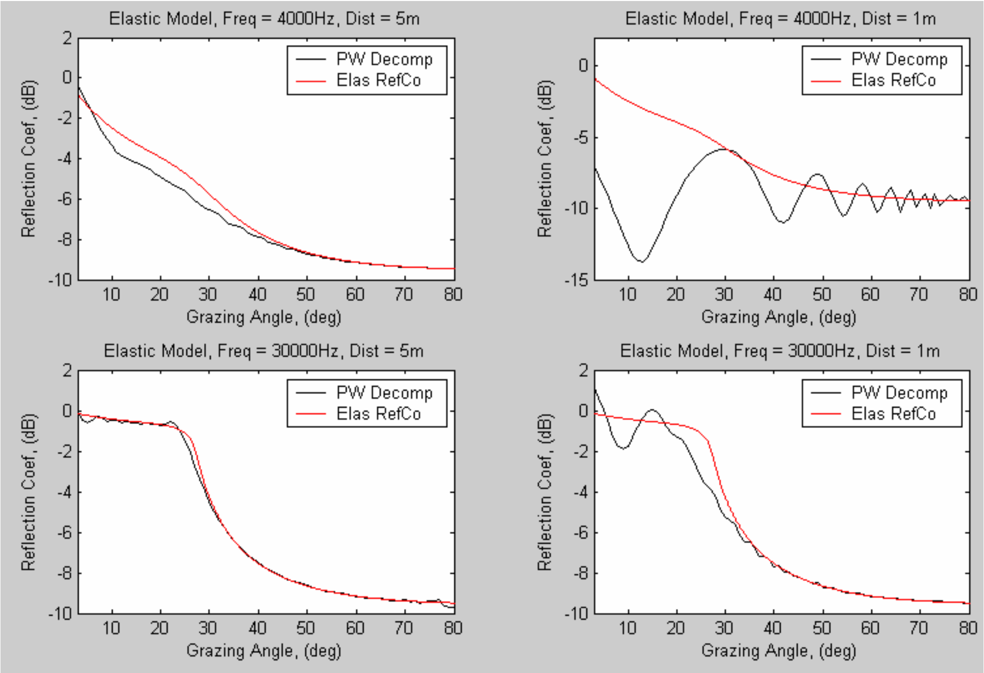

Figure 4 : Reflection coefficient (red) and measured pressure (black) are shown for a two experimental geometries. On the right, the transducers are 5 m apart and on the left, the transducers are 1m apart.

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.

RELATED PROJECTS

This project is closely related to other projects under the ONR "High Frequency Sediment Acoustics" DRI since the environmental inputs required for analysis are dependent on other projects within the DRI. A joint sea test with the Groupe d'Etude Sous-Marine d'Atlantique (GESMA) in Brest, France and Ecole Navale et Groupe des Ecoles du Poulmic is planned for June 2004 to measure the reflection coefficients from the ocean floor in the bay of Brest. We are in contact with SACLANTCEN to obtain and 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. Lastly, this study is closely connected with the electro-kinetic study being conducted here at ARL:UT, which may shed light on the fluid properties important in the squirt flow mechanism.

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