High Frequency Acoustic Reflection and Transmission in Ocean Sediments

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Award Number: N00014-03-1-0242, N00014-06-1-0766
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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

1) A comparative study of acoustic sediment interaction models including visco-elastic, Biot, BICSQS, and grain shearing and scattering models including perturbation theory, small slope approximation and finite element models through careful comparison with experimental measurements of the bistatic return, for the purpose of defining the best physical model of high-frequency acoustic interaction with the ocean floor. The demonstration of an inversion method to determine sediment parameters from reflection coefficient measurements.

2) An inversion methodology that can provide input parameters of the resulting physical model from reflection coefficient measurements.

3) New finite element modeling capability for acoustic sediment interactions.

4) A high-frequency bottom scattering database that will reveal physical processes and regimes and provide guidance to application of existing models and new model developments.

APPROACH

Our approach to this problem has five distinct areas of concentration: 1) Continued analysis of the ARL:UT SAX04 data set, to provide a solid foundation of in-situ acoustic measurements for model development. 2) Preparation for Experimental Validation of Acoustic modeling techniques (EVA) sea test in collaboration with the NATO Undersea Research Centre, which will further expand our database of in-situ acoustic measurements, 3) Development of a finite element model of scattering from rough interfaces, as an aid to understanding difficult physical phenomena that are beyond the capabilities of existing models, 4) Improving the methodology for the inversion of reflection coefficient data to overcome the effects of propagation and scattering and 5) Assembly of high-

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **High Frequency Acoustic Reflection and Transmission in Ocean Sediments**	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 Texas at Austin,Applied Research Laboratories,P.O. Box 8029,Austin,TX,78713-8029**	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

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)**	**11**	

frequency bottom scattering database that will reveal physical processes and regimes and provide guidance to application of existing models and new model developments.

WORK COMPLETED

The main achievements of 2006 and their associated tasks include:

1) Separation of the reflection from two bottom interfaces in the SAX04 reflection data set. Measurement of transmission loss through the sediment from the ARL:UT SAX04 data set. (Task 1.) This effort was led by Marcia Isakson.

2) Development of an acoustic reflection measurement method and laser profiling improvements for the EVA sea test. (Task 2.) This effort was led by Marcia Isakson and Nicholas Chotiros.

3) Development of a Finite Element Model (FEM) to model reflection and bistatic scattering, that has confirmed the spherical wave model of acoustic reflection at short range. (Task 3.) This effort was led by Marcia Isakson.

4) Measurement of reflection coefficient statistics, as a first step in the determination of the role of measurement statistics in inversion methodology. (Task 4.) This effort was led by Marcia Isakson.

5) Assembly of high-frequency bottom scattering database that will reveal physical processes and regimes and provide guidance to application of existing models and new model developments. (Task 5.) This effort was led by Nicholas Chotiros.

SAX04 Analysis.
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. From the data, two reflection coefficients were determined, one from a surficial layer of organic material and one from the underlying sediment. The transmission measurements were analyzed considering the sediment to be completely homogeneous sediment or homogeneous covered by a surficial mud layer.

EVA Sea test.
The Experimental Validation of Acoustic modeling techniques (EVA) sea test will take place in October 2006. The ARL:UT EVA data set will include reflection coefficient measurements coupled with fine scale roughness measurements. These measurements will aid in the verification of interface scattering models such as the Bottom Response from Inhomogeneities and Surface using the Small Slope Approximation (BoRIS-SSA) model from NURC and the FEM being developed at ARL:UT. The reflection coefficient measurements will be taken from the R/V Leonardo using a single source and four receivers. This setup will provide a set of reflection measurements from 7 to 70 degrees. Furthermore, a signal was developed to span the frequency range from 4 to 50 kHz, the transition region in poro-elastic theory for sandy sediments. The signal compensates for both the sending and receiving transducer response by increasing the number of cycles at frequencies that typically have low responses. The new signal has changed the dynamic range of the frequency response from 50 dB to 15

dB, a substantial improvement. Use of this signal will allow a very broad range of frequencies to be probed both at the same time and place.

The laser bottom profile system was also improved by adding additional lasers, powering the lasers directly from the ROV and improving the camera frame rate.

Finite Element Modeling.
A time harmonic finite element analysis was performed using the Comsol acoustics 2D axial symmetry application mode. A point source was located nominally 10 cm above a water/sand interface. Both half spaces were modeled as fluids using the laboratory parameters described in Camin and Isakson (2006). The unbounded geometry of the physical model had to be artificially truncated. In order to minimize reflections from these unphysical boundaries, sponge layers were added to attenuate the radiating waves. (Zampolli, 2006) The surrounding sponge layers have the same parameters as their adjacent interior domains except for the sound speed which assumes an imaginary part to introduce damping. The reflections introduced by the artificial truncation boundaries are most prominent from incident waves which approach near grazing. For this reason, we chose a circle centered on the source point as the domain boundary and a concentric annulus for the sponge layer. In the annular sponge layer the imaginary part of the sound speed is ramped up with distance from the origin, having a value of 0 at the inner radius. The ramp function we used had continuous derivatives to second order. For grazing incident radiation, this form of ramping function was found to diminish the reflections introduced by the truncation of the domain by 15 dB when compared to a linear ramp.

The model was calculated using time harmonic analysis. Then, a time domain model was constructed by calculating the full complex field for a range a frequencies from 40 to 60 kHz using Fourier synthesis. Two two-layer cases were considered. One had a smooth water-sand boundary. The other had a rough water-sand boundary. The interface roughness was characterized by a Gaussian spectra with a 1 mm RMS height and a 1 mm correlation length. This roughness was chosen to mimic the laboratory conditions described in Camin and Isakson, 2006.

Reflection Coefficient Inversion.
Because numerous properties are employed to characterize the sediment in the various models under consideration and due to the complexity of how the properties affect the reflection of an acoustic signal, a Bayesian inversion technique (Dosso, 2006) has been applied to the laboratory data set from the ARL test tank to find reasonable estimate for the sediment parameters and the uncertainties associated with these estimates. One ingredient of the Bayesian inversion theory is that the probability density function (pdf) of the measurement errors must be specified. As described in Dosso, 2006, most reflection coefficient data sets do not have well characterized measurement errors. When the distribution of absolute measurement uncertainties is not available, techniques such as maximum likelihood estimation and treating uncertainties as nuisance parameters are employed. Because the ARL test tank data had 32 independent spatial measurements, a detailed analysis of the experimental results can be performed to determine the absolute measurement probability density function. Therefore, the structure of the measurement uncertainties was investigated and the impact of the error pdf on reflection coefficient inversion was considered.

Backscatter Database.
Building upon a small database that has already been assembled with data up to 1995, a larger update database is being assembled. It has already shown that there are 3 dimensionless frequency regimes, and two different mechanisms. The analysis is being expanded to include a range of grazing angles (instead of just one). Correlations between backscattering statistics and geographical locations and water depth will be attempted. Further analysis of existing models will be performed, leading to suggestions for new model development.

RESULTS

SAX04 Analysis.
The SAX04 data set was taken on sediment that was greatly influenced by a hurricane recent to the experiment. The area on which the measurements were taken had a layer of organic material that had a sound speed similar to that of the water column on top of a sandy sediment. The reflection coefficient measurements were influenced by this surficial layer. Shown in
Figure *1* are the differences in reflected path return times from the expected return time by range from the receiving array for the lowest receiver on the VLA. There are two arrival time groups, one from an upper layer, the organic material, and from a lower layer, the sandy sediment. Note how the highest frequency reflections are from the higher layer while the lower frequency measurements probe further into the sediment. Shown in Figure 2 and Figure 3 are the reflection coefficient measurements from the lower layer, arrival times after the expected arrival time, and the upper layer, arrival times before the expected arrival time respectively. The reflection coefficient measurement for the later arrival times has the same trends as have been observed in previous work both laboratory (Camin and Isakson, 2006.) and *in situ* (Williams, 2006.). These trends include a low reflection coefficient near normal due to poro-elastic effects. Also measured was a low reflection coefficient near grazing which may be due to influences from the surficial layer or interface roughness.

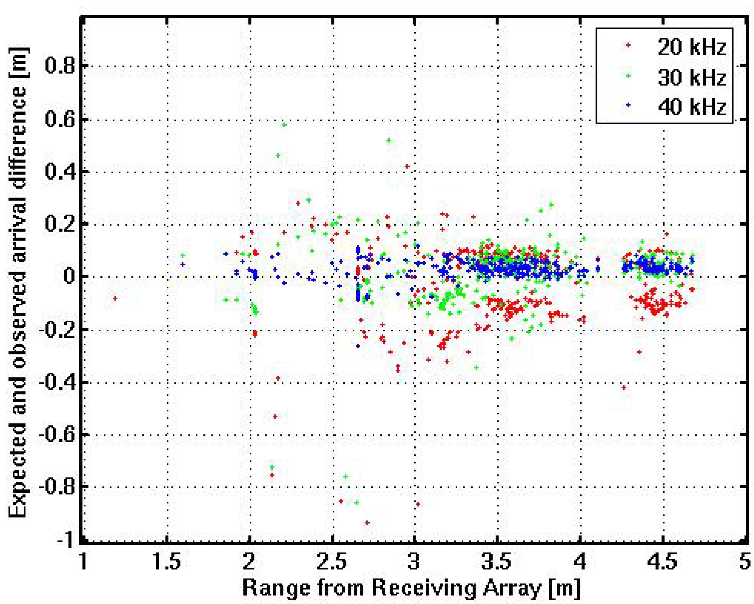

Figure 1: Differences in the expected and observed arrival heights for the lowest VLA receiver.

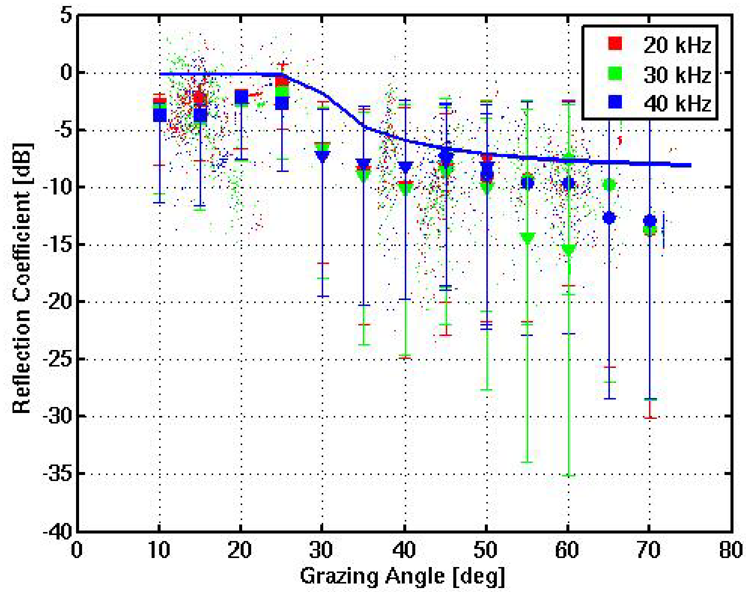

Figure 2: The reflection coefficient from the lower layer for three frequency bands compared to a visco-elastic model (blue line).

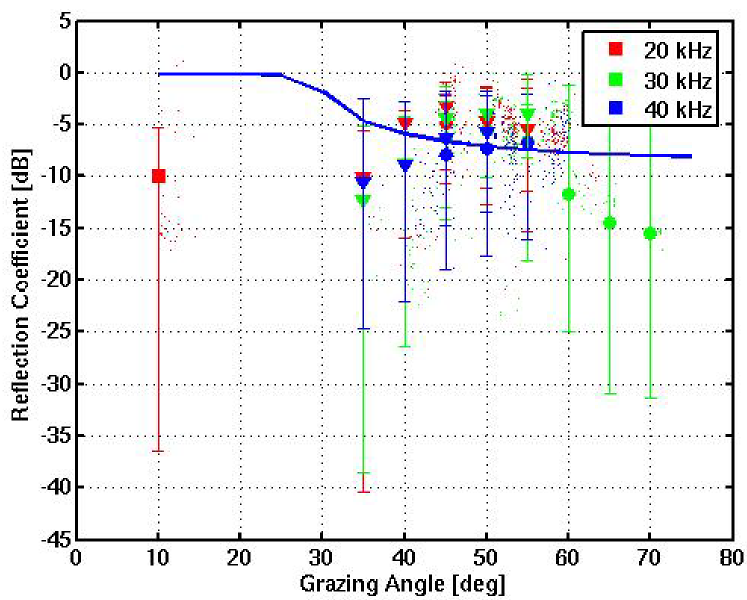

Figure 3: The reflection coefficient from the upper layer for three frequency bands compared to a visco-elastic model (blue line).

Transmission loss was also measured during SAX04 concurrent with the reflection coefficient measurements. First analysis on these data revealed that they were not consistent with a homogeneous description of the sediment. The data were also inconsistent with an overlying mud layer. Analysis of the transmission measurements to include measured topography from the reflection measurements and mud layers as measured by the NRL group (Briggs, 2005.) is ongoing.

EVA sea test.
The EVA sea test will take place in October 2006. No results from this sea test were available at the time of this report.

Finite Element Model.
Time domain solutions of the absolute pressure for both the smooth and rough sand-water interface finite element calculations are shown in
Figure *4* a,b and c,d respectively. Shown are both the full solution (a,c) and the solution with the free field subtracted from the upper (water) layer (b,d). The reflected path, direct path, and transmitted path are clearly visible.

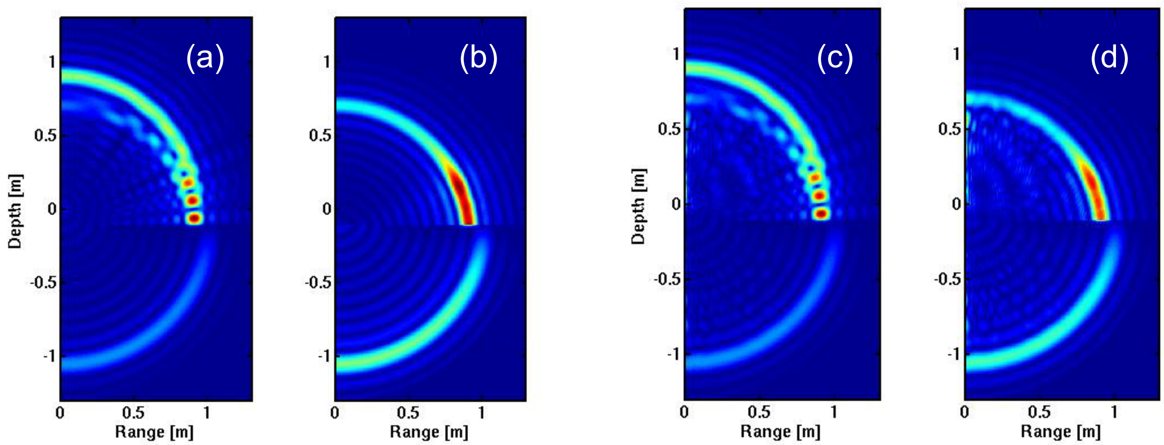

Figure 4: The absolute pressure field as calculated for finite elements for a smooth (a,b) and rough(c,d) interface. Fig. a and c are total fields, b and d have the free field subtracted from the upper layer to reveal the reflected path.

In Figure 5 is shown the FEM reflection coefficient from the smooth interface compared to the plane wave and spherical model. The spherical model is calculated using plane wave decomposition (PWD) as described in Brekhobskikh, 1980. The finite element model captures the features of the spherical reflection coefficient including the apparent reduction of the critical angle and the subcritical oscillations. For very low grazing angles, the finite element model and the PWD do not match precisely. In Figure 6 is shown the reflection coefficient from the finite element model compared to the laboratory data taken in the ARL:UT test tank and described in Camin and Isakson 2006. The model describes many of the salient features of the data set including the apparent low value of the critical angle and the increased uncertainty in the high grazing angles. However, the measured data exhibits low values of the sub-critical reflection coefficient that are not reflected in the model.

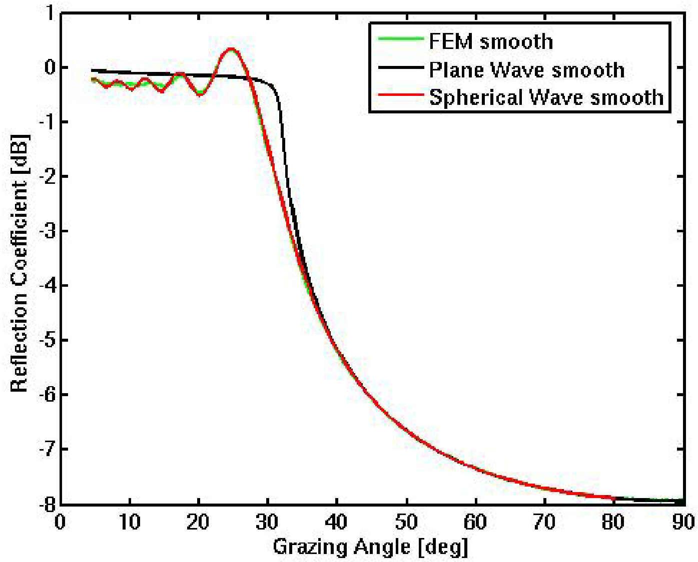

Figure 5: Finite element model from a smooth sand/water interface compared to a plane wave and spherical wave analytic model.

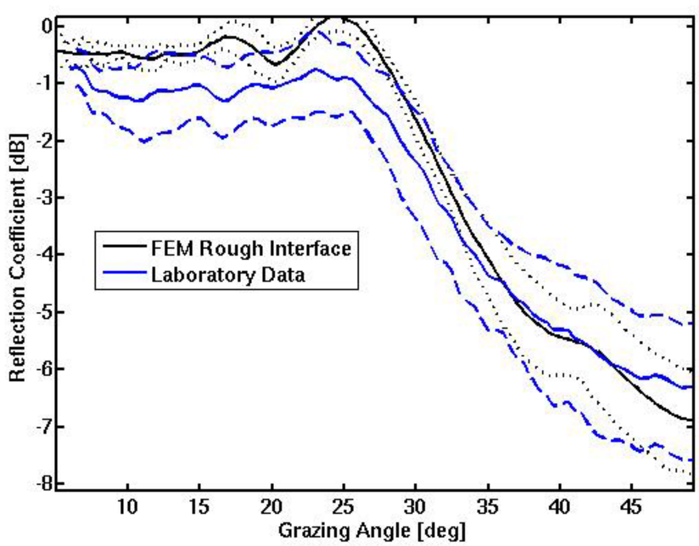

Figure 6: Laboratory data compared with FEM solution for the same geometry at 50 kHz. Reflection Coefficient Inversion.

The laboratory data set taken in the ARL:UT test tank allows the pdf of the measurement errors to be examined. Since the initial version of the Bayesian inversion that was applied to the tank data assumed a normal distribution of data errors, one must insure that the data errors are distributed normally to claim that the inversions estimates are reliable. If the data errors are not normally distributed, then the actual pdf is found from the data errors and included in the inversion process. Data errors were calculated as the normalized difference between the measured data point and the distribution mean, which were calculated for each angle and frequency. As an example, the error distribution for the entire data set is shown in Figure 7. The error distributions for the data as a function of frequency and angle were also computed. The pdf of the error distribution is difficult to ascertain by inspection.

However, the Kolmogorov-Smirnov test (KS test) can provide a quantitative test. The KS test is a comparison of an empirical distribution against a calculated distribution. In this case, the calculated distribution is the normal distribution. Shown in Figure 8 are the KS values for 5 degree grazing angle ranges from 10 to 50 degrees. Also shown is the KS value for the 95% confidence interval of 1000 random Gaussian distributed data sets. This value, shown in black, indicates the accepted KS value for the distribution to be Gaussian. As shown in the figure, low grazing angle errors are not distributed normally. Therefore, they should not be considered in current inversion methodology which assumes Gaussian error distribution. This is interesting since the low grazing angles have led previous inversions to accept high values of shear wave speeds. (Worley, 2004.) The non-normal error distribution for the low grazing angles could be indicative of higher order scattering processes from the interface roughness or angle dependent coupling into bulk modes.

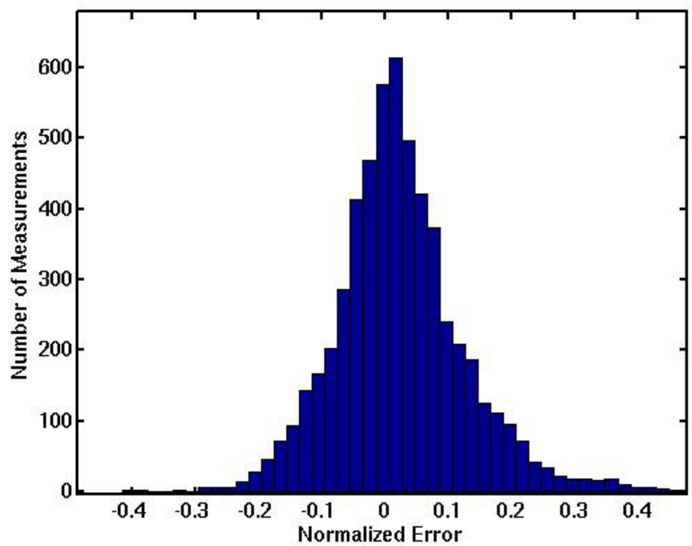

Figure 7: Distribution of data errors for the entire ARL:UT laboratory reflection coefficient data set.

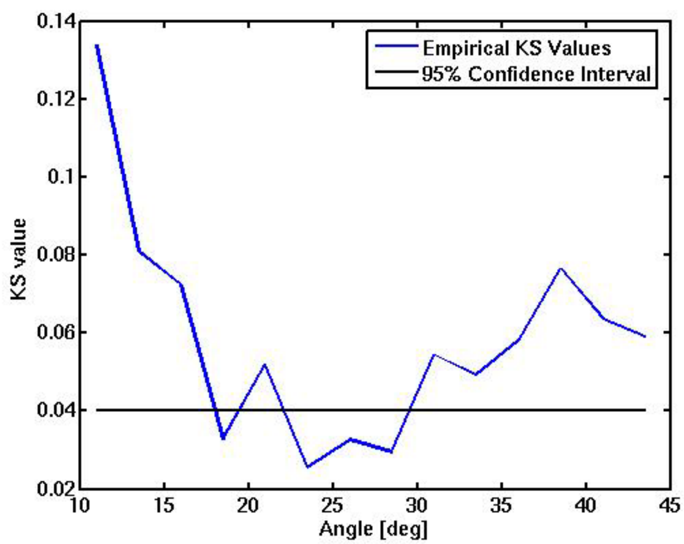

Figure 8: KS values for reflection coefficient errors as function of angle across frequencies.

Backscatter Database.
In the process of developing the new database, a number of issues relating the processing and classification of the data across different experiments and measurements methods were encountered. One such issue is described below.

Regarding the modeling and measurements of scattering strength, there has been some confusion about the data in the vicinity of the specular direction. The question is: Does the specular and near-specular data represent scattering or reflection? The former is treated as a random process while the latter as deterministic. This is illustrated by data from McKinney and Anderson 1964 in the figure below, but the issue can be seen in numerous data sets before and since.

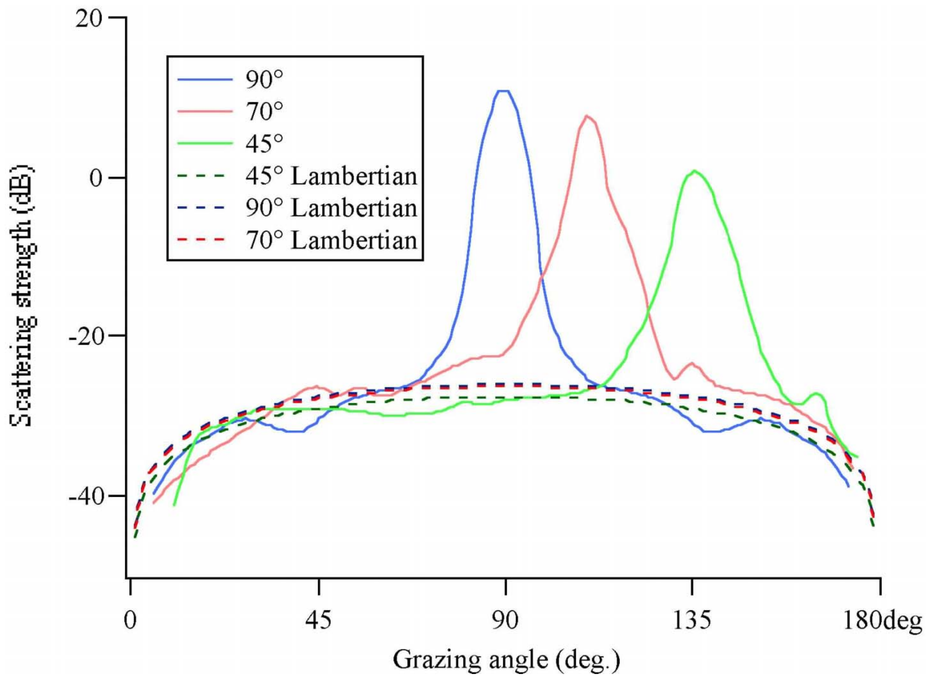

Figure 9: Bistatic data from McKinney and Anderson 1964 at 1 MHz showing three bistatic measurement curves at incidence angles 90°, 79° and 45°, measured relative to the horizontal, over a flat water-sand interface; sand mean grain size: 3.06 phi compare to best-fit Lambertian curves

This data set is particularly useful because it spans the whole range of bistatic angles, 0° to 180°. The data appears to be separable into a random scattering process that may be fitted to a Lambertian curve, plus a reflection component that peaks at the specular angle. The two processes have significant differences: (1) The level of the random scattering is dependent on beamwidth and pulse length of the measurement system, but the peak of the specular component is not. After normalization to compute the scattering strength, the magnitude of the specular component is no longer meaningful – it varies with pulse length and beamwidth. (2) The angular width of the specular peak mirrors the beam pattern of the measurement system, but the angular width of the scattering component is independent of beam width. Therefore, the two components should be modeled as two separate processes with different input parameters.

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. Also, this study shows significant variation in the reflection coefficient for even very smooth surfaces which can affect performance of current Navy models.

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. Additionally, we will collaborate with NRL, Stennis, MIT and NURC for the EVA sea test.

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