High Frequency Acoustic Reflection and Transmission in Ocean Sediments

Marcia J. Isakson
Applied Research Laboratories
The University of Texas at Austin, TX 78713-8029
phone: (512) 835-3790   fax: (512) 835-3259   email: misakson@arlut.utexas.edu

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 roughness and volume heterogeneities 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.

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.

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) Participation in the 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, and 4) Improving the methodology for the inversion of reflection coefficient data to overcome the effects of propagation and scattering.

Report Documentation Page

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

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
High Frequency Acoustic Reflection And Transmission In Ocean Sediments	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)	8. PERFORMING ORGANIZATION REPORT NUMBER
The University of Texas at Austin,Applied Research Laboratories,Austin,TX,78713	

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

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 roughness and volume heterogeneities and propagation within the sediment. The model will aid in the detection and classification of buried mines and improve SONAR performance in shallow water.

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)**	**15**	

WORK COMPLETED

The main achievements of 2007 include:

    1) Development of a statistical method of analysis for the SAX04 sea test data to isolate reflection from simultaneous processes in a complex environment.

    2) Participation in the EVA sea test which generated over 254,000 measurements of the reflection coefficient and the seafloor roughness.

    3) Preliminary analysis of the EVA sea test data including mean values and statistics of the magnitude and phase of reflection coefficient over an angle range of 7-70 degrees and a frequency range from 5 – 50 kHz.

    4) Development of a Finite Element Model (FEM) to model reflection and bistatic scattering from a rough sediment/water interface that uses interface statistics measured at the EVA sea test.

SAX04 Analysis.
Reflection measurements taken *in situ* at SAX04 to confirm models of the interaction of acoustic waves with sandy sediments were analyzed. The data set of over 5000 pings spanned a frequency range of 4.5 to 50 kHz and a grazing angle range of 10 to 89 degrees. The data were analyzed in nine frequency and 64 angle bins. The distributions of data for each angle and frequency bin were analyzed separately revealing that the reflection was occurring from patches of different types of sediment. Four different types of sediment were identified, water-sand, water-gassy sand, water-mud and mud-sand. Effects of a rippled interface were also identified. The method developed will be applicable to the parameterization of patchy ocean bottoms and in the development of methods to manage uncertainty in bistatic reflection for sonar performance modeling.

EVA Sea test.
The Experimental Validation of Acoustic modeling techniques (EVA) sea test took place in Biodola Bay of the coast of Isola d'Elba, Italy in October 2006. Reflection coefficient measurements were obtained by deploying a source and four receivers from the R/V Leonardo in the configuration shown in Figure 1. By changing the height of the source, reflection coefficient measurements were taken at an angle range of 7 –70 degrees. A previously described broadband signal was used to obtain a frequency range of 5-50 kHz for each ping. [Isakson(2006).]
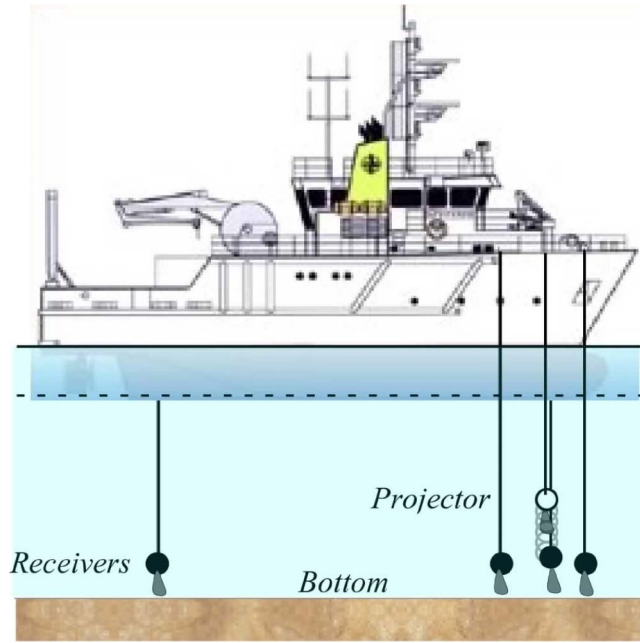
Figure 1: Experimental Set-Up for the ARL:UT EVA sea test.

The ARL:UT EVA data set contains over 254,000 reflection coefficient measurements coupled with fine scale roughness measurements. The fine scale roughness measurements were taken using a laser profiling system described in [Chotiros(2007)]. Additionally, calibration measurements were taken to determine the experimental beam pattern, frequency response and effects of propagation through the water column. The reflection data were analyzed to produce magnitude and phase of the reflection coefficient in 20 frequency bins by 40 angle bins. Significant spherical wave effects and interface roughness scattering were identified. An analytic model to correct for rough interface scattering was developed and applied to the data. [Isakson (2007).]

Finite Element Modeling.
The ARL:UT EVA experiment is being with finite elements using the Comsol 2D axial symmetry acoustics application mode. A spherical domain with a radius of 4.5 m was used to model the experiment. The water/sediment interface was modeled both as smooth and rough interface. The rough interface was simulated using an average power spectrum measured at the EVA sea test. Both the water and the sediment were modeled as non-attenuating fluids. The domain was truncated using perfectly matched layers (PML's). Comparison of the flat interface model with an analytic model revealed no effect from the truncation.

A time harmonic model was calculated for the entire field for each frequency from 5000 to 15000 Hz in 100 Hz intervals. These data were used to produce time series for receiver positions from 1 cm to 4 m from the source via Fourier synthesis. These time series were analyzed using the same data analysis method used with the experimental data to produce the magnitude and phase of the reflection coefficient. The results were compared with analytic models, OASES and the experimental data.

RESULTS

SAX04 Analysis.

The SAX04 data set was taken on sediment that was greatly influenced by a hurricane recent to the experiment. The hurricane created a complex environment which included deposited mud and gassy patches. An analysis of the time series of the reflection from the ocean bottom indicated that many of the data included both reflections from the top of the ocean floor and a buried layer. (See Figure 2.) These are labeled "early" and "late" arrivals respectively. The data were binned into distributions for nine frequency bands and 64 angles. An analysis of the distributions determined that they were multi-modal; therefore a simple mean and standard deviation were inadequate to describe the data. A typical distribution at 30 degrees and 26 kHz is shown in Figure 3. In order to uncover the constituent modes of the distribution, the data were parsed with a Gaussian distribution. The data parsing revealed up to four modes per bin. The mean value of these processes were plotted as a function of frequency and angle. (See Figure 4.) A comparison with calculated reflection coefficients revealed four processes in the data. These were reflection from sand, reflection from mud, reflection from gassy sand, and reflection from sand under a variable depth mud layer. These modes are indicated on the histogram in Figure 3. The reflection from gassy sand was further corroborated by analysis of the phase which revealed a 180 degree phase shift indicating reflection from a pressure release boundary. A distribution of these phase data are shown in Figure 5. Lastly, there were several anomalously high values of the reflection coefficient.   These were postulated to be an effect of the interface roughness. Specifically, a rippled interface can cause focus points of the reflection leading to high values of the reflection coefficient. This effect is shown graphically in Figure 6.
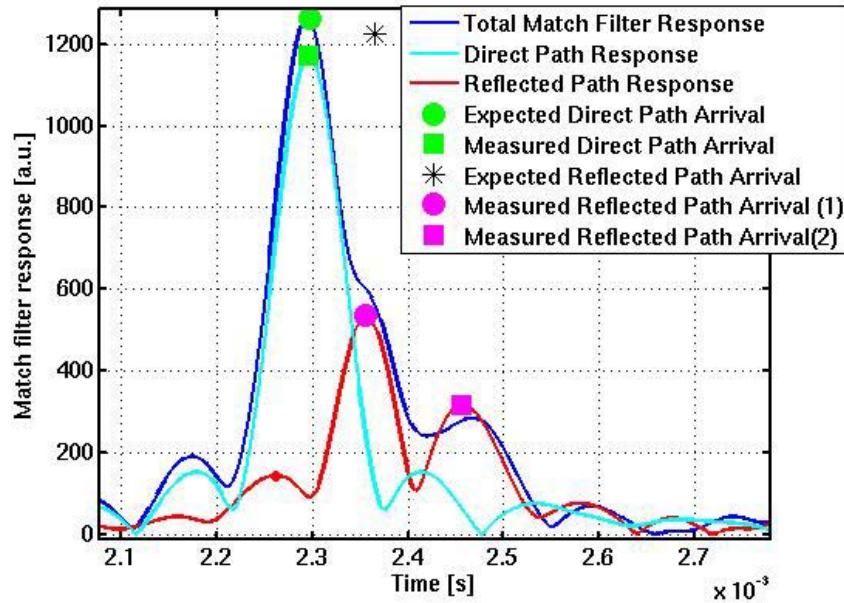

Figure 2: Measured time series of a reflection from the ocean bottom after match filtering with the expected arrival. In order to analyze the reflection, the direct path is subtracted from the total time series. (Result in red.) In addition to the direct path, a reflection from the top of the interface and a buried layer are clearly identifiable.
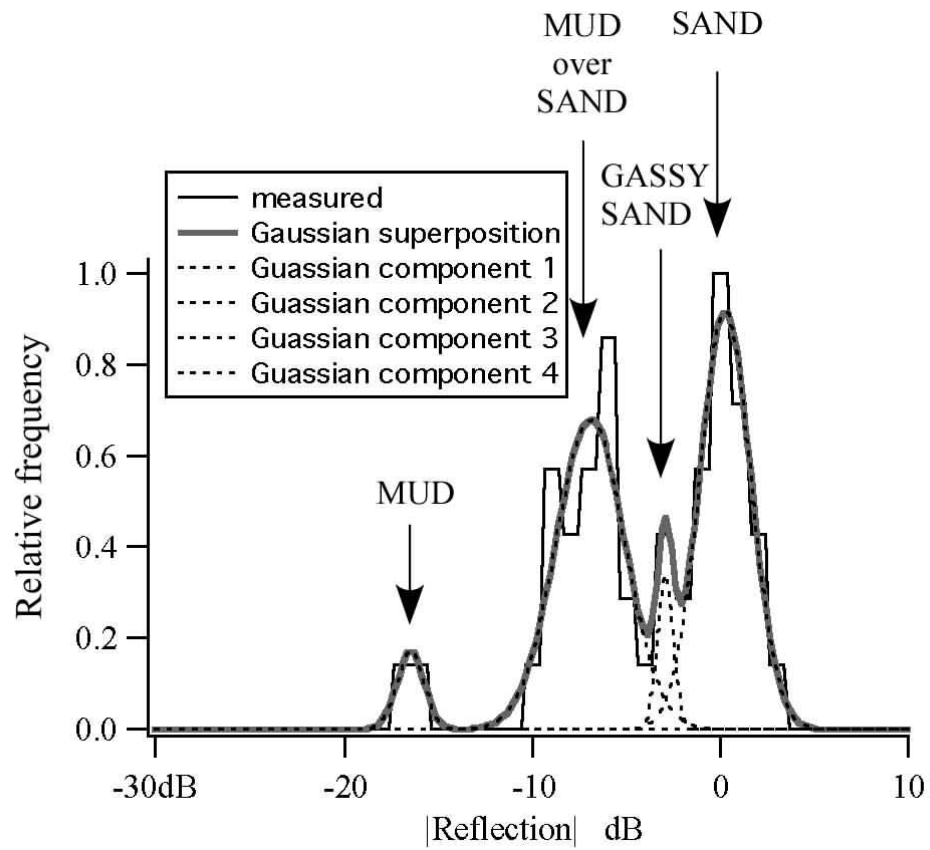
4

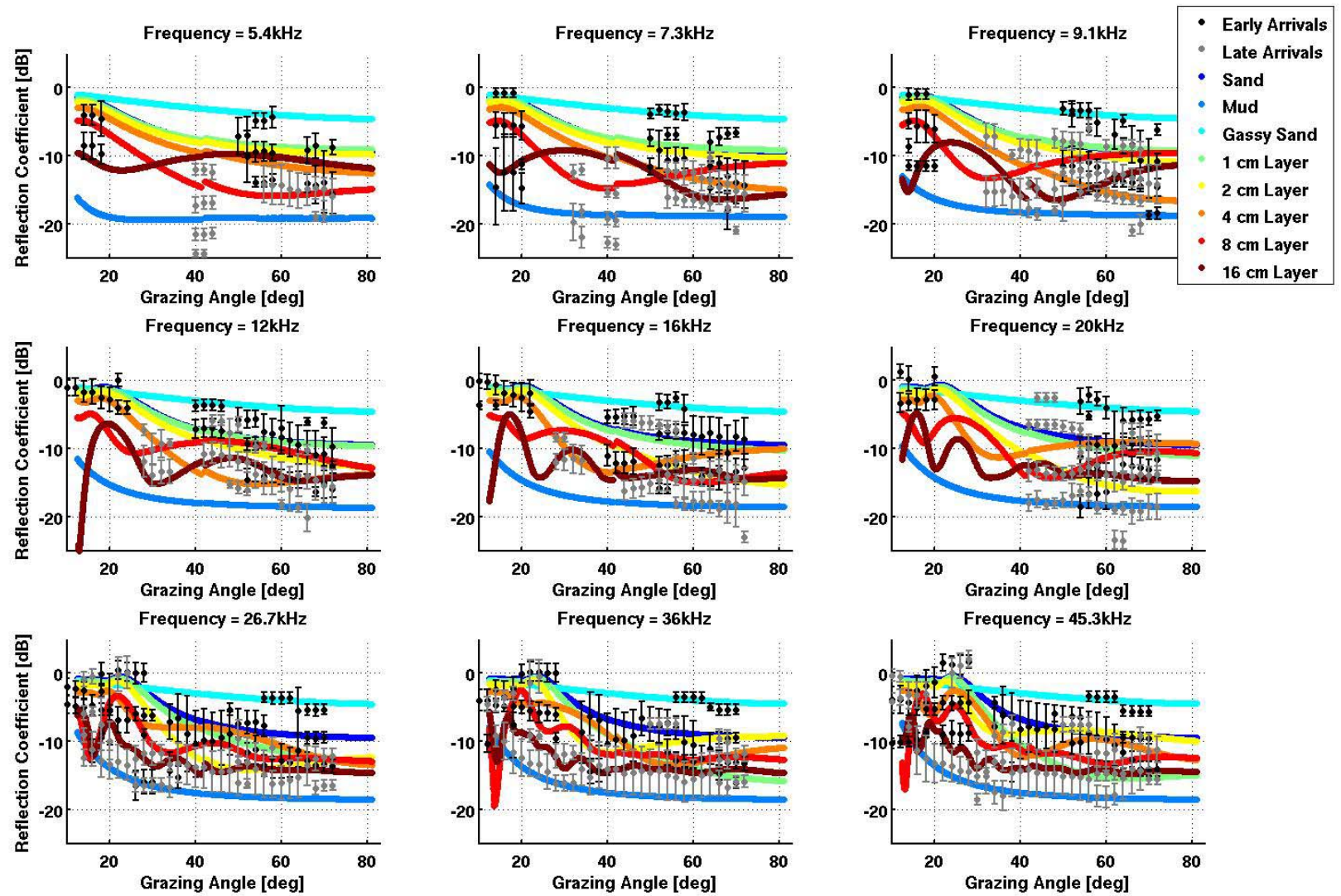*Figure 3: A typical distribution of the SAX04 data set for a 30 degrees grazing angle at 26 kHz.*

Figure 4: Results from the SAX04 Analysis. Four different processes were identified: Sand reflection, mud reflection, reflection from gassy sand and reflection from a sand layer covered with a mud layer of variable depth. The different mud layer depths are indicated by the 1 – 16 cm layer lines.
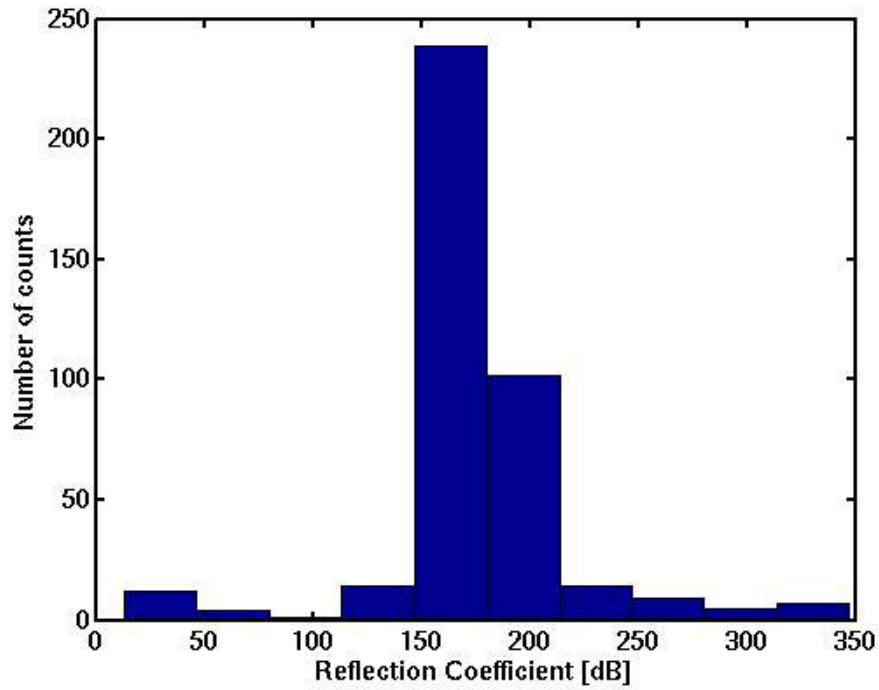
6

Figure 5: Phase distribution of the data determined to be from gassy sand.
The 180 degree phase shift relative to the replica indicates a pressure release reflection.
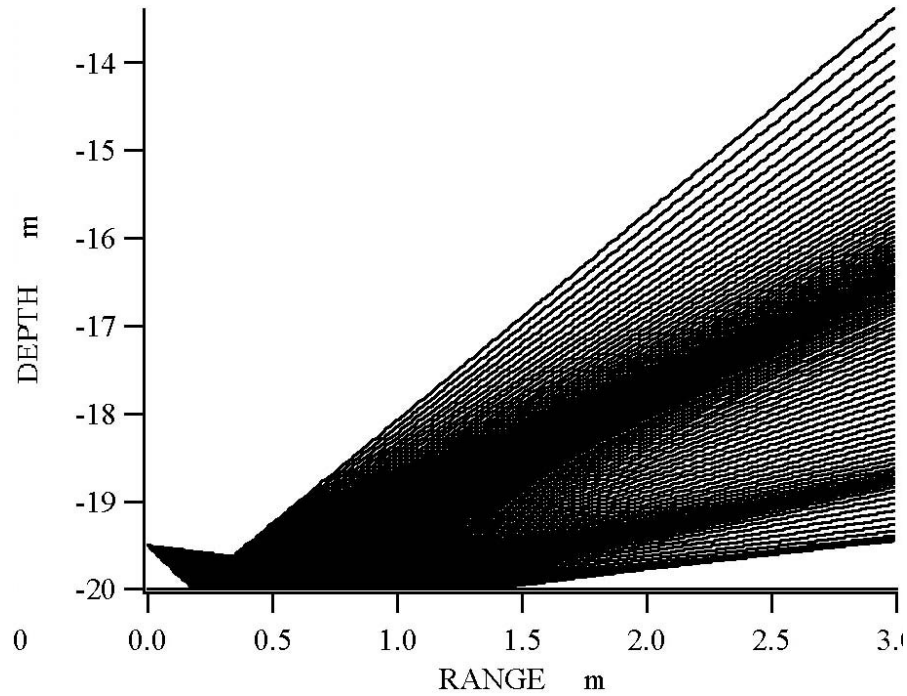

Figure 6: Focusing effect from a rippled surface with a wavelength of 2 cycles/m.
The wavelength is consistent with on site measurements by Tang(2005). Tang's
measured profile is more complicated but does include the necessary spatial frequency.

7

EVA sea test.
The EVA sea test provided the most comprehensive reflection coefficient measurements on sand for a large angle range to date. Shown in Figure 7 and Figure 8 are the magnitude and phase of the reflection coefficient compared with the elastic model. It was determined that spherical wave effects were not negligible in this experiment due to the geometry. Therefore, the elastic model is corrected for these effects using plane wave decomposition. [Brekhobskikh (1980)] The data shown are corrected for beam pattern and frequency response of the transducers by using a correction determined by a calibration experiment. It was determined that the magnitude data were affected by rough interface scattering. These effects can be quantized using a method described in Chotiros(2007). These corrections were applied to the data shown.
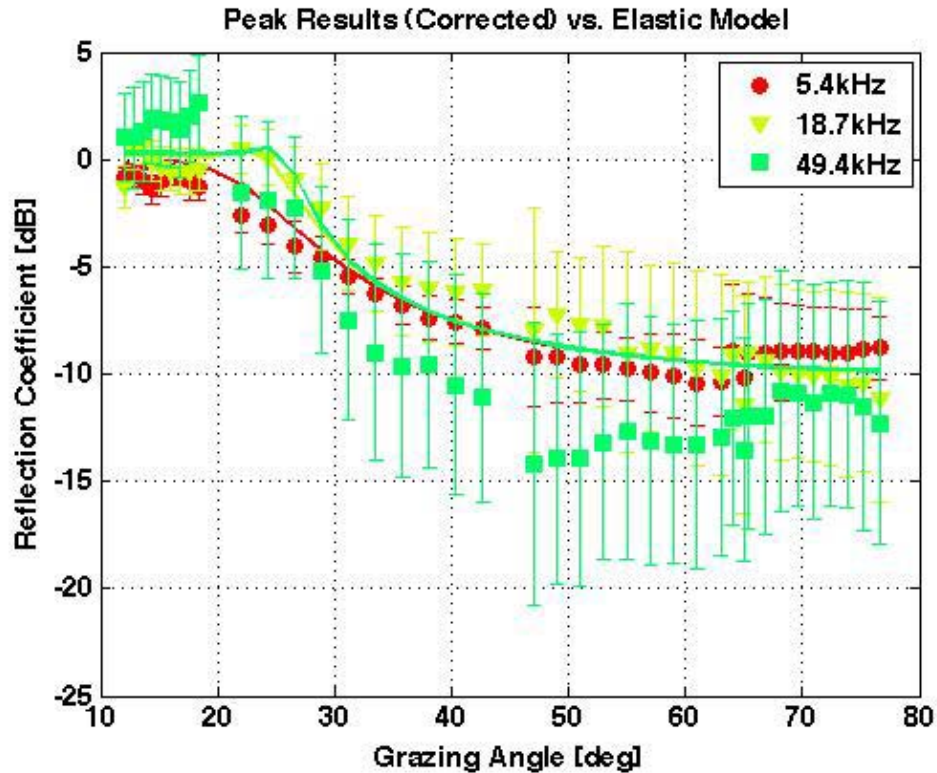

Figure 7: Magnitude of the reflection coefficient as measured at the EVA sea test corrected for scattering effects and compared with the elastic model corrected for spherical wave effects.
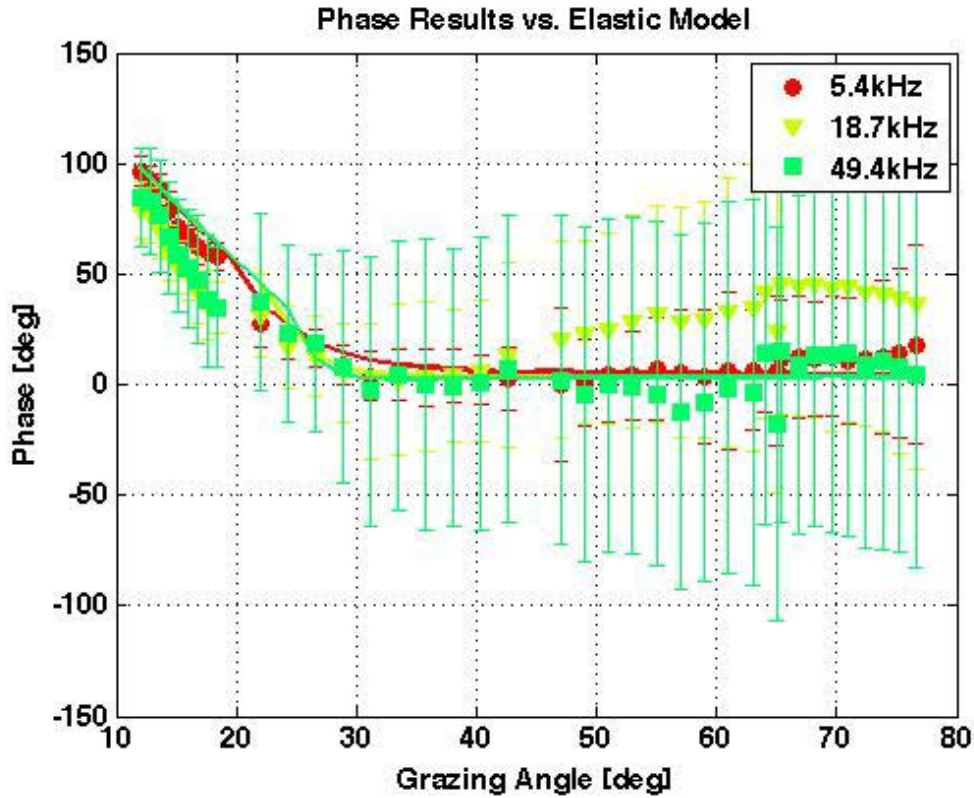
***Figure 8: Phase of the reflection coefficient as measured at the EVA sea
test compared with the elastic model corrected for spherical wave effects.***

Finite Element Model.
Finite element tools are being developed model the EVA data set. One advantage to finite element
models is the ability to calculate deterministic environments including interface roughness, range
dependent sediment properties, and inhomogeneities in both the water column and the sediment. In the
current application, finite elements were used to model the reflection from a rough interface. The
rough interface was synthesized using the roughness statistics measured at the EVA experiment using
the laser profiling system. [Chotiros (2007)] One main unknown was the effect of scattering from the
rough surface on the mean value of the reflection coefficient as a function of grazing angle and
frequency.

In this model, the time harmonic, 2D axial symmetric mode of COMSOL was used. In order to
produce time series to model the measurements at the EVA sea test, the field at a range of frequencies
from 5000 to 15000 Hz was computed in 100 Hz intervals. An example of the field at 5 kHz for both
the flat and rough interface is shown in Figure 9. Note the increased sediment penetration in the rough
interface simulation. The effect is even more pronounced at higher frequencies as shown in Figure 10
for 15 kHz. A similar domain was calculated for fluid only to produce a free field solution of just the
direct path. The field was probed at 8000 points in a regular grid and time series were synthesized at
each point. A typical time series for the rough interface reflection is shown in Figure 11.

9

From the time series, reflection coefficients from a smooth and rough interface were calculated and compared with predictions of the elastic model modified to include spherical wave effects using plane wave decomposition. For the rough interface, mean values and standard deviations were calculated from 20 different realizations of the surface realizations. These results are shown in Figure 12. For the flat surface realization, the magnitude of the reflection coefficient is virtually identical to that predicted using the elastic model with plane wave decomposition. There is only a deviation at very high grazing angles. These angles are modeled in FEM by using points very close to the source, therefore the far field approximation used in plane wave decomposition may not be accurate. For the rough interface, the reflection coefficient was measured both as a ratio of the peak of the reflected path (Peak – RC) and as a ratio of the area under the reflected peak to the area under the direct path peak. (Energy – RC). There is little difference between the values of these reflection coefficients. For low frequencies and high grazing angles, the mean value of the rough interface reflection coefficient approaches that of the flat interface. However, there is an effect at higher frequencies especially at low grazing angles.

The phase of the reflection coefficient can also be modeled using the finite element method. These results are shown in Figure 13. One interesting effect is that the phase of the flat surface reflection in FEM is not predicted by the elastic model using plane wave decomposition. There is up to a twenty degree difference between the two models at sub-critical grazing angles. However, another model was calculated using OASES which matched the phase from FEM except for high grazing angles. (See Figure 14.) These angles are modeled by probing the pressure field close to the source, an area in which the direct global matrix approach of OASES can become unstable.

One reason for the discrepency between the numerical models, OASES and FEM, and the analytic model is that the OASES model and FEM uses Fourier synthesis to compute time series from which the reflection coefficient is determined. The elastic model using PWD computes each phase measurement at a single frequency. Since both the FEM and OASES model consider the phase over a finite band and finite time peak, the phase may be influenced by the arrival of the lateral wave. The data from the experiment, also has finite bandwidth implying that the sea test measurements are more closely modeled by the full field methods of OASES and FEM rather than the analytic model. Therefore, the phase measurements from the sea test should not be compared to a simple analytic model.
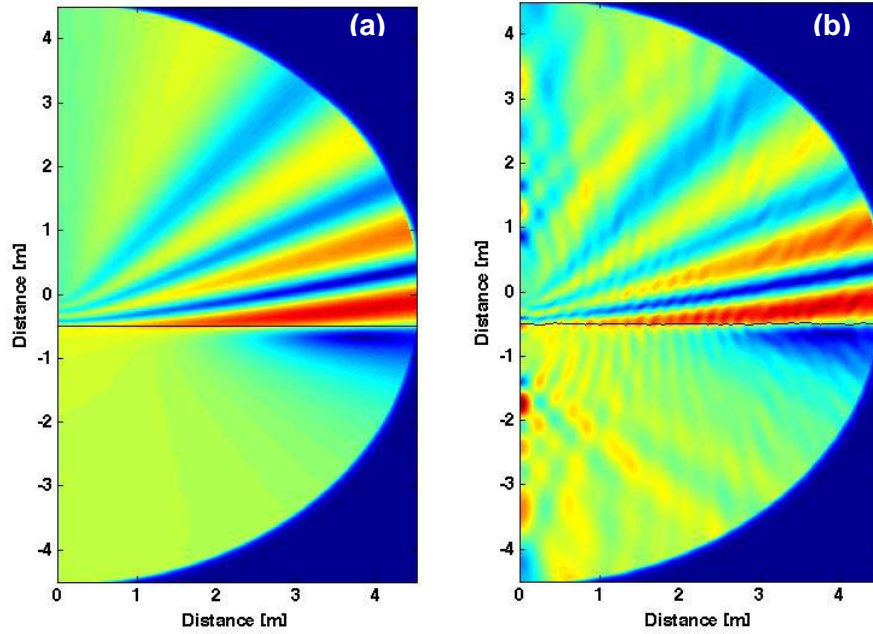
Figure 9: The calculated FEM field at 5 kHz using a flat (a) and rough (b) interface.
The rough interface was synthesized using measured roughness statistics from EVA sea test.
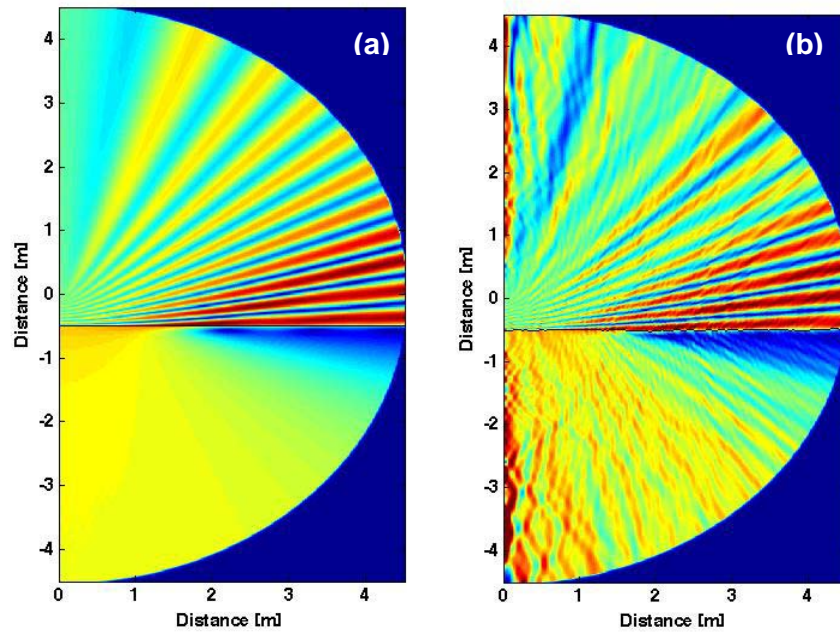

Figure 10: The calculated FEM field at 15 kHz using a flat (a) and rough (b) interface.
The rough interface was synthesized using measured roughness statistics from EVA sea test.
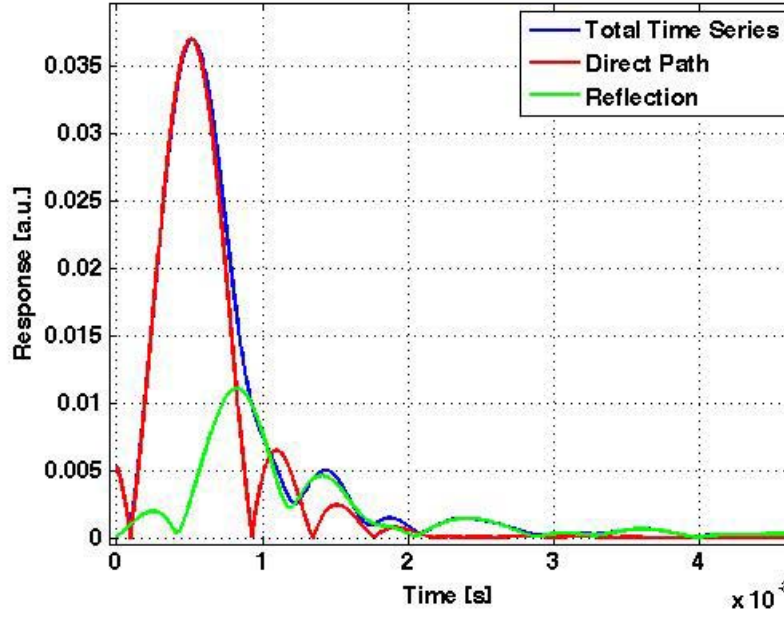
Figure 11: Typical time series produced from Fourier synthesis of time harmonic FEM field solutions for a frequency band of 1.2 kHz centered at 11 kHz. In blue is shown the calculated time series for a domain with a rough interface boundary. The solution for the free field with no boundary is shown in red. The difference, the reflection from the boundary, is shown in green.
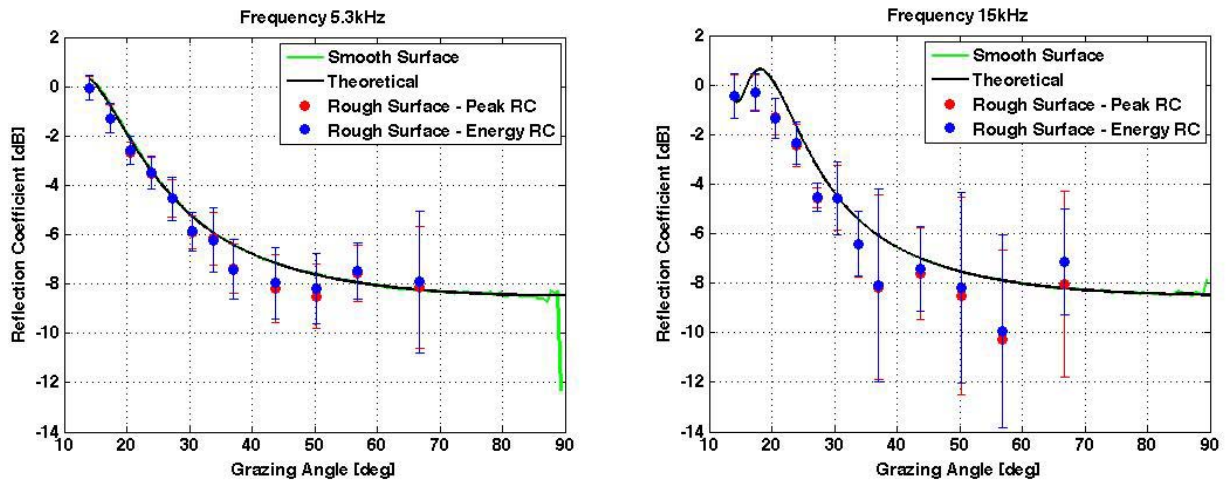

Figure 12: Reflection coefficient values from the finite element method in a 600 Hz band centered at 5.3 kHz and a 1.9 kHz band centered at 15 kHz.
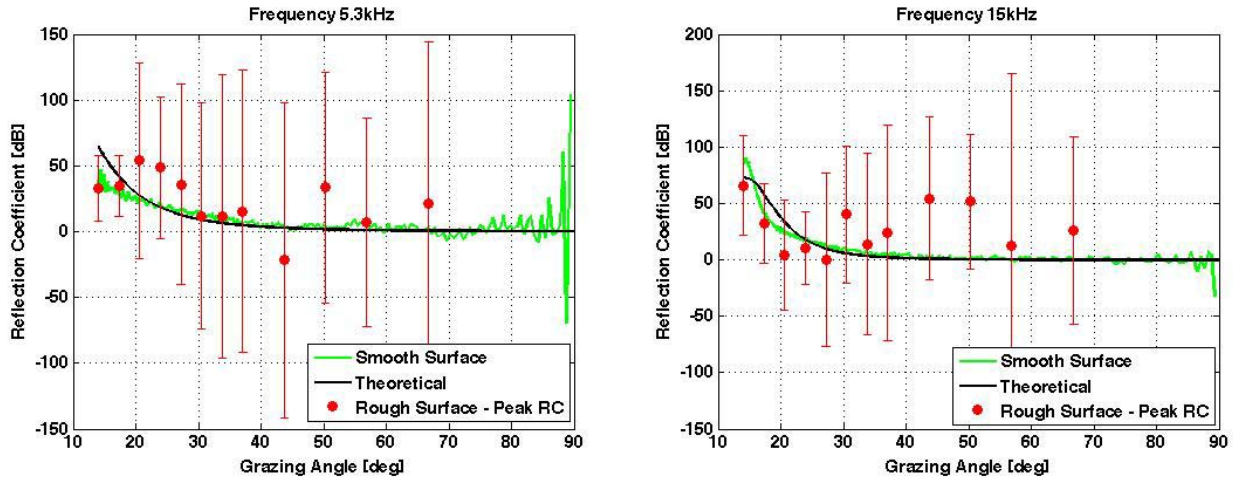
12

***Figure 13: Phase calculated from a finite element model in a 600 Hz band
centered at 5.3 kHz and a 1.9 kHz band centered at 15 kHz. Twenty realizations
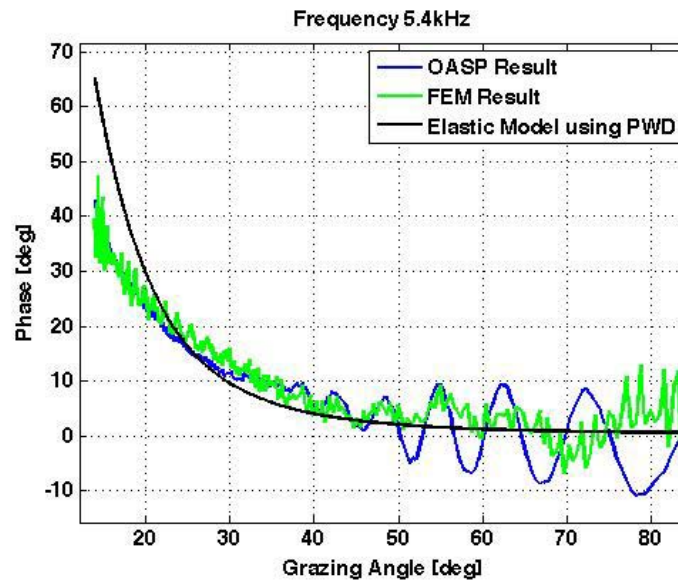are inadequate to resolve the phase after 20 degrees grazing.***

***Figure 14: OASES, FEM and analytic model results for the phase of the
reflection coefficient vs grazing angle at 5.4 kHz. The OASES model and
FEM, both produced using Fourier synthesis, produce matching results.***

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 flat interface visco-elastic medium. This study has identified the effects of a rough
interface which in addition to produce a great variability in the data also predicts significant difference

in the mean values of reflection loss at sub-critical angles at higher frequencies. This has impact in long-range propagation models for 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" thrust since the environmental inputs required for analysis are dependent on other projects within the thrust. We collaborated with the NATO Undersea Research Center both to perform the EVA sea test and for information sharing on FEM methods. Additionally, we collaborated with NRL, Stennis and MIT at the EVA sea test.

REFERENCES

Brekhovskikh, L. 1980, <u>Waves in Layered Media</u>. New York: Academic Press.

Isakson, M. J, 2006 Annual Report to the Office of Naval Research.

Chotiros, N.P. 2007 Annual Report to the Office of Naval Research.

Isakson, M.J., Chotiros, N. P., Piper, J. N. and Zampolli, M., "Measurements of the Bottom Loss Magnitude and Phase from 5 to 50 kHz and 10 to 77 degrees grazing at the Experimental Validation of Acoustic modeling techniques (EVA) Sea Test," IEEE Proceedings of the OCEANS 2007 Conference, Vancouver, B.C., Canada, October, 2007.

PUBLICATIONS

Presentations:

N. P. Chotiros, M. J. Isakson, J. N. Piper, and M. Zampolli, "High frequency signal amplitude fluctuations in shallow water," J. Acoust. Soc. Am., vol. 121, pp. 3040, 2007.

M. J. Isakson, N. P. Chotiros, J. N. Piper, and M. Zampolli, " In situ reflection coefficient measurements from 5–50 kHz from the experiments for validation of acoustic modeling techniques (EVA) sea test," J. Acoust. Soc. Am., vol. 121, pp. 3127, 2007.

M. J. Isakson, " The effects of layering on reflection coefficient and transmission measurements from a sand/water interface at the Sediment Acoustics Experiment 2004 (SAX04)," J. Acoust. Soc. Am., vol. 120, pp. 3042, 2006.

Articles:

M. J. Isakson, N. P. Chotiros, J. N. Piper, and M. Zampolli, "Measurements of the Bottom Loss Magnitude and Phase from 5 to 50 kHz and 10 to 77 degrees grazing at the Experimental Validation of Acoustic modeling techniques (EVA) Sea Test," IEEE Proceedings of the OCEANS 2007 Conference, Vancouver, B.C., Canada, October, 2007.

M. J. Isakson, N. P. Chotiros, H. J. Camin and J. N. Piper, "Reflection Coefficient Measurements in a Complex Environment at the Sediment Acoustics Experiment 2004 (SAX04)", IEEE J. Oceanic Eng. In Review.