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 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) Determination of the correct physical model of acoustic propagation through ocean sediments and scattering from sediment interfaces through the analysis of in situ measurements.
2) Development of predictive models that can account for the all of the physical processes and variability of acoustic propagation and scattering in ocean environments with special emphasis on propagation in shallow water waveguides and scattering from ocean sediments.
3) Development of the new experimental techniques to measure geo-acoustic parameters in the ocean.

APPROACH

1) *Analysis of the effects of out-of-plane scattering on backscattering*: The analysis of scattering for deterministic surfaces has often ignored the effects of out of plane scattering. A finite element approach is taken to determine the range of validity of this approximation.
2) *Inclusion of shear effects in acoustic scattering modeling*: Although much work has been done on scattering from sediments approximated by a fluid model, acoustic scattering from elastic solids with rough interfaces is less complete. In these materials, a surface wave is more easily generated which has profound effects on reflection loss. For this work, a two-dimensional finite element model is developed which allows visualization of the entire field including surface wave production.

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3) *Analysis of approximate solutions of reflection and scattering to determine model validity*: Many empirical and approximate models exist to describe the reflection loss and backscattering from ocean sediments. One of these models from the APL-UW handbook, is compared to measured data and models derived from the data to explore the validity of the approximation. This is an interesting model to consider since it is widely used for sediment characterization using normal incidence echo sounders.

WORK COMPLETED

1) *Analysis of the effects of out-of-plane scattering on backscattering:* In order to determine the effects of out-of-plane scattering on acoustic reverberation, both a finite element model and a Kirchhoff model were developed to consider a fully three-dimensional scattering event on a pressure release surface with a realistic interface roughness for ocean bottoms. This model was compared to a two-dimensional model which has been shown to be a proxy for a longitudinally invariant surface. The two-dimensional model ignores out of plane scattering. It was found that in some circumstances, the out-of-plane scattering is significant.

   The basic set up of the model is shown in Fig. 1. A tapered plane wave is incident on a three dimensional rough surface described by one of five power spectra shown in Fig. 2. The fully three-dimensional surface was compared to a longitudinally invariant surface taken from a cut of the original surface as shown in Fig. 3. This surface can be described fully in two dimensions using a simple scaling. [Joshi, 2011.] The difference in the two surfaces in Fig. 3 is that the longitudinally invariant surface will not include the effects of out-of-plane scattering. From these surfaces, an ensemble of scattering predictions at 5 kHz are made and compared to determine the effects of out-of-plane scattering.

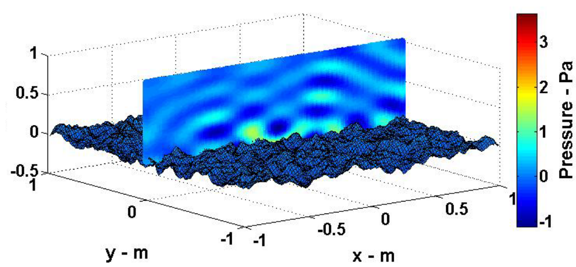

Figure 1: Set-up for three dimensional scattering calculations
[The image shows a representation of the pressure field above the rough interface.]

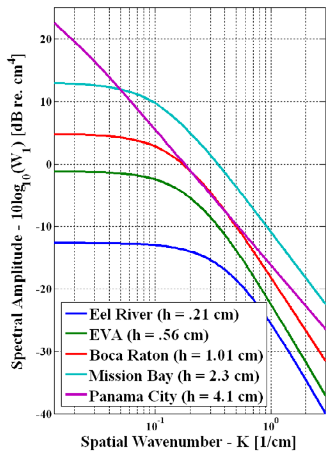

Figure 2: Power spectra used for surface realizations in three-dimensional scattering calculations [The image shows the power spectra for five rough interfaces.]

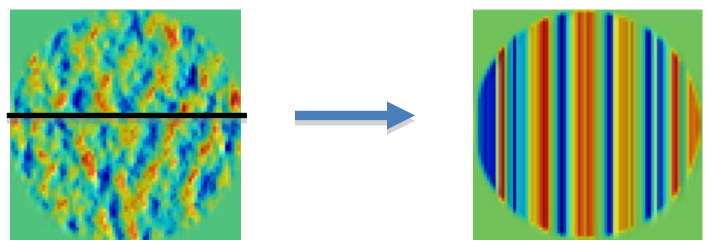

Figure 3: Cut of three dimensional surface used for approximation with no out-of-plane scattering. [The image shows a rough interface with one horizontal cut that is used to produce a second surface in which the cut is extruded in the perpendicular direction.]

2) *Inclusion of shear effects in acoustic scattering modeling*: To determine the effects of interface roughness on scattering from an elastic solid, a finite element model was developed to investigate the scattering from an elastic solid with a realistic rough interface. This method leads to additional insight over more traditional boundary element methods because the entire acoustic field can be visualized. It was found that specular scattering is significantly modified by the rough interface and additional surface waves were excited even for moderate interface roughnesses with RMS height less the 1/10 of an acoustic wavelength.

3) *Analysis of approximate solutions of reflection and scattering to determine model validity*: There are many models for determining the reflection coefficient and backscattering for ocean sediments. However, the APL-UW Manual has several empirical models that are used extensively for sediment characterization. [APL, 1994.] These models were compared with reflection measurements taken from well-characterized sediments off the coast of Isola d'Elba in 2006. Based on the grain size measured on site alone, the APL-UW empirical models correctly predict the

measured data at lower frequencies. However, when the geo-acoustic input parameters of the APL-UW model were directly measured, it failed to give the correct reflection loss, implying an underlying problem with the theoretical development. The backscattering at normal incidence was also calculated based roughness measurements taken on site and the modeled reflection coefficient. These data were compared with the APL-UW predictions. It was found that the APL-UW based on grain size incorrectly predicted the sediment type for all but the lowest frequencies.

RESULTS

1) *Analysis of the effects of out-of-plane scattering on backscattering:* Shown in Fig. 4 are the scattering predictions from the fully three dimensional and longitudinally invariant surfaces described by the power spectra in Fig. 2. Here the incident angle is 135 degrees. In the figure, the dotted lines are from the longitudinally invariant surfaces while the solid line is from the fully three-dimensional surface. As evident in the picture, the effects of out-of-plane scattering are minimal at the specular peak. However in all other directions, the out-of-plane scattering depressed the scattering strength as much as 10 dB.

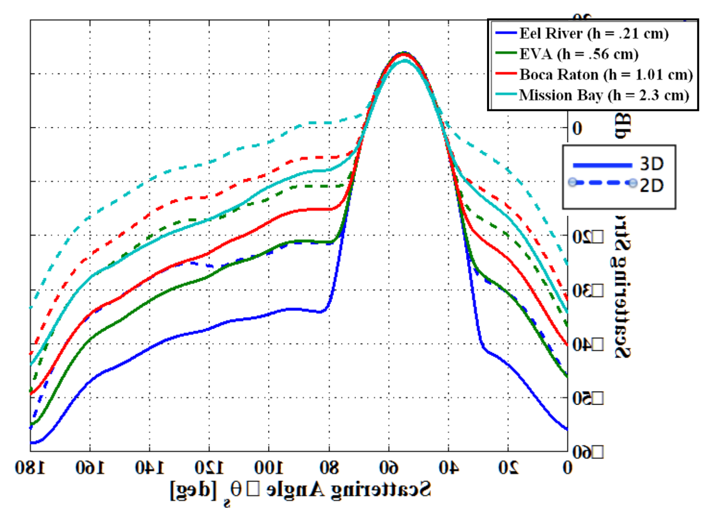

Figure 4: The scattering strength as a function of scattered angle for an incident tapered plane wave at 135 degrees on a rough surface described by the spectra in Fig. 2. The dotted lines indicate the longitudinally invariant results and the solid lines indicate the fully three-dimensional results. [The image shows four curves for backscattering using the fully three-dimensional model and four curves showing the longitudinally invariant model. The curves are very similar at the specular peak, but vary as much as 10 dB off specular.]

2) *Inclusion of shear effects in acoustic scattering modeling:* Shown in Fig. 5 are reflection loss curves from an elastic surface (calcarenite) for varying levels of roughness on the surface. There are two main effects of the roughness. First, the intromission angle becomes masked as the local value of the incidence angle is averaged over the slopes of the roughness. Also, the value of the reflection loss at highly grazing angles is decreased as more energy is scattered. It

is shown that some of this energy is converted into surface wave production. Consider Fig. 6. In this figure is shown the pressure in the upper region and the particle velocity in the lower region. Note that the range and depth are not scaled and the tapered plane wave is incident to the surface at 51 degrees. Shown are the acoustic fields for both a flat interface and an interface with an RMS roughness of 3.3 % of an acoustic wavelength. Note the production of the surface wave in the realization with the rough interface. Some of the acoustic energy is partitioned from the reflected wave into this surface wave. Additionally, more energy is transmitted into the second media due to the effects of the steeper local angles. This leads to the higher amount of reflection loss shown in Fig. 5.

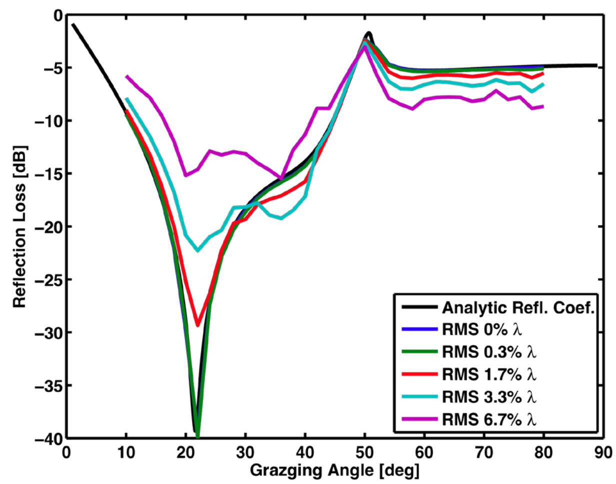

Figure 5: The reflection loss from an elastic solid (calcarenite) for varying levels of RMS roughness compared to an acoustic wavelength, λ.
[The image shows reflection loss for five values of RMS roughness of the surface from flat to 6.7% of an acoustic wavelength.]

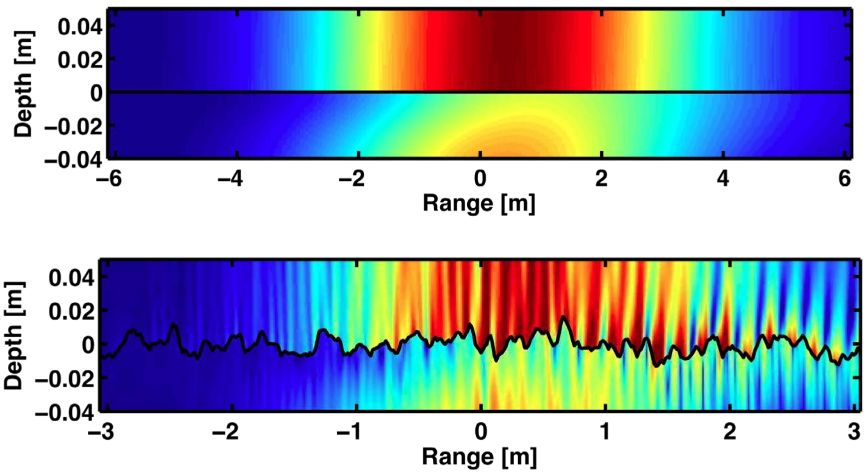

Figure 6: The pressure (upper half space) and particle velocity (lower half space) for a tapered plane wave incident at 51 degrees on a flat interface and an interface with an RMS height of 3.3% of the acoustic wavelength.
[The image shows the pressure and particle velocity for a fluid over an elastic solid respectively for a flat surface and a surface with RMS roughness of 3.3% of an acoustic wavelength. For the rough surface, significantly more energy is transmitted into the second medium and partitioned into a surface wave.]

4) *Analysis of approximate solutions of reflection and scattering to determine model validity*: Many sediment classifiers make use of empirical or approximate models of reflection loss and scattering. One of the most popular of these models is the APL-UW model. [APL-UW, 1994.] In order to assess the validity of this model, it was compared with data taken from the EVA 06 sea test. [Isakson, 2011.] The APL-UW model can be formulated in two ways. One way is to determine sediment sound speed, attenuation and density from empirical relationships based on grain size. These values are shown in Table I based on the 2.2 phi grain size measured on site at the experiment. The other method is to use the measured geo-acoustic parameters in the fluid framework for reflection coefficient available in the manual. Both of these approaches were taken and the results compared with the data are shown in Fig. 7. The relatively low frequency of 5.4 kHz was chosen since it has been shown for the interface roughness present at the experimental site, the roughness scattering has a minimal effect on reflection loss at this frequency.

   In Fig. 7, note how the empirical model correctly predicts the experimental data while the more theoretical model based on the measured geo-acoustic parameters does not. This effect can be understood by comparing the empirical values in the table with the measured values. For example, the empirical density is much less than the measured density leading to a depressed value for the reflection loss near normal incidence. Likewise, the empirically predicted sound speed is significantly lower. By modifying these parameters relative to their physical values, the empirical model adjusts for physics such as poro-elastic effects, not included in the theoretical fluid model.

Table I : GeoAcoustic Parameters from the EVA2006 Experiment

GeoAcoustic Parameter	Measured Value	APL-UW predicted Value	Units
Water Sound Speed	1529	--	m/s
Water Density	1026	--	kg/m^3
Sediment Sound Speed	1778	1721	m/s
Sediment Density	2047	1543	kg/m^3
Sediment Attenuation*	0.5	0.51	dB/m/kHz
Porosity	0.42	--	
Roughness Exponent, γ	3.15	3.25	
Roughness Spectral Strength	0.0061	0.0032	$cm^{3-\gamma}$
Roughness Wavenumber Cut-Off	0.01	--	cm^{-1}

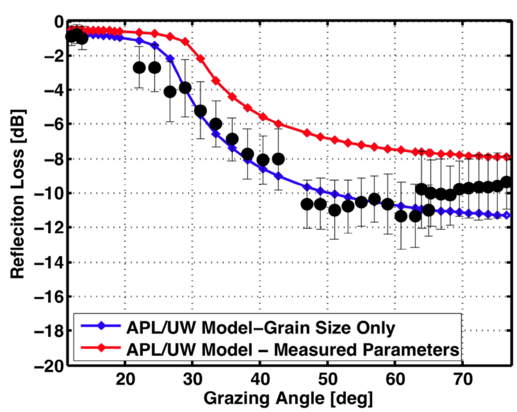

Figure 7: The measured reflection loss compared with the APL-UW model using grain size only and using measured parameters.
[The image shows data compared with an empirical model of the reflection loss and a theoretical model. The data are much more consistent with the empirical model.]

The normal incidence scattering cross section was also considered. The values for sound speed and attenuation determined from the EVA data along with the measured values of the roughness spectral strength, roughness exponent and wavenumber cut-off were used to produce the dotted curve. This curve is compared with the predicted model of normal incidence cross section for different grain types in Fig. 8. Note that the experimental sediment is classified as fine sand based on its mean grain size. Although the predictions agree with the data derived curve at low frequencies as expected from Fig. 7, as the frequency increases, the data would be classified first as clay at 20 kHz and finally approaching sand gravel at high frequencies. This occurs because of the difference in the empirical and measured values of roughness spectral strength as shown in Table I. The empirical value is approximately half of the measured value leading to a greater value of the normal incidence scattering cross section. In fact, it has been shown that grain size is a poor predictor of roughness spectral strength. [Jackson, 2007.]

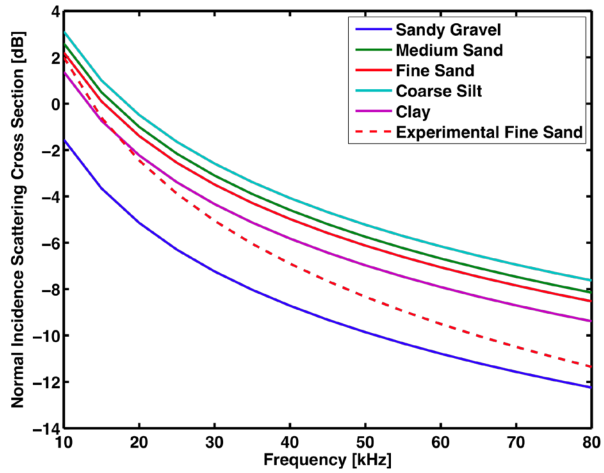

Figure 8: The APL/UW backscattering model at normal incidence using only the grain size (solid line) compared with the same model using measured input data (broken line).
[The image shows five empirical curves using five different sediment types for normal incidence scattering cross section compared with a measured data derived curve. The data derived curve is consistent with fine sand at 10 kHz, clay at 20 kHz and sandy gravel at 80 kHz.]

IMPACT/APPLICATIONS

The finite element reflection loss models could transition into a new high frequency and low frequency reflection loss (LFBL/HFBL) data curves for NAVO based on site specific characteristics. An understanding of normal incident reflection loss is critical to sediment characterization and mine burial prediction.

RELATED PROJECTS

Under the iPUMA Sediment Environmental Estimation (iSEE) program, this group is also developing sediment characterization algorithms for AUV sonars based on the measurements and models previously developed by this program. Additionally, the models developed in this research will be used to increase the fidelity of sonar trainers under the High Fidelity Active Sonar Trainer (HiFAST) program. There will be significant collaboration with Dr. Nicholas Chotiros, particularly for theoretical development of bulk acoustic/sediment modeling and laser roughness measurements.

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