Seafloor Scattering in Shallow-Water Environments

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LONG-TERM GOALS

Mud volcanoes are solid objects that form on the seafloor due to the emission of gas and fluidized sediment from the earth's interior [1]. They vary widely in size, can be exposed, proud, or buried, and are of interest to the Navy as sources of active sonar clutter [2]. The long-term goal of this work is to accurately model mud volcano scattering. The final product will make predicting and simulating scattering signatures for individual volcanoes possible, and will provide the information necessary to mitigate mud volcano clutter through improved sonar design and classification schemes.

The long-term goals of the seafloor scattering project are linked to both the forward and inverse scattering problems. The first objective is to model the time dependence of seafloor scattering based upon knowledge of the mechanisms responsible for benthic change, primarily bioturbation and sediment transport. The second is to develop acoustics as a tool for the remote sensing of benthic activity and the inversion of time-dependent seabed parameters that are used as inputs for reverberation models. Results should be of use to the Navy in understanding and predicting the time dependence of reverberation, as well as measuring the parameters necessary for reverberation models.

OBJECTIVES

The objective of the current mud volcano project is to model low-frequency scattering from a volcano using a bottom-up approach. Coincident acoustic data, bathymetry, and geoacoustic measurements are used to guide understanding and model development. As a part of this process, physical features and processes that are significant contributors to observed mud volcano scattering are identified.

Current seafloor scattering work is concerned solely with surface scattering (as opposed to volume scattering or a combination of the two), and aims to link changes in acoustic scattering with changes in the surface of the seafloor. This is achieved by deriving a first-order perturbation theory-based equation that connects the time correlation of scattered acoustic power with the time correlation of

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parameters describing the seabed surface, and assessing the result through comparison with experimental data.

APPROACH

Charles Holland collected the data necessary for modeling from a representative buried mud volcano located on the Malta Plateau. Coincident seismic reflection data and bistatic scattering data were gathered and available for analysis. In addition, the general geoacoustic properties of the area's seabed were on hand for both modeling and data analysis [3]. The bistatic data were generated using a pulsed piston source operating at 1 kHz and a 64-element horizontal linear array [4]. Both were towed at 6 knots over the top of the volcano with a source pulse repetition frequency of 0.1 Hz.

The large size of the volcano, which was estimated based upon the seismic reflection results (height ~ 5 meters, diameter ~ 200 meters), suggested a model based upon a high frequency approximation. As a result, the approach was to start with a simple, fluid-based ray and/or Kirchoff model, use the model to simulate a bistatic acoustic time series, compare the results against the experimental data, and increase the complexity of the model as necessary to incorporate mechanisms (e.g. multiple scattering, diffraction, scattering from surface roughness, etc.) that account for any observed differences.

In order to assess the utility of the derived correlation equation, sequences of acoustic scattering data were required from a seafloor for which the time-dependent topography was known. Data were collected during the SAX04 experiment located off the coast of Florida, where the primary mechanism of seafloor change at the frequencies of interest was bioturbation due to fish feeding. Topographical information for the seabed was obtained by Anthony Lyons using the NURC photogrammetry system [5], where surface height fields for an approximately .5 square meter patch of seafloor were acquired every 10 minutes over the course of several days at two different locations. Kevin Williams collected acoustic backscatter data with APL-UW's SAS rail system [6] using three different source transducers (6-10 kHz, 12-28 kHz, and 30-50 kHz). However, because data were not captured specifically for this application, time delays between sequential data acquisition sequences were both erratic and long, and the photogrammetric and acoustic data were not precisely collocated or synchronized. The processing approach was to calculate time-decorrelation as a function of frequency for both data sets, insert the acoustic results into the derived correlation equation, and compare the outcome against the measured photogrammetric results.

WORK COMPLETED

The modeling work previously described was completed. In addition, bottom loss values were calculated for the top of the volcano where returns were strong and consistent. These values aided in modeling the time-domain acoustic returns by placing constraints on the composition of the volcano. For both these calculations and the modeling work, a ray-based correction with some approximations was employed to account for passage through the mud layer covering the volcano. Corrections to the bottom loss measurements were also made to account for reflection from a curved surface. Results were presented in a talk entitled 'Low-frequency Scattering from a Mud Volcano Located Offshore Sicily' at the 151st meeting of the ASA.

An equation connecting the decorrelation of surface height field spectra with the decorrelation of acoustic backscatter was derived. Photographs captured using the NURC photogrammetry system were calibrated and processed according to standard photogrammetric methods [5] to produce surface height fields of the seafloor. A number of the results exhibited significant errors due to the presence of fish and poor water quality. However, the use of a combination of persistence and outlier filters enabled the removal of the majority of these errors. Changes generally affected under 5 percent of the values for each surface height field. Filtered results were used to calculate height spectra for the seafloor, which were subsequently employed to estimate spectral decorrelation with time. The usable frequency range was restricted to below .3 cycles/cm by the presence of what was believed to be high-frequency noise.

Raw acoustic data collected with the SAS system were beamformed using a straight sum, where the range at which results were desired determined aperture size. Beamformed data were basebanded, and the squared amplitude of the results at the desired depth correlated across the rail with results from a second sequence collected with identical settings but at a later time. Correlation values were obtained for several different frequencies and delay times, processed through the derived correlation equation, and compared with measured photogrammetric values. Results were presented at the 151st meeting of the ASA in a talk entitled 'Time Evolution of Acoustic Scattering from a Bioturbated Seafloor'.

RESULTS

Figure A1 is a plot of the bottom loss measurements for the volcano. Two theoretical curves are also displayed. Both represent possible models for the composition of the volcano, and are based upon observed similarities in the seismic reflection data between the volcano and surrounding basement. The top curve assumes that the volcano is composed of material identical to that of the basement. The bottom curve assumes the same, but also that an acoustically hard, complex top layer that is present on the basement extends up the sides and over the top of the volcano. Although it is difficult to ascertain from the figure whether one or either of the models accurately describes the composition of the volcano, the results do suggest that the material properties of the volcano are close to those of the basement.

Due to the large size of the volcano in relation to the acoustic wavelengths of interest, a geometric acoustics model [7] that neglected water refraction was selected to model scattering. The shape of the volcano was approximated by the top of a sphere. Because the bistatic data indicated that scattering was primarily coherent (see top of figure A2), the effects of surface roughness were ignored. In addition, neither multiple scattering nor shadowing was included in the model given the low height to width ratio of the volcano.

Figure A2 compares two different modeled bistatic time series with actual data for the first receiver of the HLA. The two artificial time series correspond to the two models of volcano composition mentioned previously. Both include the effects of reflection from the surrounding basement. Although the modeled results conform to the actual data remarkably well, there are a few noticeable differences. The data exhibit distortion of the incoming Ricker pulse, both for the basement, due to the presence of the complex top layer, and the volcano. This distortion of the volcano scattering is reflected in the second model only because it alone assumes that the basement layering is also present on the volcano. The levels of return from the top of the volcano for the second model also appear to be more in line with those exhibited by the data. However, the levels produced by the sides of the volcano appear to be too high. The first model better mimics the data in this regard. It may be that a combination of the two composition models, i.e. layering on top of the volcano but not the sides, more accurately represents reality. Neither model exhibits the asymmetric returns from the sides of the volcano that appear to be present in the data, suggesting that a more complex representation of either volcano shape or composition is warranted.

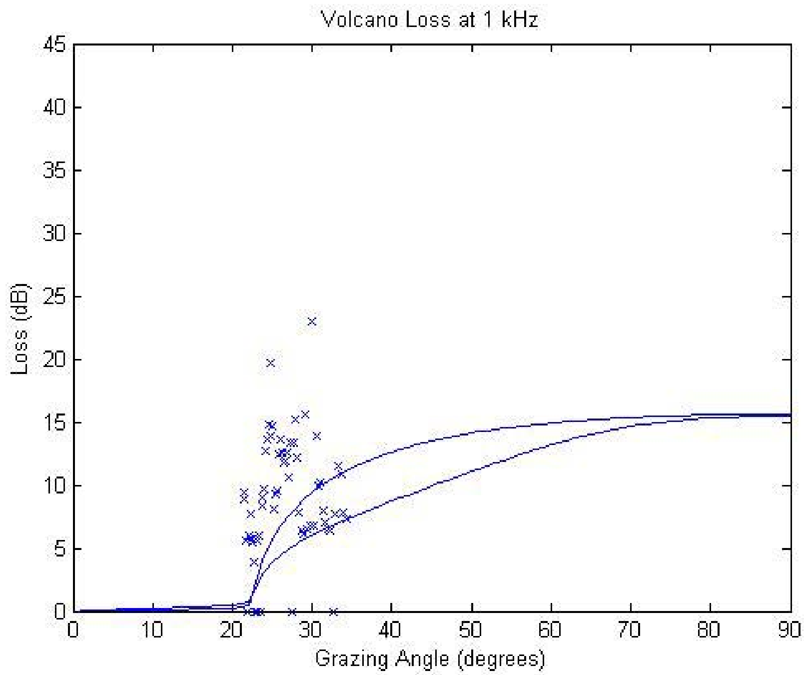

Figure A1: Mud Volcano Bottom Loss Measurements at 1 kHz. Theoretical values are represented by solid lines. The bottom curve assumes that an acoustically hard layer covers the mud volcano.

Although efforts to model acoustic scattering for mud volcanoes of this type have been successful, volcanoes can vary widely in size, shape and structure. As a result, continued work is necessary to examine the robustness of the geometric acoustics model. Smaller volcanoes and higher frequencies especially may require significant adaptations to the model, and could possibly demand a new approach altogether.

This work was primarily concerned with accurately modeling scattering at close range. However, mud volcanoes are also demonstrated sources of clutter at longer ranges [2]. The geometric acoustics scattering model needs to be combined with established propagation models, and the results compared against long-range data before it can be used to predict or simulate clutter at longer ranges with any confidence.

Assuming that first-order perturbation theory adequately models acoustic backscatter from the seafloor surface, and that volume scattering is negligible, the aforementioned correlation equation takes the form

$$corr\left[B\hat{S}C_{t1}(\theta,k), B\hat{S}C_{t2}(\theta,k)\right] = corr\left[G_{t1}(2k\sin\theta), G_{t2}(2k\sin\theta)\right]$$

where k is acoustic wavenumber, θ is angle of incidence, the correlation of backscatter at two different times is located on the left, and the correlation of surface height field spectra for the same two times is located on the right. For the equation to be accurate, Rayleigh scattering statistics must apply.

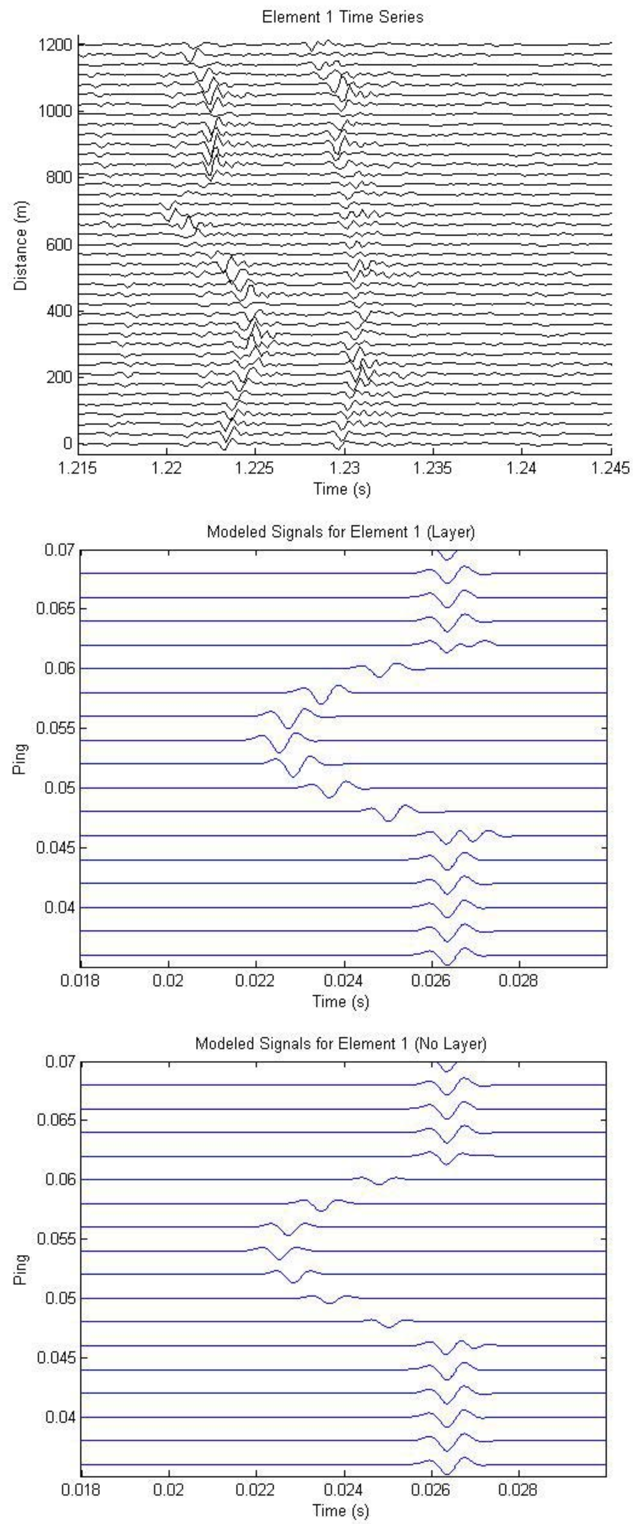

Figure A2: Top: Element 1 time series for the HLA. Multiple pings are plotted and positioned along the y-axis according to the relative location of the element at the time of the ping. Middle: Modeled time series for element 1 assuming a hard covering layer. Bottom: Modeled time series for element 1 assuming no layer.

According to this result, the decorrelation of surface height field spectra and acoustic backscatter should be equivalent given that the Bragg wavenumber transformation has been applied between acoustic frequency and seafloor spatial frequency.

Figure B1 juxtaposes multiple frequency-dependent decorrelation curves for both the photogrammetric data taken at site 1 and the acoustic data. Acoustic frequencies have been converted to their spatial frequency equivalent using the Bragg wavenumber transformation. Despite the fact that there is some evidence of non-stationarity in the photogrammetric data, decorrelation curves for absolute times have been averaged to produce curves that represent decorrelation as a function of time delay. Although the agreement between photogrammetric and acoustic results is not exact, it is reasonable given that decorrelation rates can vary widely, and that the data sets were acquired at slightly different times and locations.

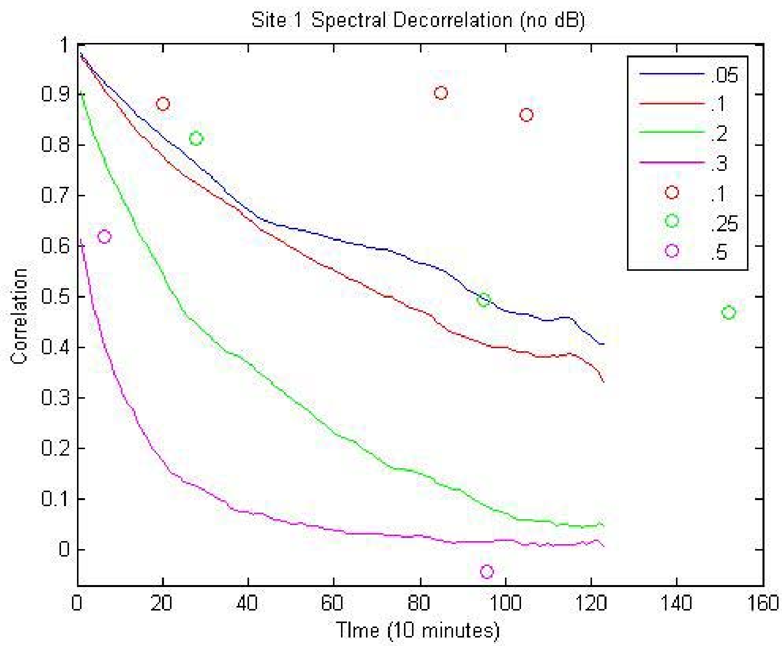

Figure B1: Spectral decorrelation for site 1 photogrammetric (curves) and acoustic (circles) data. The legend indicates spatial frequency in cycles/cm.

Figure B2 is nearly identical to B1, but plots photogrammetric decorrelation curves for site 2 instead of site 1. The agreement between photogrammetric and acoustic results is better for this site at lower frequencies, but worse at higher frequencies, likely due to the fact that high-frequency noise was more significant at site 2 than site1.

Both the photogrammetric and acoustic data indicate that seafloor surface decorrelation due to fish feeding is frequency dependent. This feature is significant for the development of acoustic systems that remotely sense benthic activity in that it may aid in mechanism classification should its functional form prove to be mechanism-specific.

Although acoustic and photogrammetric decorrelation results compared reasonably well, given that the acoustic data were sparse and the two data sets were collected at separate times and slightly different locations, the agreement is tenuous enough to suggest that a more precise comparison is warranted. Conducting a second experiment, where design is centered on this specific comparison, would therefore establish greater confidence in the ability to translate between acoustic and seafloor correlation.

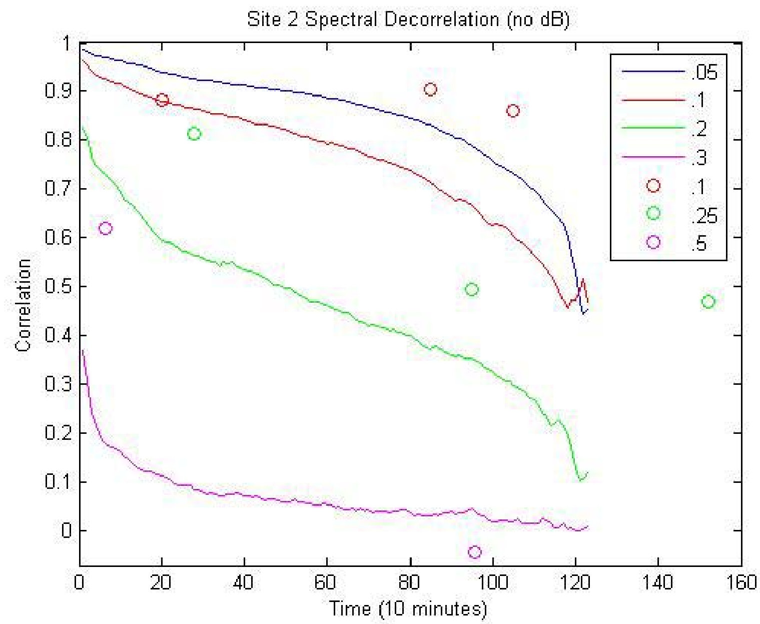

Figure B2: Spectral decorrelation for site 2 photogrammetric (curves) and acoustic (circles) data. The legend indicates spatial frequency in cycles/cm.

Developing mechanism specific models for the time evolution of seafloor topography is crucial for progression towards the stated long-term goals of modeling the time dependence of seafloor scattering and developing acoustics as a tool for the remote sensing of benthic activity. These models will likely be complex, and will require experimental verification using a photogrammetry system. Because this work involved collecting sequences of photogrammetric data where fish appeared to be the dominant source of benthic change, modeling fish pitting would be a natural candidate for immediate future work.

IMPACT/APPLICATIONS

Although a few minor features exhibited by the bistatic acoustic data remain unexplained, the geometric acoustics model developed in this work appears to adequately depict low-frequency scattering for mud volcanoes of the size considered. As a result, it should be of use in predicting and simulating mud volcano clutter.

Bottom loss values were estimated for the volcano using the geometric acoustics model to correct for curvature. The results indicate that volcanoes of this type may either not be covered by a hard, carbonate layer, as many of the mud volcanoes that have been observed visually are, or that the layer is present but too thin to be observed acoustically at low frequencies.

The ability to successfully connect seabed decorrelation with acoustic decorrelation has several positive implications. If the benthic surface decorrelation rate and its frequency dependence can be identified with particular bioturbation and sediment transport mechanisms, acoustic remote sensing of benthic activity should be possible. Conversely, if this activity can be appropriately modeled and knowledge of mechanism types and rates is available, prediction of the time evolution of acoustic scattering should also be feasible. Finally, the correlation equation can be used to determine how much delay is necessary between data acquisition sequences to obtain uncorrelated values from a single location when using acoustics to estimate statistical parameters related to seabed topography.

RELATED PROJECTS

Data for a portion of this project were collected as part of the SAX 04 experiment.

REFERENCES

[1] C. W. Holland, G. Etiope, A. Milkov, E. Michelozzi and P. Favali, "Mud Volcanoes Discovered Offshore Sicily," Marine Geology **199**, 1-6, (2003).

[2] C. W. Holland, A. L. Gerig and P. Boni, "Acoustic Clutter from Buried Submarine Mud Volcanoes," Conference Proceedings, (2004).

[3] C. W. Holland, "Coupled Scattering and Reflection Measurements in Shallow Water," IEEE J. Oceanic Eng. **27**, 454-70, (2002).

[4] L. Troiano, P. Guerrini and A. Barbagelata, "SACLANTCEN Towed and Vertical Array System Characteristics," SACLANTCEN Memorandum SM-117.

[5] A. P. Lyons, W. L. J. Fox, T. Hasiotis, and E. Pouliquen, "Characterization of the Two-Dimensional Roughness of Wave-Rippled Sea Floors Using Digital Photogrammetry," IEEE J. Oceanic Eng. **27**, 515-24, (2002).

[6] K. L. Williams, R. D. Light, V. W. Miller, and M. F. Kenney, "Bottom Mounted Rail System for Synthetic Aperture Sonar (SAS) Imaging and Acoustic Scattering Strength Measurements: Design/Operation/Preliminary Results," Conference Proceedings, Heraklion, Crete, Greece, (2005).

[7] J. J. Bowman, T. B. A. Senior, and P. L. E. Uslenghi, "Electromagnetic and Acoustic Scattering by Simple Shapes," Hemisphere Publishing, New York, NY, 1987.