

Sediment Acoustics: Wideband Model, Reflection Loss and Ambient Noise Inversion

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LONG-TERM GOALS

Physically sound models of acoustic interaction with the ocean floor including penetration, reflection and scattering in support of MCM and ASW needs.

OBJECTIVES

(1) Consolidation of the new BIC08 model of sediment acoustics, its verification in a variety of sediment types, parameter reduction and documentation in preparation for transition. (2) A new model of sediment reflection based on a mixture of models suitable for shallow water sonars for transition to NAVO. (3) Coupling of BIC08 to rough surface scattering models.

APPROACH

(1) Consolidation of the new BIC08 model: The **Biot-Stoll** grain contact **squirt** flow and shear viscous drag (BICSQS) model, which includes squirt flow at the grain-grain contacts (Chotiros, Isakson 2004), combined with improvements in squirt flow modeling, the frame virtual mass extension to account for the random grains rotation (Chotiros, Isakson 2007), and the high-frequency viscous drag correction (Chotiros, Isakson 2008) form the Biot-Stoll contact physics model of 2008 (BIC08). This model contains plausible physical processes and is able to track the measured frequency dependence of sound and shear speed and attenuation in water-saturated sandy sediments. In its present form, it is too unwieldy for practical applications. The approach is to consolidate the input parameters and reduce the parameter count, to continue to test it against experimental measurements and extend it to a wider variety of ocean sediments. In support of the modeling, new experimentation methods are envisioned, including the exploitation of ambient noise for bottom characterization using a compact, partially buried array. Through participation in future shallow-water (SW11) and sediment acoustics experiments (SAXnn), further testing is planned with a wide range of sediment types and over a broadband of frequencies, to extract model parameter values that are typical for specific classes of sediments.

(2) A new model of sediment reflection: The reflection measurements from the SAX04 experiment (Isakson, Chotiros, Camin, Piper 2007) indicate that the sediment is often inhomogeneous. Although the SAX04 experiment may be a rather extreme case, due to the passage of a number of nearby storms, the results suggest that a significant proportion of uncertainty in underwater transmission loss and

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reverberation may be due to inhomogeneity of the seafloor. This suggests a new approach to modeling bottom reflection as a random process, in which each bottom bounce contains both a deterministic as well as a random component. This approach will lead to improved bottom loss models for sonar performance prediction.

(3) Coupling of BIC08 to rough surface scattering models: Since the real ocean bottom is rough, it is necessary to be able to combine the BIC08 model with a rough interface, in order to obtain a realistic model of the bottom. For a computationally fast solution, a ray-based approach is likely to be a practical solution, but for accuracy, a finite element approach would be best. This task also includes experimental support equipment to measure seafloor roughness, to allow rough interface scattering models to be tested with at-sea experimental measurements.

WORK COMPLETED

Following the three tasks mentioned in the approach, the work completed may be divided into three corresponding sections:

(1) Consolidation of the new BIC08 model: The original Biot-Stoll model has 13 input parameters. The BICSQS extension has 14 parameters. Of the 14, five are tabulated physical properties that are well known: the densities and bulk moduli of the fluid and the grains, and the viscosity of the fluid. The next four describe the structure of the pore spaces: porosity, permeability, pore size and fluid virtual mass. The last 5 describe the frame response: frame Poisson's ratio, frame shear modulus, frame bulk modulus increment at high frequencies, and the bulk and shear relaxation frequencies. Currently the BIC08 model brings an additional 4 parameters: contact stiffness scintillation index, average number of contacts per grain, average number of elastic contacts per grain, and contact gap width. These parameters are interconnected in many ways. For example, the number of contacts per grain is a function of porosity. Work has begun on rationalizing and reducing the number of independent parameters.

(2) A new model of sediment reflection: Transmission loss measurements as a function of range and frequency were obtained from a shallow water site for the purpose of testing the concept of a patchy seafloor. An inhomogeneous seafloor, composed of a patchwork of different bottom types and hence spatially varying reflection loss, would produce random fluctuations in the transmission loss. This approach was presented to the Naval Oceanographic Office (NAVOCEANO). It generated some interest as a new way to quantify uncertainties in transmission loss (TL) in shallow water. NAVOCEANO provided a sample of measured TL to compare with the model as a way to assess its viability. A ray-based transmission loss model containing random variations in sediment reflection and the water column as a function of range was developed to compare with the measured values.

(3) Coupling of BIC08 to rough surface scattering models: The BIC08 model was formulated in a form that was compatible with existing Biot-Stoll computer code in preparation for incorporation into rough interface scattering models, including finite element models. In anticipation of experimental measurements, the laser bottom profiler was upgraded by changing the lasers from red to green and upgrading the camera from digital video (DVD) to High Definition video (HD).

RESULTS

The results are presented in the same order as the work completed:

(1) Consolidation of the new BIC08 model has made some progress. The model is capable of matching in-situ measured sound speed and attenuation in sandy ocean sediments from 100 Hz to 1 MHz. The model has been compared with a wide range of experimental data including the SAX99 and SAX04 data at high frequencies and inverted sediment sound speed and attenuation below 10 kHz from various sites in the East China Sea, the Yellow Sea and the New Jersey coast in SW06, as shown in Fig. 1. While the Biot-Stoll model can be adjusted to fit the upper and lower bounds of the data (A and B in Fig. 1), only the BIC08 model is capable of tracking the trends in the wave speeds as they traverse between the upper and lower bounds between 1 and 10 kHz. The model is also capable of explaining the apparent discrepancy between the data and the Kramers-Kronig relationship (K-K), which is commonly given as,

$$V = \frac{V(\omega_o)}{\pi} \int_{\omega_o}^{\omega} \frac{1}{\omega_1 Q} d\omega_1$$

This equation relates the sound speed V , to the quality factor Q , in a causal medium, given the speed at a reference frequency ω_o . This equation is the one that is most commonly used and it implicitly assumes that the inertia term in the medium is constant. The measured sediment sounds speed and attenuation appears to violate this equation, as shown in Fig. 2. The BIC08 model is capable of accounting for the discrepancy because it predicts an inertia term that is frequency dependent. When the K-K relationship is modified to account for a frequency-dependent inertia $\rho(\omega)$, the equation becomes,

$$V = \frac{\rho(\omega_o)}{\rho(\omega)} \frac{V(\omega_o)}{\pi} \int_{\omega_o}^{\omega} \frac{1}{\omega_1 Q} d\omega_1$$

Using the modified K-K equation, and an estimate of the frequency-dependent inertia term from BIC08, the agreement with data is achieved. Finally, in an effort to reduce the number of input parameters, connections have been established between the frame bulk and shear relaxation frequencies and the area and thickness of the contact fluid film. However, there are some inconsistencies that need to be resolved before a reduction in the number of input parameters can be achieved. The BIC08 model contains the main physical processes responsible for acoustic reflection and penetration of the seafloor. It has been extensively tested against sandy ocean sediments and it will be extended to cover a wider range of sediment types as more data become available.

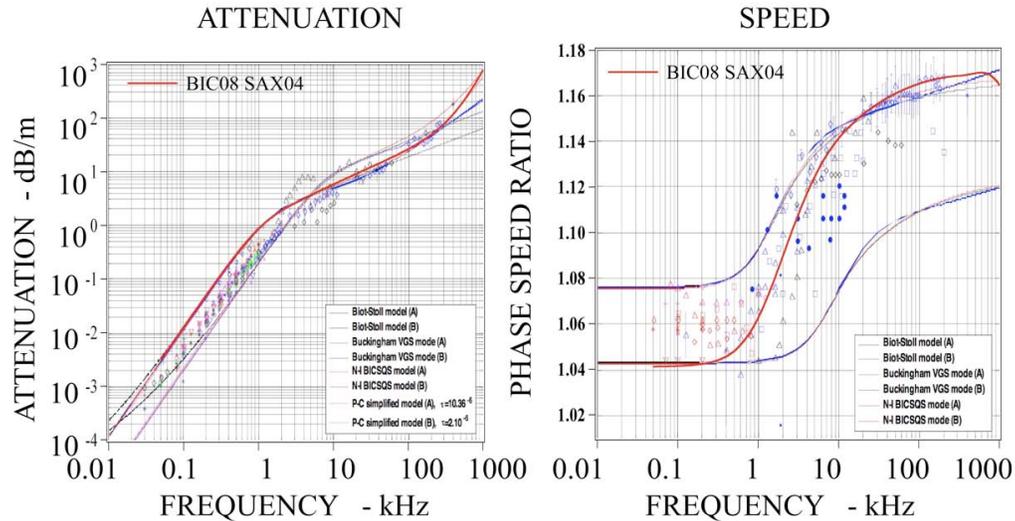


Fig. 1. Comparison of models with measured attenuation (left) and speed (right) in sandy ocean sediments. The data include measurements from SAX99 and SAX04 at high frequencies and inversions at lower frequencies from 24 sites in the East China Sea, Yellow Sea, and the New Jersey coast (SW06) from Zhou, Zhang and Chotiros 2008.

[There are two panels, the left shows sound attenuation vs frequency and the right sound speed vs frequency. The panels show a number of model curves including upper and lower bound Biot-Stoll models, and the BIC08 model for SAX04, overlaid on in-situ measurements from SAX99, SAX04 SW06, ASIAEX and other experiments in the East China Sea and Yellow Sea. The attenuation data shows a dependence on frequency to the power of approximately 2 for frequencies below 1 kHz. The speed data show strong dispersion in the band from 1 to 10 kHz.]

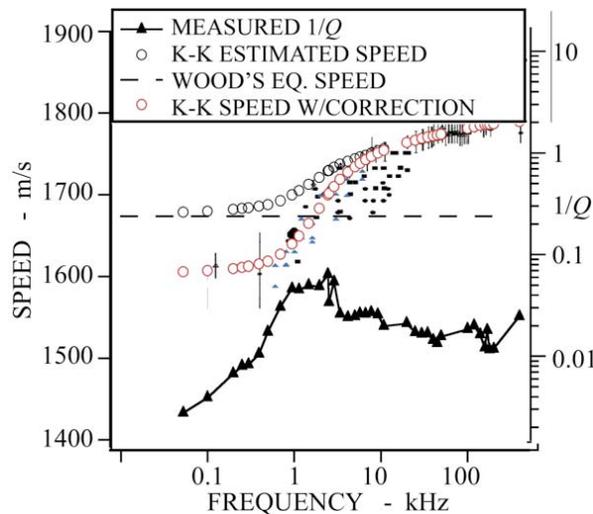


Fig. 2. Comparison of in-situ measurements of sediment sound speed and attenuation from SAX99, SAX04 and SW06 with the commonly used Kramers-Kronig equation (black circles) and the modified equation for frequency-dependent inertia (red circles). The attenuation is given in terms of the inverse quality factor.

[A graph of measured sediment sound speed and attenuation vs frequency from SAX99, SAX04 and SW06. The attenuation is presented in the form of the inverse quality factor. The data is overlaid by the Kramers-Kronig estimate of sound speed from measured attenuation, by both the commonly used equation and by the modified equation that allows for frequency-dependent inertia, showing the improved fit with the modified equation.]

(2) A new model of sediment reflection was presented to NAVOCEANO. The results suggest that fluctuations in the travel time due to bottom roughness and random changes in the phase of the bottom reflection were important contributors to the TL uncertainty. This result is interesting because it is inconsistent with the common assumption (Jensen 1981) that the 1/3 octave TL is equivalent to the incoherent sum of modes or rays. An incoherent sum is insensitive to the effects of phase and travel time fluctuations. The analysis is tentative because it was based on a ray model, which is useful for providing physical insight, but limited in accuracy particularly at low frequencies. It appears to be supported by the measured TL data provided by NAVOCEANO. The data included 4 TL runs, of which 2 were obtained under identical conditions, except for a 20 km displacement, as illustrated in Fig. 3. The difference in TL between these 2 runs represents the random component of the TL fluctuations. It was possible to match the statistics of the TL difference using a layered model of the bottom with random variations in layer thickness. The effects of range dependence in the sound speed profile were also estimated but, in this case, they were found to be small compared to the bottom effects. This approach to sediment reflection modeling is being pursued with a view to improving current models that are used in sonar performance predictions.

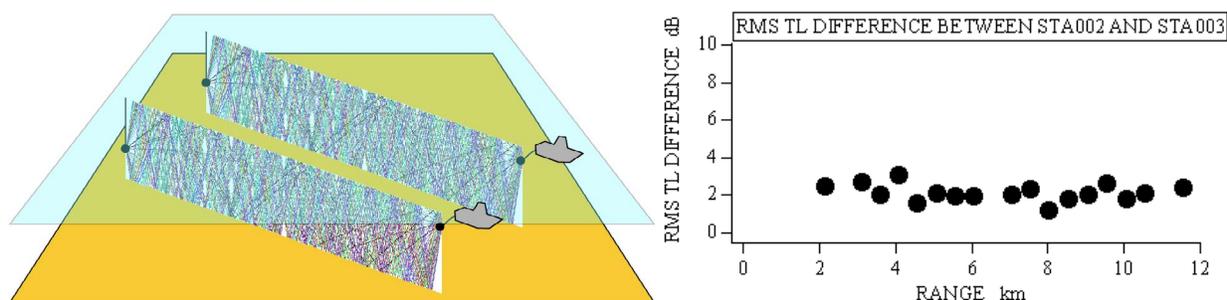


Fig. 3. Illustration of two TL measurement tracks displaced by approximately 20 km (left). The bathymetry under the two tracks are practically identical for ranges less than 12 km. The difference in measured TL in the band from 63 to 315 Hz is an indication of the random component of the TL (right).

[There are two panels. The left panel is an illustration of two TL tracks displaced by approximately 20 km. The right panel shows the difference in measure TL from the two tracks as a function of range in the band 63-315 Hz with values of around 2 dB.]

(3) Coupling of BIC08 to rough surface scattering models: The upgraded laser bottom profiler has a much wider swath width than the previous model while maintaining the same resolution. This was made possible by the use of green lasers which have a smaller intrinsic attenuation than the red lasers in sea water, and the new HD camera has sufficient resolution to support the wider swath width. The swath width and image quality of the previous and upgraded profilers are compared in Fig. 4. The improved swath width will be very useful for roughness measurement in the next sea test involving scattering and reflection from a rough seafloor.

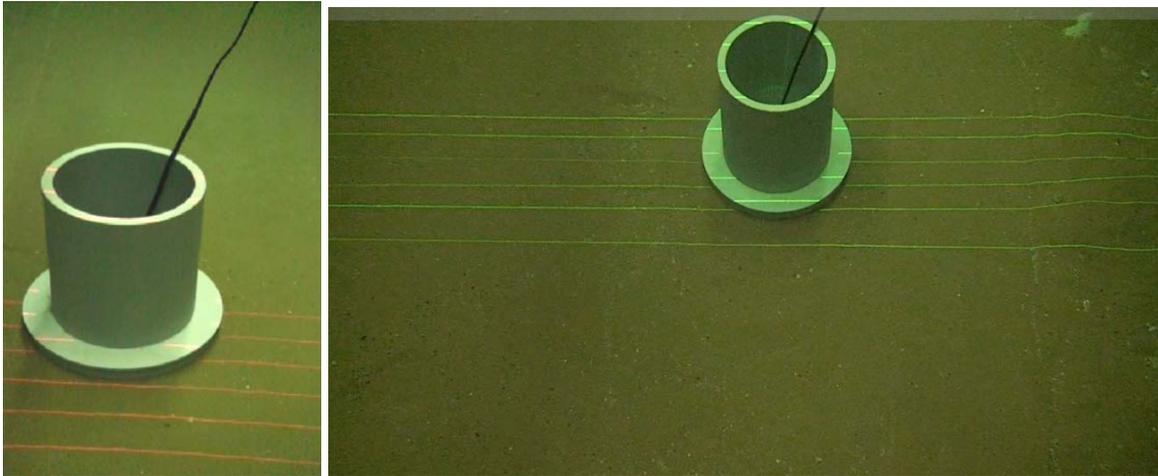


Fig. 4. Images from the previous (left) and upgraded (right) laser profilers. The previous unit used red lasers and a DVD quality camera, while the upgraded unit uses green lasers and a HD quality camera. The images show the same test target under the laser profilers. The test target has a horizontal dimension of 0.33 m (13 inches).

[There are 2 panels. The left panel shows a video frame from the previous laser profiler showing red laser stripes draped over a test target. The right panel shows a video image from the upgraded profiler showing green laser stripes draped over the same test target and a wider swath.]

IMPACT/APPLICATIONS

The results will impact Navy underwater acoustic propagation models, particularly where reflection of sound from and penetration of sound into the ocean bottom are concerned. It will also impact the future structure of oceanographic databases maintained by Navy offices, including the Naval Oceanographic Office. Predictions of sediment sound speeds will need to be revised. A summary of the findings was presented to the Naval Oceanographic Office on 11 May 2009.

RELATED PROJECTS

This project is closely related to most projects under the Underwater Acoustics: High Frequency Sediment Acoustics Thrust, and the on-going series of sediment acoustics experiments. Some results from this project may transition into the Ocean Bottom Characterization Initiative (OBCI) project.

REFERENCES

1. Chotiros, N. P., and M. J. Isakson, 2008, High-frequency dispersion from viscous drag at the grain-grain contact in water-saturated sand: *J. Acoust. Soc. Am.*, v. 124, p. EL296-301.
2. Chotiros, N. P., and M. J. Isakson, 2007, Acoustic virtual mass of granular media: *J. Acoust. Soc. Am.*, v. 121, p. EL70-EL76.
3. Chotiros, N. P., and M. J. Isakson, 2004, A broadband model of sandy ocean sediments: Biot-Stoll with contact squirt flow and shear drag: *J. Acoust. Soc. Am.*, v. 116, p. 2011-2022.
4. Isakson, M. J., N. P. Chotiros, H. J. Camin, and J. N. Piper, 2007, Reflection coefficient measurements in a complex environment at the Sediment Acoustics experiment 2004, (SAX04). : *IEEE J. Oceanic Eng.*, submitted.

5. Jensen, F. B., 1981, Sound propagation in Shallow water: A detailed description of the acoustic field close to surface and bottom: *J. Acoust. Soc. Am.*, v. 70, p. 13971-1406.
6. Zhou, J.-X., X.-Z. Zhang, and N. P. Chotiros, 2008, Sound attenuation coefficients in sandy and silty seabottoms from low- to mid-frequency field measurements in shallow water: *J. Acoust. Soc. Am.*, v. 124, p. 2467.

PUBLICATIONS

1. N. P. Chotiros and M. J. Isakson, "High-frequency dispersion from viscous drag at the grain-grain contact in water-saturated sand," *J. Acoust. Soc. Am.* 124(5) EL296-301, 2008. [published, refereed]
2. N. P. Chotiros and M. J. Isakson, "Comments on "On pore fluid viscosity and the wave properties of saturated granular materials including marine sediments" [*J. Acoust. Soc. Am.* 122, 1486-1501 (2007)]," *J. Acoust. Soc. Am.*, submitted 2009. [submitted, refereed]
3. N. P. Chotiros, "Non-Rayleigh distributions in underwater acoustic reverberation in a patchy environment," *IEEE J. Oceanic Eng.*, submitted 2009. [submitted, refereed]
4. K. R. Loeffler and N. P. Chotiros, "The Calibration of a Laser Profiling System for Seafloor Micro-topography Measurements," *IEEE J. Oceanic Eng.*, vol. submitted, 2009. [submitted, refereed]
5. N. P. Chotiros and M. J. Isakson, "Reverberation statistics in shallow water as a function of sonar configuration and environmental variability," *International Symposium on Underwater Reverberation and Clutter*, Lerici, Italy, September 8 - 12, 2008, 2008. [published]
6. N. P. Chotiros, "Wave speed dispersion in Fluid-Saturated Granular Media Due to Grain Contact Physics," *Poromechanics IV: Proceedings of the Fourth Biot Conference on Poromechanics*, H. I. Ling, A. Smyth, R. Betti Eds., 8-10 June 2009, Columbia University, New York, pp. 455-460, 2009. [published, refereed]
7. J.-X. Zhou, X.-Z. Zhang, and N. P. Chotiros, "Sound attenuation coefficients in sandy and silty seabottoms from low- to mid-frequency field measurements in shallow water," *J. Acoust. Soc. Am.*, vol. 124, pp. 2467, 2008. [published]
8. M. J. Isakson and N. P. Chotiros, "The effects of roughness on the frequency dependence of specular scattering," *J. Acoust. Soc. Am.*, vol. 124, pp. 2583, 2008. [published]
9. N. P. Chotiros, M. J. Isakson, J.-X. Zhou, and D. P. Knobles, "Low- to mid-frequency model of attenuation and dispersion," *J. Acoust. Soc. Am.*, vol. 124, pp. 2468, 2008. [published]
10. N. P. Chotiros, "Broadband sediment acoustics models 100 Hz to 1 MHz", *Shallow Water 06 Workshop*, February 10-12, 2009, University of Texas at Austin. [published]
11. N. P. Chotiros, "Reverberation statistics", *ONR 2009 HIFAST Workshop*, August 25-26, 2009, University of Texas at Austin. [published]