Laboratory and Field Studies of the Acoustics of Multiphase Ocean Bottom Materials

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LONG-TERM GOALS

The long-term scientific objective of this project is to increase our understanding of sound propagation in ocean bottom sediments, including water-saturated sands and muds, gas-bearing sands and muds, and sediments which support seagrass. This in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. The proposed study includes continued analysis of data collected during Shallow Water 06 (SW06), development of apparatus and procedures for propagation and sediment studies for the next planned shallow water experiment (referred to herein as SW12) and continued laboratory studies of the acoustics of the multiphase sediment materials mentioned above. Another goal for the out years is to develop techniques and apparatus for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The origin of this project was an Entry Level Faculty Award in 2005, then a follow-on grant for 2008–2009. In this time, impedance tube and resonator methods, originally developed by the author for the investigation of bubbly liquids [1, 2], have been successfully modified for the investigation of ocean bottom sediments [3, 4]. In addition, the technique has been applied to the study of gassy sediments [5, 6] and seagrasses [7, 8]. In Refs. [3] through [8], sound speeds have been measured from 100 Hz up to 300 kHz. This work resulted in the author being awarded the 2007 A.B. Wood medal in underwater acoustics [9]. Analysis of SW06 data has also resulted in sound speed and attenuation inferences down to 40 Hz [10]. We now continue the use of these experimental methods to investigate sound propagation in multiphase ocean bottom sediments. The four primary goals are:

1. Continue our laboratory investigations of various artificial (glass beads, reconstituted sands, muds) and natural sediments using the low frequency laboratory techniques mentioned above. The objective is to obtain sound speed and attenuation measurements with sufficient knowledge of the measurement uncertainty to facilitate meaningful model comparison on a wider range of sediment types than we have been able to achieve thus far. Our previous work was focused primarily on cleaned and sieved sands. We will be extending our measurements into more

realistic and complex sediments that contain additional material such as shell fragments, larger non-sand particles, silt and clay particles, and muds, gas-bearing sediments and seagrass.

2. There is ongoing debate in the community over the nature of low-frequency sound propagation in granular sediments, specifically the degree of dispersion and what controls it. Low-frequency dispersion has been observed *in situ* (during SAX99 [11] for example), but other times is absent, such as on the Malta Plateau and areas on the New Jersey shelf [12]. A related issue is the wide range of variability observed in sound speed [4] and reflection coefficient measurements [13], even in well-controlled laboratory conditions. The mechanism that governs the lowest frequency range has been proclaimed to be either the presence of small amounts of gas trapped in crevices on the sand grains themselves [14], or extra inertia due to rotation of sand grains [15]. The laboratory methods undertaken here offer the ability to control for cause and effect by careful preparation of sediment samples. We now have a pressure vessel (see Fig. 1) that allows us to conduct our acoustic resonator sound speed measurements at a range of hydrostatic pressures from zero to 300 m equivalent depth. This device can help us evaluate the trapped-gas explanation for low sound speeds at low frequency. If the low frequency sound speed is controlled by the presence of gas trapped perpetually (and immune from degassing) in sand grain crevices, than the gas volume, and hence the sound speed, will be a function of the hydrostatic pressure. If the low frequency sound speed is controlled by grain rotational inertia, then the hydrostatic pressure will not effect the low frequency sound speed. We are investigating this phenomenon using our resonator technique within our pressure vessel, with an eye for including this apparatus on SW12 for the shipboard evaluation of sediment samples brought up from the bottom.

3. We have adopted a technique to control the porosity of granular sediments in the laboratory and we have conducted an initial round of high frequency (300–800 kHz) sound speed and attenuation measurements. The apparatus is shown in the upper frame of Fig. 2, and typical results are shown in the lower frame. These measurements reveal for the first time (to the knowledge of the author) a transition from a Biot-like behavior, to a highly attenuating, multiple-scattering-controlled regime. No current single model is capable of handling this transition. As the demand for high-resolution detection and classification grows, sonar frequencies will increase and a unified model that can bridge these regimes will become necessary. We are developing and using this technique to systematically study the acoustics of granular sediments, with variable porosity independent of grain size or sediment type, through a wider frequency range than shown in Fig. 2. Reflection coefficient measurements are also available using the same apparatus, and provide measurements of the reflection coefficient as a function of frequency, porosity, and angles of incidence.

4. Finally, we continue to analyze data from SW06, and to make preparations for participation in SW12. An example of our recent analysis is the attenuation versus frequency inversion shown in Fig. 3. Future analysis will include inversion for frequency dependence of the low frequency sound speed in addition to attenuation, and the investigation of measurement error bounds. This part of the effort will also include the development of the combustive sound source (CSS) for towable water column deployment, and for use as a shear source on the ocean bottom. The former is to provide impulsive shots for propagation measurements, and the latter is to provide a means to infer shear properties through inversion of geophone measurements as described in Refs. [16, 17].

APPROACH

We are continuing the use of the resonator method [4, 18] for measuring acoustic properties and the new apparatus for high frequency measurements shown in Fig. 2. For the former, we have added the capability to control the hydrostatic pressure and temperature of the sediment samples, so that measurements can be done at simulated ocean depths, which is important for gas-bearing sediments. The pressure vessel is shown in Fig. 1. For the latter, we have adopted a technique that allows for the control of porosity, [19] and has been applied to new high frequency (above 50 kHz) measurements, presented below. We also incorporated a normal incidence reflection measurement capability into this system. This new system allows for the simultaneous measurement of sound speed, attenuation, and normal incidence reflection in water-saturated granular materials as a function of frequency and porosity. Finally, the combustive sound source (CSS) is under continued development for use in future ONR-sponsored ocean acoustics experiments. The CSS will serve as a replacement for explosive charges and air guns in future basic research sea tests.

The personnel for this project are: Preston S. Wilson serves as PI and is an Associate Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Associate Research Professor at the University's Applied Research Laboratories (ARL:UT). In addition to oversight, Wilson contributes significantly to many tasks, including modeling, instrument and experiment design, construction and operation. Kevin T. Hinojosa, a UT Aerospace Engineering junior and an Undergraduate Research Assistant on the project, serves as an electromechanical technician and provides machine shop, procurement and software support. Theodore F. Argo IV is a UTME Ph.D. student who contributes to all aspects of the project. Another UT MS student, Christopher J. Wilson is also working on the seagrass acoustics portion of this project. Chris is primarily funded by a fellowship he holds, but he contributes to this effort.

WORK COMPLETED

Objective 1—Laboratory sediment and multiphase ocean bottom materials investigation:
Our recent work on the acoustics of seagrass species *Thalassia testudinum, Syringodium filiforme and Halodule wrightii* was extended. Measurements and analysis of sound speed in a gassy sediment, as a function of over pressure were obtained. A new time-of-flight sediment sound speed and attenuation apparatus was constructed.

Objective 2 —Low frequency dispersion due to gas content as a function of pressure: Experiments were completed with hydrate-bearing sediment and measurements of sound speed were obtained as a function of hydrostatic pressure.

Objective 3—Porosity-control sediment acoustics measurements: Refinement and expansion of the apparatus was undertaken. New parts have been made and the revised apparatus is under construction.

Objective 4—SW06 Data Analysis & Prep for SW12: Further development of the CSS for NAVO ocean surveys was conducted, which impacts ONR code 32 interest in the CSS for future use in basic ocean acoustics sea tests. A DURIP was received for the construction of a CSS for use in future ONR sea tests. Continued analysis of data from SW06 was conducted.

RESULTS

Objective 1— Laboratory Sediment Investigation: Previous results [8] definitively showed that a two-phase effective-fluid model (water and air) was insufficient to describe the acoustics of seagrass leaves in water. The work in the present FY definitively showed that three-phase effective fluid models are also insufficient to describe the acoustics of seagrass leaves in water. All the potential simple models have been tested and none of them are capable of predicting the sound speed in a seagrass meadow. We have now determined that one must have knowledge of the gas content, the tissue elastic properties, and the tissue structure, in order to predict the sound speed in a seagrass meadow. This was accomplished using our resonator method to measure sound speed, and we obtained micro-CT 3-D image scans of the same tissue specimens, which yields the 3-D geometry of the structure, including the gas and tissue relative volumes. A low-resolution example of such a scan is shown in Fig. 4. These results are currently in press. [20]

Objective 2 —Low frequency dispersion due to gas content as a function of pressure: Significant sound speed dispersion as a function of hydrostatic pressure was observed in the hydrate-bearing sediment samples. As the pressure was reduced, the hydrate transitioned from a solid-liquid mixture, to a solid-liquid-gas mixture. Results are shown in Fig. 5. The sound speeds reported are for frequencies below 1000 Hz. Dispersion from around 1400 m/s down to 200 m/s was observed.

Objective 3—Porosity-control sediment acoustics measurements: This apparatus was redesigned for higher accuracy and improved ease of use. Final construction of the revised apparatus is currently underway, and there are no new results to report for this objective.

Objective 4—SW06 Data Analysis & Prep for SW12: The combustive sound source (CSS) was deployed by the PI and ARL:UT colleagues in SW06. Subsequent data analysis this year built upon the previous year's analysis [10, 21] and has further shown that CSS is a viable alternative to small explosive charges and better than light bulb implosions. Both short- and long-range broadband propagation in SW06 has been modeled in an uncertain inhomogeneous waveguide. A typical result is shown in Fig. 6. These and additional results are presented in a new paper, currently in press. [22] The results of the study suggest that the coherent structure of low frequency long-range propagation in an area of the New Jersey continental shelf known for its environmental complexity can be successfully simulated with a coarse sampling of environmental parameters such as the sound speed profile, the bathymetry, and the geoacoustic profile.

IMPACT/APPLICATIONS

The Biot-based description of sound propagation within sandy marine sediments is gaining support in the ocean acoustics and related research communities, but we are also coming to the conclusion that it not fully adequate. The new laboratory results reported here indicate that the Biot-Stoll model [23] correctly predicts the porosity dependency of high frequency sound speed in water saturated sand. Low frequency (53–2000 Hz) attenuation data [10] from SW06 are also well described by Biot-Stoll and clearly follow the low frequency limiting slope of frequency squared. We are continuing our efforts to get ever-more-broadband and more accurate laboratory measurements with an increased understanding of the measurement uncertainties.

As our understanding of sound propagation in the ocean bottom increases, one application will be to update the models used in operational sonar systems and environmental surveys. A better description of bottom interaction will increase our ability to detected, localize and classify targets in littoral environments. The same can be said for buried objects. Finally, the CSS continues to provide useful data from SW06 and will be a useful tool for ocean acoustics experiments.

TRANSITIONS

This PI receive $225k in the current fiscal from the Naval Oceanographic Office for further development of the combustive sound source (CSS) as a replacement for explosives in ocean surveys. This PI received $249k from the ONR Code 332 to perform laboratory measurements of the sound speed in methane hydrates, using the resonator method developed with the present grant, covering FY08, 09 and 10. This PI continued a project originally started in 2009, funded by Shell Oil, to use bubbles to reduce the radiated noise from offshore drilling operations. Much of this PI's experience with bubbles was due to a project previously funded by ONR and also due to the current grant.

RELATED PROJECTS

SAX99: Sediment Acoustics Experiment 1999
From the project web page: SAX99 addresses high-frequency sound penetration into, propagation within, and scattering from the shallow-water seafloor at a basic research (6.1) level.
http://www.apl.washington.edu/programs/SAX99/Program/prog.html

SAX04: Sediment Acoustics Experiment 2004
From the project web page: The overall objective of SAX04 is to better understand the acoustic detection at low grazing angles of objects, such as mines, buried in sandy marine sediments. One component of the SAX04 work is designed to collect data and gain a greater understanding of high-frequency sound penetration into, propagation within, and scattering from the shallow water seafloor at a basic research level. A second component is designed to provide data directly on acoustic detections of buried mine-like objects at low grazing angles.
http://www.apl.washington.edu/projects/SAX04/summary.html

Other ARL:UT sediment researchers: Marcia Isakson and Nicholas Chotiros both conduct research on sound propagation in marine sediments. Many ONR PIs conduct research on modeling of sound propagation in shallow water waveguides.

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HONORS/AWARDS/PRIZES

Christopher Wilson, a UT graduate student who's research is funded via the present grant won Best Student Paper Award at the 2009 Texas Bays and Estuaries Meeting in Port Aransas, TX. Christopher Wilson also won the 2010 E. J. Lund Founders Fund Fellowship to continue to support his research, which is also supported by this grant

Fig. 1. The pressure vessel used for simulating the hydrostatic pressure at ocean depths up to 300 m is shown. The present acoustic resonator apparatus can be operated within this pressure vessel to investigate the hypothesis that trapped crevice gas controls the low frequency sound speed in water-saturated sand sediments.

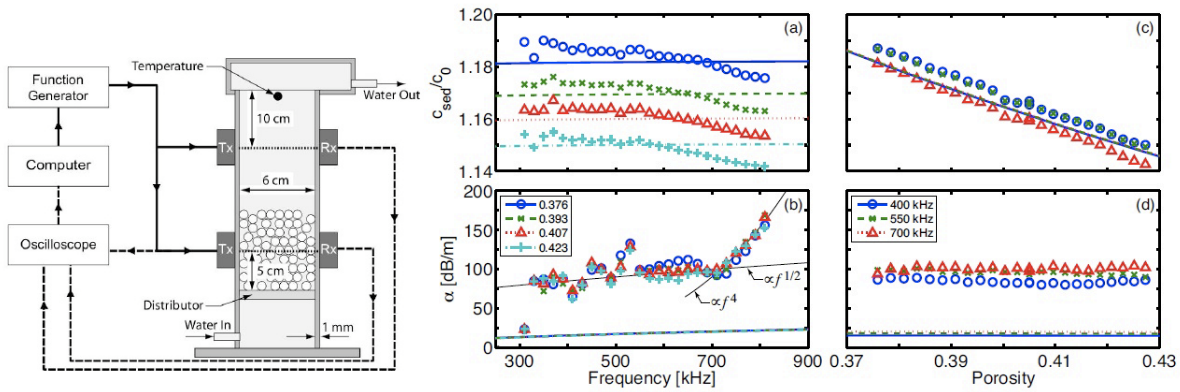

Fig. 2 On the top, a schematic diagram of the porosity control apparatus is shown. Solid (dashed) lines denote the transmitted (received) electrical signal paths. The glass beads are not drawn to scale. Water flowing into the bottom of the column causes motion of the sediment grains, with the resulting porosity after cessation of the flow dependent upon the flow rate. Sound speed and attenuation are measured using the pairs of Rx-Tx transducers. A typical measurement of sound speed (a) and attenuation (b) versus frequency, for various porosities is shown in the middle frame. Sound speed (c) and attenuation (d) versus porosity for three frequencies is shown on the right. The solid lines represent predictions of the effective density fluid model [24]. Biot-like ($f^{1/2}$) behavior is seen below about 700 kHz, but at higher frequencies, the attenuation follows f^4, which suggests a multiple scattering mechanism. Figure (c) also shows that porosity is a very good indicator of sound speed, while attenuation (d) is independent of porosity.

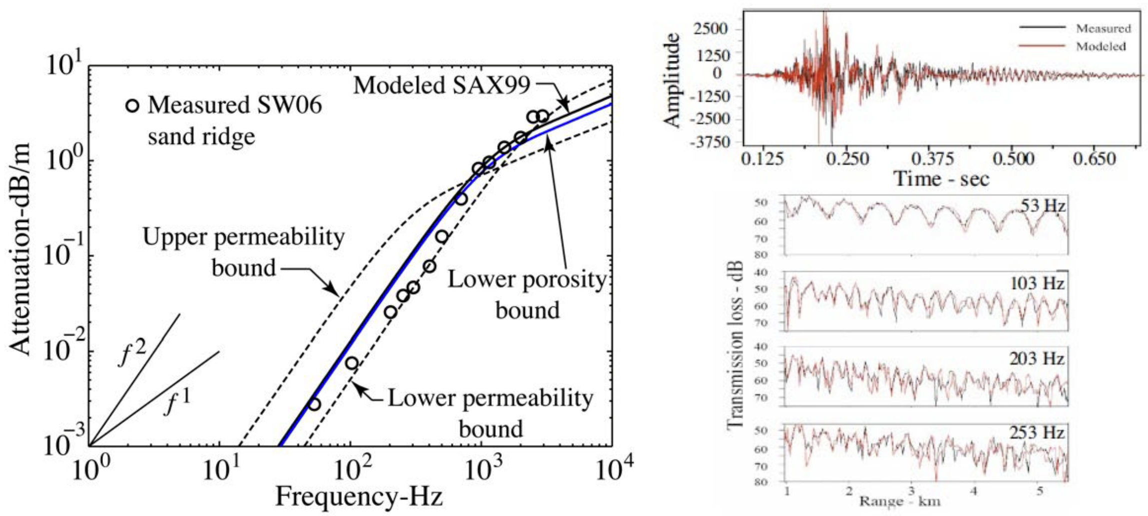

Fig. 3. Attenuation as a function of frequency for a sandy sediment from SW06 is shown. The data points (left frame, open circles) are attenuation values inferred from propagation and transmission loss data. First, sound speed in the sand layer was obtained from fitting time domain data (upper right, black) with a propagation model (red). These signals were generated with the CSS, and this type of inversion requires an impulsive source because the dispersion seen in the plot is strongly effected by the sound speed in the upper-most sediment layer. Then narrow-band long-range transmission loss data (lower right, black), which is sensitive to the attenuation in the upper-most sediment layer, was fitted with a TL model (red). The values of attenuation in the propagation model that achieved the best fit at each frequency are the open circle data points in the plot on the left, above. The data are compared to the Biot-Stoll model for a range of permeabilities and porosities. Good agreement between the inferred attenuation data and the Biot-Stoll model is found [10].

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Fig. 4 Three-dimensional representations of Syringodium from CT imagery. Aerenchyma (air-filled structures) are evident as the contrasting pixel color in the middle of each leaf. The same data that yields such images can be used to determine the global volume ratio of tissue and air.

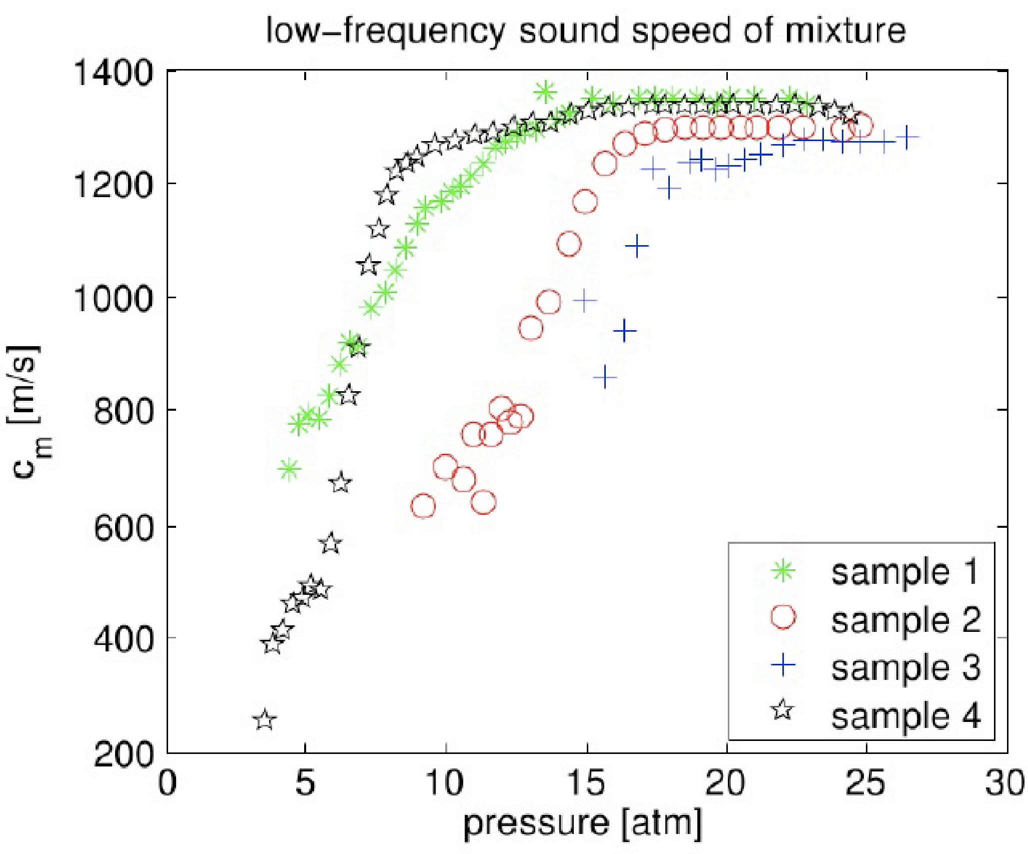

Fig. 5. Measured sound speeds of hydrate mixtures.

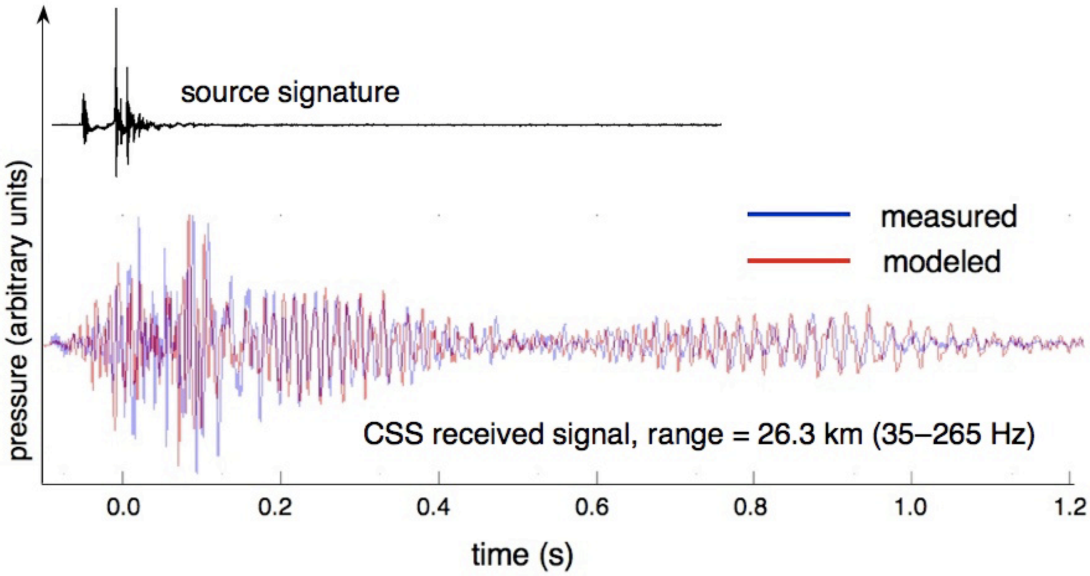

Fig. 6. Broadband propagation modeling from SW06. The upper curve is the CSS Event 26 source signature, deployed at 26 m depth. The lower curves are measured and modeled propagation 26 km downrange from the soruce.