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14. ABSTRACT
The primary purpose of this work was to conduct laboratory and field studies of the acoustics of sandy ocean bottom sediments, with sufficient control of experimental uncertainly to make meaningful comparisons to existing and developing models. The work began with a focus on low frequencies, below the Biot transition frequency, but expanded in frequency range to cover frequencies above the Biot transition frequency. Initially, the work was focused on sandy sediments, but additional multiphase ocean-bottom materials were eventually studied, too, including gas-bearing sediments and seagrass. The work was initially focused on laboratory measurements, but expanded to include work during the large-scale, ONR-sponsored at-sea experiment Shallow Water '06. Results of a large number of associated laboratory and field measurements are presented along with model comparisons, for the various ocean bottom materials mentioned above.

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sound propagation, ocean bottom sediments, granular sediments, dispersion, attenuation, gas-bearing sediments, seagrass

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Using an Impedance Tube

for fiscal years 2005–2007

and

Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques

for fiscal years 2008–2009

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PRESTON S. WILSON

Austin, Texas
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Executive Summary

The exact acoustic behavior of water-saturated, granular, ocean-bottom sediments remains an active area of research despite at least 50 years of study. The primary purpose of this work was to conduct laboratory and field studies of the acoustics of sandy ocean bottom sediments, with sufficient control of experimental uncertainly to make meaningful comparisons to existing and developing models. The work began with a focus on low frequencies, below the Biot transition frequency, and ended up expanding in frequency range to cover frequencies above the Biot transition frequency, as well. Initially, the work was focused on sandy sediments, but additional multiphase ocean-bottom materials were eventually studied, too, including gas-bearing sediments, seagrass, and methane hydrates. The work was initially focused on laboratory measurements, but expanded to include work on the large-scale, ONR-sponsored at-sea experiment Shallow Water '06. The grant was initially awarded for three years, in which it was titled "Investigation of the Acoustics of Marine Sediments Using an Impedance Tube" and then extended for two additional years and retitled "Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques."

The results of the grant are presented in Chs. 2 through 6, which also correspond to the fiscal years in which the work was performed. In each of the above chapters, the goals, work completed, and results are summarized. Publication lists are also provided in each chapter for that fiscal year.

The primary results are briefly noted here:

1) The combustive sound source (CSS) was deployed in SW06 to provide an environmentally safe alternative to commercially available air guns and SUS charges.

2) Evidence for low frequency sound speed dispersion in sandy sediments was found both in the laboratory measurements and in inferences obtained from SW06 measurements.

3) Laboratory-measured absolute values of the sound speed, including dispersion, for water-saturated sand was found to agree with the Biot model from 2 kHz through 300 kHz, which is from about the middle of the transition frequency range, to well into the high-frequency asymptotic range.

4) The slope of the frequency-dependent attenuation, inferred from SW06 ocean acoustics measurements, was found to agree with that predicted by Biot-based models from 40 Hz to 2 kHz.

5) A simple expression, based on Wood's equations, was found to describe the low-frequency sound speed in shallow, fluid-like, gas-bearing sediments. Only sediment bulk density, ambient pressure, and gas void fraction is required to predict the sound speed below the resonance frequency of the largest bubble.

6) Laboratory measurements of the low-frequency sound speed in three seagrass species were obtained. Although seagrass tissue encloses significant volume fractions of air, and resides in the host-medium of seawater, it was found that Wood's equation was not sufficient to describe the observed sound speed. Knowledge of the seagrass tissue elastic properties and tissue geometrical micro-structure is required to predict the effective sound speed in seagrass beds.

7) A porosity control technique was developed for creating laboratory sediment beds of variable porosity.

8) High frequency negative dispersion was found in artificial, water-saturated, glass bead sediments.

9) The Biot model was found to describe the mean porosity dependence of the measured sound speeds using the technique described in 8), but not the negative dispersion.

10) Sound speed measurements on gas-bearing muddy sediments from the continental shelf of the Beaufort sea were obtained.

11) Despite 5 years of work on this grant and untold numbers of others, there is still an insufficient amount of quality acoustic measurement data to adequately support the existing modeling efforts for the acoustics of granular sediments. More experiments are needed, with better knowledge and control of the input parameters, and with better understanding of measurement uncertainty, in order to test exiting and developing models, and to fully understand sound propagation in water-saturated granular sediments.

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for fiscal years 2008–2009

Chapter 1: Introduction

This is the final report for the Office of Naval Research grant "Investigation of the Acoustics of Marine Sediments Using an Impedance Tube" active for fiscal years 2005–2007 and "Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques" active for fiscal years 2008–2009. Both titles were funded under the grant N00014-05-1-0260.

The main goal of this project was to increase our understanding of sound propagation in ocean bottom sediments, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. This included granular sediments, gas-bearing sediments, and seagrass beds. The focus of this work was on obtaining laboratory and *in situ* measurements of sound propagation in these materials, and comparison of these data with existing models.

The results of these studies are presented in Chapters 2 through 6, which also correspond to the fiscal years in which the work was conducted. Specific goals and objectives, the approach, work completed, and results are presented for each chapter. Yearly publications are presented in each chapter. The report concludes with a summary and a bibliography listing the most important peer-reviewed papers that have come from this work.

Investigation of the Acoustics of Marine Sediments Using an Impedance Tube

Chapter 2: Summary of Work Conducted FY2005

LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of the plane wave reflection coefficients from laboratory and *in situ* sediments using impedance tube methods, [1] in the frequency range of approximately 500 Hz to tens of kHz. This approach will also yield measurements of the acoustic impedance, sediment sound speed, attenuation, and complex density through the use of appropriate model inversions and data analysis. [2] These measurements will span a frequency range in which there is little experimental data and help to verify competing theoretical models [3-10] on sound propagation in marine sediments. An overview of the state-of-the-art in both experiment and modeling is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation.

Initial impedance tube work [2] has indicated that the coupling between the sediment and the impedance tube walls must be accounted for, in order to infer the intrinsic sediment attenuation from measurements performed in an impedance tube. Therefore, an initial objective is to develop an appropriate model that describes this coupling, and to develop a new impedance tube that exploits this model, i.e. minimizes the coupling, and allows for accurate recovery of intrinsic sediment attenuation from the measurements.

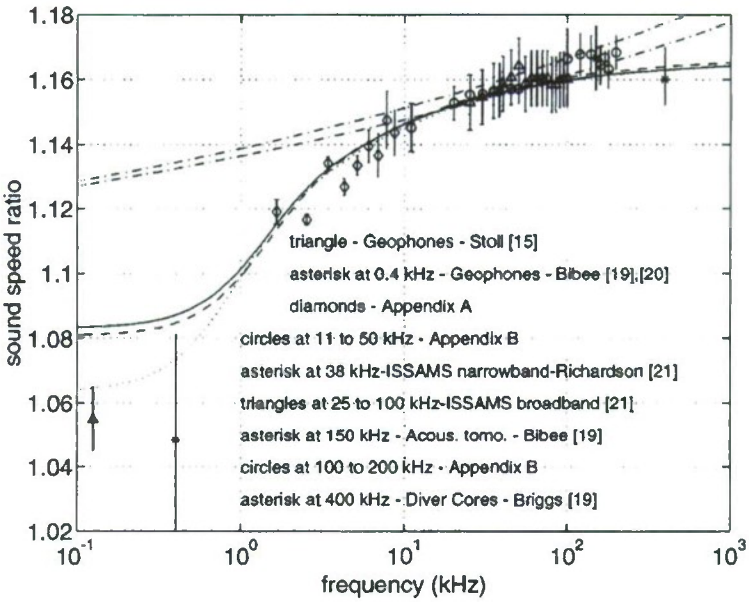


Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [26]. The theoretical curves are: solid line=Biot/Stoll [9]; dashed line=Williams [10], dash-dot lines=Buckingham's model for two values of fluid viscosity [8]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [26].)

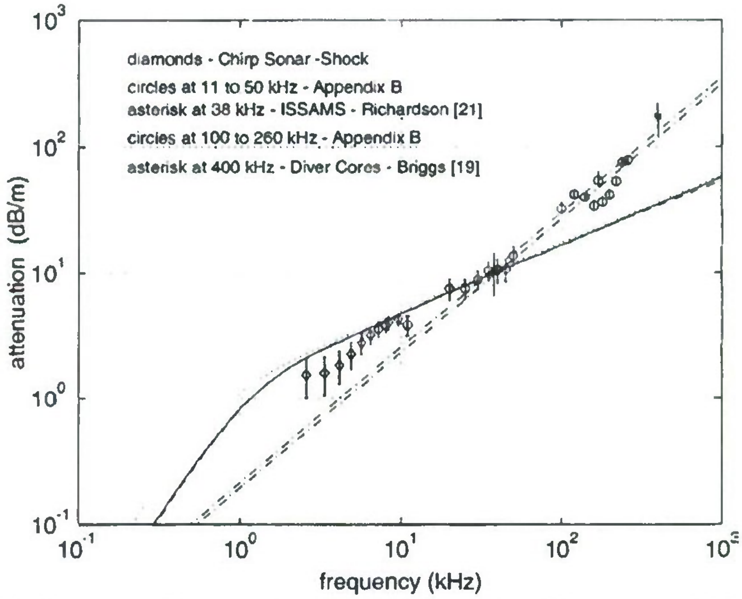


Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [26].) Also note that there is attenuation data below about 3 kHz.

APPROACH

The impedance tube technique and has been adopted as a standard technique [11-13] for measuring the acoustic properties of small samples of materials in air. With support from the Office of Naval Research Ocean Acoustics Program, this author and colleagues at Boston University developed an impedance tube technique and apparatus for use in measuring the acoustic properties of materials with water or other liquids as the host medium. [1] A number of engineering problems relating to the acoustic coupling between the fill-liquid and the tube walls, and to the perturbing effects of the measuring apparatus itself were overcome. The original apparatus was developed for and successfully used to measure sound speed and attenuation in bubbly liquids in a frequency range of 5–9 kHz. [14] The device proved to be the most accurate and precise water-filled impedance tube reported in the open literature. The uncertainty in the measured reflection coefficient for this device is +/- 0.14 dB in magnitude and +/- 0.8° in phase.

In the current project, we are building a larger, new and improved impedance tube for use with marine sediments. It will operate in the frequency range in which dispersion is expected (about 500 Hz to 30 kHz) in typical sandy sediments. We are investigating a new impedance measurement technique [15] that does not require movement of the pressure sensor, and will minimize errors due to sensor position uncertainty. Further, we will incorporate new modeling that will better account for the coupling between the sediment and the tube walls and thereby provide a more accurate quantification of experimental error. This modeling will be based on and extended from existing work for lossy fluid coupling in elastic waveguides, [16, 17] additional sample-wall boundary effects, [18] sample-fluid boundary effects [19] and asymmetric excitation. [20] The instrument will be used in the laboratory to investigate artificial and natural sediments *in vitro*.

In the final year of the project, we plan to modify the laboratory device for use on the ocean bottom for *in situ* characterization of sediments. There are two possible versions of the *in situ* device, and these were explored in an earlier study. [21] In one of the versions, the impedance tube will penetrate the ocean bottom and a reflection coefficient will be measured inside the tube. In the other version, the impedance tube will not penetrate the sediment, but will sit flush on the bottom. The impedance measurements can be made, regardless of the exact configuration and will contain information about the material properties of the ocean bottom. The interpretation of those measurements will require appropriate modeling. For example, the penetrating version could be modeled using the classic theory of Levine and Schwinger [22] for sound radiation from an open tube, in which the sediment sound speed would be a parameter. The flush-deployed version may be modeled with a finite-element numerical model such as described in [23], again with material properties as parameters. In both case, the impedance measured by the impedance tube would be compared to the appropriate model and sediment parameters varied until measured and modeled impedances are in agreement. Additional modeling beyond that described in [22] and [23] is anticipated, to obtain useful inversions for material parameters in both cases, but the raw impedance measurements themselves may prove to be useful.

The personnel for this project are: Preston S. Wilson serves as PI and is an Assistant Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Assistant 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. Paul A. Waters is an Undergraduate Research Assistant on the project and is a UTME senior. Waters serves as an electromechanical technician and provides machine shop, procurement and software support, and oversees purchasing. Finally, Jacob G. Migliazzo is a Graduate Research Assistant, a UTME Master of Science student and contributes to all aspects of the project.

WORK COMPLETED

In the proposed course of work, the first year was devoted to design and construction of the impedance tube facility and verification of its operation via measurement of "known" materials. The facility includes the impedance tube itself, the sensors and electronics that run and monitor the experiments, and apparatus that performs supporting functions, such as water degassing and sediment preparation. Much of the primary (impedance tube) and support apparatus has been constructed. Part of the system, including the impedance tube itself is shown in Fig. 2. Some of the characteristics of the proof-of-concept system [2] are being reused, and it is primarily hardware related to those aspects that have been completed at this time. Within this category is the framework that supports the impedance tube, a thin-walled impedance tube (which serves as a place holder while the heavy-walled tube is being constructed), the sensor positioning system and the water degassing system. The primary acoustic sensors have been specified (B&K 8103's) and will be purchased shortly. (The manufacturer provided a sample that passed our evaluation.) A B&K charge amp, which will provide signal conditioning has also been purchased. A National Instruments data acquisition system is being specified. The sediment preparation system is partially completed. Finally, the heavy-walled impedance tube (1.8 m in length, 5 cm o.d., 2.5 cm i.d., weighing 200 pounds) was procured from a supplier. This aspect of the project was critical, and it took some time to find a supplier who could provide the tube. The concentricity of the tube, and the inner surface finish of the tube must be completed with a high degree of precision. Further, the material (304 stainless steel) and length of the tube limit the number of potential suppliers. A picture of the heavy-walled tube is shown in Fig. 3. Flange work is currently be added to the heavy-walled tube, and it will shortly be ready for installation in the apparatus.

In addition to the experimental apparatus construction, a literature review has been completed. The purpose of this review was to assemble information that will help us optimize the impedance measurement process, model sound propagation in the tube, and interpret the measurements, as discussed in the APPROACH section of this document. A number of important references [16-20] have been located and we have begun the implementation and analysis of some of those models.

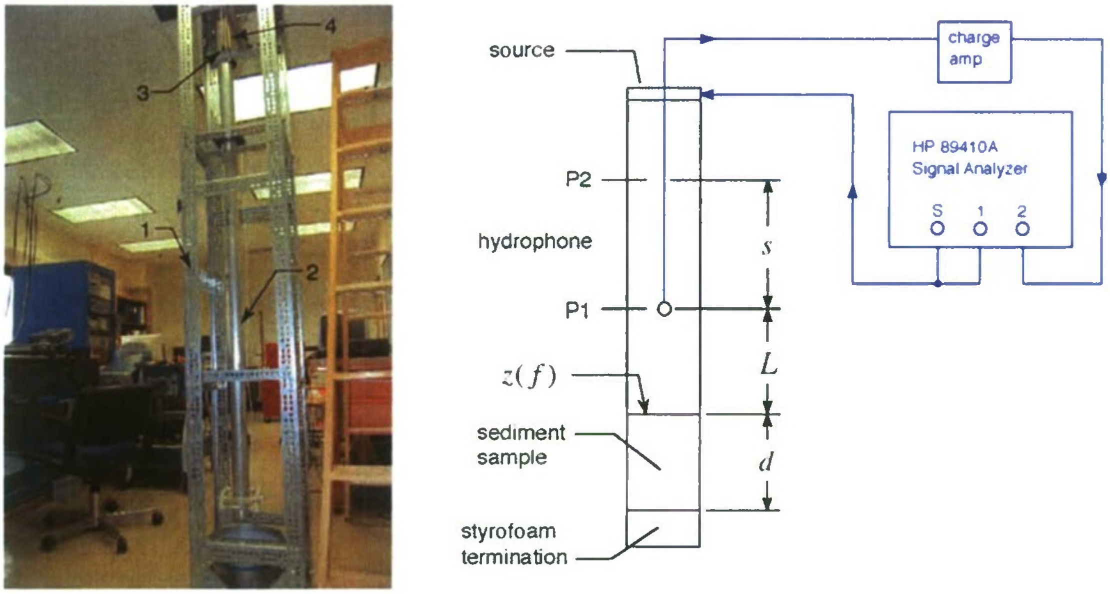


Fig. 2. On the left is shown a photograph of part of the impedance tube system in our laboratory, including the supporting framework (1), the impedance tube (2), the hydrophone (3), and the hydrophone positioning system (4). The tube in the picture is a temporary place holder for the heavy-walled tube, while it undergoes machine shop operations. On the right is a schematic diagram of the impedance tube system.

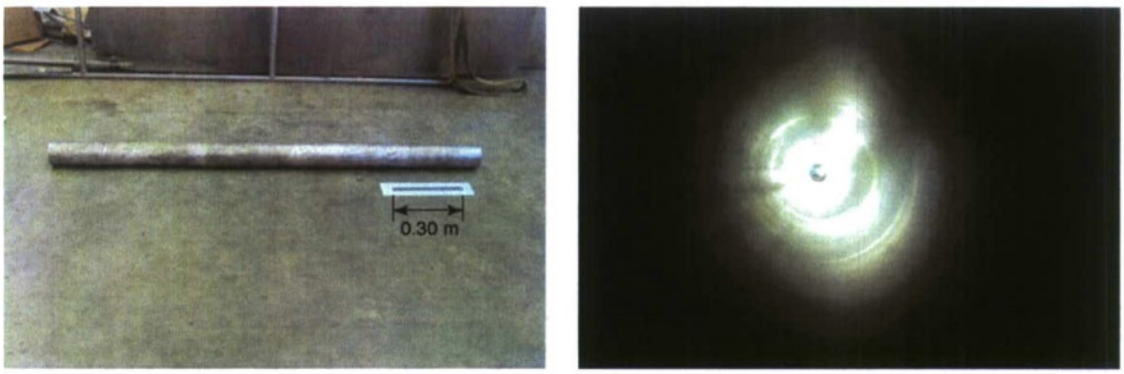


Fig. 3. On the left is shown a photograph of the heavy-walled impedance tube during machine shop operations. The 0.30 m length machinist's rule indicates the size of the tube, which is 1.83 m in length. On the right, the view down the center of the tube is shown, illuminated from the far end with a flashlight, after gun drilling and honing. Note the smoothness of the inner tube wall.

RESULTS

We are 7 months into this project, and most of the work has been devoted to developing the proposed experimental apparatus. We have also implemented some additional models of sound propagation within elastic-walled waveguides, the purpose being to allow for more advanced interpretation of the measured data, and to more fully quantify experimental error. Since the experiment is not yet ready to run, we do not have any new measurements, but we have applied some of the new modeling to an existing data set, and generated some new results, described below.

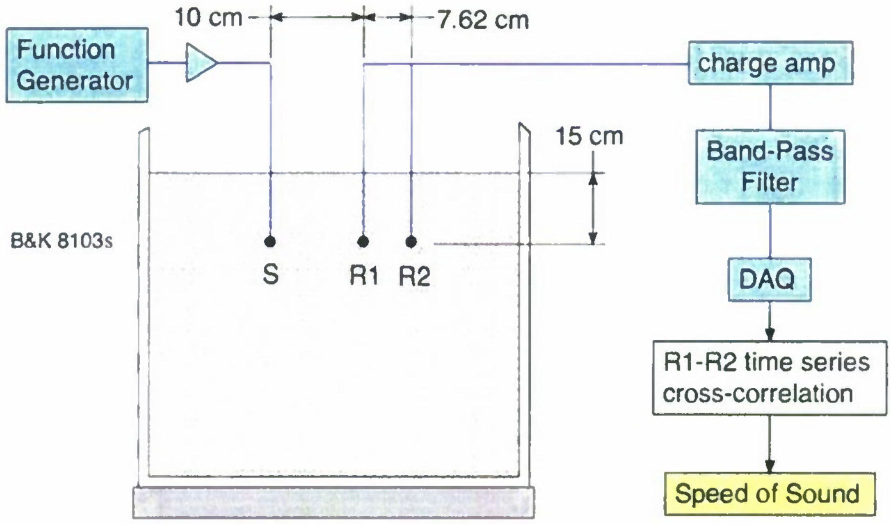


Fig. 4. A schematic diagram of the time-of-flight experiment is shown. A large thin-walled cylindrical container was filled with 60°C degassed water and sorted and washed medium grain blasting sand. Three B&K 8103 hydrophones were placed in the sediment and time-of-flight measurements were obtained after cooling. A function generator and power amplifier were used to drive one of the 8103s as a source. The remaining two 8103s were used as receivers. Their signals were conditioned with a charge amp and a band-pass filter. The voltage signals were acquired with a digital oscilloscope and cross correlated to extract the time-of-flight. Sound speed was then calculated from the 7.62 cm sensor separation distance.

Measurements of the sound speed of an artificial water-saturated, sandy-sediment contained within a thin-walled cylindrical tank were obtained by the author and co-workers in a previous study. [24] Schematic diagrams of the experimental apparatus and procedure are shown in Figs. 4 & 5. Above 20 kHz, the sediment sound speed was measured directly using time-of-flight. Below 20 kHz, the frequency-dependent sound speed was inferred from the measured resonance frequencies of the system by initially approximating the thin-walled cylinder as pressure-release. Both symmetric and asymmetric modes of the system were excited. An elastic waveguide model for symmetric modes was then used to infer the free-field sediment sound speed from that measured within the tank, for the *symmetric modes only.* Our current effort has resulted in a model for *asymmetric* modes, and has allowed us to analyze the remaining data from Ref. [24]. The sound speed dispersion for the sandy sediment is shown in Fig. 6. This dispersion is fairly well-described by Williams' Effective Density Fluid Model [EDFM], without any fitting of the material input parameters. [10] We do observe speeds that are slightly lower than the EDFM prediction, though. We also observe about a 2 % variation in the sound speed at different locations within the sediment, even though the sediment is composed entirely of one type of sand, with no shell or rock fragments, and appears to be homogeneous.

The significance of this result is the following: There is very little experimental sound speed data from well-controlled and well-characterized sandy sediments in the frequency range in which dispersion is expected to appear (below about 10 kHz). This new data represents one of the only experiments in which both high and low frequency sound

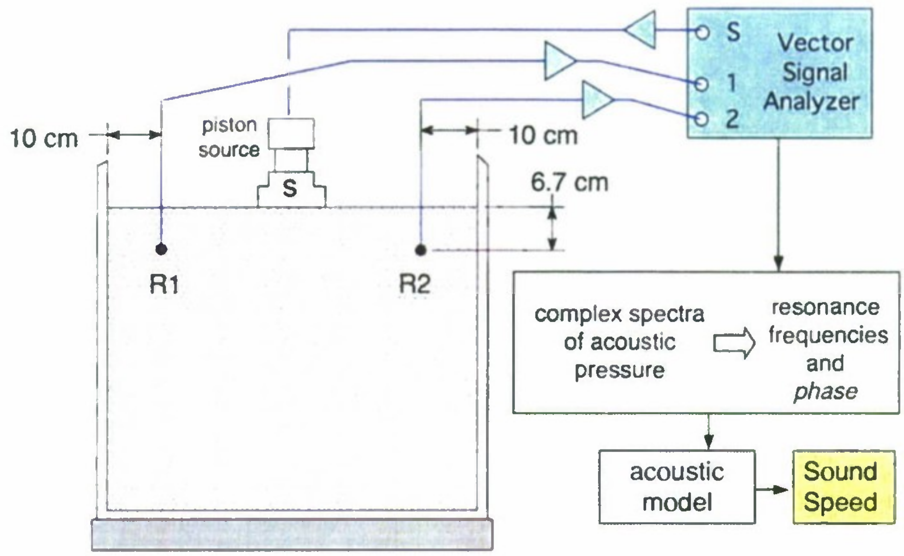


Fig. 5. A schematic diagram of the resonance experiment is shown. A constant-velocity tonpiltz source was used to excite the system. By placing it in the center, symmetric modes were excited. By placing the source midway between the center and the wall, asymmetric modes were excited. The source was driven with periodic chirps and the pressure spectra were recorded at positions R1 and R2. Analysis of the spectra yielded resonance frequencies which were in turn related to the frequency-dependent sound speed of the sediment. The effect of the finite impedance of the tank walls was accounted for, and found to be small.

speed measurements have been obtained within the same volume of sediment. With the experimental errors well-characterized, we can confidently conclude that dispersion is present, and that it is closely modeled by the EDFM, yet, there is some over-prediction at the lower frequencies. This adds to a small, but growing collection of data in support of a Biot-based model for sound propagation in sandy marine sediments. It also adds to a small collection of data that is over predicted by current Biot-based models.

Another conclusion one might draw, although with less confidence, is that residual gas may contribute to this over prediction, and that residual gas is difficult (if not impossible) to remove from sediment particles that have been exposed to gas. Finally, these results underscore the statistical nature of sound propagation in a granular material, and indicate that even for a sediment composed of "homogeneous" granular material, one will encounter variation in the acoustic properties. These new results, the data analysis and experimental description are reported in [25]. Our current experimental work seeks to add to this data, but for a wider range of frequencies, including attenuation, and with greater accuracy.

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. More research is needed and is certainly underway to increase our understanding of sound propagation in the ocean

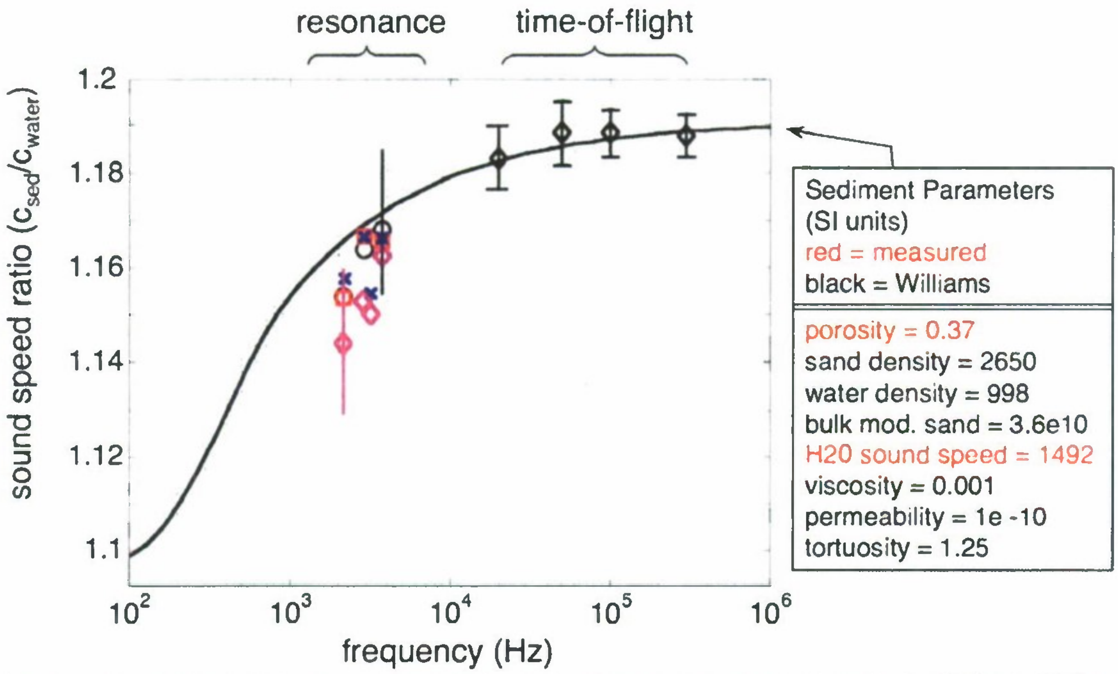


Fig. 6. Normalized sound speed measurements, the result of new analysis, are compared to the EDFM (solid line). Black circles and red squares were obtained at two different sediment locations, with the sound source in center, and hence were inferred from the resonance frequencies of axisymmetric modes. Blue x's and magenta diamonds were obtained at the same two sediment locations, but with the sound source located off-center, and hence were inferred from the resonance frequencies of asymmetric modes. Black diamonds are from the time-of-flight measurements. Error bars represent length and time uncertanties, but due to the close grouping of some of the data, they are not shown for every data point. The material parameters (in pure SI units) required for evaluation of the EDFM are shown in the table to the left of the plot. The values shown in red were measured and specifically refer to the sediment in this study. The values shown in black were taken from Ref. [10], for a similar type of sand. No adjustment of material parameters was conducted, nor was any fitting performed. The EDFM agrees very well with the time-of-flight measurements, within the range of measurement uncertainty in each case. The upper third of the resonance-based measurements are in agreement with the EDFM, but the degree of agreement diminishes as frequency continues down. For the lowest few frequencies, the data points and the upper limit of the error bars are over-predicted by the EDFM.

bottom. As this process progresses, one application will be to update the models used in operational sonar systems. 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.

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.

REFERENCES

[1] P.S. Wilson, R.A. Roy, and W.M. Carey, "An improved water-filled impedance tube," *J. Acoust. Soc. Am.* **113**, pp. 3245–3252 (2003).

[2] P.S. Wilson and R.A. Roy, "Acoustic Characterization of Marine Sediments by Impedance Tube," Boston University, Final Report NUWC Grant No. N61331-02-1-G002, 2003.

[3] E.L. Hamilton, "Prediction of in-situ acoustic and elastic properties of marine sediments," *Geophysics* **36**, pp. 266–284 (1971).

[4] L.D. Hampton, "Acoustic properties of sediments," *J. Acoust. Soc. Am.* **42**, pp. 882–890 (1967).

[5] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range," *J. Acoust. Soc. Am.* **28**, pp. 168–178 (1956).

[6] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range," *J. Acoust. Soc. Am.* **28**, pp. 179–191 (1956).

[7] N.P. Chotiros, "Biot model of sound propagation in water-saturated sand," *J. Acoust. Soc. Am.* **97**, pp. 199–214 (1995).

[8] M.J. Buckingham, "Wave propagation, stress relaxation and grain-to-grain shearing in saturated, unconsolidated marine sediments," *J. Acoust. Soc. Am.* **108**, pp. 2796–2815 (2000).

[9] R.D. Stoll and T.K. Kan, "Reflection of acoustic waves at a water–sediment interface," *J. Acoust. Soc. Am.* **70**, pp. 149–156 (1981).

[10] K.L. Williams, "An effective density fluid model for acoustic propagation in sediments derived from Biot theory," *J. Acoust. Soc. Am.* **110**, pp. 2276–2281 (2001).

[11] J.Y. Chung and D.A. Blaser, "Transfer function method of measuring in-duct acoustic properties. I. Theory," *J. Acoust. Soc. Am.* **68**, pp. 907–913 (1980).

[12] J.Y. Chung and D.A. Blaser, "Transfer function method of measuring in-duct acoustic properties. II. Experiment," *J. Acoust. Soc. Am.* **68**, pp. 914–921 (1980).

[13] ASTM, "Standard Designation E 1050-90: Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System." West Conshohocken, PA: American Society for Testing and Materials, 1990.

[14] P.S. Wilson, R.A. Roy, and W.M. Carey, "Phase speed and attenuation in bubbly liquids inferred from impedance measurements near the individual bubble resonance frequency," *J. Acoust. Soc. Am.* **117**, pp. 1895–1910 (2005).

[15] Y.S. Choy and L. Huang, "Measurement of in-duct acoustic properties by using a single microphone with fixed position," *J. Acoust. Soc. Am.* **116**, pp. 3498 (2004).

[16] L. Elvira-Segura, "Acoustic wave dispersion in a cylindrical elastic tube filled with a viscous liquid," *Ultrasonics* **37**, pp. 537 (2000).

[17] B. Mert, H. Sumali, and O.H. Campanella, "A new method to measure viscosity and intrinsic sound velocity of liquids using impedance tube principles at sonic frequencies," *Rev. Sci. Inst.* **75**, pp. 2613 (2004).

[18] K.-J. Dunn, "Sample boundary effect in acoustic attenuation of fluid-saturated porous cylinders," *J. Acoust. Soc. Am.* **81**, pp. 1259 (1987).

[19] A.A. Gubaidullin, O.Y. Kuchugurina, D.M.J. Smeulders, and C.J. Wisse, "Frequency-dependent acoustic properties of a fluid/porous solid interface," *J. Acoust. Soc. Am.* **116**, pp. 1474 (2004).

[20] C.R. Fuller and F.J. Fahy, "Characteristics of wave propagation and energy distributions in cylindrical elastic shells filled with fluid," *J. Sound Vib.* **81**, pp. 501–518 (1982).

[21] J.I. Dunlop, "Measurement of acoustic attenuation in marine sediments by impedance tube," *J. Acoust. Soc. Am.* **91**, pp. 460–469 (1992).

[22] H. Levine and J. Schwinger, "On the radiation of sound from an unflanged circular pipe," *Physical Review* **73**, pp. 383–406 (1948).

[23] M. Zampolli, et al., "Progress in hybrid finite-element/propagation tool modeling of scattering from objects in underwater waveguides," *J. Acoust. Soc. Am.* **115**, pp. 2580 (2004).

[24] P.S. Wilson, R.A. Roy, and W.M. Carey, "Development of an impedance tube technique for in-situ classification of marine sediments," *J. Acoust. Soc. Am.* **113**, pp. 2318 (2003).

[25] P.S. Wilson and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," presented at IEEE Oceans '05 Europe, Brest, France, 2005.

[26] K.L. Williams, D.R. Jackson, E.I. Thorsos, D. Tang, and S.G. Schock, "Comparison of sound speed and attenuation measured in a sandy sediment to predictions based on the Biot theory of porous media," *IEEE J. Ocean. Eng.* **27**, pp. 413–428 (2002).

PUBLICATIONS

P.S. Wilson and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," in *Proceedings of the IEEE Oceans '05 Europe Conference*, Brest, France, June 20-23, 2005. [refereed, in press]

P.S. Wilson and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," *IEEE Journal of Oceanic Engineering*, 2005. [refereed]

Investigation of the Acoustics of Marine Sediments Using an Impedance Tube

Chapter 3: Summary of Work Conducted FY2006

LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of the plane wave reflection coefficients from laboratory and *in situ* sediments using impedance tube methods, [1] in the frequency range of approximately 500 Hz to tens of kHz. This approach will also yield measurements of the acoustic impedance, sediment sound speed, attenuation, and complex density through the use of appropriate model inversions and data analysis. [2] These measurements will span a frequency range in which there is little experimental data and help to verify competing theoretical models [3-10] on sound propagation in marine sediments. An overview of the state-of-the-art in both experiment and modeling is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation.

Initial impedance tube work [2] indicated that the coupling between the sediment and the impedance tube walls must be accounted for, in order to infer the intrinsic sediment attenuation from measurements performed in an impedance tube. Therefore, an initial objective was to develop an appropriate model that describes this coupling, and to develop a new impedance tube that exploits this model, i.e. minimizes the coupling, and allows for accurate recovery of intrinsic sediment attenuation from the measurements.

A secondary objective, added by the program management to this project late this fiscal year, was for the PI to participate in the Shallow Water '04 experiment, specifically to provide and deploy the Combustive Sound Source [11] from the R/V Knorr.

APPROACH

The impedance tube technique and has been adopted as a standard technique [12-14] for measuring the acoustic properties of small samples of materials in air. With support from the Office of Naval Research Ocean Acoustics Program, this author and colleagues at Boston University developed an impedance tube technique and apparatus for use in measuring the acoustic properties of materials with water or other liquids as the host medium. [1] A number of engineering problems relating to the acoustic coupling between the fill-liquid and the tube walls, and to the perturbing effects of the measuring apparatus itself were overcome. The original apparatus was developed for and successfully used to measure sound speed and attenuation in bubbly liquids in a frequency range of 5–9 kHz. [15] The device proved to be the most accurate and precise water-filled impedance tube reported in the open literature. The uncertainty in the measured reflection coefficient for this device is +/- 0.14 dB in magnitude and +/- 0.8° in phase.

In the current project, we are building a larger, new and improved impedance tube for use with marine sediments. It will operate in the frequency range in which dispersion is expected (about 500 Hz to 30 kHz) in typical sandy sediments. We are investigating two new impedance measurement techniques [16, 17] that do not require movement of the sensors, and will minimize errors due to sensor position uncertainty. Further, we will incorporate new modeling that will better account for the coupling between the sediment and the tube walls and thereby provide a more accurate quantification of experimental error. This modeling will be based on and extended from existing work for lossy fluid coupling in elastic waveguides, [17, 18] additional sample-wall boundary effects, [19] sample-fluid boundary effects [20] and asymmetric excitation. [21] The instrument will be used in the laboratory to investigate artificial and natural sediments *in vitro*.

In the final year of the project, we plan to modify the laboratory device for use on the ocean bottom for *in situ* characterization of sediments. There are two possible versions of the *in situ* device, and these were explored in an earlier study. [22] In one of the versions, the impedance tube will penetrate the ocean bottom and a reflection coefficient will be measured inside the tube. In the other version, the impedance tube will not penetrate the sediment, but will sit flush on the bottom. The impedance measurements can be made, regardless of the exact configuration and will contain information about the material properties of the ocean bottom. The interpretation of those measurements will require appropriate modeling. For example, the penetrating version could be modeled using the classic theory of Levine and Schwinger [23] for sound radiation from an open tube, in which the sediment sound speed would be a parameter. The flush-deployed version may be modeled with a finite-element numerical model such as described in [24], again with material properties as parameters. In both case, the impedance measured by the impedance tube would be compared to the appropriate model and sediment parameters varied until measured and modeled impedances are in agreement. Additional modeling beyond that described in [23] and [24] is anticipated, to obtain useful inversions for material parameters in both cases, but the raw impedance measurements themselves may prove to be useful.

The personnel for this project are: Preston S. Wilson serves as PI and is an Assistant Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Assistant 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. Paul A. Waters was an Undergraduate Research Assistant on the project from the start of the Fiscal year until 31 Dec. 2006. Waters served as an electromechanical technician and provided machine shop, procurement and software support, and oversaw purchasing. Waters graduated and was replaced on 1 June 2006, by Ryan L. Renfrow, a UTME senior. Jacob G. Migliazzo was a Graduate Research Assistant on this project from the start of the fiscal year until 31 May 2006. Migliazzo left the project on 31 May 2006, for an internship at Bose. On 1 June 2006, Theodore F. Argo IV, a UTME Ph.D. student replaced Migliazzo and contributes to all aspects of the project.

WORK COMPLETED

Primary Objective—Laboratory Sediment Investigation: Construction of the impedance tube itself was completed this year, along with a support structure to hold the tube vertically and a scaffold to afford personnel access to the top of the tube. A variety of terminations were completed, including an air-backing chamber and a housing that holds a piston, for excitation from the bottom. The latter is in support of the new impedance measurement technique [17] mentioned previously that is being evaluated. This technique (referred to as the Mert method) may prove beneficial because it does not require any sensors to be placed inside the tube. Instead, excitation is provided at the bottom of the tube, via the piston previously mentioned, and force and acceleration is measured between the piston and the prime mover. The apparatus as it was at the beginning of the fiscal year is shown in Fig. 2. The apparatus in its current state is shown in Fig. 3, which also includes a schematic diagram of the Mert impedance measurement technique being evaluated. A Wilcoxon electromechanical shaker, equipped with force and acceleration sensors, and a pair of conditioning amplifiers were purchased and installed. A high accuracy A-D/D-A board was also purchased to provide a dedicated data acquisition for the project. LabVIEW software was acquired and programmed to operate the impedance tube system, in all of its various configurations. Impedance measurements using the technique shown in Fig. 2 were performed with distilled water and a reconstituted natural sand sediment. Preliminary results from the Mert method were also obtained on water samples, and water-saturated sand and glass bead samples.

An opportunity became available this FY (at no cost to this grant) to collaborate with the Seafloor Sciences Group at NRL-SSC on an experiment with gas-bearing sediments. An unprecedented set of contemporaneous acoustic measurements and computed x-ray tomography imaging scans were obtained on a variety of reconstituted natural sediments. These experiments were conducted at NRL-SSC in January 2006. A 1-D acoustic resonator technique was used to measure the sound speed inside the sediment samples. The imaging scans yielded the bubble size distribution and the total void fraction (gas content) of the sediment. This collaboration also yielded permeability measurements on a sand sample that that had been the subject of a previous study. [25, 26] The new permeability measurement was a significant addition to the results and yielded a new interpretation of the data.

Secondary Objective—SW06 Experiment: The Combustive Sound Source (CSS), which had been dormant for 9 years, was recalled to service for the SW06 experiment. The following was undertaken to make the CSS ready for deployment from the R/V Knorr. An electrolytic hydrogen/oxygen generator was purchased and equipment was fabricated to inject gas into the CSS chamber while the CSS was deployed from the fantail A-frame of the Knorr. The original ignition box and cable were refurbished. A number of spark plugs were purchased, since they are somewhat consumable. A National Instruments data acquisition system was purchased and existing hydrophones were equipped with extension cables for use on the Knorr. All of the equipment was shipped to Woods Hole and loaded on the R/V Knorr on 22 August. The PI boarded the Knorr on 23 August and worked with the science team on many aspects of the experiments, in addition to deployment of the CSS. The PI departed the R/V Knorr on 5 Sept and returned to Woods Hole via the R/V Oceanus on 6 Sept 2006.

RESULTS

Primary Objective— Laboratory Sediment Investigation: Preliminary results from the new impedance tube system have been obtained and are shown in this section. This includes measurements with the original method and the new Mert method. Figs. 4 and 5 show the impedance of water-filled and water-saturated-sand-filled transmission lines made with the original method. A model prediction is shown for the water-filled case. Good agreement between measurement and model indicates a good understanding of the impedance tube system for liquids. The model predictions for the sediment cases have not yet been completed, nor have we extracted sound speed and attenuation yet. One can observe expected qualitative differences between Figs 4 and 5. For example, we expect the sediment to have a faster sound speed and higher attenuation than the water and those effects are visible. The peaks and troughs are less sharp in the sediment case, which indicates higher attenuation. They are shifted to a higher frequency in the sediment case, which indicates a higher sound speed. A typical impedance measurement for distilled water, obtained by the new Mert method, is shown in Fig. 6. Impedance tube measurements and data analysis will continue. Both methods used so far yield good agreement between measurement and prediction for a known sample material, distilled water. Further work is underway to invert material parameters for the sediment case, in which the sample/tube wall coupling is more complicated.

The collaborative work with NRL-SSC resulted in the measurement of sound speed of a reconstituted gas-bearing natural Kaolinite sediment. Contemporaneous measurements of the bubble size distribution were also attained. A single image from the tomography scan is shown in Fig. 7. From this data, the overall sample void fraction was found to be $\chi = 0.0045 \pm 0.001$. The density was also measured and found to be $\rho = 1581 \pm 1.58$ kg/m^3. The acoustic experiment and the resulting sound speed measurement are shown in Fig. 8. This Kaolinite sample was very fluid-like, yet it could still suspend bubbles. It was found that the sound speed observed in the acoustic experiment was perfectly consistent with the sound speed predicted by Wood's Equation, which is a mixture rule for bubbly liquids, in which the sound speed depends only on the gas-free sediment bulk density and the void fraction. To the PI's knowledge, this is the first quantitative verification of Wood's Equation for a gas-bearing sediment.

Last year we reported on the analysis of a data set in which the sound speed of a water-saturated sediment was inferred from the measured resonances of a right circular cylinder shaped plastic tank filled with water-saturated sand. Figs. 9 and 10 describe the experiment and the details are described elsewhere. [25, 26] The permeability was not measured in the original experiment and a canonical value from the literature was used in the initial analysis. The data and the corresponding William's EDFM [10] prediction are shown in Fig. 11. Thanks to NRL-SSC, we now have a measurement of the permeability of the sediment and it differs from the canonical value, which results in much better agreement between the data and the EDFM prediction. The new permeability and the corresponding model curve are also shown in Fig. 11. It now appears that the data is very well described by the EDFM throughout the experimental frequency range. The significance is the following: This result supports the notion that the EDFM *does not* over predict mid-frequency sound speeds and that when free gas is absent from a water saturated sandy sediment, the EDFM correctly predicts the sound speed near the transition frequency and above.

<u>Secondary Objective—SW06 Experiment:</u> The CSS was successfully deployed from the R/V Knorr during SW06. On the order of 50 shots were delivered. In its current state of development, CSS deployment and operation requires a crew of 5 and about 30 minutes between shots. Acoustically, the CSS is an excellent broadband/impulsive energy source, but the efficiency and speed of operation could be greatly improved. A typical shot is shown in Fig. 12. The usable frequency range of this shot is from 10 Hz to 5 kHz, with a peak energy spectral density of 170 dB re 1 μPa^2-s/Hz at 1m occurring at about 20 Hz.

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 current results indicate that the EDFM correctly predicts the mid and high frequency sound speed in water saturated sand. We are continuing our efforts to get low frequency measurements. As our understanding of sound propagation in the ocean bottom increases, one application will be to update the models used in operational sonar systems. 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. The CSS performed very well during SW06 and may prove to be a very useful tool for ocean acoustics experiments in the future.

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.

REFERENCES

[1] P.S. Wilson, R.A. Roy, and W.M. Carey, "An improved water-filled impedance tube," *J. Acoust. Soc. Am.* **113**, pp. 3245–3252 (2003).

[2] P.S. Wilson and R.A. Roy, "Acoustic Characterization of Marine Sediments by Impedance Tube," Boston University, Final Report NUWC Grant No. N61331-02-1-G002, 2003.

[3] E.L. Hamilton, "Prediction of in-situ acoustic and elastic properties of marine sediments," *Geophysics* **36**, pp. 266–284 (1971).

[4] L.D. Hampton, "Acoustic properties of sediments," *J. Acoust. Soc. Am.* **42**, pp. 882–890 (1967).

[5] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range," *J. Acoust. Soc. Am.* **28**, pp. 168–178 (1956).

[6] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range," *J. Acoust. Soc. Am.* **28**, pp. 179–191 (1956).

[7] N.P. Chotiros, "Biot model of sound propagation in water-saturated sand," *J. Acoust. Soc. Am.* **97**, pp. 199–214 (1995).

[8] M.J. Buckingham, "Wave propagation, stress relaxation and grain-to-grain shearing in saturated, unconsolidated marine sediments," *J. Acoust. Soc. Am.* **108**, pp. 2796–2815 (2000).

[9] R.D. Stoll and T.K. Kan, "Reflection of acoustic waves at a water–sediment interface," *J. Acoust. Soc. Am.* **70**, pp. 149–156 (1981).

[10] K.L. Williams, "An effective density fluid model for acoustic propagation in sediments derived from Biot theory," *J. Acoust. Soc. Am.* **110**, pp. 2276–2281 (2001).

[11] P.S. Wilson, J.L. Ellzey, and T.G. Muir, "Experimental investigation of the combustive sound source," *Oceanic Engineering, IEEE Journal of* **20**, pp. 311 (1995).

[12] J.Y. Chung and D.A. Blaser, "Transfer function method of measuring in-duct acoustic properties. I. Theory," *J. Acoust. Soc. Am.* **68**, pp. 907–913 (1980).

[13] J.Y. Chung and D.A. Blaser, "Transfer function method of measuring in-duct acoustic properties. II. Experiment," *J. Acoust. Soc. Am.* **68**, pp. 914–921 (1980).

[14] ASTM, "Standard Designation E 1050-90: Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System." West Conshohocken, PA: American Society for Testing and Materials, 1990.

[15] P.S. Wilson, R.A. Roy, and W.M. Carey, "Phase speed and attenuation in bubbly liquids inferred from impedance measurements near the individual bubble resonance frequency," *J. Acoust. Soc. Am.* **117**, pp. 1895–1910 (2005).

[16] Y.S. Choy and L. Huang, "Measurement of in-duct acoustic properties by using a single microphone with fixed position," *J. Acoust. Soc. Am.* **116**, pp. 3498 (2004).

[17] B. Mert, H. Sumali, and O.H. Campanella, "A new method to measure viscosity and intrinsic sound velocity of liquids using impedance tube principles at sonic frequencies," *Rev. Sci. Inst.* **75**, pp. 2613 (2004).

[18] L. Elvira-Segura, "Acoustic wave dispersion in a cylindrical elastic tube filled with a viscous liquid," *Ultrasonics* **37**, pp. 537 (2000).

[19] K.-J. Dunn, "Sample boundary effect in acoustic attenuation of fluid-saturated porous cylinders," *J. Acoust. Soc. Am.* **81**, pp. 1259 (1987).

[20] A.A. Gubaidullin, O.Y. Kuchugurina, D.M.J. Smeulders, and C.J. Wisse, "Frequency-dependent acoustic properties of a fluid/porous solid interface," *J. Acoust. Soc. Am.* **116**, pp. 1474 (2004).

[21] C.R. Fuller and F.J. Fahy, "Characteristics of wave propagation and energy distributions in cylindrical elastic shells filled with fluid," *J. Sound Vib.* **81**, pp. 501–518 (1982).

[22] J.I. Dunlop, "Measurement of acoustic attenuation in marine sediments by impedance tube," *J. Acoust. Soc. Am.* **91**, pp. 460–469 (1992).

[23] H. Levine and J. Schwinger, "On the radiation of sound from an unflanged circular pipe," *Physical Review* **73**, pp. 383–406 (1948).

[24] M. Zampolli, et al., "Progress in hybrid finite-element/propagation tool modeling of scattering from objects in underwater waveguides," *J. Acoust. Soc. Am.* **115**, pp. 2580 (2004).

[25] P.S. Wilson, J.C. Wilbur, W.M. Carey, and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," appearing in Oceans 2005 - Europe, Vol. 1 of 2, pp. 239–243 (2005) [ISBN 0-7803-9103-9].

[26] P.S. Wilson, A. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," *J. Acoust. Soc. Am.*, accepted for publication, June 2006.

[27] K.L. Williams, D.R. Jackson, E.I. Thorsos, D. Tang, and S.G. Schock, "Comparison of sound speed and attenuation measured in a sandy sediment to predictions based on the Biot theory of porous media," *IEEE J. Ocean. Eng.* **27**, pp. 413–428 (2002).

PUBLICATIONS

P.S. Wilson, A. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," *J. Acoust. Soc. Am.*, (2006). [refereed, in press]

FIGURES

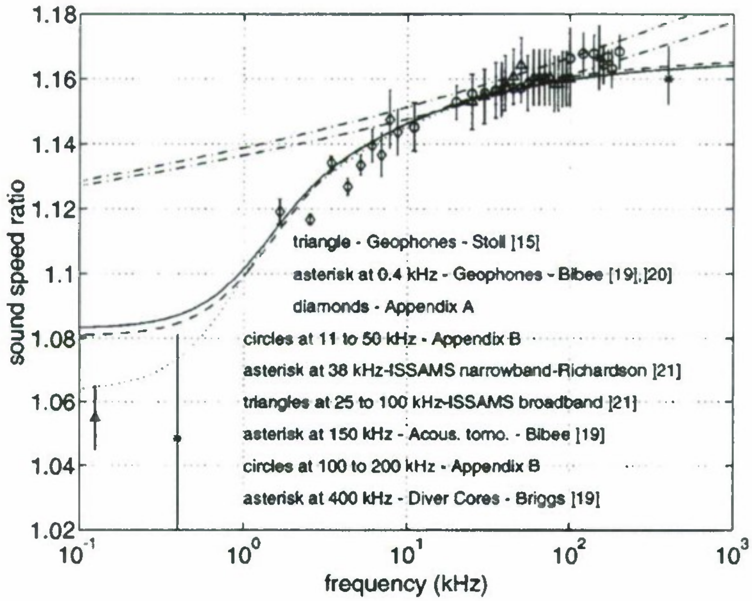


Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [27]. The theoretical curves are: solid line=Biot/Stoll [9]; dashed line=Williams [10], dash-dot lines=Buckingham's model for two values of fluid viscosity [8]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [27].)

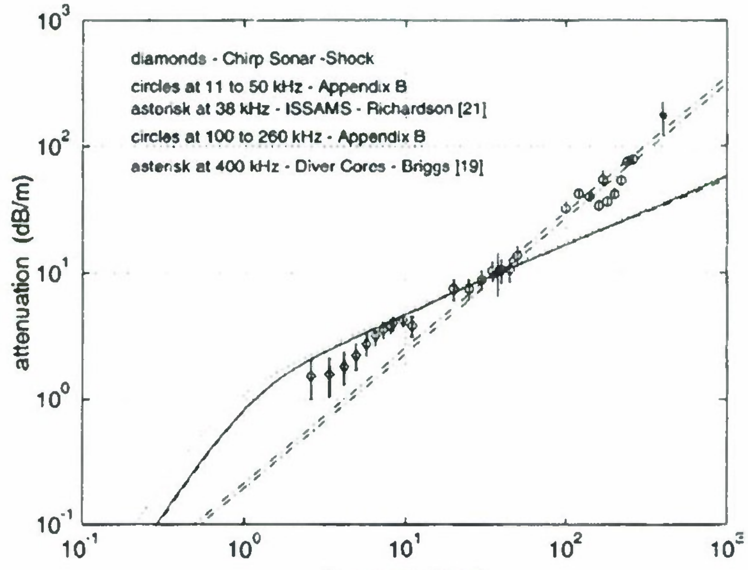
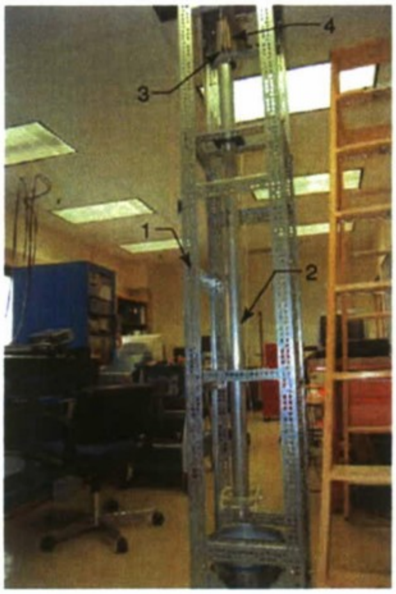


Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [27].) Also note that there is attenuation data below about 3 kHz.



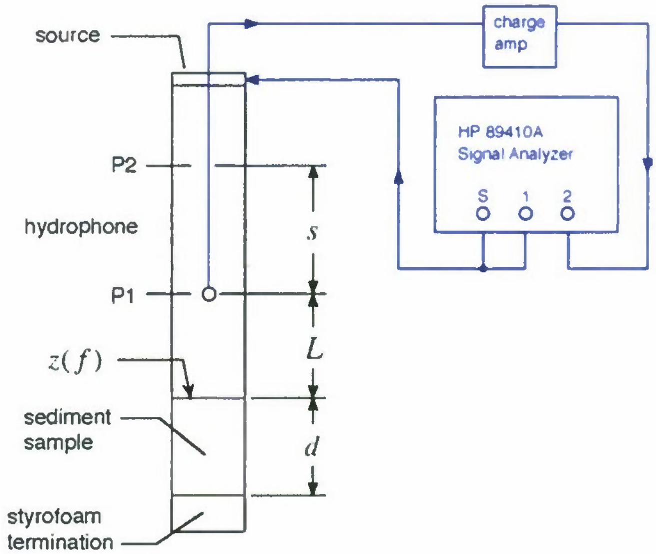


Fig. 2. The photograph on the left documents the state of the impedance tube system at the beginning of this fiscal year. Some key components: the supporting framework (1), the impedance tube (2), the hydrophone (3), and the hydrophone positioning system (4). On the right is a schematic diagram of the impedance tube system.

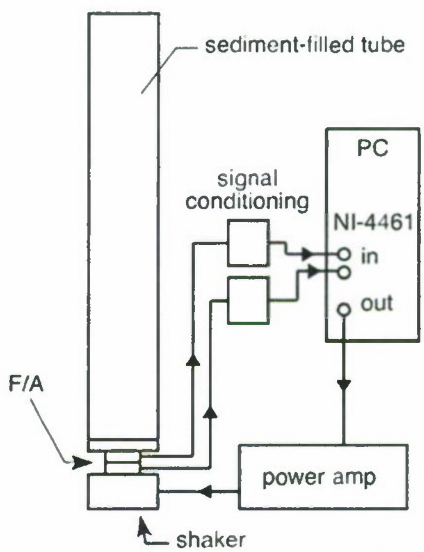


Fig. 3. On the left is shown a photograph of the impedance tube facility with components: the support frame and tube (1), the computer and data acquisition system (2), and the scaffolding (3). On the right, the view down the center of the tube is shown, illuminated from the far end with a flashlight, after gun drilling and honing. Note the smoothness of the inner tube wall.

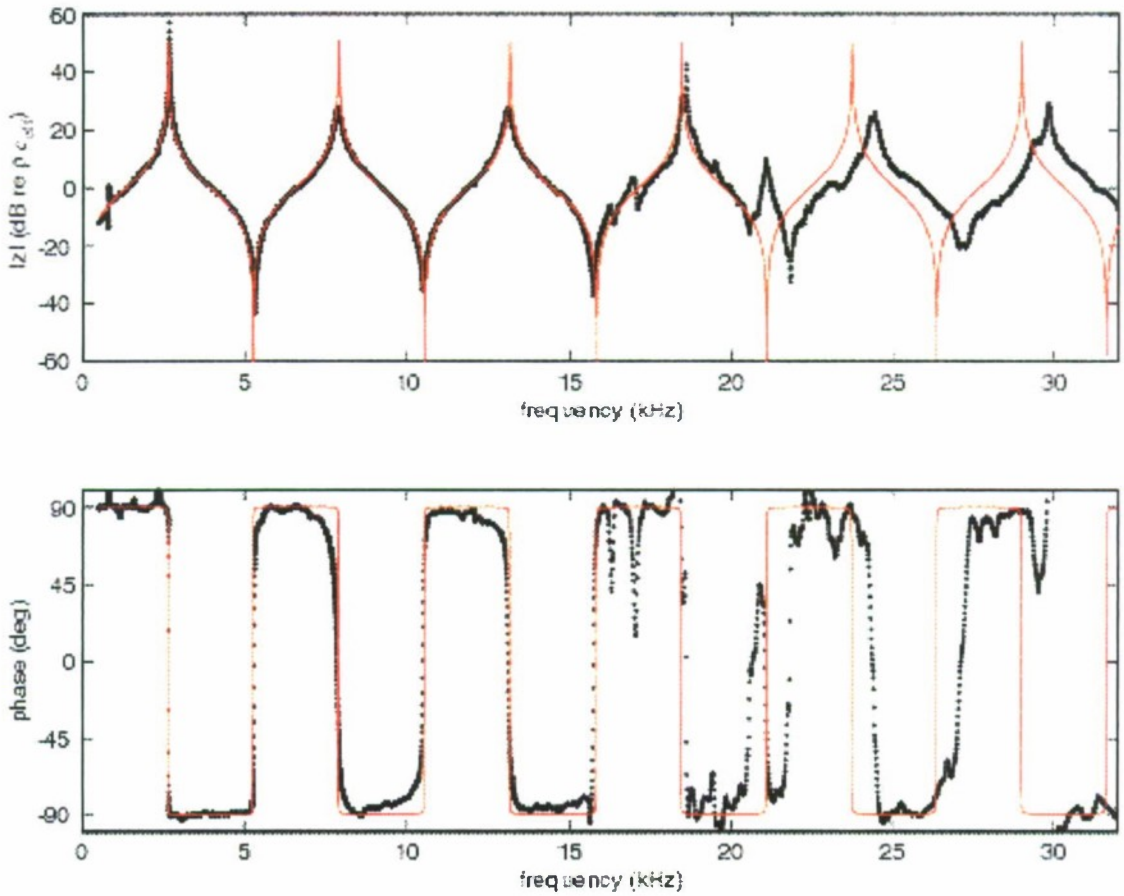


Fig. 4. The magnitude and phase of the measured impedance of the water-filled sample holder terminated with styrofoam is plotted with black dots. Above 15 kHz, the plane wave assumption required for the impedance measurement is of diminishing validity, resulting in erroneous results. The predicted impedance is plotted with the solid red line.

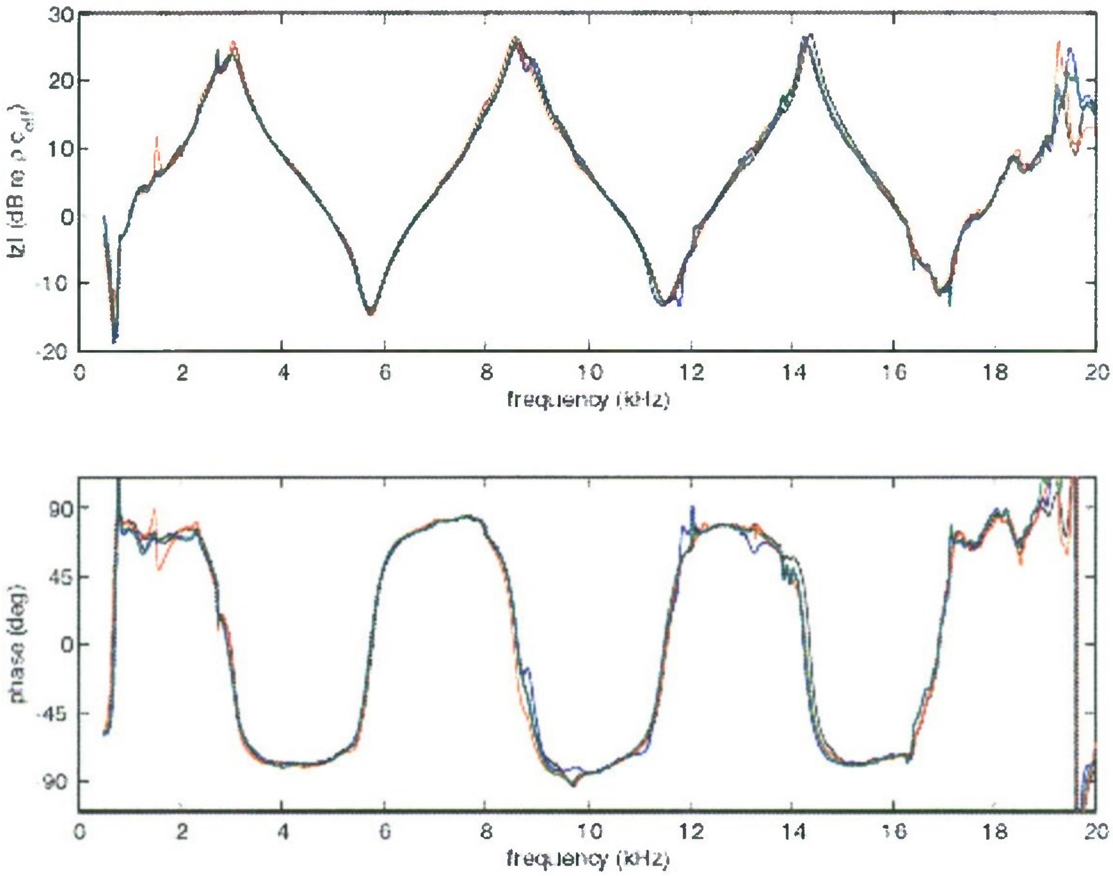


Fig. 5. Measured impedance of unwashed/unsieved and washed/sieved reconstituted sand sediment samples plotted together for comparison. The red and black curves are for the unwashed case and the blue and green curves are for the washed case. Little significant difference is seen. Note that the frequency scale is different than that in Fig. 4.

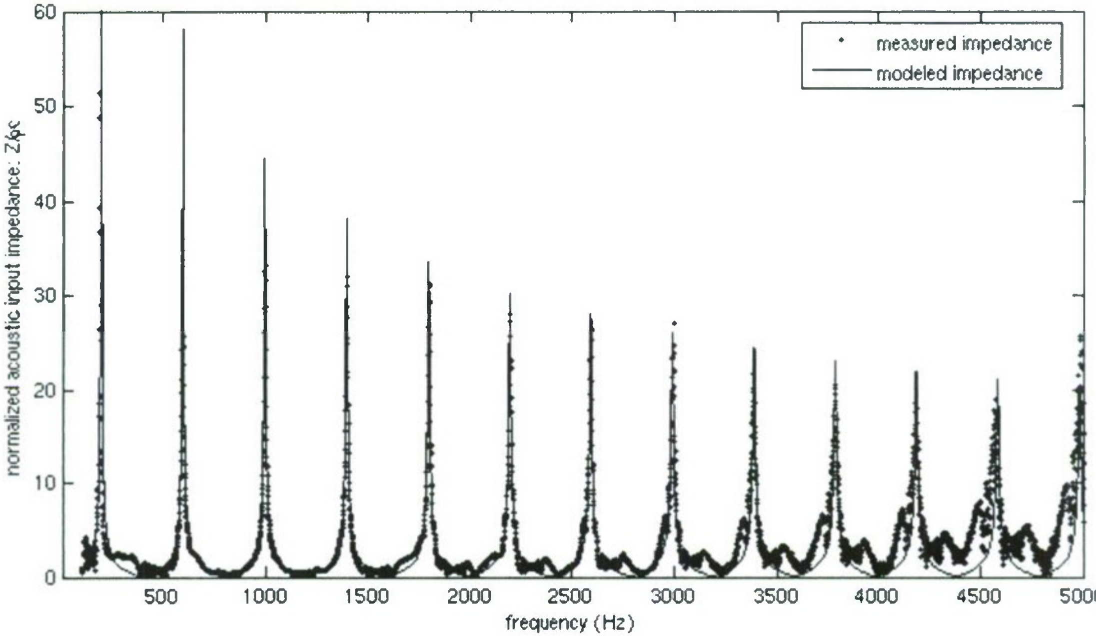


Fig. 6. Impedance of a 1.8 meter long column of water measured using the Mert method [17]. The solid line is the predicted impedance using tabulated values of water density and temperature-dependent sound speed. The dots are the measurement data. Good agreement is seen between predicted and measured values. This indicates that the new Mert method is accurate and it will be beneficial because it will allow us to reach down to lower frequencies.

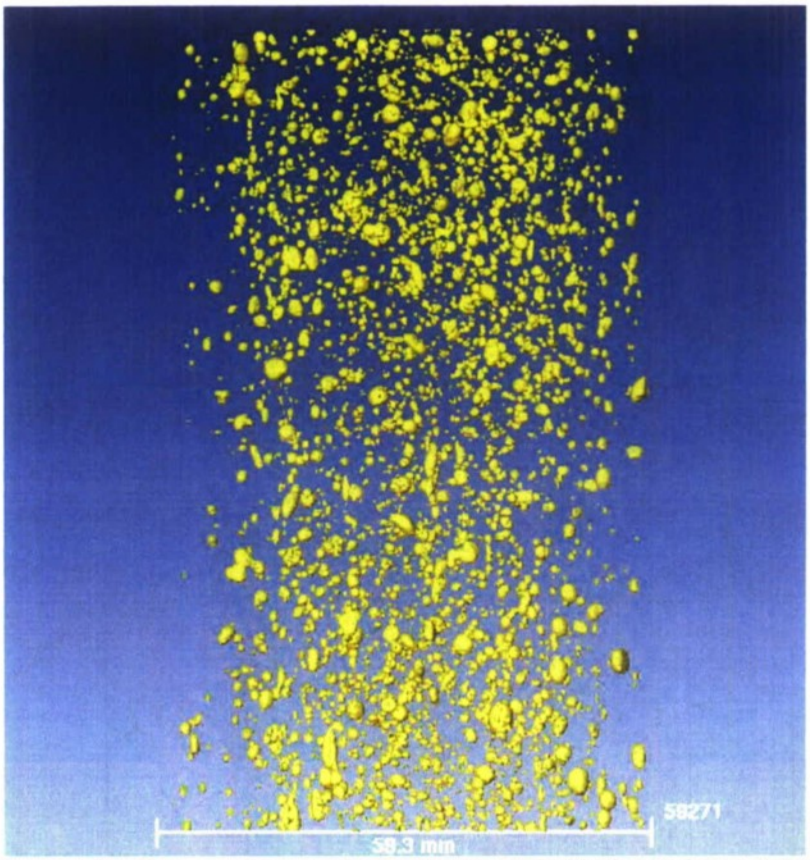


Fig. 7. A single image from the computed x-ray tomography scan of the Kaolinite sediment sample contained with the 1-D acoustic resonator. The yellow blobs are air bubbles.

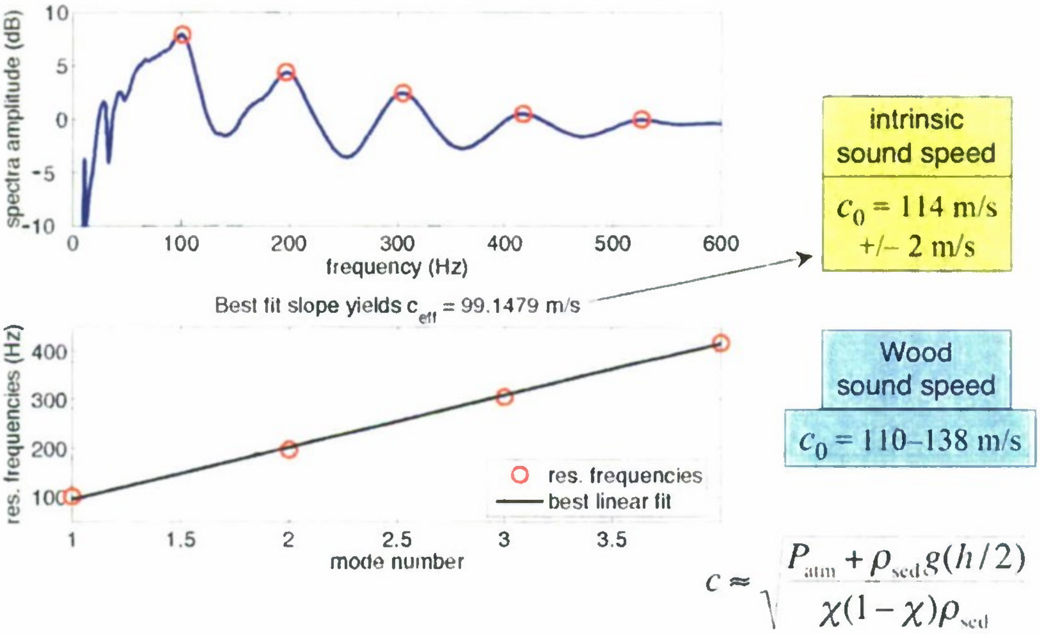


Fig. 8. The top plot shows the pressure spectrum and resonance frequencies measured in a 1-D resonator filled with reconstituted bubbly Kaolinite sediment. The bottom plot shows the resonance frequencies as a function of mode number, the slope of which yields the sediment sound speed. The resulting sound speed is shown in the yellow box. Wood's equation is shown at bottom right and was used to predict the sound speed. The void fraction χ was obtained from the imaging analysis, as discussed in Fig. 7. The sediment density was also measured. The remaining parameters are the atmospheric pressure P_{atm}, the acceleration due to gravity g, and the sediment column height h. The prediction with no fitting is shown in the blue box. The range of predicted values represent measurement uncertainty in the model input parameters.

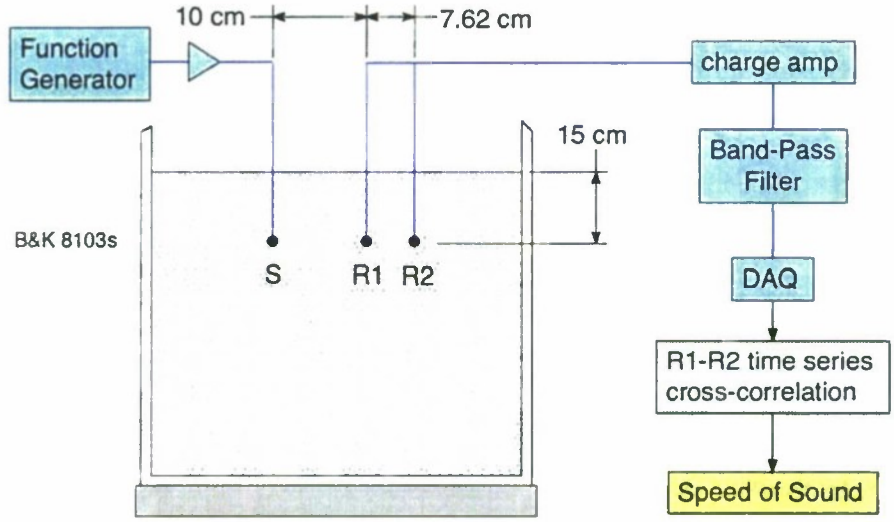


Fig. 9. A schematic diagram of the time-of-flight experiment is shown. A large thin-walled cylindrical container was filled with 60°C degassed water and sorted and washed medium grain blasting sand. Three B&K 8103 hydrophones were placed in the sediment and time-of-flight measurements were obtained after cooling. A function generator and power amplifier were used to drive one of the 8103s as a source. The remaining two 8103s were used as receivers. Their signals were conditioned with a charge amp and a band-pass filter. The voltage signals were acquired with a digital oscilloscope and cross correlated to extract the time-of-flight. Sound speed was then calculated from the 7.62 cm sensor separation distance.

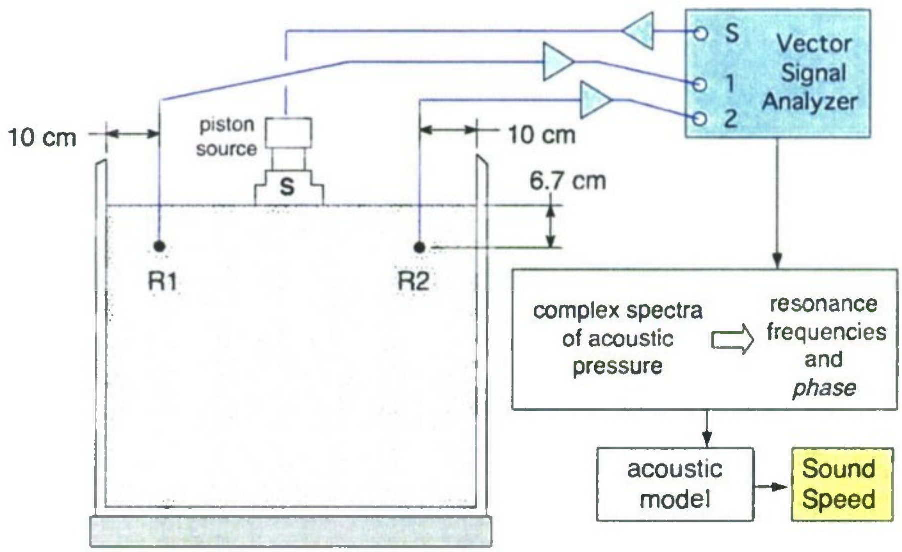


Fig. 10. A schematic diagram of the resonance experiment is shown. A constant-velocity tonpiltz source was used to excite the system. By placing it in the center, symmetric modes were excited. By placing the source midway between the center and the wall, asymmetric modes were excited. The source was driven with periodic chirps and the pressure spectra were recorded at positions R1 and R2. Analysis of the spectra yielded resonance frequencies which were in turn related to the frequency-dependent sound speed of the sediment. The effect of the finite impedance of the tank walls was accounted for, and found to be small.

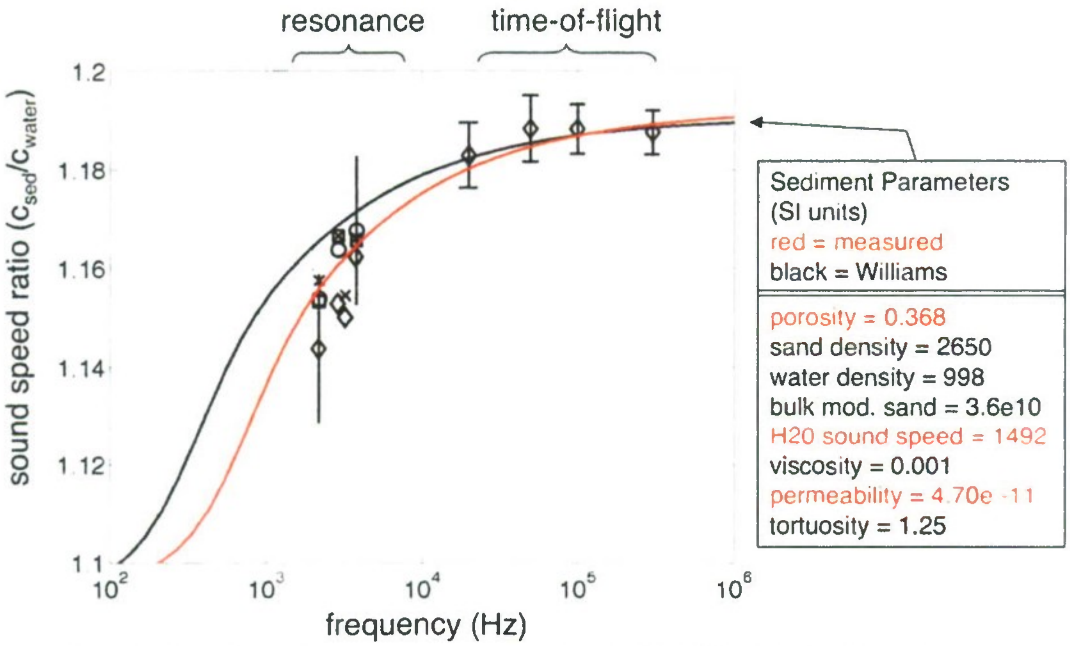


Fig. 11. Normalized sound speed measurements are compared to the EDFM (solid lines). The red curve corresponds to the EDFM prediction using the new permeability and porosity measurements. The black curve is from the previous analysis, in which we did not have a measurement of permeability, but used a canonical value from the literature. Error bars represent length and time uncertanties, but due to the close grouping of some of the data, they are not shown for every data point. The material parameters (in pure SI units) used for evaluation of the red EDFM curve are shown in the table to the right of the plot. The values shown in red were measured and specifically refer to the sediment in this study. The values shown in black were taken from Ref. [10], for a similar type of sand. No adjustment of material parameters was conducted, nor was any fitting performed. The EDFM agrees very well with the time-of-flight measurements, within the range of measurement uncertainty in each case. All of the resonance-based measurements are now in agreement with the EDFM, within the range of measurement unvertainty. One can now conclude that the EDFM accurately predicts the sound speeds in this well-degased water-saturated sand sediment.

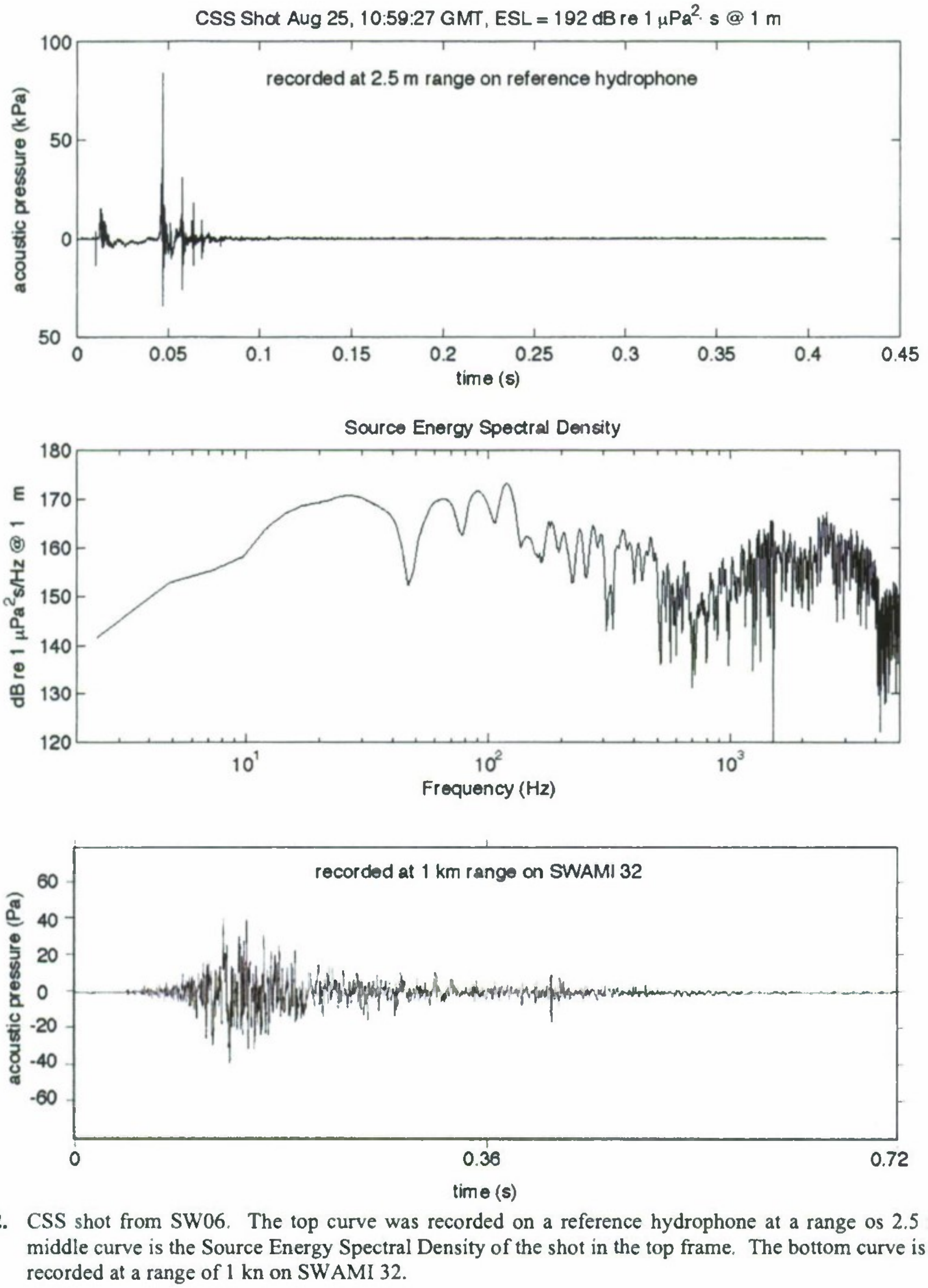


Fig. 12. CSS shot from SW06. The top curve was recorded on a reference hydrophone at a range os 2.5 m. The middle curve is the Source Energy Spectral Density of the shot in the top frame. The bottom curve is the shot recorded at a range of 1 kn on SWAMI 32.

Investigation of the Acoustics of Marine Sediments Using an Impedance Tube

Chapter 4: Summary of Work Conducted FY2007

LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of the plane wave reflection coefficients from laboratory and *in situ* sediments using impedance tube [1] and acoustic resonator tube [2, 3] methods, in the frequency range of approximately 300 Hz to tens of kHz. This approach will also yield measurements of the acoustic impedance, sediment sound speed, attenuation, and complex density through the use of appropriate model inversions and data analysis. These measurements will span a frequency range in which there is little experimental data and help to verify competing theoretical models [4-11] on sound propagation in marine sediments. An overview of the state-of-the-art in both experiment and modeling is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation. Initial impedance tube work [12] indicated that the coupling between the sediment and the impedance tube walls must be accounted for, in order to infer the intrinsic sediment attenuation from measurements performed in an impedance tube. Therefore, an initial objective was to develop an appropriate model that describes this coupling, and to develop a new impedance tube that exploits this model, i.e. minimizes the coupling, and allows for accurate recovery of intrinsic sediment attenuation from the measurements.

A secondary objective has been to investigate other ocean-bottom materials of opportunity utilizing the techniques and measurement instrumentation developed for this work. To date these materials have been gas-bearing sediments and seagrasses. Finally, the author participated in SW06 last FY and therefore a tertiary objective this FY was to participate in the analysis of some of the SW06 data in collaboration with other ONR PIs.

APPROACH

The impedance tube technique and has been adopted as a standard technique [13-15] for measuring the acoustic properties of small samples of materials in air. With support from the Office of Naval Research Ocean Acoustics Program, this author and colleagues at

Boston University developed an impedance tube technique and apparatus for use in measuring the acoustic properties of materials with water or other liquids as the host medium. [16] A number of engineering problems relating to the acoustic coupling between the fill-liquid and the tube walls, and to the perturbing effects of the measuring apparatus itself were overcome. The original apparatus was developed for and successfully used to measure sound speed and attenuation in bubbly liquids in a frequency range of 5–9 kHz. [17] The device proved to be the most accurate and precise water-filled impedance tube reported in the open literature. The uncertainty in the measured reflection coefficient for this device is +/- 0.14 dB in magnitude and +/- 0.8° in phase.

In the current project, we are building a larger, new and improved impedance tube for use with marine sediments. It operates in the frequency range in which dispersion is expected (about 300 Hz to 30 kHz) in typical sandy sediments. It has been used to make measurements, which are presented below, but we are continuing to refine the technique and instrumentation. Two impedance measurement techniques can be utilized with the apparatus, [18, 19] which do not require movement of the sensors, and minimize errors due to sensor position uncertainty. The apparatus is also being used with the resonator method [2, 3] of measuring material properties. Finally, we have incorporated new modeling that will better account for the coupling between the sediment and the tube walls and thereby provide a more accurate quantification of experimental error. This modeling is based on and extended from existing work for lossy fluid coupling in elastic waveguides, [19, 20] additional sample-wall boundary effects, [21] sample-fluid boundary effects [22] and asymmetric excitation. [23] The instrument will be used in the laboratory to investigate artificial and natural sediments *in vitro*.

The personnel for this project are: Preston S. Wilson serves as PI and is an Assistant Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Assistant 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. Ryan L. Renfrow, a UTME senior and an Undergraduate Research Assistant on the project, serves as an electromechanical technician and provided machine shop, procurement and software support. Theodore F. Argo IV is a UTME Ph.D. student who contributes to all aspects of the project.

WORK COMPLETED

Primary Objective—Laboratory Sediment Investigation: Much time was devoted to developing a new impedance measurement technique, [19] referred to as the Mert method (after the method's originator) and outlined in Fig. 2. Excitation is provided at the bottom of the tube, and force and acceleration is measured between the piston and the prime mover. While this technique seemed like a great idea (removing the sensors from the medium), and worked successfully with a shorter tube down to 2 kHz, we experienced difficulty extrapolating the measurement technique to a larger tube and a lower frequency. For reference, measurements on water-saturated sand sediments made

last year with a shorter tube (minimum frequency = 2 kHz) are shown in Fig. 3. Results obtained with distilled water using the new, longer tube and an appropriately scaled-up source, with a minimum frequency range of a few hundred Hz are shown in Fig. 4. Results in the new tube with water-saturated sand are shown in Fig. 5. Several things are of note in these figures. The low frequency tube is exhibiting the expected behavior only at the nulls in impedance magnitude for the water-filled case. This would be enough information to extract sound speed at each null frequency, but the low-frequency tube is not working well at all with water-saturated sand. This is due to poor coupling and high losses at the piston interface. This problem is currently being resolved through the use of a water-filled interface layer.
While we have not abandoned the Mert method, we did obtain measurements with water-saturated sand using the resonator method (Fig. 2) in the new low frequency tube. A comparison will be drawn in Figs. 6–8 between these latest measurements and a previous set of measurements.

Secondary Objectives—Gas-bearing Sediments: An opportunity became available in the previous FY (at no cost to this grant) to collaborate with the Seafloor Sciences Group at NRL-SSC on an experiment with gas-bearing sediments. An unprecedented set of contemporaneous acoustic measurements and computed x-ray tomography imaging scans were obtained on a variety of reconstituted natural sediments. These experiments were conducted at NRL-SSC in January 2006. Our 1-D acoustic resonator technique [3] was used to measure the sound speed inside the sediment samples. A high frequency (400 kHz) time-of-flight technique (using the Kevin Briggs ear-muffs apparatus [24]) was also used to measure the sound speed. The imaging scans yielded the bubble size distribution and the total void fraction (gas content) of the sediment. We found that Wood's equation was all that was necessary to describe the sound speed in a gas-bearing fluid-like sediment composed of kaolinite, distilled water and gas bubbles. Further analysis of the data collected at NRL-SSC last FY resulted in an invited paper and presentation in this FY. [26]

This collaboration also yielded permeability measurements on a sand sample that that had been the subject of a previous study. [25] The new permeability measurement was a significant addition to the results and yielded a new interpretation of the data and a new publication. [2]

Secondary Objectives—Seagrass Acoustics: Opportunity became available in the previous and present FY (at no cost to this grant) to collaborate with a seagrass biologist, Dr. Kenneth Dunton, of the University of Texas Marine Science Institute on an experiment with sediments containing seagrasses. The resonator technique was used to measure the effective low frequency acoustic properties of three gulf-coast species, *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). The work led to an invited paper and presentation in this FY [27] and a manuscript has been submitted. [28]

Tertiary Objective—SW06 Data Analysis: The combustive sound source (CSS) was deployed by this author and ARL:UT colleagues in SW06. Subsequent data analysis this year has shown that CSS is a viable alternative to small explosive charges and better than light bulb implosions. CSS signals have been used for geoacoustic inversion [29] and for estimation of the frequency dependency of a sandy sediment sound speed. [30]

RESULTS

<u>Primary Objective— Laboratory Sediment Investigation:</u> A pair of sound speed measurements made with two different samples of water saturated sand are presented. In both cases, the material is reconstituted water-saturated sand in distilled water. Two different sands were used, as shown in Fig. 6, with different grain size distributions, as shown in Fig. 7. The sound speeds extracted from the well-sorted sand appear in the upper frame of Fig. 8 along with the Williams EDFM prediction. [11] We are now capable of performing most of the necessary measurements of the sand physical properties, including wet and dry density measurements (which lead to porosity), and permeability via ASTM D-2434. [31]. The measurements in the upper frame have now been published, [2] having been only submitted for publication this time last year. The sound speeds extracted from poorly-sorted sand appear in the lower part of Fig. 8. Note that there is a much greater spread in the measured mid-frequency sound speeds for the poorly-sorted case, but in both cases, there is ample evidence of dispersion. The EDFM does a good job of describing the well-sorted case, but a poorer job of describing the poorly-sorted case.

<u>Secondary Objectives—Gas-bearing Sediments:</u> The collaborative work with NRL-SSC resulted in the measurement of sound speed of a reconstituted gas-bearing kaolinite sediment and a natural mud from Bay St. Louis, MS. Contemporaneous measurements of the bubble size distribution were also obtained. A single image from the tomography scan is shown in Fig. 9. From this data, the overall sample void fraction was found. The acoustic experiment and the resulting sound speed measurement are shown in Fig. 10. This kaolinite sample was very fluid-like, yet it could still suspend bubbles. It was found that the sound speed observed in the acoustic experiment was perfectly consistent with the sound speed predicted by Wood's Equation, which is a mixture rule for bubbly liquids, in which the sound speed depends only on the gas-free sediment bulk density and the void fraction. To the PI's knowledge, this is the first quantitative verification of Wood's Equation for a gas-bearing sediment. Note that these results indicate that the only bulk sediment property required for the prediction of sound speed in shallow, fluid-like gas bearing sediments is the bulk sediment density and the total gas volume fraction. None of the other typical Biot sediment parameters are needed, nor is the bubble size distribution needed. Also note that the traditional high frequency time-of-flight measurement technique failed in the gassy kaolinite due to excessive attenuation.

The results for the Bay St. Louis (BSL) mud sample are shown in Fig. 11, but here, the simplified Wood's equation does not accurately describe the observed sound speed. A potential explanation is that, the bubbles were not evenly distributed (as they were in the kaolinite) and because of this inhomogeneity, the effective sound speed was perhaps also nonuniform, causing failure of the data analysis applied here. Another potential explanation is that the BSL mud exhibited higher shear rigidity than the kaolinite, causing the fluid model to fail. Note that there is a significant difference between the low frequency (200–800 Hz) measured sound speed (287 m/s) and the high frequency sound speed (1520 m/s @ 400 kHz), verifying expectation qualitatively.

Secondary Objectives—Seagrass Acoustics: Experiments were conducted using the resonator technique to asses the hypothesis that seagrass is acoustically dominated by its gas content, and that Wood's equation could be used to model sound propagation in seagrass beds as an effective medium. A typical result for the species *Thalassia testudinum* (turtle grass) is shown in Fig. 12. The two curves show plant volume fraction V_{leaves}/V_{tot} (measured by acoustic and image-based techniques) as a function of the number of leaves placed inside the resonator. The black curve yields an acoustically-determined plant internal void fraction $\chi_{leaf,\,a} = 0.034$, via best fit of the equation at the top of the figure. The actual plant internal void fraction, determined using microscopic cross-section image analysis (Fig. 13), was found to be $\chi_{leaf} = 0.23$. Similar results were found the *Thalassia testudinum* (turtle grass) rhizomes (underground root structures) and the leaves and rhizomes of the other two species tested, *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). This refutes the above hypothesis and indicates that forward models of sound propagation and scattering in seagrass beds will require not only knowledge of the gas content, but knowledge of the plant tissue properties and structures, too. Therefore, understanding the acoustics of seagrass will be a significantly more difficult problem than previously thought. Additional details of this work are presented in [27] and the work has been submitted for publication. [28]

Tertiary Objective—Sediment Attenuation in SW06: The frequency dependency of a sandy sediment sound speed along a track in SW06 was analyzed [30] and found to exhibit low frequency attenuation in good agreement with predictions of the EDFM. [11] The results are shown in Fig. 14, and the new low frequency attenuation values show a slope proportional to the frequency squared, in contrast to higher frequency attenuation values which show a slope proportional to the square root of frequency.

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 EDFM [11] correctly predicts the mid (0.8–5 kHz) and high frequency (20–300 kHz) sound speed in water saturated sand, but there is more variability in the measured data than can be explained by the EDFM for poorly-sorted sands. Low frequency (80–2000 Hz) attenuation data from SW06 are also well described by EDFM and clearly follow the low frequency limiting slope of frequency squared. We are continuing our efforts to get ever-lower- frequency and more accurate laboratory measurements with and increased understanding of the measurement uncertainties.

Fluid-like shallow gas-bearing sediments were shown to have acoustic properties that depend only on the sediment bulk density and the void fraction as given by a simplified version of Wood's Equation. Two types of tissue from three different species of seagrass where shown to depend on tissue acoustic properties in addition to the gas content, and hence were not described by Wood's equation.

As our understanding of sound propagation in the ocean bottom increases, one application will be to update the models used in operational sonar systems. 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. The CSS performed very well during SW06 is proving to be a useful tool for ocean acoustics experiments.

TRANSITIONS

This PI is slated to receive $500k over two years (starting in 2008) 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 $15.7k from the Naval Surface Warfare Center-Panama City to perform laboratory measurements of sound speed on gas-bearing sediments collected during a mine hunting exercise, using the resonator method developed with the present grant.

This PI received $110k from the Naval Research Laboratory to study the acoustic properties of methane hydrates using the resonator method developed with the present 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.

REFERENCES

[1] P.S. Wilson, R.A. Roy, and W.M. Carey, "Development of an impedance tube technique for in-situ classification of marine sediments," *J. Acoust. Soc. Am.* **113**, pp. 2318 (2003).

[2] P.S. Wilson, A.H. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in an artificial water-saturated sand sediment," *J. Acoust. Soc. Am.* **121**, pp. 824–832 (2007).

[3] P.S. Wilson and T.F. Argo IV, "Resonator Measurements of Sediment Sound Speeds," Applied Research Laboratories, The University of Texas at Austin ARL-TR-07-02, 18 October 2006.

[4] E.L. Hamilton, "Prediction of in-situ acoustic and elastic properties of marine sediments," *Geophysics* **36**, pp. 266–284 (1971).

[5] L.D. Hampton, "Acoustic properties of sediments," *J. Acoust. Soc. Am.* **42**, pp. 882–890 (1967).

[6] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range," *J. Acoust. Soc. Am.* **28**, pp. 168–178 (1956).

[7] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range," *J. Acoust. Soc. Am.* **28**, pp. 179–191 (1956).

[8] N.P. Chotiros, "Biot model of sound propagation in water-saturated sand," *J. Acoust. Soc. Am.* **97**, pp. 199–214 (1995).

[9] M.J. Buckingham, "Wave propagation, stress relaxation and grain-to-grain shearing in saturated, unconsolidated marine sediments," *J. Acoust. Soc. Am.* **108**, pp. 2796–2815 (2000).

[10] R.D. Stoll and T.K. Kan, "Reflection of acoustic waves at a water–sediment interface," *J. Acoust. Soc. Am.* **70**, pp. 149–156 (1981).

[11] K.L. Williams, "An effective density fluid model for acoustic propagation in sediments derived from Biot theory," *J. Acoust. Soc. Am.* **110**, pp. 2276–2281 (2001).

[12] P.S. Wilson and R.A. Roy, "Acoustic Characterization of Marine Sediments by Impedance Tube," Boston University, Final Report NUWC Grant No. N61331-02-1-G002, 2003.

[13] J.Y. Chung and D.A. Blaser, "Transfer function method of measuring in-duct acoustic properties. I. Theory," *J. Acoust. Soc. Am.* **68**, pp. 907–913 (1980).

[14] J.Y. Chung and D.A. Blaser, "Transfer function method of measuring in-duct acoustic properties. II. Experiment," *J. Acoust. Soc. Am.* **68**, pp. 914–921 (1980).

[15] ASTM, "Standard Designation E 1050-90: Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System." West Conshohocken, PA: American Society for Testing and Materials, 1990.

[16] P.S. Wilson, R.A. Roy, and W.M. Carey, "An improved water-filled impedance tube," *J. Acoust. Soc. Am.* **113**, pp. 3245–3252 (2003).

[17] P.S. Wilson, R.A. Roy, and W.M. Carey, "Phase speed and attenuation in bubbly liquids inferred from impedance measurements near the individual bubble resonance frequency," *J. Acoust. Soc. Am.* **117**, pp. 1895–1910 (2005).

[18] Y.S. Choy and L. Huang, "Measurement of in-duct acoustic properties by using a single microphone with fixed position," *J. Acoust. Soc. Am.* **116**, pp. 3498 (2004).
[19] B. Mert, H. Sumali, and O.H. Campanella, "A new method to measure viscosity and intrinsic sound velocity of liquids using impedance tube principles at sonic frequencies," *Rev. Sci. Inst.* **75**, pp. 2613 (2004).
[20] L. Elvira-Segura, "Acoustic wave dispersion in a cylindrical elastic tube filled with a viscous liquid," *Ultrasonics* **37**, pp. 537 (2000).
[21] K.-J. Dunn, "Sample boundary effect in acoustic attenuation of fluid-saturated porous cylinders," *J. Acoust. Soc. Am.* **81**, pp. 1259 (1987).
[22] A.A. Gubaidullin, O.Y. Kuchugurina, D.M.J. Smeulders, and C.J. Wisse, "Frequency-dependent acoustic properties of a fluid/porous solid interface," *J. Acoust. Soc. Am.* **116**, pp. 1474 (2004).
[23] C.R. Fuller and F.J. Fahy, "Characteristics of wave propagation and energy distributions in cylindrical elastic shells filled with fluid," *J. Sound Vib.* **81**, pp. 501–518 (1982).
[24] M.D. Richardson and K.B. Briggs, "In situ and laboratory geoacoustic measurements in soft mud and hard-packed sand sediments: Implications for high-frequency acoustic propagation and scattering," *Geo-Marine Letters* **16**, pp. 196–203 (1996).
[25] P.S. Wilson, J.C. Wilbur, W.M. Carey, and R.A. Roy, "Evidence of dispersion in a water-saturated granular sediment," presented at Oceans 2005 - Europe, Brest, France, 2005.
[26] P.S. Wilson, A.H. Reed, W.T. Wood, and R.A. Roy, "Low frequency sound speed measurements paired with computed x-ray tomography imaging in gas-bearing reconstituted natural sediments," in *Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustics Measurements: Technologies and Results*, J. S. Papadakis and L. Bjørnø, Eds. Heraklion, Greece, 2007, pp. 21–29, ISBN 978-960-88702-5-3.
[27] P.S. Wilson and K.H. Dunton, "Seagrass acoustics: Results of an experimental laboratory investigation," in *Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustics Measurements: Technologies and Results*, J. S. Papadakis and L. Bjørnø, Eds. Heraklion, Greece, 2007, pp. 383-390, ISBN 978-960-88702-5-3.
[28] P.S. Wilson and K.H. Dunton, "An investigation of seagrass as an effective acoustic medium," *J. Acoust. Soc. Am.* **in review** (2007).
[29] G.R. Potty, et al., "Geoacoustic inversion using combustive sound source signals," *J. Acoust. Soc. Am.* **121**, pp. 3055 (2007).
[30] D.P. Knobles, P.S. Wilson, and S.E. Cho, "Determination of frequency dependence of sediment attenuation in shallow water using the combustive sound source," *J. Acoust. Soc. Am.* **121**, pp. 3126 (2007).
[31] ASTM, "Standard Designation D 2434-68: Standard Test Method for Permeability of Granular Soils." West Conshohocken, PA: American Society for Testing and Materials, 2006.
[32] K.L. Williams, D.R. Jackson, E.I. Thorsos, D. Tang, and S.G. Schock, "Comparison of sound speed and attenuation measured in a sandy sediment to

predictions based on the Biot theory of porous media," *IEEE J. Ocean. Eng.* **27**, pp. 413–428 (2002).

PUBLICATIONS

[1] P.S. Wilson, A.H. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in an artificial water-saturated sand sediment," *J. Acoust. Soc. Am.* **121**, pp. 824–832 (2007). [published, refereed]

[2] P.S. Wilson and K.H. Dunton, "Seagrass acoustics: Results of an experimental laboratory investigation," in *Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustics Measurements: Technologies and Results*, J. S. Papadakis and L. Bjørnø, Eds. Heraklion, Greece, 2007, pp. 383–390, ISBN 978-960-88702-5-3. [published, refereed]

[3] P.S. Wilson, A.H. Reed, W.T. Wood, and R.A. Roy, "Low frequency sound speed measurements paired with computed x-ray tomography imaging in gas-bearing reconstituted natural sediments," in *Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustics Measurements: Technologies and Results*, J. S. Papadakis and L. Bjørnø, Eds. Heraklion, Greece, 2007, pp. 21–29, ISBN 978-960-88702-5-3. [published, refereed]

[4] T.F. Argo IV and P.S. Wilson, "The linear acoustic behavior of a bubble confined between parallel plates," in *Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustics Measurements: Technologies and Results*, J. S. Papadakis and L. Bjørnø, Eds. Heraklion, Greece, 2007, pp. 519–526, ISBN 978-960-88702-5-3. [published, refereed]

[5] P.S. Wilson, "From bubbles to sediments to seagrass: Wood's equation in underwater acoustics," in *International Conference on Detection and Classification of Underwater Targets*, Vol. 29, Pt. 6. Hertfordshire, UK: Institute of Acoustics, 2007, pp. 138–146. [published, refereed]

[6] P.S. Wilson and K.H. Dunton, "An investigation of seagrass as an effective acoustic medium," *J. Acoust. Soc. Am.* **in review** (2007). [refereed]

[7] G.R. Potty, et al., "Geoacoustic inversion using combustive sound source signals (A)," *J. Acoust. Soc. Am.* **121**, pp. 3055 (2007).

[8] D.P. Knobles, P.S. Wilson, and S.E. Cho, "Determination of frequency dependence of sediment attenuation in shallow water using the combustive sound source (A)," *J. Acoust. Soc. Am.* **121**, pp. 3126 (2007).

[9] M.J. Isakson and P.S. Wilson, Review of: D.R. Jackson and M.D. Richardson, *High-Frequency Seafloor Acoustics*. New York: Springer, 2007, appearing in *J. Acoust. Soc. Am.*, **in press** (2007).

[10] P.S. Wilson and T.F. Argo IV, "Resonator Measurements of Sediment Sound Speeds," Applied Research Laboratories, The University of Texas at Austin ARL-TR-07-02, 18 October 2006. [published]

HONORS/AWARDS/PRIZES

This grant's PI, Preston S. Wilson of The University of Texas at Austin received the A.B. Wood medal from the Institute of Acoustics in the United Kingdom.

A B WOOD MEDAL

The A B Wood medal and attendant prize is awarded in alternate years to acousticians domiciled in the UK or Europe and in the USA or Canada. It is aimed at younger researchers, preferably under the age of 35 in the year of the Award, whose work is associated with the sea. Following his graduation from Manchester University in 1912, Albert Beaumont Wood became one of the first two research scientists at the Admiralty to work on antisubmarine defence. He designed the first directional hydrophone and was well known for the many contributions he made to the science of underwater acoustics and for the help he gave to younger colleagues. The medal was instituted after his death by his many friends on both sides of the Atlantic and was administered by the Institute of Physics

FIGURES

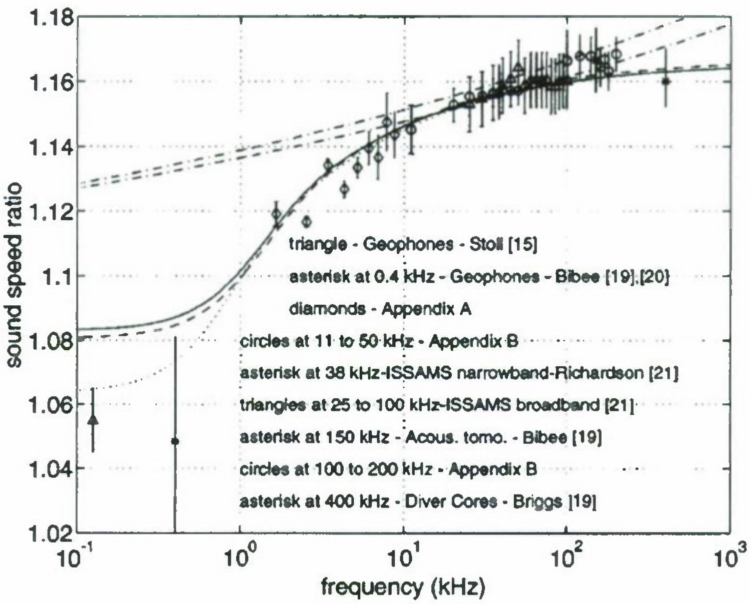


Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [32]. The theoretical curves are: solid line=Biot/Stoll [10]; dashed line=Williams [11], dash-dot lines=Buckingham's model for two values of fluid viscosity [9]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [32].)

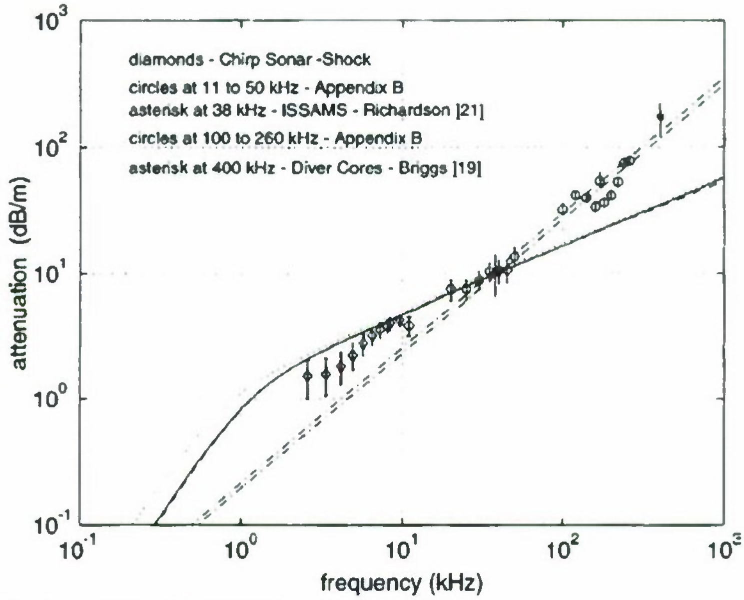


Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [32].) Also note that there is attenuation data below about 3 kHz.

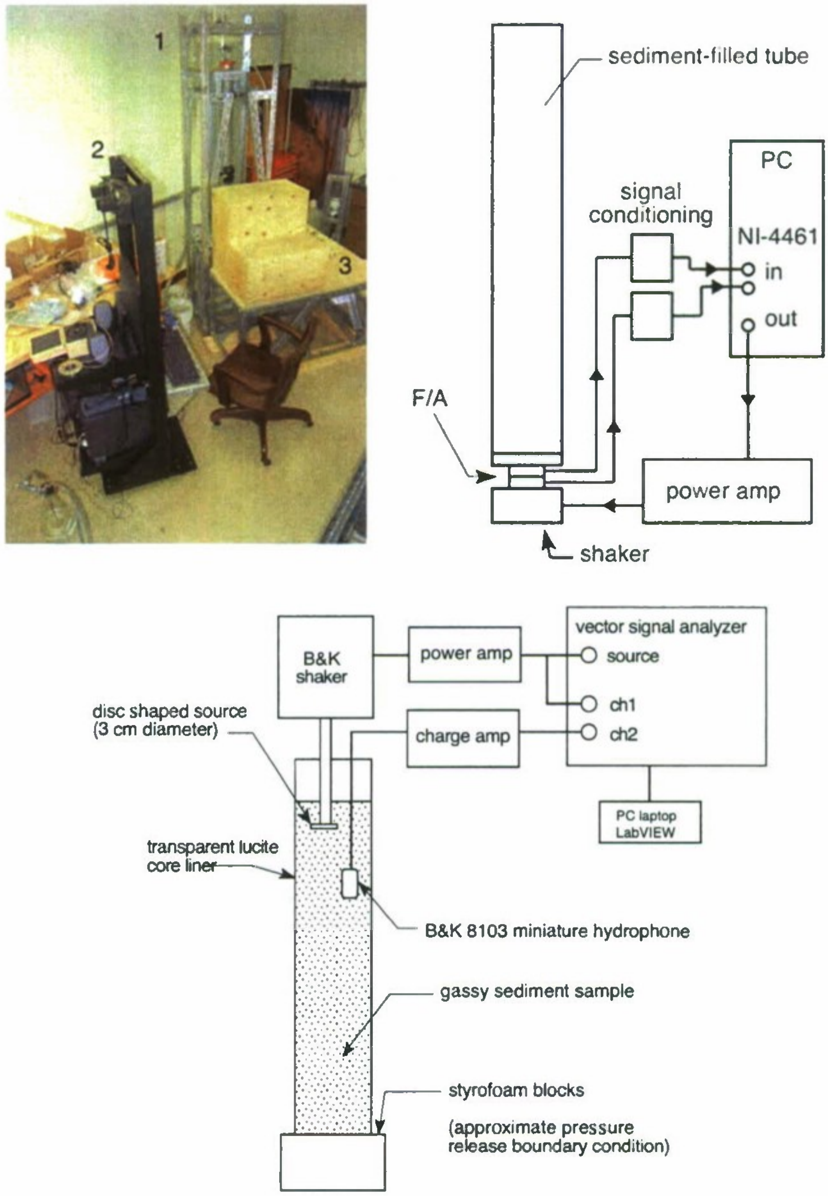


Fig. 2. The upper left is a photograph of the impedance tube facility: the support frame and tube (1), the computer and data acquisition system (2), and the scaffolding (3). On the upper right, the schematic of the Mert apparatus [19] is shown. In the lower frame, a schematic of the resonator method is shown.

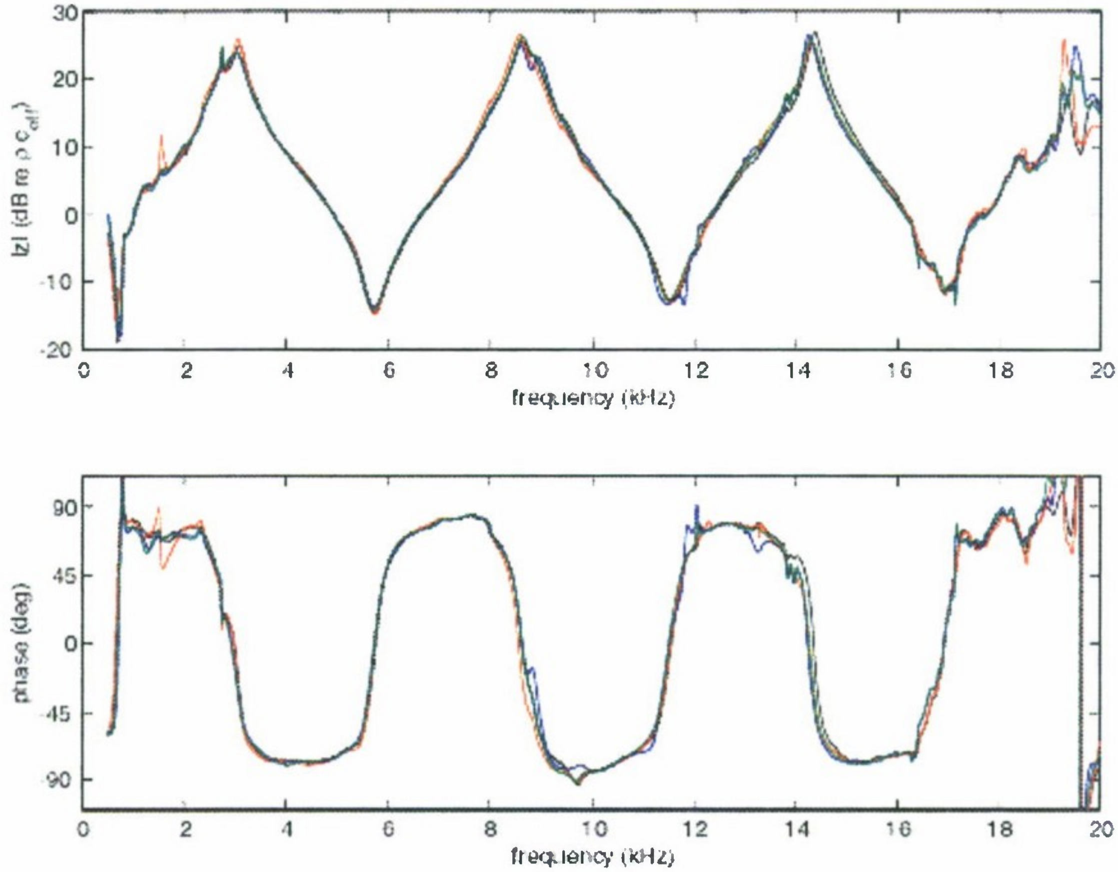


Fig. 3. A short (min frequency = 2 kHz) impedance tube was used last year to obtain the data shown here, which is included for comparison to new data in Figs. 5–6. Measured impedance of unwashed/unsieved and washed/sieved reconstituted sand sediment samples plotted together for comparison. The red and black curves are for the unwashed case and the blue and green curves are for the washed case. Little significant difference is seen.

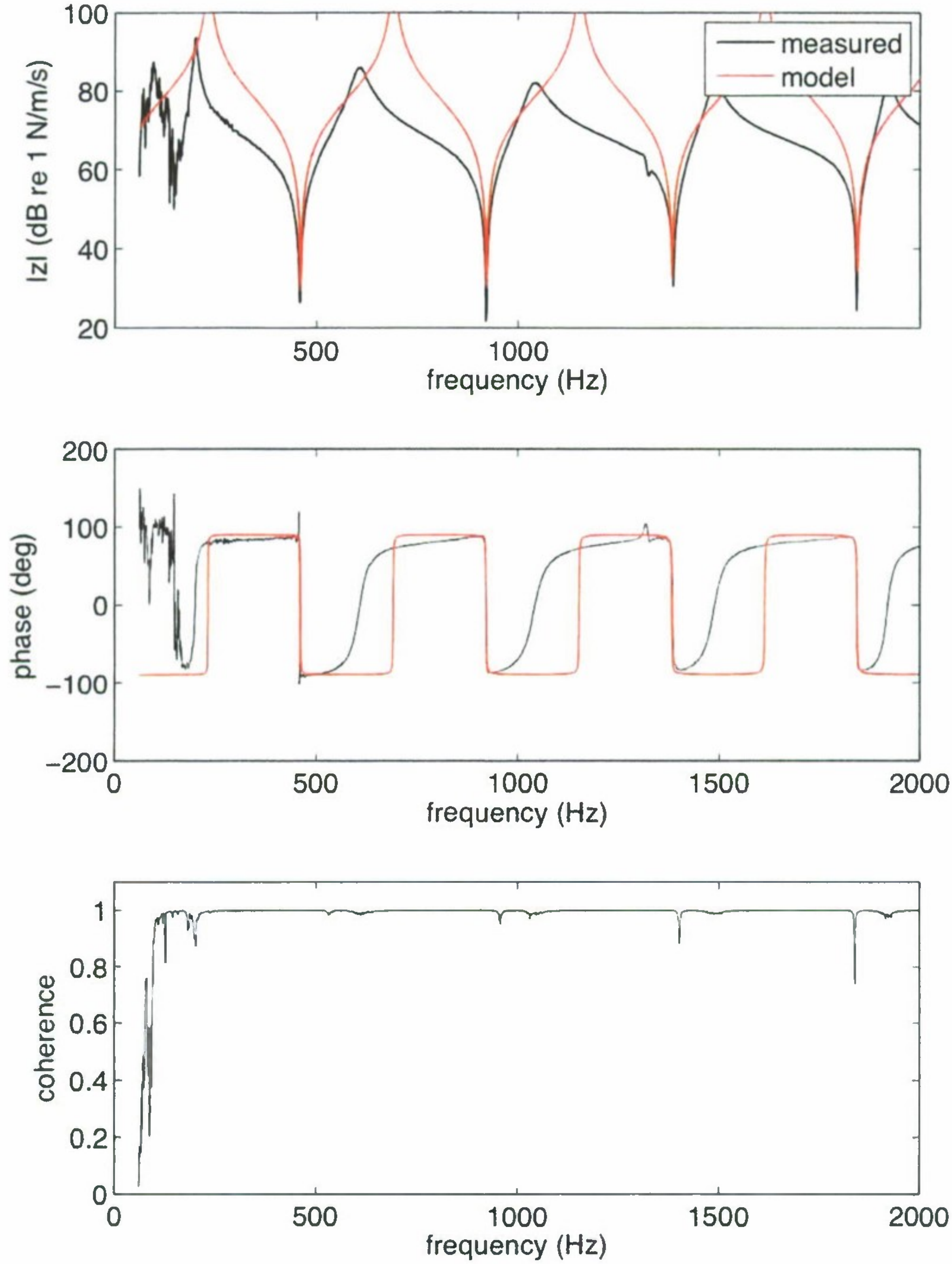


Fig. 4. The long (min frequency = 200 Hz) impedance tube developed this year was used to obtain the data shown here. The material that filled the tube was distilled water. Note that the measured and predicted impedance magnitude and phase do not agree, except for at the minima in magnitude and the corresponding frequencies in phase.

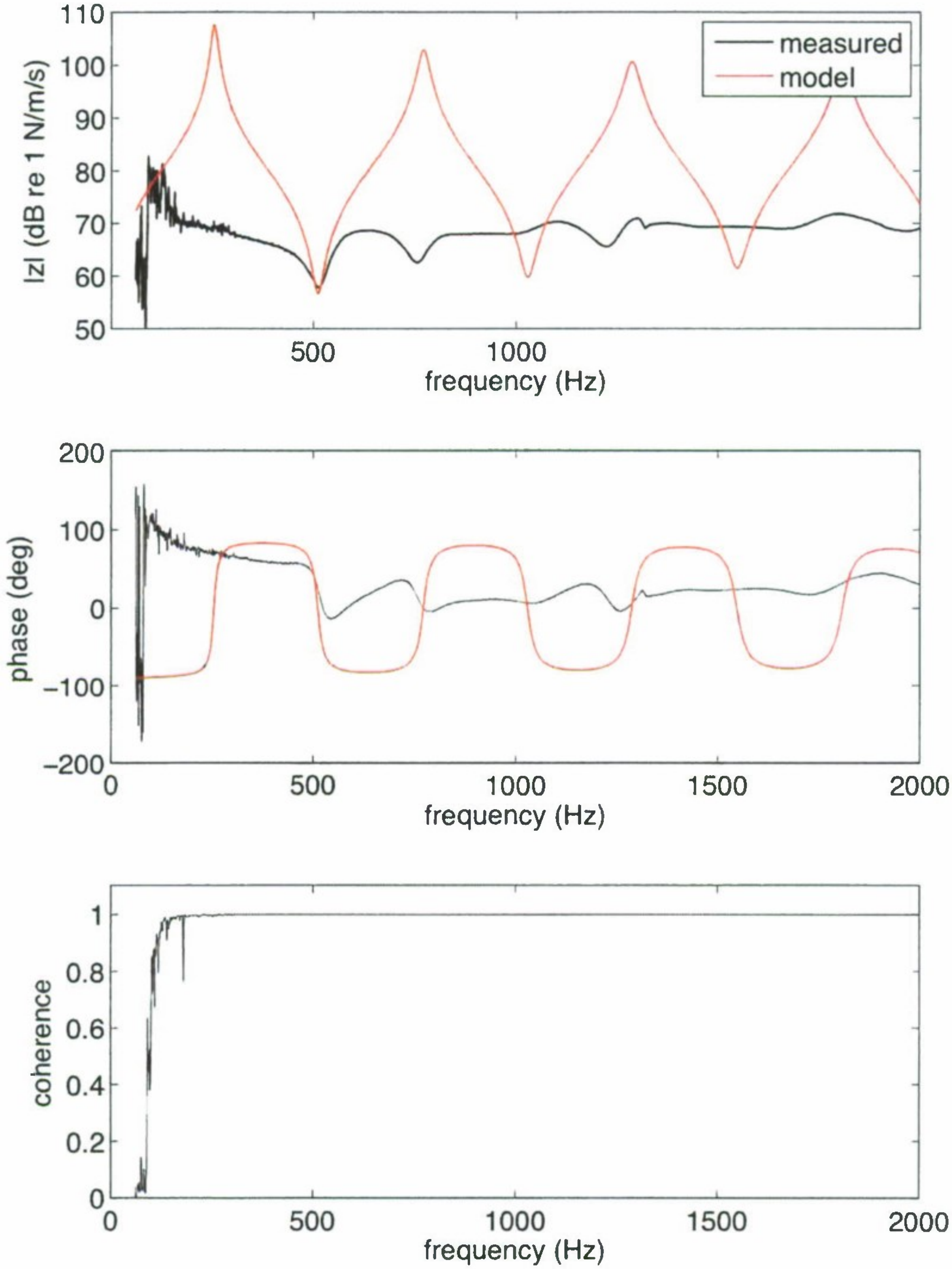


Fig. 5. The long (min frequency = 200 Hz) impedance tube developed this year was used to obtain the data shown here. The material that filled the tube was reconstituted water-saturated sand. Note that the measured and predicted impedance magnitude and phase agree even less than in Fig. 4.

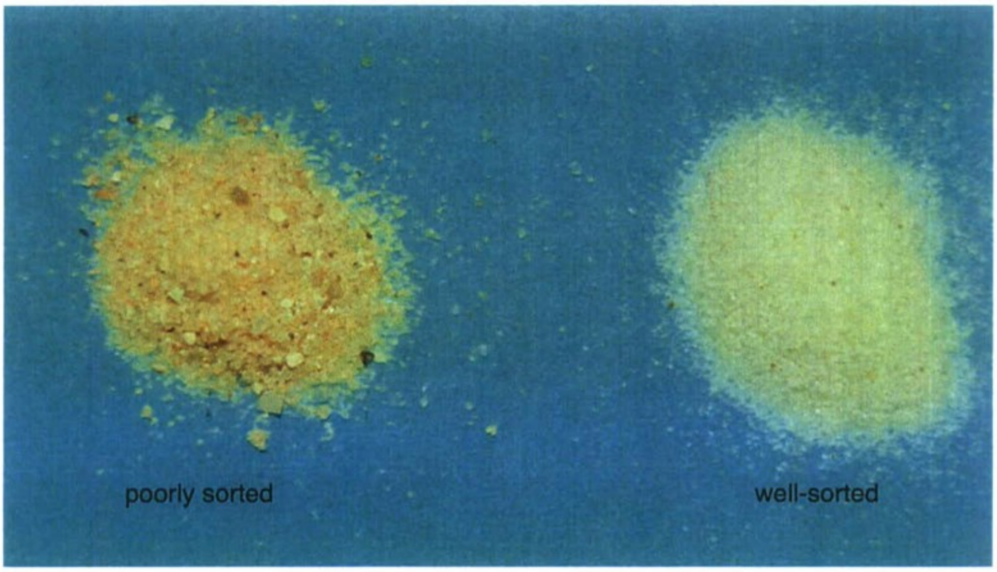


Fig. 6. The photo shows two samples of sand. On the left, the sample is poorly sorted. The presence of larger grains adds a long tail to the grain size distribution function. On the right, the sample is well-sorted.

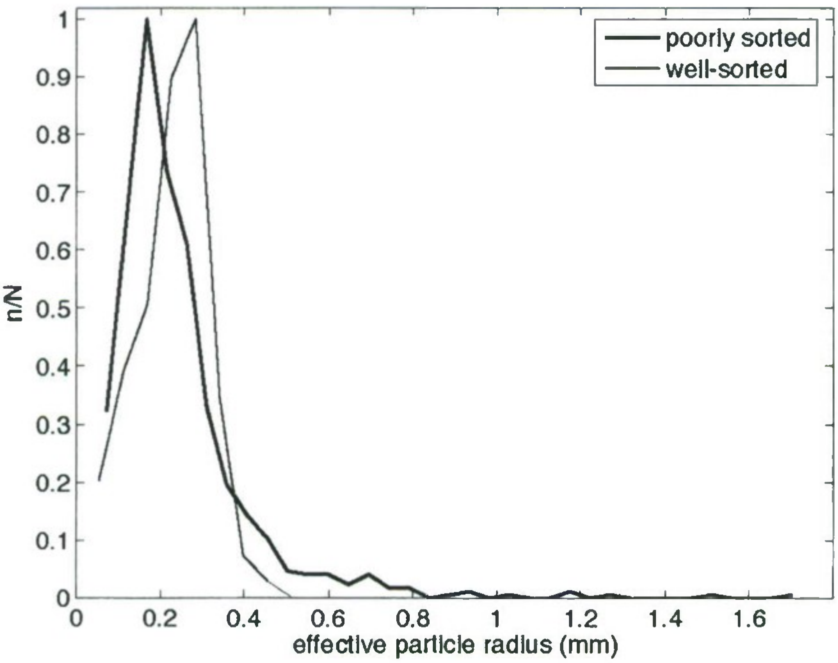


Fig. 7. Measured grain size distribution functions for the two samples of sand shown above.

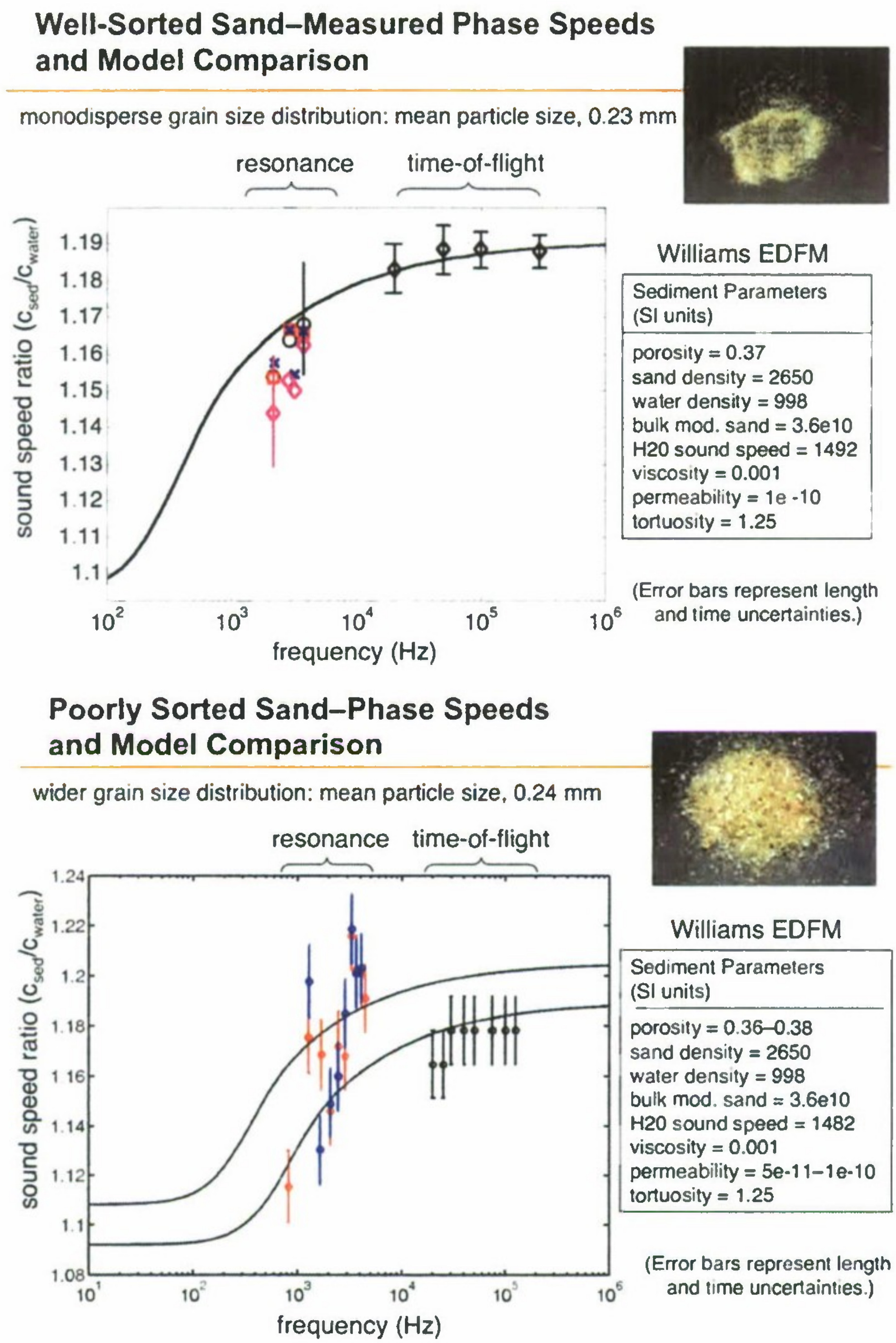


Fig. 8. The measured sound speed for well-sorted and poorly sorted sand sediments are shown above in the upper and lower frames, respectively. There is greater variation in the measurements for the poorly sorted sand. In both cases, the different colors represent measurements in different sub-regions of each sample. The upper figure was adapted from [2].

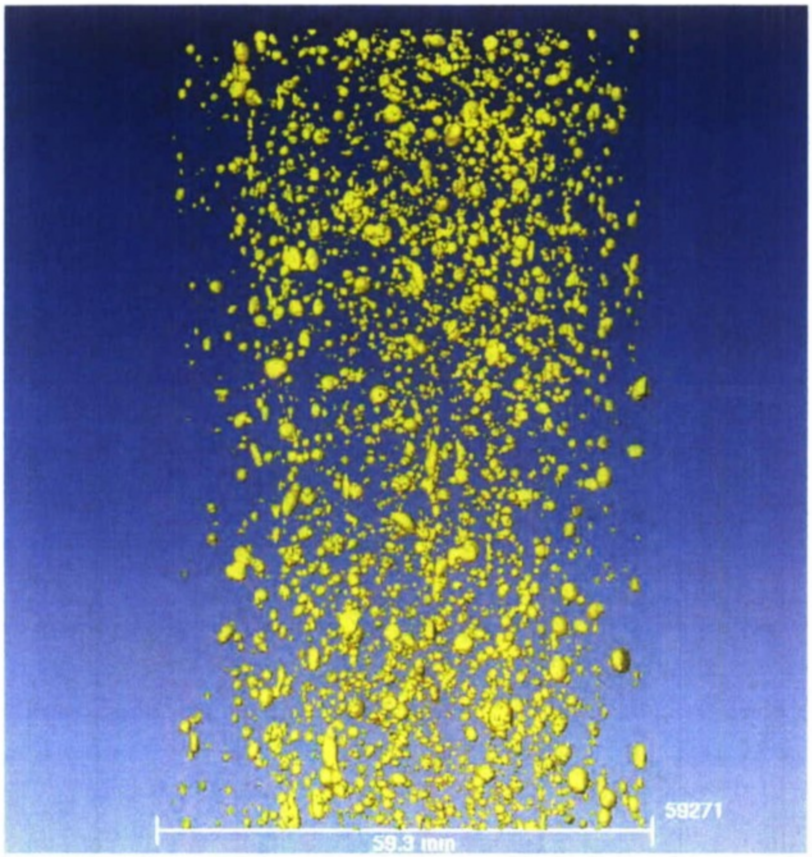
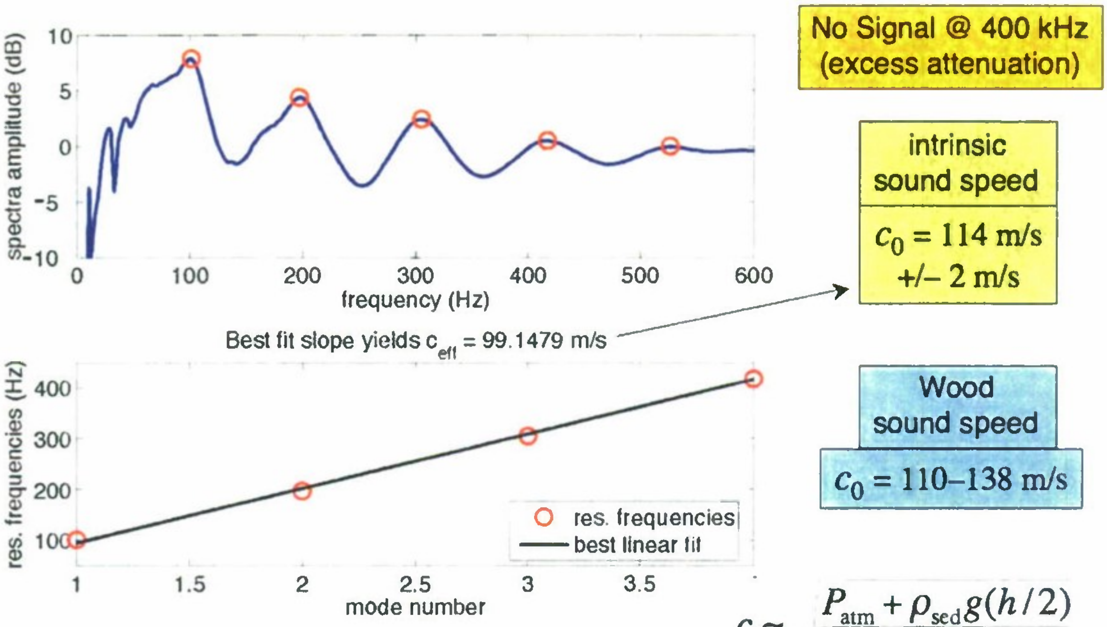


Fig. 9. A single image from the computed x-ray tomography scan of the kaolinite sediment sample contained within the 1-D acoustic resonator. The yellow blobs are air bubbles. The data was manipulated to give the volume of each bubble, and the total void fraction and the effective spherical bubble size distribution were determined.



$$c \approx \sqrt{\frac{P_{atm} + \rho_{sed} g (h/2)}{\chi(1-\chi)\rho_{sed}}}$$

Fig. 10. The top plot shows the pressure spectrum and resonance frequencies measured in a 1-D resonator filled with reconstituted bubbly kaolinite sediment. The bottom plot shows the resonance frequencies as a function of mode number, the slope of which yields the sediment sound speed. The resulting sound speed is shown in the yellow box. A simplified version of Wood's equation is shown at bottom right and was used to predict the sound speed. The void fraction χ was obtained from the image analysis, as discussed in Fig. 9. The sediment density was also measured. The remaining parameters are the atmospheric pressure P_{atm} , the acceleration due to gravity g, and the sediment column height h. The prediction with no fitting is shown in the blue box. The range of predicted values represent measurement uncertainty in the model input parameters. The simplified Wood's equation accurately describes the measured sound speed. In the orange box on the upper right, the high frequency time-of-flight measurement is shown, which in this case yielded no result.

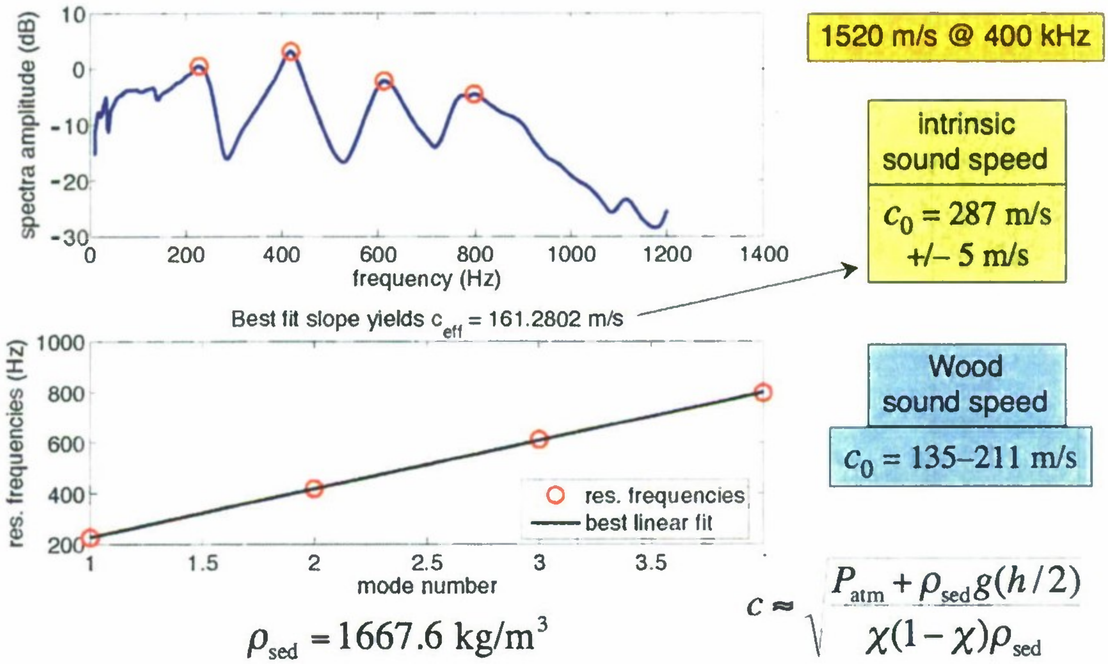


Fig. 11. The top plot shows the pressure spectrum and resonance frequencies measured in a 1-D resonator filled with a natural mud sediment collected from Bay St. Louis near NRL-SSC. The bottom plot shows the resonance frequencies as a function of mode number, the slope of which yields the sediment sound speed. The resulting sound speed is shown in the yellow box. A simplified version of Wood's equation is shown at bottom right and was used to predict the sound speed. The void fraction χ was obtained from image analysis, similar to that shown in Fig. 9. The sediment density was also measured. The remaining parameters are the atmospheric pressure P_{atm}, the acceleration due to gravity g, and the sediment column height h. The prediction with no fitting is shown in the blue box. The range of predicted values represent measurement uncertainty in the model input parameters. The simplified Wood's equation does NOT accurately describe the measured sound speed. In the orange box on the upper right, the high frequency time-of-flight measurement is shown.

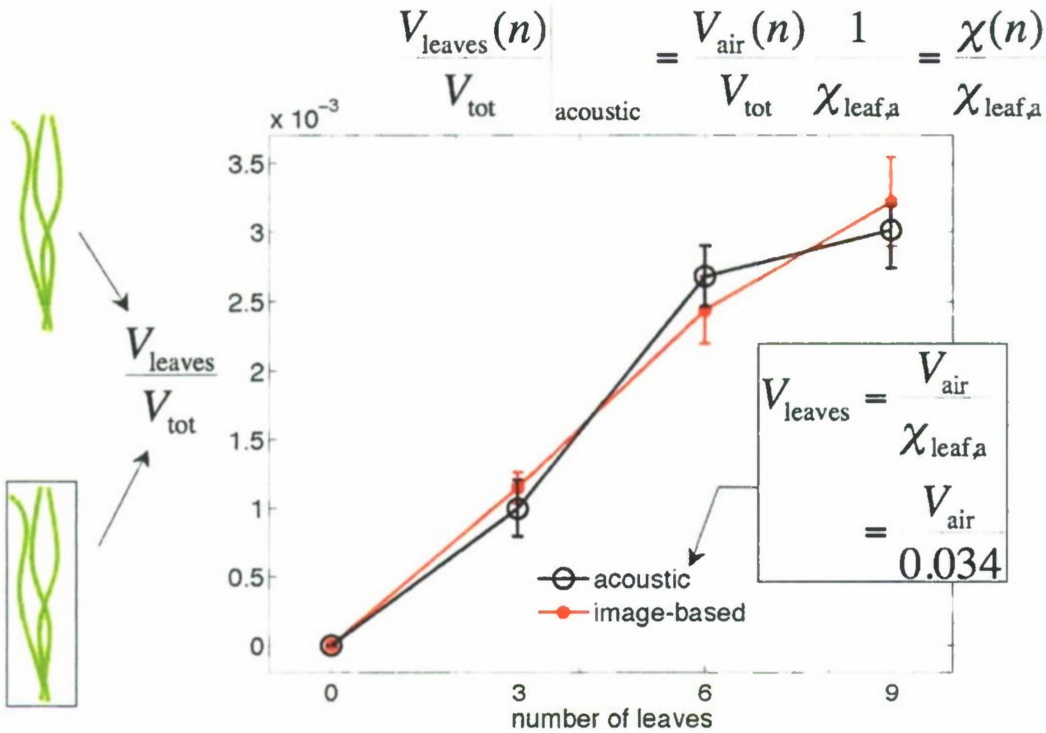


Fig. 12. The apparent acoustic volume fraction of thalassia leaves is compared to the volume fraction obtained by image analysis of the leaf physical volume. The black curve yields an internal leaf void fraction of 0.034.

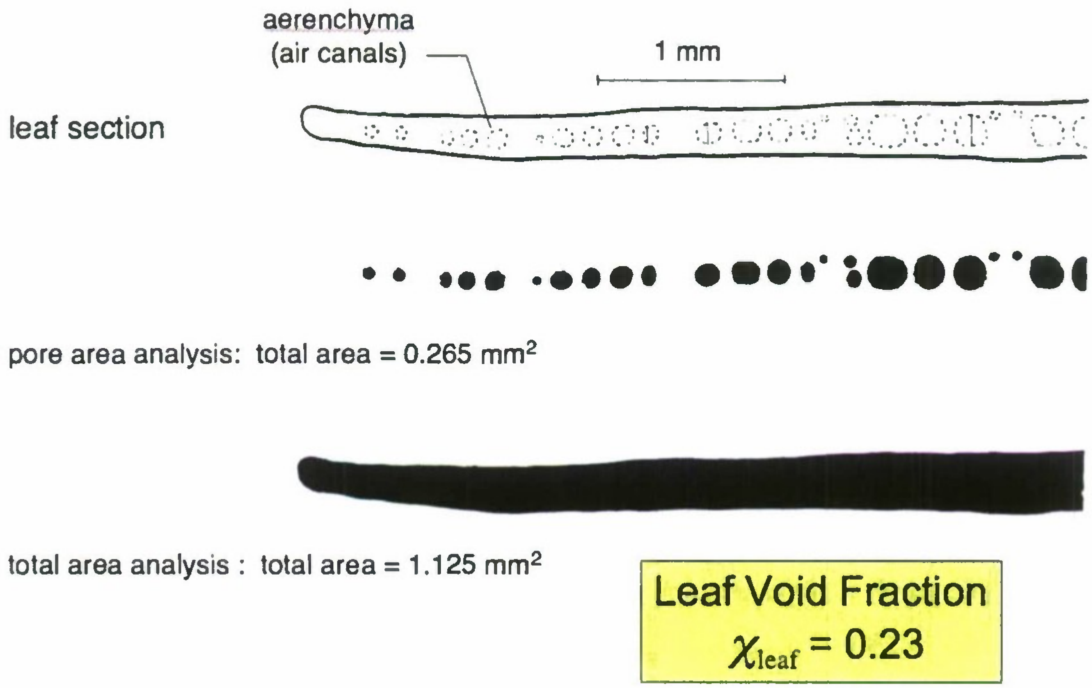


Fig. 13. The actual internal leaf void fraction was determined to be 0.23 from this microscopic cross-section image analysis.

Current 1st order results compared to SAX

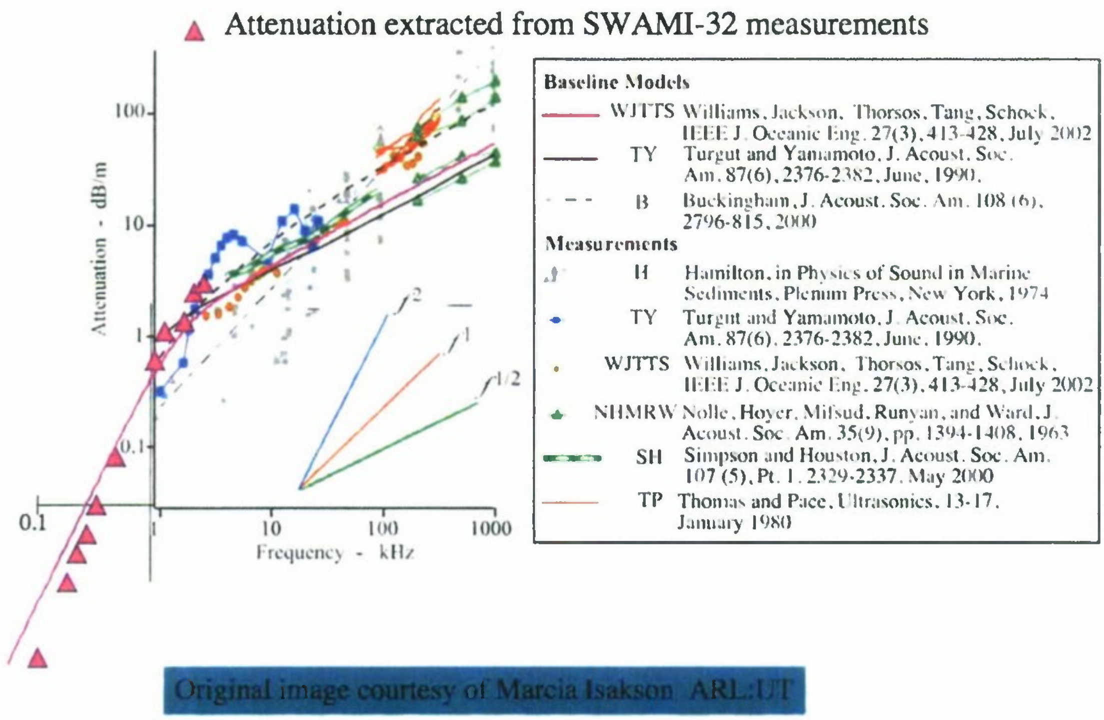


Fig. 14. The large purple triangles represent sandy sediment attenuation values inferred by matching measured long range transmission loss curves from SW06 with model predictions in which the sediment attenuation is the only fit parameter. The purple curve is the prediction of the EDFM with input parameters from SAX99. Note that these extrapolated attenuation values go below 100 Hz and clearly show a different slope than the higher frequency measurements.

Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques

Chapter 5: Summary of Work Conducted FY2008

LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of the plane wave reflection coefficients from laboratory and *in situ* sediments using impedance tube [1] and acoustic resonator tube [2, 3] methods, in the frequency range of approximately 300 Hz to tens of kHz. This approach will also yield measurements of the acoustic impedance, sediment sound speed, attenuation, and complex density through the use of appropriate model inversions and data analysis. These measurements will span a frequency range in which there is little experimental data and help to verify competing theoretical models [4-11] on sound propagation in marine sediments. An overview of the state-of-the-art in both experiment and modeling is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation. Initial impedance tube work [12] indicated that the coupling between the sediment and the impedance tube walls must be accounted for, in order to infer the intrinsic sediment attenuation from measurements performed in an impedance tube. Therefore, an initial objective was to develop an appropriate model that describes this coupling, and to develop a new impedance tube that exploits this model, i.e. minimizes the coupling, and allows for accurate recovery of intrinsic sediment attenuation from the measurements.

A secondary objective has been to investigate other ocean-bottom materials of opportunity utilizing the techniques and measurement instrumentation developed for this work. To date these materials have been gas-bearing sediments and seagrasses. Finally, the author participated in SW06 and therefore a tertiary objective this FY was to participate in the analysis of some of the SW06 data in collaboration with other ONR PIs.

APPROACH

The impedance tube technique and has been adopted as a standard technique [13-15] for measuring the acoustic properties of small samples of materials in air. With support from the Office of Naval Research Ocean Acoustics Program, this author and colleagues at Boston University developed an impedance tube technique and apparatus for use in measuring the acoustic properties of materials with water or other liquids as the host medium. [16] A number of engineering problems relating to the acoustic coupling between the fill-liquid and the tube walls, and to the perturbing effects of the measuring apparatus itself were overcome. The original apparatus was developed for and successfully used to measure sound speed and attenuation in bubbly liquids in a frequency range of 5–9 kHz. [17] The device proved to be the most accurate and precise water-filled impedance tube reported in the open literature. The uncertainty in the measured reflection coefficient for this device is +/- 0.14 dB in magnitude and +/- 0.8° in phase.

In the current project, we are building a larger, new and improved impedance tube for use with marine sediments. It operates in the frequency range in which dispersion is expected (about 300 Hz to 30 kHz) in typical sandy sediments. It has been used to make measurements, which are presented below, but we are continuing to refine the technique and instrumentation. Two impedance measurement techniques can be utilized with the apparatus, [18, 19] which do not require movement of the sensors, and minimize errors due to sensor position uncertainty. The apparatus is also being used with the resonator method [2, 3] of measuring material properties. Finally, we have incorporated new modeling that will better account for the coupling between the sediment and the tube walls and thereby provide a more accurate quantification of experimental error. This modeling is based on and extended from existing work for lossy fluid coupling in elastic waveguides, [19, 20] additional sample-wall boundary effects, [21] sample-fluid boundary effects [22] and asymmetric excitation. [23] The instrument is being used in the laboratory to investigate artificial and natural sediments *in vitro*. A technique was adopted this year that allowed for the control of porosity, [24] and has been applied to new high frequency (above 50 kHz) measurement, presented below.

The personnel for this project are: Preston S. Wilson serves as PI and is an Assistant Professor in the Mechanical Engineering Department at the University of Texas at Austin (UTME), and is also an Assistant 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. Ryan L. Renfrow, a UTME senior and an Undergraduate Research Assistant on the project, serves as an electromechanical technician and provided machine shop, procurement and software support. Theodore F. Argo IV is a UTME Ph.D. student who contributes to all aspects of the project.

WORK COMPLETED

Primary Objective—Laboratory Sediment Investigation: The difficulties discussed last year using the low frequency measurement methods outlined in Fig. 2, and illustrated in Fig. 3, have been successfully attributed to the Janssen effect, [25] which will apply to any vertical impedance or resonator tube technique in which the column becomes too long, relative to a length scale of structure created by the sediment grains distributing the overburden load to the walls in force chains. The result is that the material exhibits a highly inhomogeneous stiffness that significantly differs from that seen in the unconfined material, and hence appears to significantly alter wave propagation. A visualization of this is shown in Fig. 4. [26] To overcome this problem, the new long resonator tube which was formerly deployed in a vertical orientation, has now been deployed horizontally. Significant engineering effort has been expended to reorient the experimental apparatus and the associated sample handling system. New measurements of low frequency sound speed and attenuation are expected from this system in the near future.

We began a collaboration with a research group in the University of Texas at Austin's physics department that studies the dynamics of granular material and also with a group at The Max Plank Institute for Dynamics and Self-Organization (Göttingen, Germany). We adapted a technique they jointly developed [24] to create samples of water-saturated granular materials with variable porosity using a fluidization technique. We have conducted a series of sound speed and attenuation measurements at high frequencies (100–750 kHz) in glass-bead sediments with a porosity range from 0.38 to 0.44 and compared them to the predictions of the Biot-Stoll model. [10]

Secondary Objectives—Gas-bearing Sediments: We continued our collaboration with the Seafloor Sciences Group at NRL-SSC on the acoustics of gas-bearing sediments. An unprecedented set of contemporaneous acoustic measurements and computed x-ray tomography imaging scans were obtained on a variety of reconstituted natural sediments at NRL-SSC in January 2006. Our 1-D acoustic resonator technique [2] was used to measure the sound speed inside the sediment samples. A high frequency (400 kHz) time-of-flight technique (using the Kevin Briggs ear-muffs apparatus [27]) was also used to measure the sound speed. The imaging scans yielded the bubble size distribution and the total void fraction (gas content) of the sediment. A model was developed this year to describe the low frequency sound speed in shallow, fluid-like gas bearing sediments, based on a simplified Wood's equation, and it was found to agree with measurements in a sediment of kaolinite, distilled water and gas bubbles, which resulted in a new publication. [28]

Secondary Objectives—Seagrass Acoustics: Our previous collaboration with the seagrass biologist, Dr. Kenneth Dunton, of the University of Texas Marine Science Institute on the acoustics of sediments containing seagrasses has continued. Our acoustic resonator technique was used to make additional measurements of the effective low frequency acoustic properties of three gulf-coast species, *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). Additional measurements and analysis were conducted this fiscal year which resulted in a manuscript which is currently accepted for publication pending revision. [29]

Tertiary Objective—SW06 Data Analysis: The combustive sound source (CSS) was deployed by this author and ARL:UT colleagues in SW06. Subsequent data analysis this year built upon last year's analysis and has further shown that CSS is a viable alternative to small explosive charges and better than light bulb implosions. Geoacoustic inversion using CSS signals has been optimized, resulting in a publication [30] and further analysis of the frequency dependency of a sandy bottom on the New Jersey shelf has resulted in a new publication. [31]

RESULTS

Primary Objective— Laboratory Sediment Investigation: The fluidized bed apparatus that was designed and constructed to measure the sound speed and attenuation in water-saturated sediments as a function of frequency and porosity is shown in Fig. 5. Water is pumped up through the bead sample, which fluidizes the sediment. The height of the sediment column increases in proportion to the flow rate. When the flow is terminated, the sample settles back to an equilibrium porosity that is higher than the original randomly packed porosity. The resulting equilibrium porosity is a function of the flow rate and flow rate history in a known way, hence one can prepare a sediment of a particular porosity. High frequency measurements of the speed of sound in water-saturated glass bead sediments (bead radius = 250 μm) are presented and compared to the Biot-Stoll model [10] in Fig. 6 for three porosities. These are preliminary results and additional analysis is required to fully understand the dispersion seen in this data. It is clear that the Biot-Stoll model correctly predicts the effect of porosity.

Secondary Objectives—Gas-bearing Sediments: The collaborative work with NRL-SSC resulted in the measurement of sound speed of a reconstituted gas-bearing kaolinite sediment and a natural mud from Bay St. Louis, MS. Contemporaneous measurements of the bubble size distribution were also obtained. Further analysis of this data set was conducted in the current fiscal year and the results were published. [28] A single image from the tomography scan is shown in Fig. 7. From this data, the overall sample void fraction was found. The acoustic experiment and the resulting sound speed measurement are shown in Fig. 8. This kaolinite sample was very fluid-like, yet it could still suspend bubbles. It was found that the sound speed observed in the acoustic experiment was perfectly consistent with the sound speed predicted by Wood's Equation, which is a mixture rule for bubbly liquids, in which the sound speed depends only on the gas-free sediment bulk density and the void fraction. To the PI's knowledge, this is the first quantitative verification of Wood's Equation for a gas-bearing sediment. Note that these results indicate that the only bulk sediment property required for the prediction of sound speed in shallow, fluid-like gas bearing sediments is the bulk sediment density and the total gas volume fraction. None of the other typical Biot sediment parameters are needed, nor is the bubble size distribution needed. Also note that the traditional high frequency time-of-flight measurement technique failed in the gassy kaolinite due to excessive attenuation.

Secondary Objectives—Seagrass Acoustics: Additional experiments were conducted using the resonator technique to asses the hypothesis that seagrass is acoustically dominated by its gas content, and that Wood's equation could be used to model sound propagation in seagrass beds as an effective medium. A typical result for the species *Thalassia testudinum* (turtle grass) is shown in Fig. 9. The two curves show plant volume fraction V_{leaves}/V_{tot} (measured by acoustic and image-based techniques) as a function of the number of leaves placed inside the resonator. The black curve yields an acoustically-determined plant internal void fraction $\chi_{leaf,\,a} = 0.034$, via best fit of the equation at the top of the figure. The actual plant internal void fraction, determined using microscopic cross-section image analysis (Fig. 10), was found to be $\chi_{leaf} = 0.23$. Similar results were found the *Thalassia testudinum* (turtle grass) rhizomes (underground root structures) and the leaves and rhizomes of the other two species tested, *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). The above hypothesis is refuted and indicates that forward models of sound propagation and scattering in seagrass beds will require not only knowledge of the gas content, but knowledge of the plant tissue properties and structures, too.

A comparison of the ratio of the image-based to acoustically determined void fractions for both leaves and rhizomes of all three species reveal some interesting differences (Fig. 11) that reflect the acoustic importance of the tissue. A ratio of unity indicates plants that behave acoustically like air bubbles in water. An increasing ratio indicates increasing tissue stiffness, which effectively reduces the acoustic contrast of the internal gas and thereby reduces the acoustic contrast of the plant. For all three species, the rhizome tissue is stiffer than the leaf tissue, and there is a large difference between the two tissues for both *Thalassia* and *Halodule*. *Syringodium* exhibits the highest tissue stiffness of the three species, and the leaf and tissue stiffness is of similar magnitude. The high stiffness of *Syringodium* leaves may be explained by the cylindrical shape of its above-ground photosynthetic tissues. Volumetric excitation of the pore space places the circumferential tissue in tension, with hoop-like structures resisting expansion. For all three species, the rhizomes are circular in cross section with internal gas-filled pores, similar to *Syringodium* leaves. In contrast, the leaves of *Thalassia* and *Halodule* are flat and there is little tissue to resist the expansion. These results have been accepted for publication pending a minor revision. [29]

Tertiary Objective—Sediment Attenuation in SW06: The frequency dependency of a sandy sediment sound speed along a track in SW06 was analyzed [31] and found to exhibit low frequency attenuation in good agreement with predictions of the Biot-Stoll model. [10] The results are shown in Fig. 12, and the new low frequency attenuation values show a slope proportional to the frequency squared.

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 thc conclusion that it not fully adequate. Thc new laboratory rcsults reportcd here indicatc that the Biot-Stoll model [10] correctly predicts the porosity dependency of high frequency sound speed in water saturated sand. Low frequency (53–2000 Hz) attenuation data from SW06 are also well describcd by Biot-Stoll and clcarly follow thc low frequcncy limiting slope of frequency squared. We are continuing our efforts to get ever-lower- frequency and more accurate laboratory measurements with and increased understanding of the measurement uncertainties.

Fluid-like shallow gas-bearing sediments were shown to have acoustic properties that depend only on the sediment bulk density and the void fraction as given by a simplified version of Wood's Equation. Two types of tissue from threc different specics of seagrass wherc shown to depend on tissue acoustic properties in addition to the gas content, and hcnce wcre not described by Wood's equation.

As our understanding of sound propagation in the ocean bottom increases, onc application will be to update the models used in operational sonar systcms and cnvironmental surveys. A better description of bottom interaction will increase our ability to detectcd, localize and classify targets in littoral environmcnts. The same can be said for buried objects. Thc CSS performed very well during SW06 is proving to be a useful tool for occan acoustics cxperiments.

TRANSITIONS

This PI receive $275k in the current fiscal from the Naval Oceanographic Office for further dcvelopment of the combustive sound source (CSS) as a replacement for explosives in ocean surveys.

This PI reccived $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.

This PI will be starting a project in 2009, funded by Shell Oil, to use bubblcs to rcduce 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 duc 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.cdu/programs/SAX99/Program/prog.html

SAX04: Sediment Acoustics Experiment 2004
From the projcct 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.

REFERENCES

[1] P.S. Wilson, R.A. Roy, and W.M. Carey, "Development of an impedance tube technique for in-situ classification of marine sediments," *J. Acoust. Soc. Am.* **113**, pp. 2318 (2003).

[2] P.S. Wilson and T.F. Argo IV, "Resonator Measurements of Sediment Sound Speeds," Applied Research Laboratories, The University of Texas at Austin ARL-TR-07-02, 18 October 2006.

[3] P.S. Wilson, A.H. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in an artificial water-saturated sand sediment," *J. Acoust. Soc. Am.* **121**, pp. 824–832 (2007).

[4] E.L. Hamilton, "Prediction of in-situ acoustic and elastic properties of marine sediments," *Geophysics* **36**, pp. 266–284 (1971).

[5] L.D. Hampton, "Acoustic properties of sediments," *J. Acoust. Soc. Am.* **42**, pp. 882–890 (1967).

[6] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range," *J. Acoust. Soc. Am.* **28**, pp. 168–178 (1956).

[7] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range," *J. Acoust. Soc. Am.* **28**, pp. 179–191 (1956).

[8] N.P. Chotiros, "Biot model of sound propagation in water-saturated sand," *J. Acoust. Soc. Am.* **97**, pp. 199–214 (1995).

[9] M.J. Buckingham, "Wave propagation, stress relaxation and grain-to-grain shearing in saturated, unconsolidated marine sediments," *J. Acoust. Soc. Am.* **108**, pp. 2796–2815 (2000).

[10] R.D. Stoll and T.K. Kan, "Reflection of acoustic waves at a water–sediment interface," *J. Acoust. Soc. Am.* **70**, pp. 149–156 (1981).

[11] K.L. Williams, "An effective density fluid model for acoustic propagation in sediments derived from Biot theory," *J. Acoust. Soc. Am.* **110**, pp. 2276–2281 (2001).

[12] P.S. Wilson and R.A. Roy, "Acoustic Characterization of Marine Sediments by Impedance Tube," Boston University, Final Report NUWC Grant No. N61331-02-1-G002, 2003.

[13] J.Y. Chung and D.A. Blaser, "Transfer function method of measuring in-duct acoustic properties. I. Theory," *J. Acoust. Soc. Am.* **68**, pp. 907–913 (1980).

[14] J.Y. Chung and D.A. Blaser, "Transfer function method of measuring in-duct acoustic properties. II. Experiment," *J. Acoust. Soc. Am.* **68**, pp. 914–921 (1980).

[15] ASTM, "Standard Designation E 1050-90: Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System." West Conshohocken, PA: American Society for Testing and Materials, 1990.

[16] P.S. Wilson, R.A. Roy, and W.M. Carey, "An improved water-filled impedance tube," *J. Acoust. Soc. Am.* **113**, pp. 3245–3252 (2003).

[17] P.S. Wilson, R.A. Roy, and W.M. Carey, "Phase speed and attenuation in bubbly liquids inferred from impedance measurements near the individual bubble resonance frequency," *J. Acoust. Soc. Am.* **117**, pp. 1895–1910 (2005).

[18] Y.S. Choy and L. Huang, "Measurement of in-duct acoustic properties by using a single microphone with fixed position," *J. Acoust. Soc. Am.* **116**, pp. 3498 (2004).

[19] B. Mert, H. Sumali, and O.H. Campanella, "A new method to measure viscosity and intrinsic sound velocity of liquids using impedance tube principles at sonic frequencies," *Review of Scientific Instruments* **75**, pp. 2613 (2004).
[20] L. Elvira-Segura, "Acoustic wave dispersion in a cylindrical elastic tube filled with a viscous liquid," *Ultrasonics* **37**, pp. 537 (2000).
[21] K.-J. Dunn, "Sample boundary effect in acoustic attenuation of fluid-saturated porous cylinders," *J. Acoust. Soc. Am.* **81**, pp. 1259 (1987).
[22] A.A. Gubaidullin, O.Y. Kuchugurina, D.M.J. Smeulders, and C.J. Wisse, "Frequency-dependent acoustic properties of a fluid/porous solid interface," *J. Acoust. Soc. Am.* **116**, pp. 1474 (2004).
[23] C.R. Fuller and F.J. Fahy, "Characteristics of wave propagation and energy distributions in cylindrical elastic shells filled with fluid," *Journal of Sound and Vibration* **81**, pp. 501–518 (1982).
[24] M. Schroter, D.I. Goldman, and H.L. Swinney, "Stationary state volume fluctuations in a granular medium," *Physical Review E (Statistical, Nonlinear, and Soft Matter Physics)* **71**, pp. 030301–4 (2005).
[25] M. Sperl, "Experiments on corn pressure in silo cells – translation and comment of Janssen's paper from 1895," *Granular Matter* **8**, pp. 59-65 (2006).
[26] J. Geng, D. Howell, E. Longhi, R.P. Behringer, G. Reydellet, L. Vanel, E. Clément, and S. Luding, "Footprints in Sand: The Response of a Granular Material to Local Perturbations," *Physical Review Letters* **87**, pp. 035506 (2001).
[27] M.D. Richardson and K.B. Briggs, "In situ and laboratory geoacoustic measurements in soft mud and hard-packed sand sediments: Implications for high-frequency acoustic propagation and scattering," *Geo-Marine Letters* **16**, pp. 196-203 (1996).
[28] P.S. Wilson, A.H. Reed, W.T. Wood, and R.A. Roy, "The low-frequency sound speed of fluid-like gas-bearing sediments," *J. Acoust. Soc. Am.* **123**, pp. EL99–EL104 (2008).
[29] P.S. Wilson and K.H. Dunton, "Laboratory investigation of the acoustic response of seagrass tissue in the frequency band 0.5–2.5 kHz," *J. Acoust. Soc. Am.* **in revision** (2008).
[30] G.R. Potty, J.H. Miller, P.S. Wilson, J.F. Lynch, and A. Newhall, "Geoacoustic inversion using combustive sound source signals," *J. Acoust. Soc. Am.* **124**, pp. EL146–EL150 (2008).
[31] D.P. Knobles, P.S. Wilson, S. Cho, and J.A. Goff, "Seabed acoustics of a sand ridge on the New
Jersey continental shelf," *J. Acoust. Soc. Am.* **124**, pp. EL151–EL156 (2008).
[32] K.L. Williams, D.R. Jackson, E.I. Thorsos, D. Tang, and S.G. Schock, "Comparison of sound speed and attenuation measured in a sandy sediment to predictions based on the Biot theory of porous media," *IEEE Journal of Oceanic Engineering* **27**, pp. 413–428 (2002).

PUBLICATIONS

[1] P.S. Wilson, A.H. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in an artificial water-saturated sand sediment," *J. Acoust. Soc. Am.* **121**, pp. 824–832 (2007). [published, refereed]

[2] P.S. Wilson and K.H. Dunton, "Seagrass acoustics: Results of an experimental laboratory investigation," in *Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustics Measurements: Technologies and Results*, J. S. Papadakis and L. Bjørnø, Eds. Heraklion, Greece, 2007, pp. 383–390, ISBN 978-960-88702-5-3. [published, refereed]

[3] P.S. Wilson, A.H. Reed, W.T. Wood, and R.A. Roy, "Low frequency sound speed measurements paired with computed x-ray tomography imaging in gas-bearing reconstituted natural sediments," in *Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustics Measurements: Technologies and Results*, J. S. Papadakis and L. Bjørnø, Eds. Heraklion, Greece, 2007, pp. 21–29, ISBN 978-960-88702-5-3. [published, refereed]

[4] T.F. Argo IV and P.S. Wilson, "The linear acoustic behavior of a bubble confined between parallel plates," in *Proceedings of the 2nd International Conference and Exhibition on Underwater Acoustics Measurements: Technologies and Results*, J. S. Papadakis and L. Bjørnø, Eds. Heraklion, Greece, 2007, pp. 519–526, ISBN 978-960-88702-5-3. [published, refereed]

[5] P.S. Wilson, "From bubbles to sediments to seagrass: Wood's equation in underwater acoustics," in *International Conference on Detection and Classification of Underwater Targets*, Vol. 29, Pt. 6. Hertfordshire, UK: Institute of Acoustics, 2007, pp. 138–146. [published, refereed]

[6] P.S. Wilson and K.H. Dunton, "An investigation of seagrass as an effective acoustic medium," *J. Acoust. Soc. Am.* **in review** (2007). [refereed]

[7] G.R. Potty, et al., "Geoacoustic inversion using combustive sound source signals (A)," *J. Acoust. Soc. Am.* **121**, pp. 3055 (2007).

[8] D.P. Knobles, P.S. Wilson, and S.E. Cho, "Determination of frequency dependence of sediment attenuation in shallow water using the combustive sound source (A)," *J. Acoust. Soc. Am.* **121**, pp. 3126 (2007).

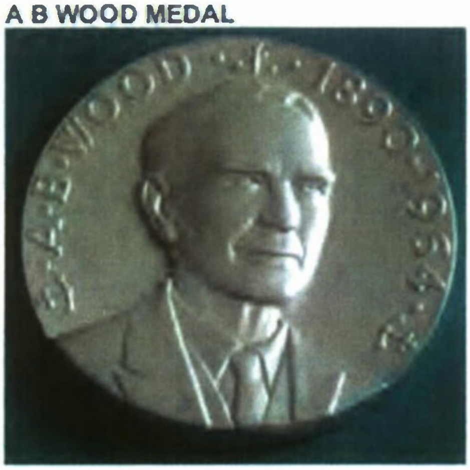
[9] M.J. Isakson and P.S. Wilson, Review of: D.R. Jackson and M.D. Richardson, *High-Frequency Seafloor Acoustics*. New York: Springer, 2007, appearing in *J. Acoust. Soc. Am.*, **in press** (2007).

[10] P.S. Wilson and T.F. Argo IV, "Resonator Measurements of Sediment Sound Speeds," Applied Research Laboratories, The University of Texas at Austin ARL-TR-07-02, 18 October 2006. [published]

HONORS/AWARDS/PRIZES

This grant's PI, Preston S. Wilson of The University of Texas at Austin received the A.B. Wood medal from the Institute of Acoustics in the United Kingdom.

A B WOOD MEDAL



The A B Wood medal and attendant prize is awarded in alternate years to acousticians domiciled in the UK or Europe and in the USA or Canada. It is aimed at younger researchers, preferably under the age of 35 in the year of the Award, whose work is associated with the sea. Following his graduation from Manchester University in 1912, Albert Beaumont Wood became one of the first two research scientists at the Admiralty to work on antisubmarine defence. He designed the first directional hydrophone and was well known for the many contributions he made to the science of underwater acoustics and for the help he gave to younger colleagues. The medal was instituted after his death by his many friends on both sides of the Atlantic and was administered by the Institute of Physics

FIGURES

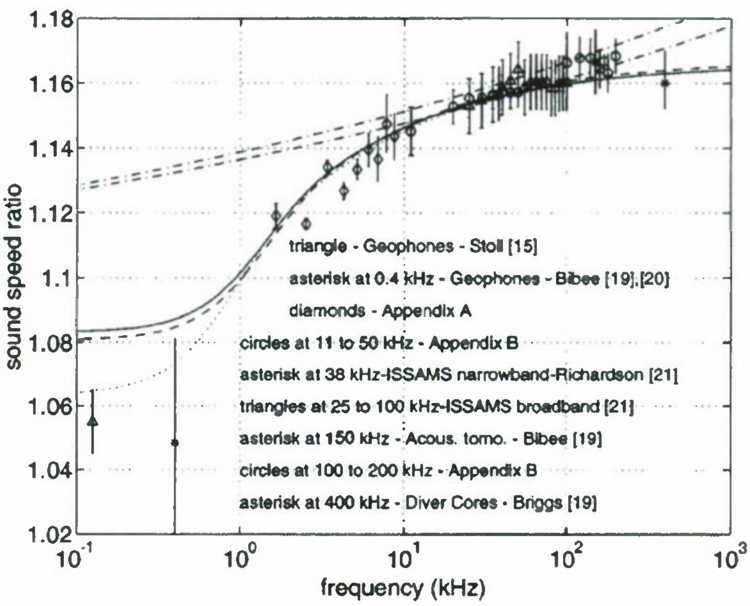


Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [32]. The theoretical curves are: solid line=Biot/Stoll [10]; dashed line=Williams [11], dash-dot lines=Buckingham's model for two values of fluid viscosity [9]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [32].)

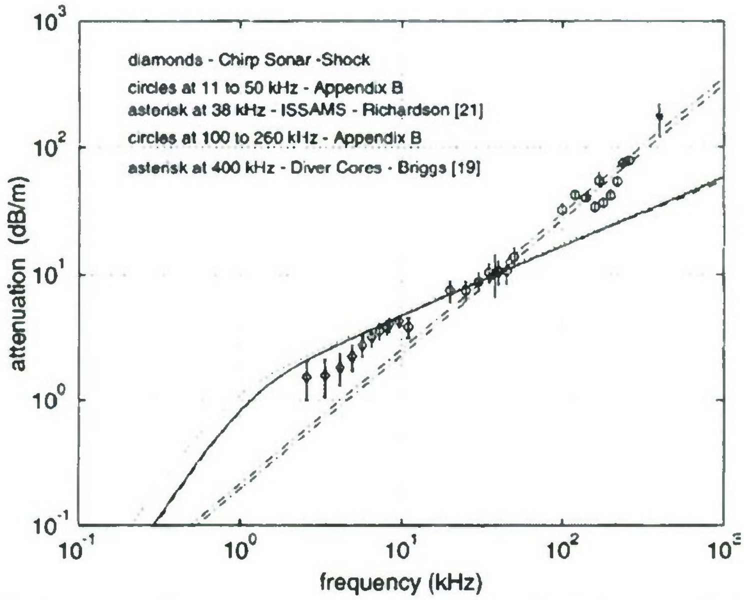


Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [32].) Also note that there is attenuation data below about 3 kHz.

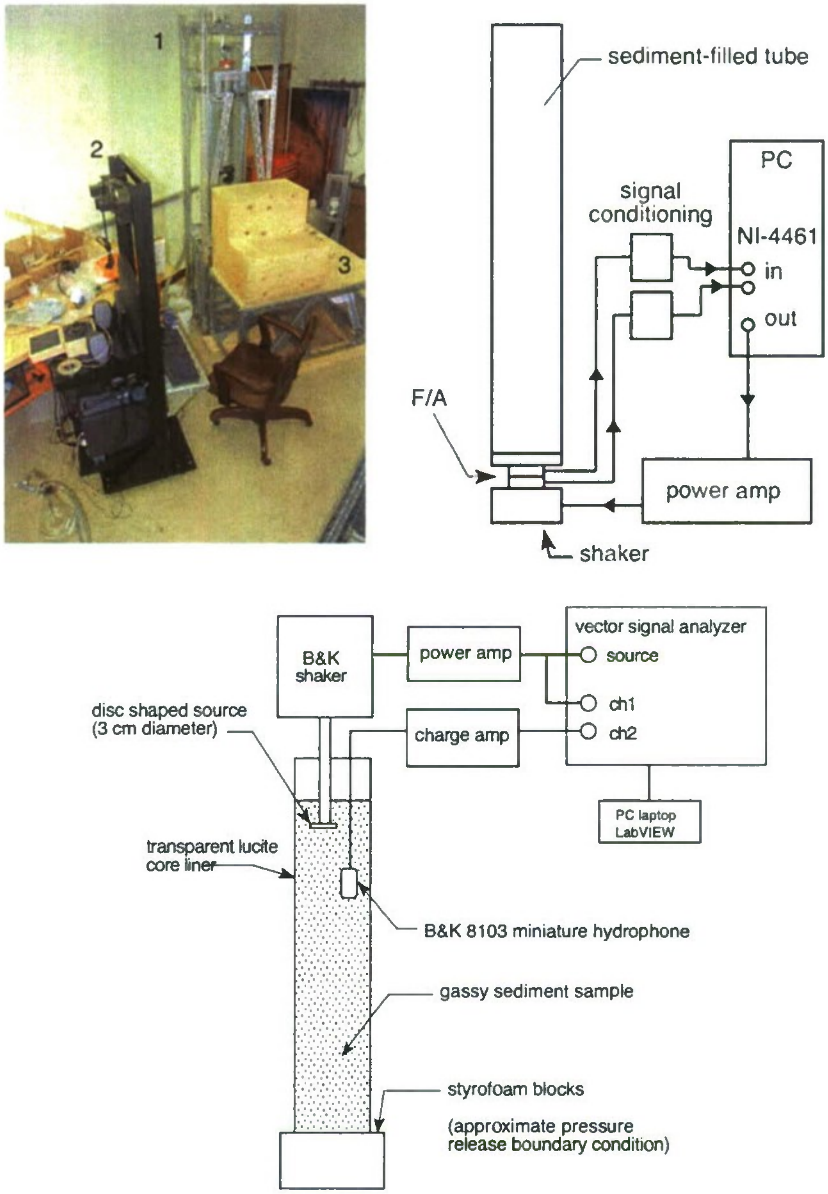


Fig. 2. The upper left is a photograph of the impedance tube facility: the support frame and tube (1), the computer and data acquisition system (2), and the scaffolding (3). On the upper right, the schematic of the Mert apparatus [19] is shown. In the lower frame, a schematic of the resonator method is shown.

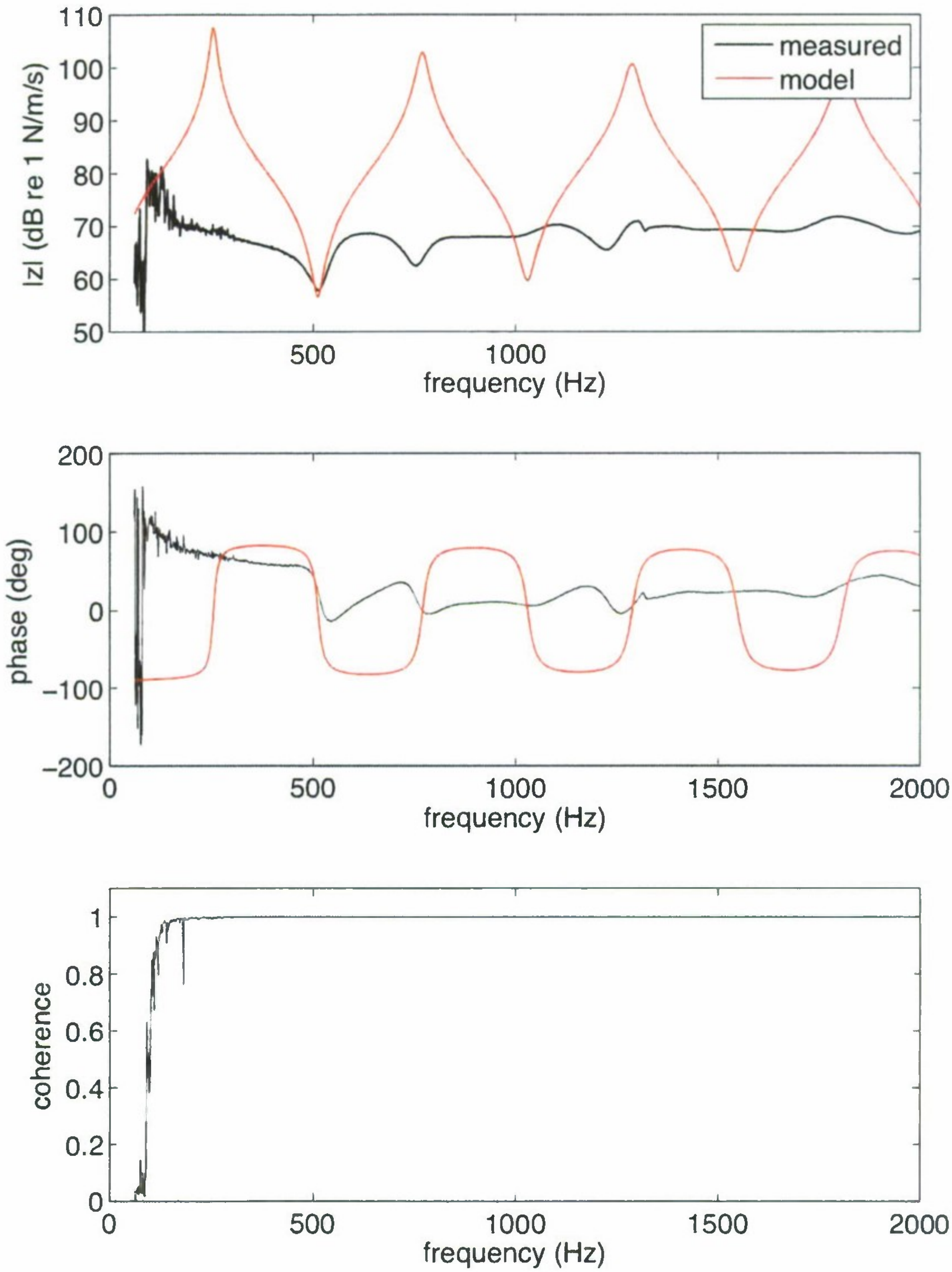


Fig. 3. The long (min frequency = 200 Hz) impedance tube developed last fiscal year was used to obtain the data shown here. The material that filled the tube was a reconstituted water-saturated sand sediment. The magnitude of the impedance is shown in the upper plot. The phase and coherence are shown in the lower two plots. The predicted characteristic acoustic resonances (minima of the upper red curve) are absent from the measured data (black curve).

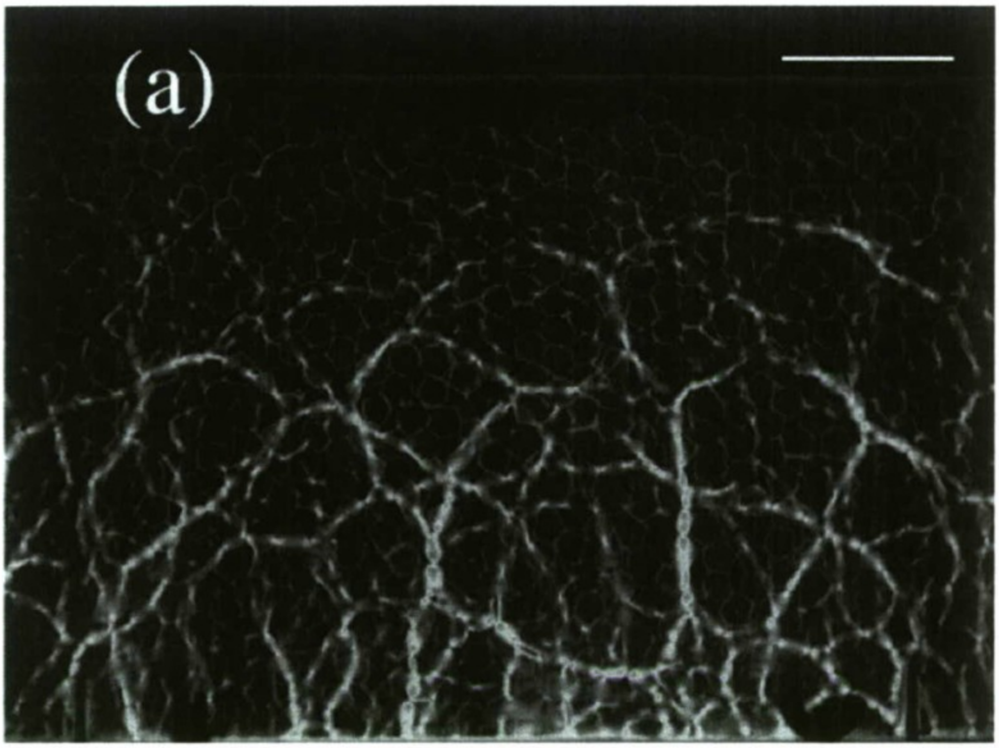


Fig. 4. A two-dimensional packing of photoelastic pentagonal beads is shown under hydrostatic load. [26] The beads under stress appear lighter in comparison to beads not under stress. Hence force chains are seen carrying the load in an inhomogeneous pattern. The white vertical bar is 5 cm.

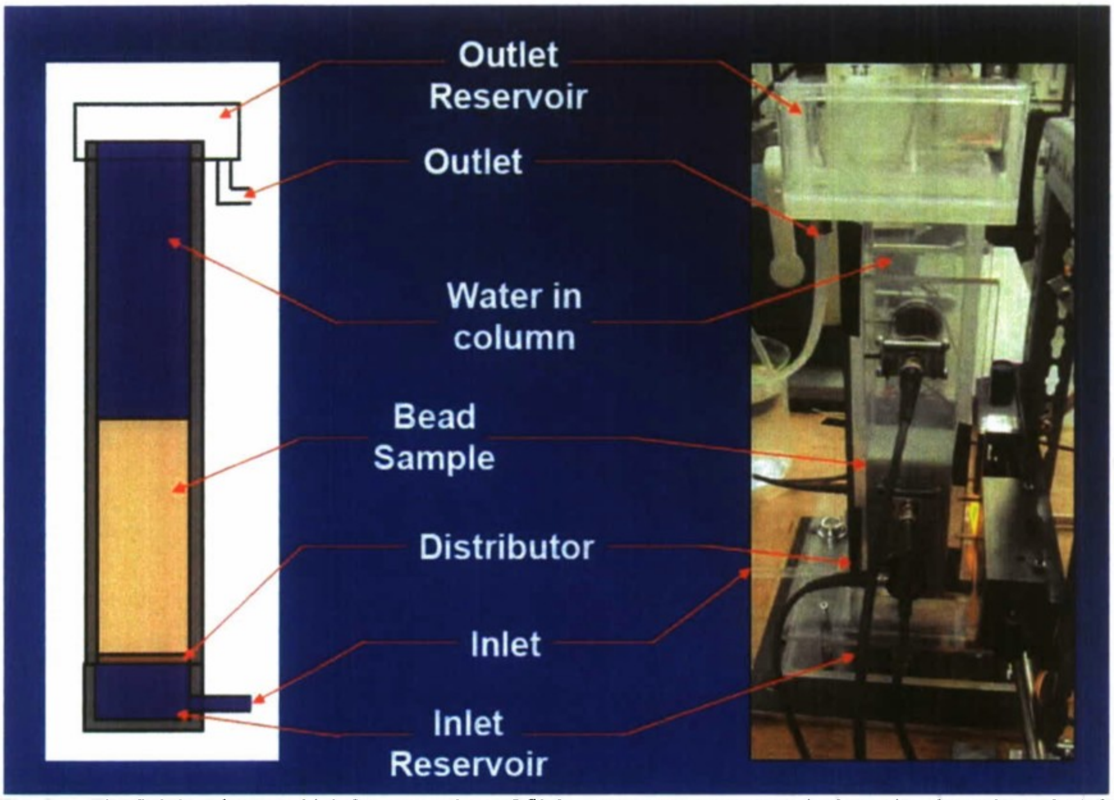


Fig. 5. The fluidized bed and high frequency time-of-flight measurement apparatus is shown in schematic on the left, and in a photo on the right. The BNC cables on the near face of the apparatus are the acoustic transdcuers.

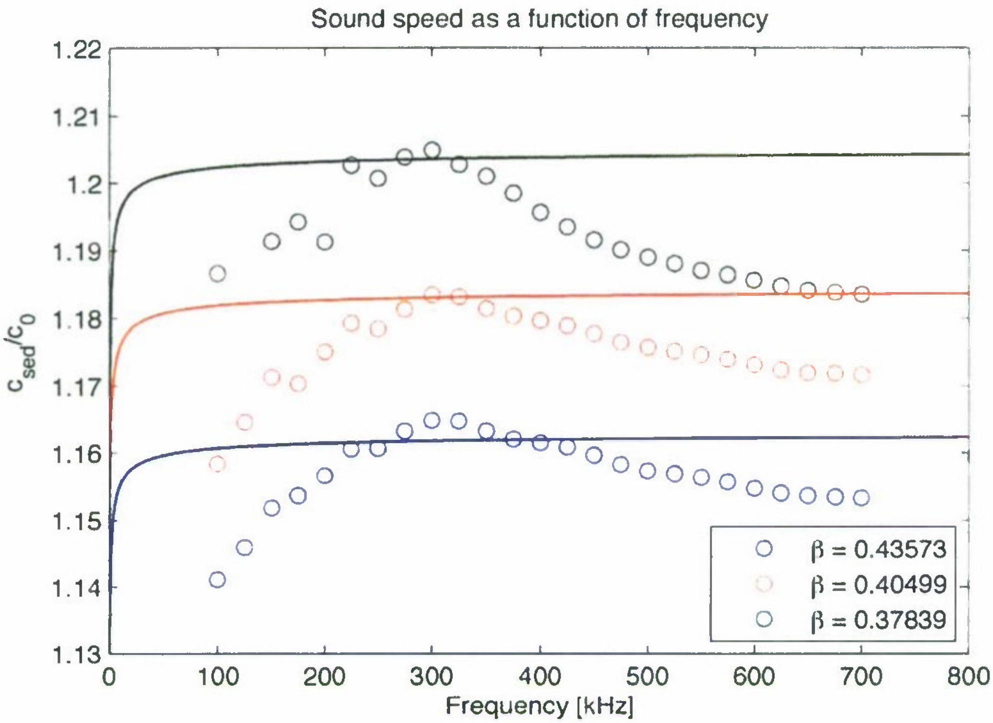


Fig. 6. High frequency time-of-flight measurements of the sound speed in water-saturated glass bead sediments are presented as a function of frequency for three porosities. The sound speed is observed to rise with positive dispersion through 300 kHz and then negative dispersion is observed. The solid lines represent predictions of the Biot-Stoll model. [10]

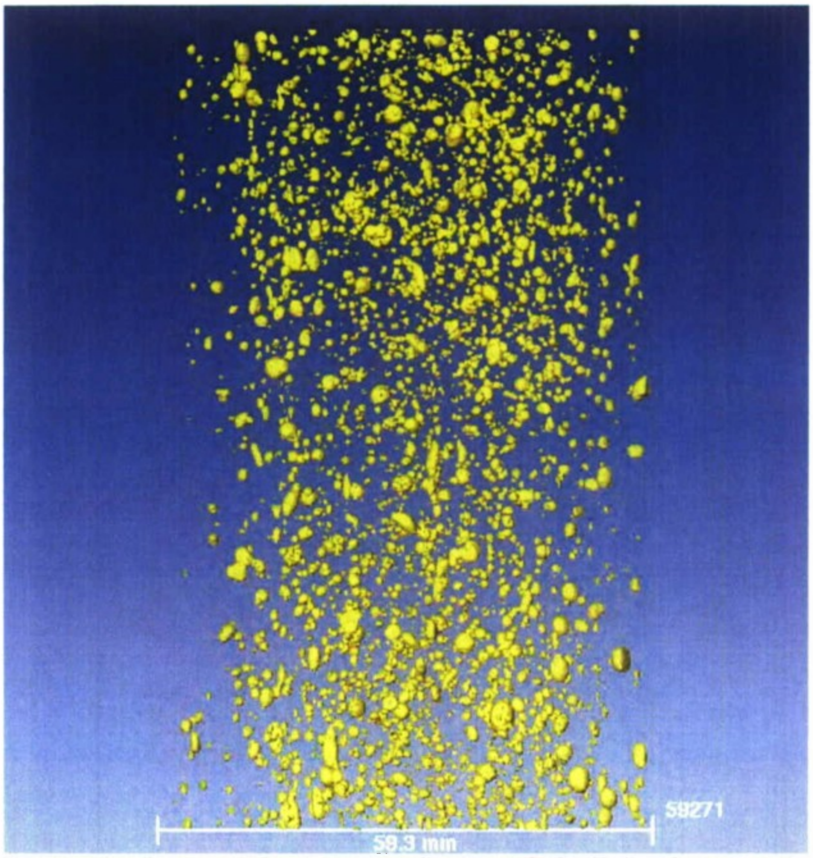
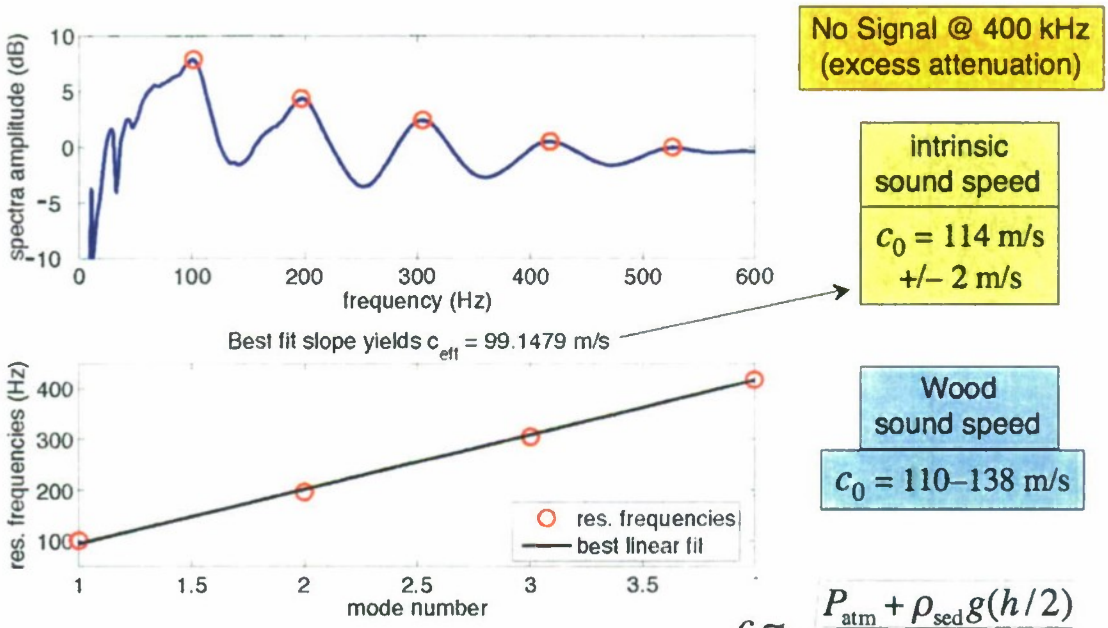


Fig. 7. A single image from the computed x-ray tomography scan of the kaolinite sediment sample contained within the 1-D acoustic resonator. The yellow blobs are air bubbles. The data was manipulated to give the volume of each bubble, and the total void fraction and the effective spherical bubble size distribution were determined.



$$c \approx \sqrt{\frac{P_{atm} + \rho_{sed} g(h/2)}{\chi(1-\chi)\rho_{sed}}}$$

Fig. 8. The top plot shows the pressure spectrum and resonance frequencies measured in a 1-D resonator filled with reconstituted bubbly kaolinite sediment. The bottom plot shows the resonance frequencies as a function of mode number, the slope of which yields the sediment sound speed. The resulting sound speed is shown in the yellow box. A simplified version of Wood's equation is shown at bottom right and was used to predict the sound speed. The void fraction χ was obtained from the image analysis, as discussed in Fig. 9. The sediment density was also measured. The remaining parameters are the atmospheric pressure P_{atm}, the acceleration due to gravity g, and the sediment column height h. The prediction with no fitting is shown in the blue box. The range of predicted values represent measurement uncertainty in the model input parameters. The simplified Wood's equation accurately describes the measured sound speed. In the orange box on the upper right, the high frequency time-of-flight measurement is shown, which in this case yielded no result.

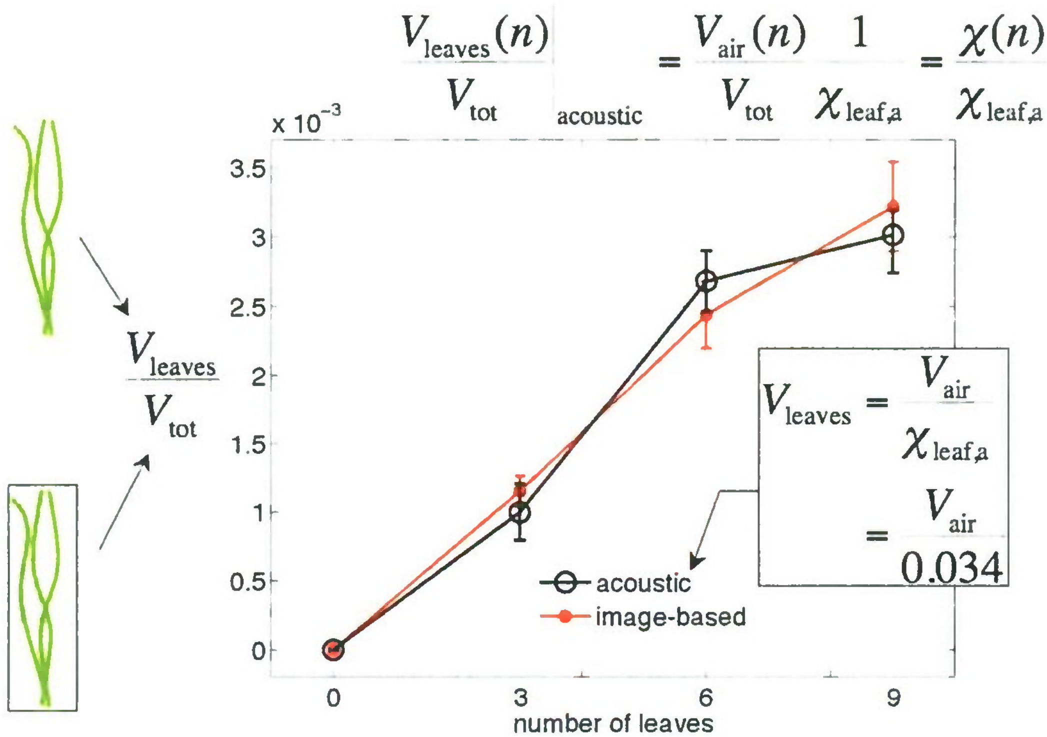


Fig. 9. The apparent acoustic volume fraction of thalassia leaves is compared to the volume fraction obtained by image analysis of the leaf physical volume. The black curve yields an internal leaf void fraction of 0.034.

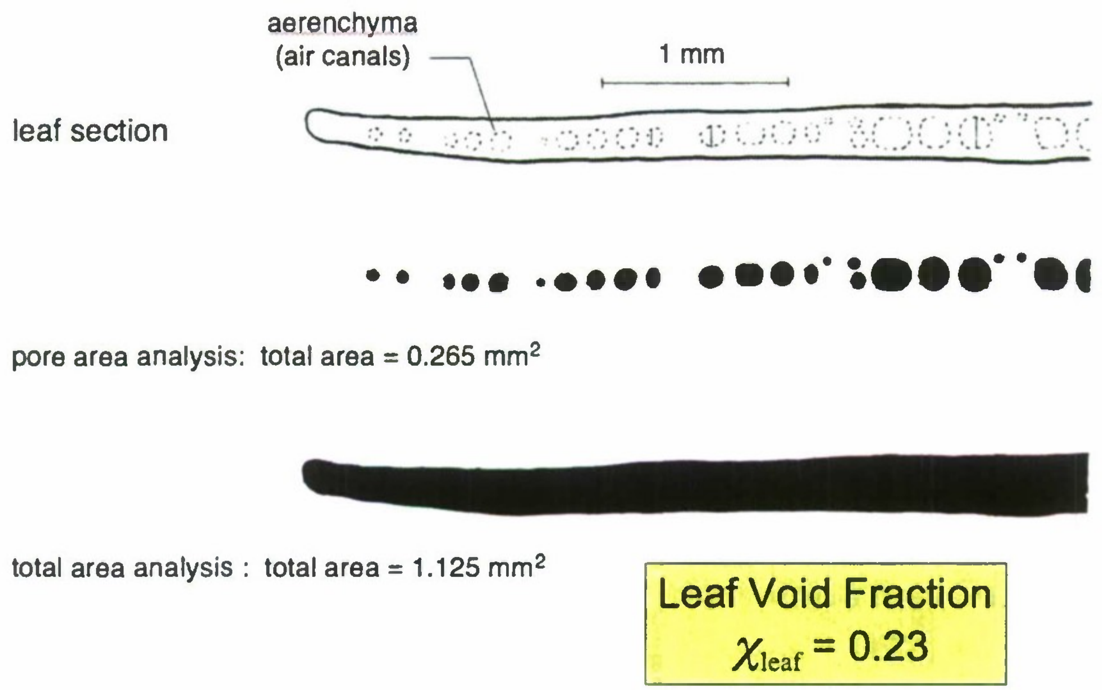


Fig. 10. The actual internal leaf void fraction was determined to be 0.23 from this microscopic cross-section image analysis.

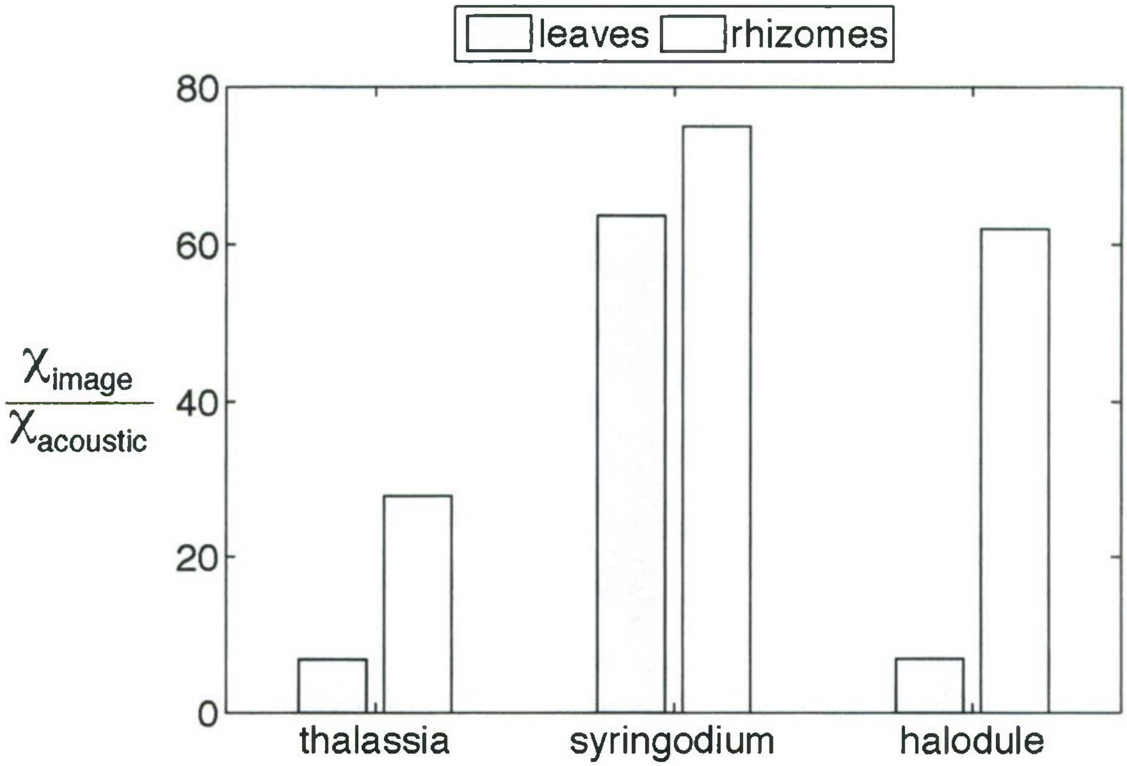


Fig. 11. The ratio of the image-based to acoustically determined void fractions for both leaves and rhizomes of each species. This ratio is a measure of the importance of the tissue acoustic parameters. A ratio of unity indicates plants that behave acoustically like air bubbles in water. An increasing ratio indicates increasing tissue stiffness, which effectively reduces the acoustic contrast of the internal gas and also reduces the acoustic contrast of the plant.

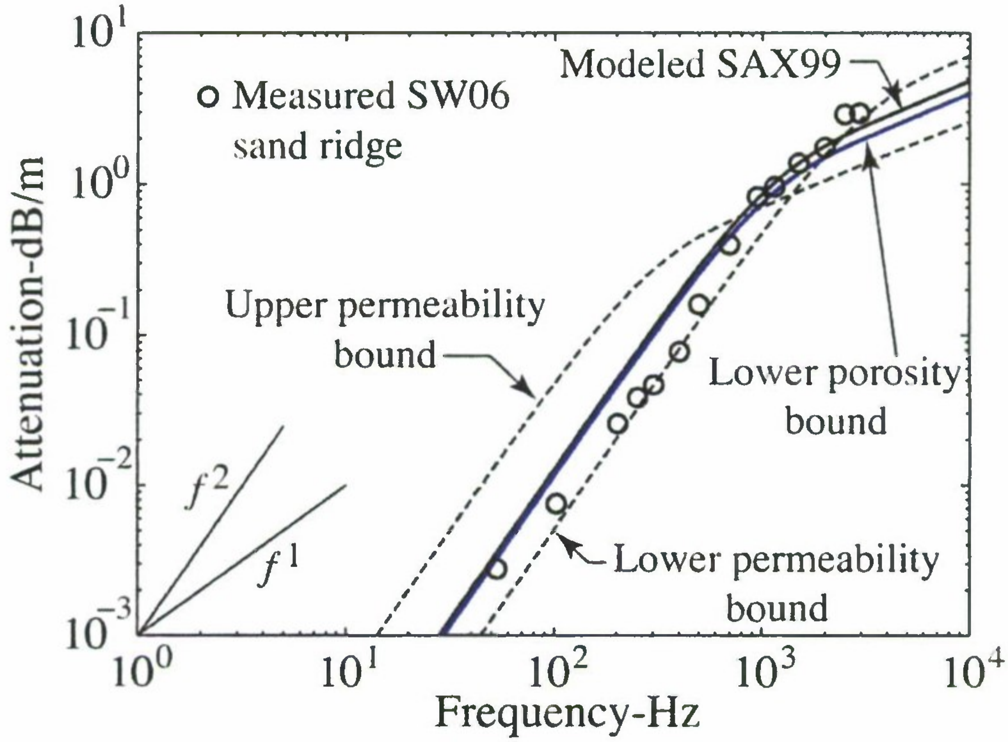


Fig. 14. The large purple triangles represent sandy sediment attenuation values inferred by matching measured long range transmission loss curves from SW06 with model predictions in which the sediment attenuation is the only fit parameter. The purple curve is the prediction of the EDFM with input parameters from SAX99. Note that these extrapolated attenuation values go below 100 Hz and clearly show a different slope than the higher frequency measurements.

Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques

Chapter 6: Summary of Work Conducted FY2009

LONG-TERM GOALS

The main goal of this project is to increase our understanding of sound propagation in ocean bottom sediments, including ocean bottom multiphase material such as gas-bearing sediments and seagrass, which in turn benefits buried object detection, sonar operation and acoustic communications in shallow water. Another goal for the out years is to develop the proposed research apparatus into an operational system for *in situ* classification of ocean bottoms for Naval fleet operations.

OBJECTIVES

The primary objective is to obtain experimental measurements of sound speed and attenuation in a variety of natural and artificial ocean bottom sediments, including multiphase materials such as gas-bearing sediments and seagrass. These measurements are conducted using an acoustic resonator tube [1, 2] method, in the frequency range of approximately 300 Hz to tens of kHz, and using a traditional time-of-flight approach at frequencies from a few hundred kHz up to a few MHz. These measurements will span a frequency range in which there is little experimental data obtained with a single sediment parcel, and thereby help to verify existing [3-10] and developing [11-13] theoretical models for sound propagation in these materials. An overview of the state-of-the-art in both direct experimental measurement and modeling for water-saturated sand from a single location is shown in Fig. 1. Note the lack of data below a few kHz and the inability of a single model to correctly describe both the sound speed and the attenuation, although new models [11-13] yet to be fully unified and applied to this data may show better agreement at high and low frequencies. New collections of sound speed and attenuation data inferred from shallow water propagation measurements have also recently been analyzed and published [14] which show good agreement between the average, global behavior of granular marine sediment and the Biot-based model, at least in that the model can bound the data within a reasonable range of input parameters. Despite these recent advances, measurement still lags behind modeling for all the ocean bottom materials discussed thus far. Our goal is to provide measurements on single parcels of sediment with sufficient accuracy, precision and understanding of measurement uncertainty to validate the modeling efforts. We also seek to observe the effect of varying grain size, distributions of grain size, and particle shape, the latter to investigate grain contact physics. Gas bearing sediments are present in many parts of the world, and there has been even less experimental verification of the acoustic behavior of these sediments. We seek to apply our measurement/modeling comparison approach to gas bearing sediments, too. Finally, seagrass can partially or fully obscure mines, and we are also interested in understanding the acoustic behavior of this material, with the aim to eventually exploit phenomena associated with the seagrass tissue gas content, or the free gas that is resirated by seagrass during photosynthesis. A secondary objective has been to continue to analyze data collected during the ONR sea test Shallow Water 06 (SW06) and to develop new measurement instrumentation for future ONR basic ocean acoustics sea tests.

APPROACH

In this fiscal year, for our primary research objective, we have focused on the resonator method [1, 2] of measuring acoustic properties and have constructed a new apparatus for high frequency measurements. For the former, we have added the capability to control the hydrostatic pressure of the sediment samples, so that measurements can be done at simulated ocean depths, which is important for gas-bearing sediments. The resonator apparatus and pressure vessel are shown in Fig. 2. For the latter, we have adopted a technique that allows for the control of porosity, [15] 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. Reflection measurements on glass bead sediments have recently been conducted, but the analysis of this data is not complete. For the secondary objective, shallow water acoustic propagation data from the recent SW06 experiment has been analyzed and compared to model predictions. Finally, the combustive sound source (CSS) is being developed 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

Primary Objectives—Laboratory Sediment Investigation:

We began a collaboration with a research group in the University of Texas at Austin's physics department that studies the dynamics of granular material and also with a group at The Max Plank Institute for Dynamics and Self-Organization (Göttingen, Germany). We adapted a technique they jointly developed [15] to create samples of water-saturated granular materials with variable porosity using a fluidization technique. We have conducted a series of sound speed and attenuation measurements [16] at high frequencies (300–800 kHz) in glass-bead sediments with a porosity range from 0.38 to 0.44 and compared them to the predictions of the Biot-Stoll model. [9] The apparatus and results are shown in Fig. 3.

Leveraging funding from another project, the PI participated in the arctic research cruise Methane in the Arctic Shelf (MITAS) aboard the USCGC Polar Sea in the Beaufort Sea, on the continental shelf off the North Slope of Alaska in September 2009. The goal of this cruise was to study methane transport from sediments containing methane hydrate, up through the sediment, into the water column, and ultimately the atmosphere. Our part was to measure the acoustic properties of gas-bearing sediments, but we also had the opportunity to measure the sound speeds in a number of silt, mud and clay sediments. Data analysis is currently underway. Some images of the cruise are shown in Fig. 4.

Primary Objectives —Gas-bearing Sediments: We continued our collaboration with the Seafloor Sciences Group at NRL-SSC on the acoustics of gas-bearing sediments. Gas bearing sediments were found during MITAS as mentioned above. Our 1-D acoustic resonator technique [1] was used to measure the sound speed inside the sediment samples. A high frequency (400 kHz) time-of-flight technique using an NRL core logger was also used to measure the high frequency sound speed.

Primary Objectives—Seagrass Acoustics: Our previous collaboration with the seagrass biologist, Dr. Kenneth Dunton, of the University of Texas Marine Science Institute on the acoustics of sediments containing seagrasses has continued. Our acoustic resonator technique was used to make additional measurements of the effective low frequency acoustic properties of three gulf-coast species, *Thalassia testudinum* (turtle grass), *Syringodium filiforme* (manatee grass), and *Halodule wrightii* (shoal grass). These measurements are similar to those previously discussed [17] but have now been accompanied by micro x-ray computed tomography imagery of the leaf and rhizome tissue. Analysis of this data will allow us to determine the volume of gas and the volume of tissue, which in turn will allow us to determine the acoustic properties of the tissue itself. This work is currently underway.

A seagrass acoustics tank facility was constructed this FY using leveraged funds from another internal UT source. This tank will be used to conduct controlled experiments on photosynthetic bubble production and its effect on the acoustics of seagrass beds. Construction of the apparatus was begun this summer and is currently ongoing.

Secondary Objective—SW06 Data Analysis: The combustive sound source (CSS) was deployed by this author and ARL:UT colleagues in SW06. Subsequent data analysis this year built upon last year's analysis [18, 19] and has further shown that CSS is a viable alternative to small explosive charges and better than light bulb implosions.

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 larger version of the SW06 CSS was constructed and free-field testing was conducted using funds provided by NAVO. An increased source level, was achieved over the SW06 version of CSS.

RESULTS

Primary Objectives— Laboratory Sediment Investigation: The porosity control apparatus that was designed and constructed to measure the sound speed and attenuation in water-saturated sediments as a function of frequency and porosity is shown in Fig. 3. Water is pumped up through the bead sample, which fluidizes the sediment. The height of the sediment column increases in proportion to the flow rate. When the flow is terminated, the sample settles back to an equilibrium porosity that is higher than the original randomly packed porosity. The resulting equilibrium porosity is a function of the flow rate and flow rate history in a known way, hence one can prepare sediment of a particular porosity. This work is the first that we know of to systematically investigate both frequency and porosity in a single sediment sample. As shown in Fig. 3(a)–(d), we found that the Biot model does a good job of describing the porosity-dependency of granular sediment (spherical glass beads, radius = 250 μm) sound speed at high frequencies. The Biot model underpredicts attenuation at these frequencies, a result others have also observed. [13, 20, 21] We also observed for the first time (to our knowledge) in a single sediment sample, a transition in the frequency dependency of attenuation from the Biot $f^{1/2}$ regime to the f^4 multiple scattering regime. The latter has been observed before, [22] but a transition from one regime to the other so rapidly does appear to have been observed previously. This work is currently under revision and will soon yield a new publication. [16]

Regarding our work on the Polar Sea in the arctic ocean research cruise MITAS: In years past, the shelf area off the Alaskan North Slope (the location of the US's strategic petroleum reserve and the Alaskan pipeline) has been iced over for much of the year, but now, due to climate change, there is open water for a significant part of the year. Standard surface ships can now operate in this region, hence the acoustic properties of this shelf area are of interest. We found primarily silt, mud and clay sediments with perhaps one in ten coring locations showing gravel, and almost no sand. Some of the cores had significant free gas content. Horizontal variation across these sediment types was observed, but there was very little vertical variation in the cores. A typical sound speed profile with a strong surface layer both on the slope and on the shelf is shown in Fig. 4.

Primary Objectives—Gas-bearing Sediments: The collaborative work with NRL-SSC on the Polar Sea during MITAS resulted in the measurement of sound speed in naturally occurring methane gas-bearing sediments. A preliminary low frequency sound speed result is shown in Fig. 5, for a mud sediment sample that contained a homogeneous distribution of methane bubbles. The sound speed was found to be about 200 m/s below 2 kHz and it rose to 1200 m/s at the highest frequency that was used in the measurement. This sound speed dispersion is qualitatively similar to that predicted by Anderson and Hampton [23] and also shown in Fig. 5. Our standard correction for the elastic waveguide effect [2] has yet to be incorporated as this data was just collected the week prior to this report. Contemporaneous core logging measurements, including high frequency sound speed and attenuation, denisty, and magnetic susceptibility were obtained by NRL, and lithostratigraphy and geo/bio chemistry analyses were conducted by other MITAS researchers. This collection of data will ultimately be used to fully characterize the sediment material.

Secondary Objective—SW06 Data Analysis: The combustive sound source (CSS) was deployed by the PI and ARL:UT colleagues in SW06. Subsequent data analysis this year built upon last year's analysis [18, 19] 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 revision. [24] 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.

A larger version of the SW06 CSS was constructed and free-field testing was conducted using funds provided by NAVO. An increased source level, was achieved over the SW06 version of CSS, as shown in Fig. 7. The new CSS provides a peak acoustic pressure of 246 dB re 1 μPa @ 1 m, and a peak energy spectral density of 190 dB re 1 $\mu Pa^2 \cdot s/Hz$, with significant energy from below 10 Hz to above 1000 Hz. The utilization of air, as opposed to oxygen was also tested. The resulting signal, also shown in Fig. 7, is less broadband than the hydrogen/oxygen signal, but contains more low frequency energy.

Secondary Objective—Acoustics of Bubbly Liquid: Work completed in a previous years, that was partially supported by this grant was published or presented this year. We studied bubble growth due to rectified diffusion with the goal of helping to assess the effect of sonar on marine mammals. We found that acoustic excitation at realistic levels due to sonar transmissions, would not greatly increase the rate of bubble growth in supersaturated marine mammal tissue, over that of static diffusion alone. [25] This is in part because the actual acoustic pressure level in front of a sonar transducer in never as high as the source level value. The source level is a level that is measured in the far field and scaled back to a range of 1 m, but because of near field diffraction effects, the maximum pressure in front of a radiator is much lower, say about 215 dB re 1 μPa for a source level of 235 dB. We also investigated the use of a laser doppler velocimeter to measure bubble dynamics. [26, 27]

Educational Activities: Our work with bubbles and acoustic resonators previously described lent itself perfectly to two publications [28, 29]{Grecnc, 2009 #5; Wilson, 2008, wilson:2008} and two presentations [30, 31] geared toward education in underwater acoustics.

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 [9] correctly predicts the porosity dependency of high frequency sound speed in water saturated sand. Low frequency (53–2000 Hz) attenuation data [19] 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.

Gas-bearing mud sediments were shown to have significant dispersion, with very low sound speeds below about 1 kHz, and an increasing sound speed as frequency increases, as qualitatively predicted by Anderson and Hampton. [23] During the MITAS cruise, the continental shelf above the North Slope of Alaska was found to have slit, mud and clay sediments, and the water column was found to have a prominent sound channel between the surface and 400 m depth. With arctic ice retreating ever further north each year, the coastal regions north of Alaska will likely become area of operation for the Navy. The acoustical environment in this area in absence of the ice pack at the surface is largely unexplored. This area should be considered as a site for future ONR shallow water acoustic experiments.

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 $120k 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 started a project 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.

REFERENCES

[1] P.S. Wilson and T.F. Argo IV, "Resonator Measurements of Sediment Sound Speeds," Applied Research Laboratories, The University of Texas at Austin ARL-TR-07-02, 18 October 2006.

[2] P.S. Wilson, A.H. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in an artificial water-saturated sand sediment," *J. Acoust. Soc. Am.* **121**, pp. 824–832 (2007).

[3] E.L. Hamilton, "Prediction of in-situ acoustic and elastic properties of marine sediments," *Geophysics* **36**, pp. 266–284 (1971).

[4] L.D. Hampton, "Acoustic properties of sediments," *J. Acoust. Soc. Am.* **42**, pp. 882–890 (1967).

[5] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range," *J. Acoust. Soc. Am.* **28**, pp. 168–178 (1956).

[6] M.A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid. II. Higher frequency range," *J. Acoust. Soc. Am.* **28**, pp. 179–191 (1956).

[7] N.P. Chotiros, "Biot model of sound propagation in water-saturated sand," *J. Acoust. Soc. Am.* **97**, pp. 199–214 (1995).

[8] M.J. Buckingham, "Wave propagation, stress relaxation and grain-to-grain shearing in saturated, unconsolidated marine sediments," *J. Acoust. Soc. Am.* **108**, pp. 2796–2815 (2000).

[9] R.D. Stoll and T.K. Kan, "Reflection of acoustic waves at a water–sediment interface," *J. Acoust. Soc. Am.* **70**, pp. 149–156 (1981).

[10] K.L. Williams, "An effective density fluid model for acoustic propagation in sediments derived from Biot theory," *J. Acoust. Soc. Am.* **110**, pp. 2276–2281 (2001).

[11] N.P. Chotiros and M.J. Isakson, "A broadband model of sandy ocean sediments: Biot–Stoll with contact squirt flow and shear drag," *J. Acoust. Soc. Am.* **116**, pp. 2011 (2004).

[12] N.P. Chotiros and M.J. Isakson, "Acoustic virtual mass of granular media," *J. Acoust. Soc. Am.* **121**, pp. EL70–EL76 (2007).
[13] 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**, pp. EL296-EL301 (2008).
[14] J.-X. Zhou, X.-Z. Zhang, and D.P. Knobles, "Low-frequency geoacoustic model for the effective properties of sandy seabottoms," *J. Acoust. Soc. Am.* **125**, pp. 2847-2866 (2009).
[15] M. Schroter, D.I. Goldman, and H.L. Swinney, "Stationary state volume fluctuations in a granular medium," *Physical Review E (Statistical, Nonlinear, and Soft Matter Physics)* **71**, pp. 030301–4 (2005).
[16] T.F. Argo IV, M.D. Guild, P.S. Wilson, M. Schroter, C. Radin, and H.L. Swinney, "Sound speed and attenuation in water-saturated glass beads as a function of frequency and porosity," *The Journal Of The Acoustical Society Of America Express Letters* **in revision** (2009).
[17] P.S. Wilson and K.H. Dunton, "Laboratory investigation of the acoustic response of seagrass tissue in the frequency band 0.5–2.5 kHz," *J. Acoust. Soc. Am.* **125**, pp. 1951–1959 (2009).
[18] G.R. Potty, J.H. Miller, P.S. Wilson, J.F. Lynch, and A. Newhall, "Geoacoustic inversion using combustive sound source signals," *J. Acoust. Soc. Am.* **124**, pp. EL146–EL150 (2008).
[19] D.P. Knobles, P.S. Wilson, S. Cho, and J.A. Goff, "Seabed acoustics of a sand ridge on the New Jersey continental shelf," *J. Acoust. Soc. Am.* **124**, pp. EL151–EL156 (2008).
[20] B.T. Hefner and K.L. Williams, "Sound speed and attenuation measurements in unconsolidated glass-bead sediments saturated with viscous pore fluids," *J. Acoust. Soc. Am.* **120**, pp. 2538-2549 (2006).
[21] K.I. Lee, V.F. Humphrey, B.-N. Kim, and S.W. Yoon, "Frequency dependencies of phase velocity and attenuation coefficient in a water-saturated sandy sediment from 0.3 to 1.0 MHz," *J. Acoust. Soc. Am.* **121**, pp. 2553-2558 (2007).
[22] L. Schwartz and T.J. Plona, "Ultrasonic propagation in close-packed disordered suspensions," *Journal of Applied Physics* **55**, pp. 3971-3977 (1984).
[23] A.L. Anderson and L.D. Hampton, "Acoustics of gas bearing sedimets II. Measurements and models," *J. Acoust. Soc. Am.* **67**, pp. 1890–1903 (1980).
[24] D.P. Knobles, J.A. Goff, R.A. Koch, S.M. Joshi, P.S. Wilson, and J.A. Shooter, "Modeling broadband acoustic propagation in an uncertain inhomogeneous shallow water ocean waveguide," *I.E.E.E. Journal of Oceanic Engineering* **in revision** (2009).
[25] Y.A. Ilinskii, P.S. Wilson, and M.F. Hamilton, "Bubble growth by rectified diffusion at high gas supersaturation levels," *J. Acoust. Soc. Am.* **124**, pp. 1950-1955 (2008).
[26] T.F. Argo IV and P.S. Wilson, "Measurement of the resonance frequency of a bubble using a laser Doppler vibrometer (A)," *J. Acoust. Soc. Am.* **125**, pp. 2557 (2009).
[27] T.F. Argo IV, P.S. Wilson, and V. Palan, "Measurement of the resonance frequency of single bubbles using a laser Doppler vibrometer," *J. Acoust. Soc. Am.* **123**, pp. EL121–EL125 (2008).
[28] P.S. Wilson and R.A. Roy, "An audible demonstration of the speed of sound in bubbly liquids," *American Journal of Physics* **76**, pp. 975-981 (2008).
[29] C.A. Greene, T.F. Argo Iv, and P.S. Wilson, "A Helmholtz resonator experiment for the Listen Up project," *Proceedings of Meetings on Acoustics* **5**, pp. 025001-7 (2009).
[30] C.A. Greene, T.F. Argo Iv, and P.S. Wilson, "A Helmholtz resonator experiment for the Listen Up project," *The Journal of the Acoustical Society of America* **124**, pp. 2568-2568 (2008).
[31] T.F. Argo IV, C.A. Greene, and P.S. Wilson, "A simple experiment for understanding resonant air columns," *The Journal of the Acoustical Society of America* **125**, pp. 2625-2625 (2009).
[32] K.L. Williams, D.R. Jackson, E.I. Thorsos, D. Tang, and S.G. Schock, "Comparison of sound speed and attenuation measured in a sandy sediment to predictions based on the Biot theory of porous media," *IEEE Journal of Oceanic Engineering* **27**, pp. 413–428 (2002).

PUBLICATIONS

[1] Y.A. Ilinskii, P.S. Wilson, and M.F. Hamilton, "Bubble growth by rectified diffusion at high gas supersaturation levels," *The Journal of the Acoustical Society of America* **124**, pp. 1950–1955 (2008). [published, refereed]

[2] P.S. Wilson and R.A. Roy, "An audible demonstration of the speed of sound in bubbly liquids," *American Journal of Physics* **76**, pp. 975–981 (2008). [published, refereed]

[3] C.A. Greene, T.F. Argo IV, and P.S. Wilson, "A Helmholtz resonator experiment for the Listen Up project," *Proceedings of Meetings on Acoustics* **5**, pp. 025001–7 (2009). [published, refereed]

[4] P.S. Wilson and K.H. Dunton, "Laboratory investigation of the acoustic response of seagrass tissue in the frequency band 0.5–2.5 kHz," *The Journal of the Acoustical Society of America* **125**, pp. 1951–1959 (2009). [published, refereed]

[5] T.F. Argo IV, M.D. Guild, P.S. Wilson, M. Schroter, C. Radin, and H.L. Swinney, "Sound speed and attenuation in water-saturated glass beads as a function of frequency and porosity," *The Journal Of The Acoustical Society Of America Express Letters* **in revision** (2009).

[6] D.P. Knobles, J.A. Goff, R.A. Koch, S.M. Joshi, P.S. Wilson, and J.A. Shooter, "Modeling broadband acoustic propagation in an uncertain inhomogeneous shallow water ocean waveguide," *I.E.E.E. Journal of Oceanic Engineering* **in revision** (2009).

[7] T.F. Argo IV, M.D. Guild, P.S. Wilson, C. Radin, M. Schroter, and H.L. Swinney, "Laboratory measurements of sound speed and attenuation in water-saturated artificial sediments as a function of porosity (A)," *The Journal of the Acoustical Society of America* **124**, pp. 2469 (2008).

[8] G.R. Potty, P. Wilson, J.F. Lynch, A. Newhall, and J.H. Miller, "Attenuation inversions using broadband acoustic sources (A)," *The Journal of the Acoustical Society of America* **124**, pp. 2502 (2008).

[9] C.A. Greene, T.F. Argo IV, and P.S. Wilson, "A Helmholtz resonator experiment for the Listen Up project (A)," *The Journal of the Acoustical Society of America* **124**, pp. 2568 (2008).

[10] T.F. Argo IV and P.S. Wilson, "Measurement of the resonance frequency of a bubble using a laser Doppler vibrometer (A)," *The Journal of the Acoustical Society of America* **125**, pp. 2557 (2009).

[11] T.F. Argo IV, C.A. Greene, and P.S. Wilson, "A simple experiment for understanding resonant air columns (A)," *The Journal of the Acoustical Society of America* **125**, pp. 2625 (2009).

[12] C.W. Wilson, P.S. Wilson, and K.H. Dunton, "Exploring the unique acoustic characteristics of seagrasses," presented at *Benthic Ecology Meeting 2009*. Corpus Christi, TX, 2009.

[13] C.W. Wilson, P.S. Wilson, and K.H. Dunton, "Exploring the unique acoustic characteristics of seagrasses," presented at *Texas Bays and Estuaries Meeting*. The Unviersity of Texas Marine Science Institute, Port Aransas, TX, 2009.

HONORS/AWARDS/PRIZES

On December 15, 2009, this grant's PI, Preston S. Wilson was awarded tenure and promoted to Associate Professor in the Mechanical Engineering Department at the University of Texas at Austin, effective September, 1 2009.

Theodore F. Argo IV, a Ph.D. student supported by this grant, won third prize in the Best Student Paper Award of the Acoustical Oceanography Technical Committee of the Acoustical Society of America, for his paper entitled "Laboratory measurements of sound speed and attenuation in water-saturated artificial sediments as a function of porosity," which was given at the Fall 2008 Meeting of the ASA in Miami.

FIGURES

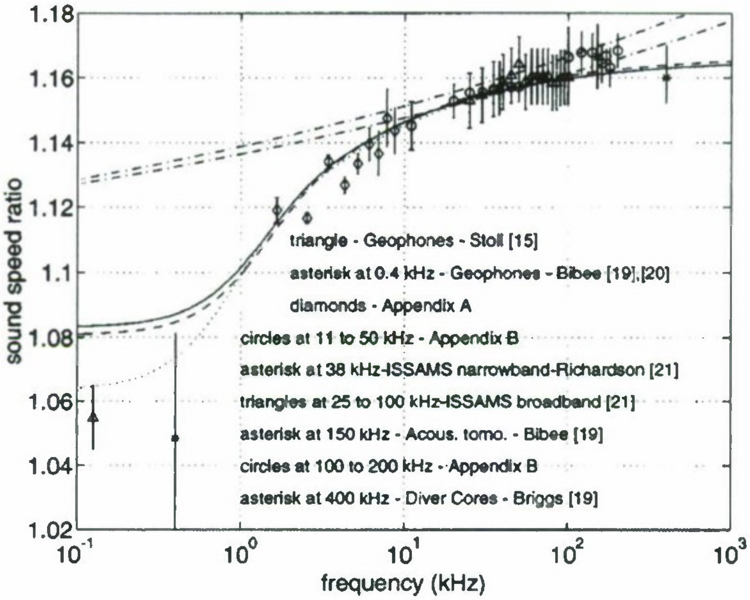


Fig. 1-a. State-of-the-art model/data comparison for the sound speed in a sandy water-saturated sediment. The citations in the legend refer to those in Ref. [32]. The theoretical curves are: solid line=Biot/Stoll [9]; dashed line=Williams [10], dash-dot lines=Buckingham's model for two values of fluid viscosity [8]; dotted line=best fit Biot/Stoll model for input parameters outside of measured values. Note the scarcity of data from the low-kHz and below. Also note that the Biot and Williams models do a better job of predicting the data than the Buckingham model does. (Figure adapted from [32].)

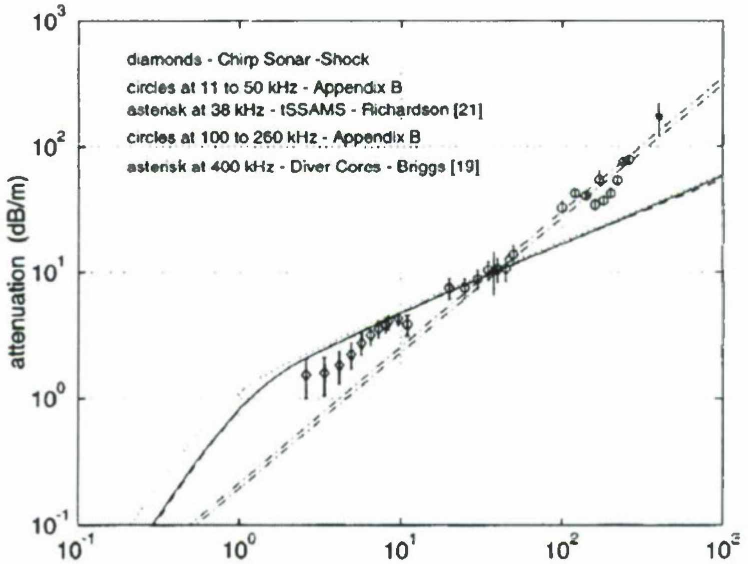


Fig. 1-b. Same as Fig. 1-a, except for attenuation. Note that here, the Buckingham model does a better job of predicting the data than the Biot and Williams models do. (Figure adapted from [32].) Also note that there is no attenuation data below about 3 kHz.

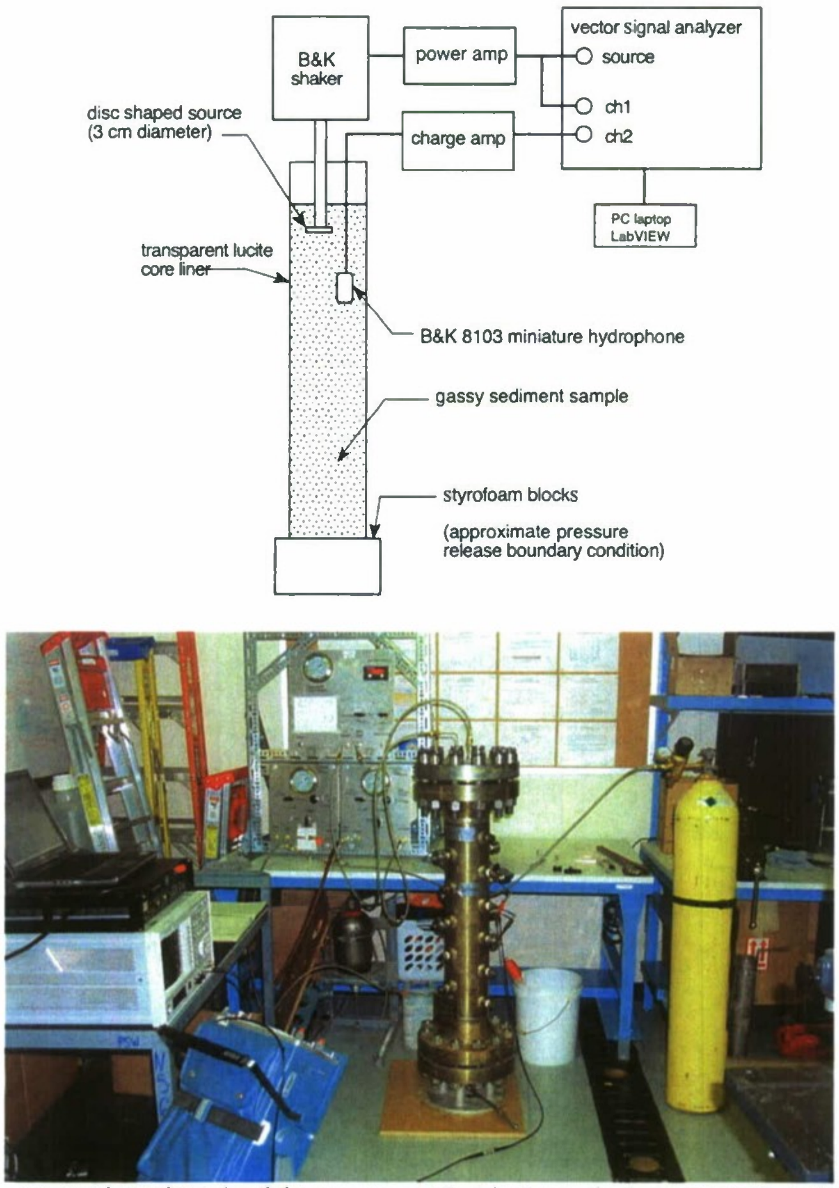


Fig. 2. The upper panel, a schematic of the resonator method is shown. In the lower panel, a photograph of the pressure vessel is shown. The resonator apparatus can be operated inside the pressure vessel to make measurements of sediment sound speed at simulate ocean depths up to 1000 m.

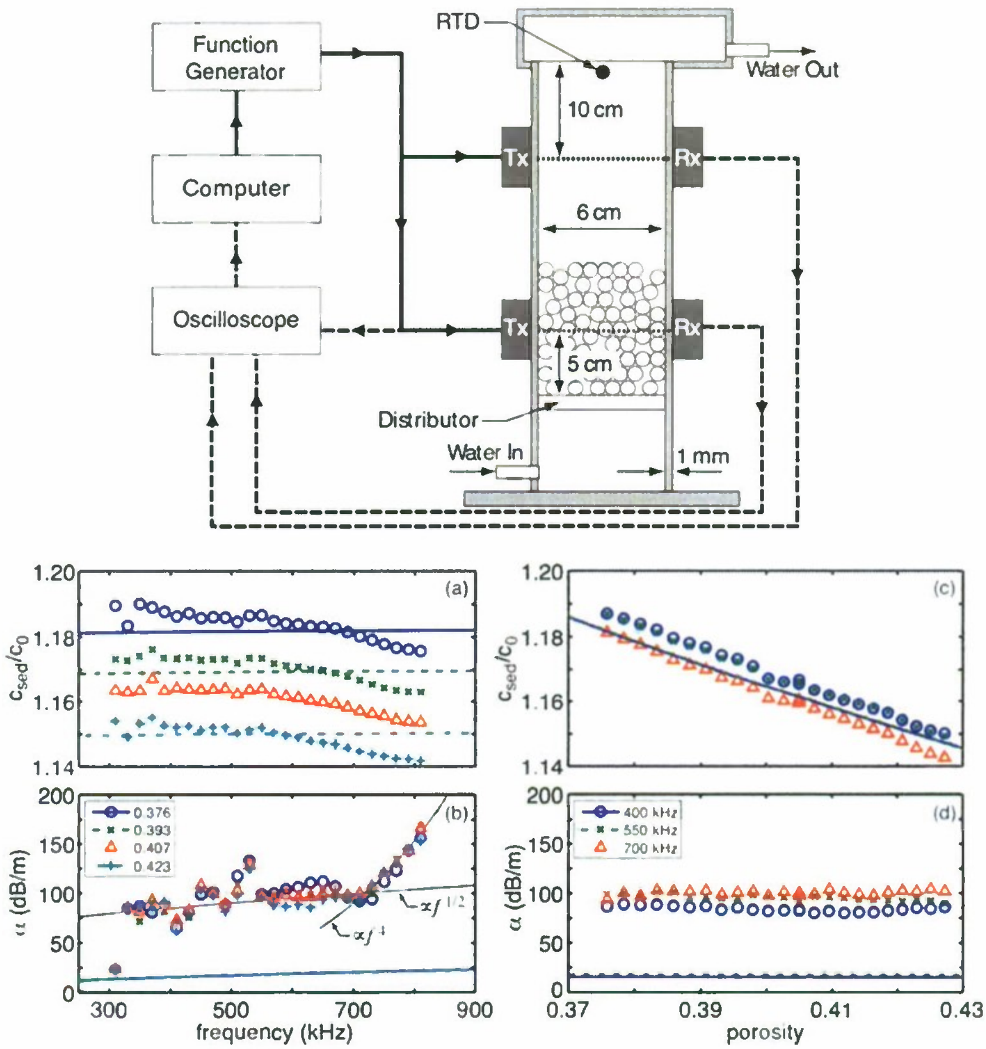


Fig. 3. Upper panel: The high frequency time-of-flight measurement and porosity control apparatus is shown in schematic. Lower panel: Sound speed (a) and attenuation (b) measurements are shown as a function of frequency for four porosities. Predictions of the Williams' effective density fluid model (EDFM) are shown with colored solid and dashed lines. Frequency-dependency trend lines are shown with thin, solid black lines. Notice the shift from $f^{1/2}$ to f^{4} behavior near 700 kHz. Sound speed (c) and attenuation (d) are shown as a function of porosity for three frequencies. Colored solid and dashed lines are EDFM predictions.

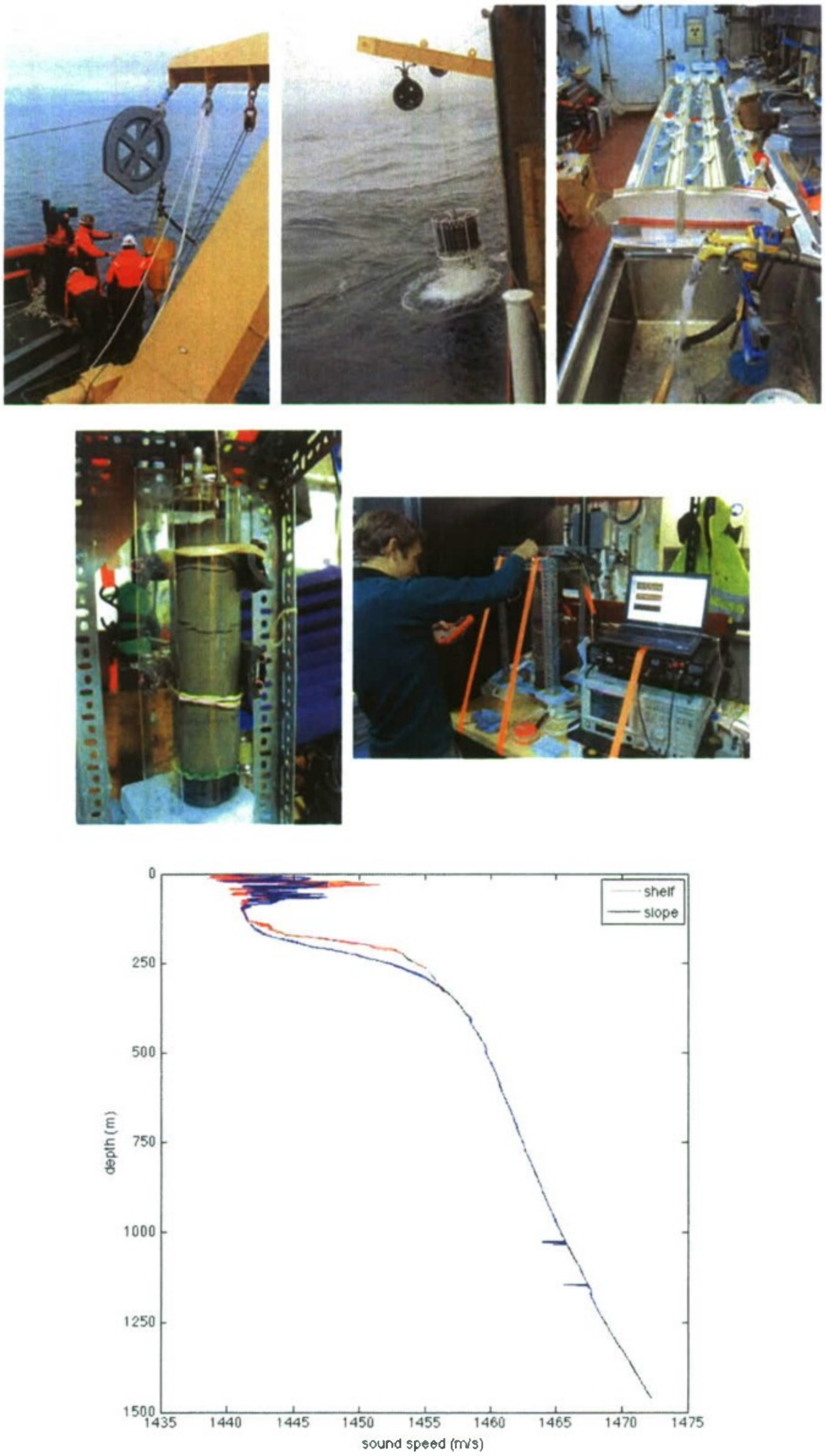


Fig. 4. Images from arctic research cruise MITAS aboard the USCGC Polar Sea in the Beaufort Sea. Top Row L to R: Sediment coring operations , CTD casting, sediment pore water sampling. Middle Row L to R: gas-bearing mud sediment core, acoustic resonator measurements onboard Polar Sea. Bottom Row: Strong sound channel revealed in sound speed profile for both on shelf (red) and in deeper water (blue).

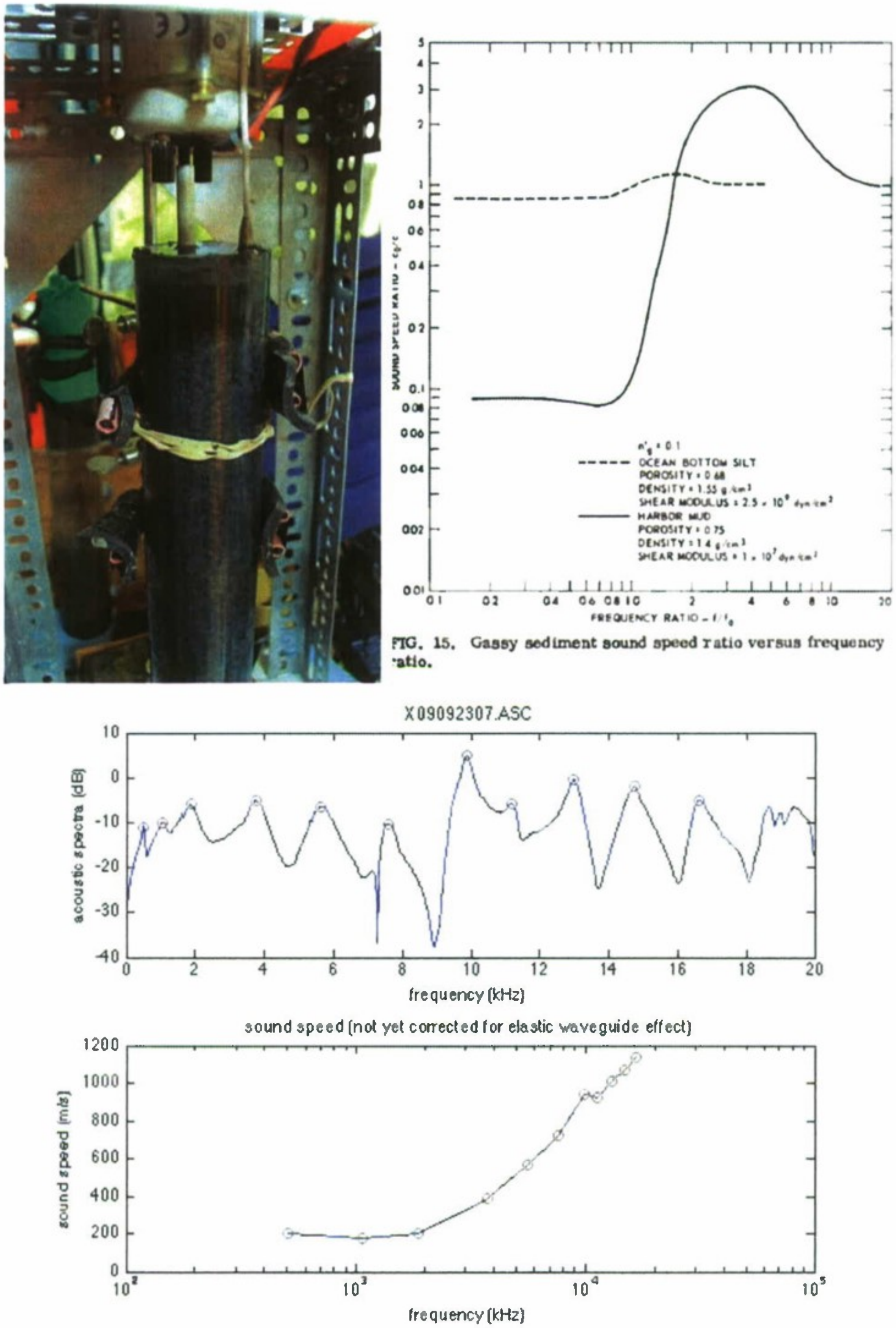


Fig. 5. Top left: A gas-bearing mud sediment from the Alaskan shelf under the Beaufort Sea. Top Right: Predicted sound speed in a gas-bearing sediment from Anderson and Hampton. [23] Bottom: Qualitatively similar sound speed measurements obtained from our 1-D resonator system.

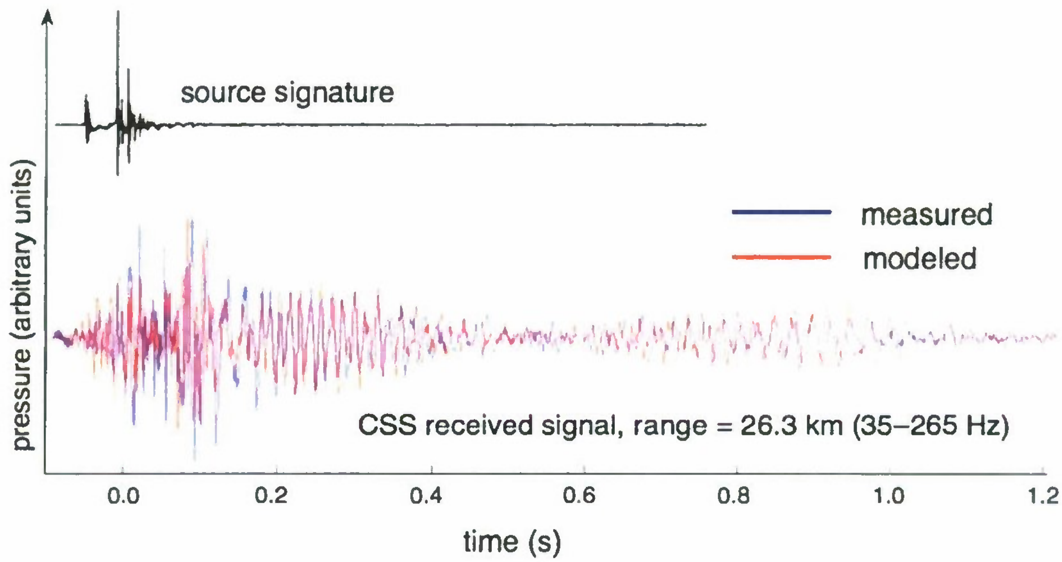


Fig. 6. Broadband propagation modeling from SW06. The upper curve is the CSS Event 26 source signature, deployed at 26 m depth. The lower curves are measured and modeled propagation 26 km downrange from the soruce.

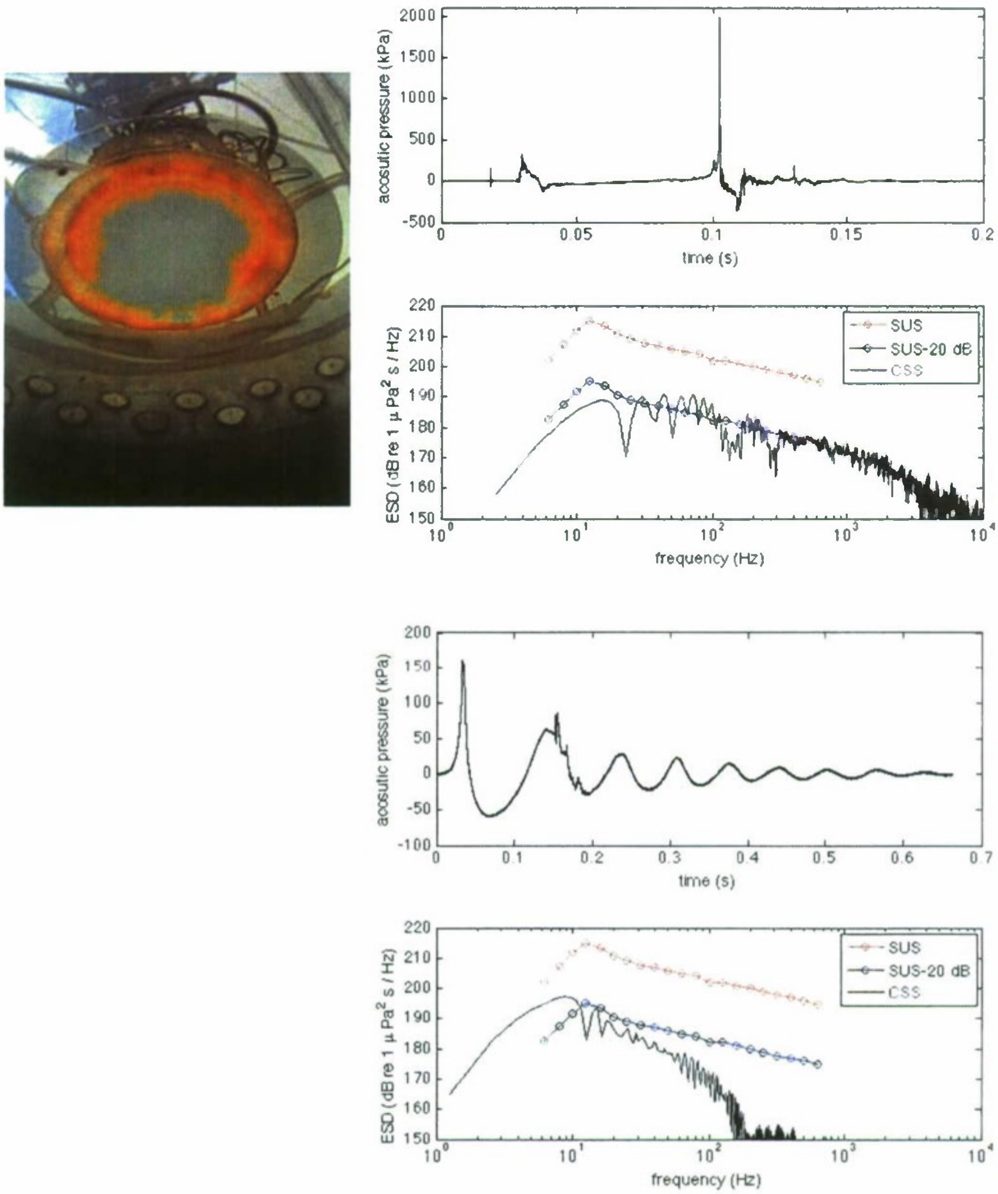


Fig. 7. Upper Left Photo: Combustion and bubble activity produced by the CSS is shown. Upper Right: The radiated acoustic pressure of an increased-output CSS burning hydrogen and oxygen is shown in the upper frame. The corresponding energy spectral density is shown in the lower frame for CSS, for a SUS charge and for a SUS-charge less 20 dB. Lower Right: Same as upper right, except that air was used as the oxidizer instead of oxygen.

Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques

Chapter 7: Conclusions

The exact acoustic behavior of water-saturated, granular, ocean-bottom sediments remains an active area of research despite at least 50 years of study. The primary purpose of this work was to conduct laboratory and field studies of the acoustics of sandy ocean bottom sediments, with sufficient control of experimental uncertainly to make meaningful comparisons to existing and developing models. The work began with a focus on low frequencies, below the Biot transition frequency, and ended up expanding in frequency range to cover frequencies above the Biot transition frequency, as well. Initially, the work was focused on sandy sediments, but additional multiphase ocean-bottom materials were eventually studied, too, including gas-bearing sediments, seagrass, and methane hydrates. The work was initially focused on laboratory measurements, but expanded to include work on the large-scale, ONR-sponsored at-sea experiment Shallow Water '06. The grant was initially awarded for three years, in which it was titled "Investigation of the Acoustics of Marine Sediments Using an Impedance Tube" and then extended for two additional years and retitled "Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques."

The results of the grant are presented in Chs. 2 through 6, which also correspond to the fiscal years in which the work was performed. In each of the above chapters, the goals, work completed, and results are summarized. Publication lists are also provided in each chapter for that fiscal year.

The primary results are briefly noted here:

1) The combustive sound source (CSS) was deployed in SW06 to provide an environmentally safe alternative to commercially available air guns and SUS charges.
2) Evidence for low frequency sound speed dispersion in sandy sediments was found both in the laboratory measurements and in inferences obtained from SW06 measurements.

3) Laboratory-measured absolute values of the sound speed, including dispersion, for water-saturated sand was found to agree with the Biot model from 2 kHz through 300 kHz, which is from about the middle of the transition frequency range, to well into the high-frequency asymptotic range.

4) The slope of the frequency-dependent attenuation, inferred from SW06 ocean acoustics measurements, was found to agree with that predicted by Biot-based models from 40 Hz to 2 kHz.

5) A simple expression, based on Wood's equations, was found to describe the low-frequency sound speed in shallow, fluid-like, gas-bearing sediments. Only sediment bulk density, ambient pressure, and gas void fraction is required to predict the sound speed below the resonance frequency of the largest bubble.

6) Laboratory measurements of the low-frequency sound speed in three seagrass species were obtained. Although seagrass tissue encloses significant volume fractions of air, and resides in the host-medium of seawater, it was found that Wood's equation was not sufficient to describe the observed sound speed. Knowledge of the seagrass tissue elastic properties and tissue geometrical micro-structure is required to predict the effective sound speed in seagrass beds.

7) A porosity control technique was developed for creating laboratory sediment beds of variable porosity.

8) High frequency negative dispersion was found in artificial, water-saturated, glass bead sediments.

9) The Biot model was found to describe the mean porosity dependence of the measured sound speeds using the technique described in 8), but not the negative dispersion.

10) Sound speed measurements on gas-bearing muddy sediments from the continental shelf of the Beaufort sea were obtained.

11) Despite 5 years of work on this grant and untold numbers of others, there is still an insufficient amount of quality acoustic measurement data to adequately support the existing modeling efforts for the acoustics of granular sediments. More experiments are needed, with better knowledge and control of the input parameters, and with better understanding of measurement uncertainty, in order to test exiting and developing models, and to fully understand sound propagation in water-saturated granular sediments.

Final Report: ONR Grant N00014-05-1-0260

Investigation of the Acoustics of Marine Sediments Using an Impedance Tube

for fiscal years 2005–2007

and

Continued Investigation of the Acoustics of Marine Sediments Using Impedance Tube and Acoustic Resonator Techniques

for fiscal years 2008–2009

Appendix
Most Important Peer-Reviewed Publications Resulting from Grant

[1] P.S. Wilson, A.H. Reed, J.C. Wilbur, and R.A. Roy, "Evidence of dispersion in an artificial water-saturated sand sediment," The Journal of the Acoustical Society of America **121**, 824–832 (2007).

[2] T.F. Argo IV, P.S. Wilson, and V. Palan, "Measurement of the resonance frequency of single bubbles using a laser Doppler vibrometer," The Journal of the Acoustical Society of America **123**, EL121–EL125 (2008).

[3] D.P. Knobles, P.S. Wilson, S. Cho, and J.A. Goff, "Seabed acoustics of a sand ridge on the New Jersey continental shelf," The Journal Of The Acoustical Society Of America **124**, EL151–EL156 (2008).

[4] G.R. Potty, J.H. Miller, P.S. Wilson, J.F. Lynch, and A. Newhall, "Geoacoustic inversion using combustive sound source signals," The Journal Of The Acoustical Society Of America **124**, EL146–EL150 (2008).

[5] P.S. Wilson, A.H. Reed, W.T. Wood, and R.A. Roy, "The low-frequency sound speed of fluid-like gas-bearing sediments," The Journal of the Acoustical Society of America **123**, EL99–EL104 (2008).

[6] P.S. Wilson and R.A. Roy, "An audible demonstration of the speed of sound in bubbly liquids," American Journal of Physics **76**, 975-981 (2008).

[7] P.S. Wilson and K.H. Dunton, "Laboratory investigation of the acoustic response of seagrass tissue in the frequency band 0.5–2.5 kHz," The Journal of the Acoustical Society of America **125**, pp. 1951–1959 (2009).

[8] D.P. Knobles, J.A. Goff, R.A. Koch, S.M. Joshi, P.S. Wilson, and J.A. Shooter, "Modeling broadband acoustic propagation in an uncertain inhomogeneous shallow water ocean waveguide," I.E.E.E. Journal of Oceanic Engineering in press (July 2010).