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

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LONG-TERM GOALS

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

OBJECTIVES/APPROACH

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

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1) Continue our laboratory investigations of various artificial and natural multiphase ocean bottom materials using the tube and resonator-based laboratory techniques mentioned above as well as traditional time-of-flight techniques. The objective is to obtain sound speed and attenuation measurements with sufficient knowledge of the measurement uncertainty to facilitate meaningful model comparison on a wider range of sediment types than we have been able to achieve thus far. Our previous work was focused primarily on cleaned and sieved sands. We extended our measurements into more realistic and complex sediments that contain additional material such as shell fragments, larger non-sand particles, silt and clay particles, and muds, gas-bearing sediments methane hydrate bearing sediments, seagrass and kelp.

2) We continue to analyze data from SW06, and to make preparations for participation in future sea tests. The PI is co-supervisor of Jason Sagers, one of the recipients of the Special Awards in Ocean Acoustics Graduate Fellowships. This part of the effort will also include the development of the combustive sound source (CSS) for towable water column deployment, and for use as a shear source on the ocean bottom. The former is to provide impulsive shots for propagation measurements, and the latter is to provide a means to infer shear properties through inversion of geophone measurements as described in Refs. [11, 12].

3) The PI is serving as co-chief scientist for an upcoming shallow water sea test, namely the sediment characterization experiment scheduled to go to sea in the 2013–14 timeframe. The objective of my part of this work now is to help plan the future test, in coordination with the two other upcoming sea tests on reverberation and shelf/slope effects.

4) A new thrust this year is the development of an acoustic inversion technique to determine the 3-D sound speed distribution in parcels of ocean. The goal of this acoustic remote sensing technique is to provide increased knowledge of the ocean waveguide sound speed distribution for forward propagation models and also to provide input parameters to large-scale numerical ocean dynamics models. The technique greatly extends the footprint of CTD-based or thermistor-chain-based temperature surveys.

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 senior 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. UT Marine Science PhD student, Christopher J. Wilson works on the seagrass acoustics portion of this project. Chris is primarily funded by a fellowship he holds, but he contributes to this effort. Jason Sagers is funded by an ONR graduate fellowship and does analysis of SW06 data. Christopher Bender is funded on an ARL IR&D and works on the inversion technique, and is co-supervised by Megan Ballard.

WORK COMPLETED and RESULTS

Objective 1—Laboratory sediment and multiphase ocean bottom materials investigation: A new specialized laboratory time-of-flight measurement apparatus was completed and a large dataset of sound speed and attenuation measurements was acquired with monodisperse glass beads, bi-disperse glass beads of varying proportion, two types of sand, and sand with shell hash. The goal of this work is to attempt to understand the wide variability of acoustic properties exhibited by ocean sediments. By systematically varying the constituents from mono- to polydisperse one can see increased variability. A collection of data from this measurement campaign is shown in Figs. 1, 2, 3 and 4. The statistical nature of this data will be assesed and comparison to models will be undertaken in future work. This data shows that sound speed and attenuation variability as a function of frequency is proportional to the disorder within the sample. Work completed last year using the variable porosity apparatus was published and in April 2011 was the second-most-downloaded paper in JASA. [13]

Again using the low frequency resonator measurement apparatus, we investigated the acoustic response of kelp forests using live plants collected in nature but investigated in the laboratory. The purpose of these measurements was to obtain for the first time the sound speed within a kelp forest. This work has application in ocean acoustic modeling for shallow water environments which contain kelp (along the western US coast from California to Alaska). Example measurements are shown in Fig. 5. Measured low frequency (Wood limit) sound speeds (m/s) as a function of internal kelp air volume, within an artificial forest of two species of kelp, *Macrocystis pyrifera* (left) and *Egregia menziessi* (right). As we found with sea grass, the acoustic properties are controlled by tissue acoustic properties as well as air content, and Wood's Equation alone is insufficient to predict the sound speed within a kelp forest. Work completed last year on seagrass acoustic properties was published. [14]

The acoustic properties of bubbly water is well-studied in ocean acoustics, but one simple aspect that had not until this year was the effect of increased pressure on the sound speed in a bubbly mixture. Previous work by this PI [6] had focused on the sound speed in gas-bearing muds in very shallow water. The present work focused on just the speed of sound in bubble mixtures at elevated hydrostatic pressures, as might be found in deeper gas-bearing sediments, including sediments that contain methane hydrate. A temperature and pressure controlled apparatus was used to simulate ocean bottom conditions and the resonator technique was used to measure the sound speed in mixtures containing gas bubbles in water. Both air and sulfer hexafloride were used. The former was used to investigate a near-ideal gas, the latter a real gas. The apparatus is shown in Fig. 6 and results for air and sulfer hexaflouride are shown in Fig. 7. Although not directly studied, we can show through the Van der Walls equation of state, and our measurements with air and sulfer hexaflouride, that methane will need to be treated as a real gas for depths below 30 m. Or in other words, the sound speed in methane gas bearing sediments below a depth of 30 m can not be modeled using the traditional Wood's equation. A modified form that takes into account the real compressibility of the methane gas must be used instead. This can easily be done using the Van der Walls equation of state, and this modified Woods equation works well, as shown in Fig. 7.

Work completed last year on sound propagation through very large bubbles (i.e. fish schools) was published. [15]

Objective 2 —SW06 Analysis and Future Sea Test Prep:
Jason Sagers, a Graduate Fellowship Special Awards in Ocean Acoustics recipient, is studying the effect of internal waves on shallow water acoustic fluctuations using data collected from SW06. This PI is serving as co-supervisor. Some example data ana analysis is shown in Fig. 8, where various regimes of internal wave activity has been correlated with fluctuations in received acoustic intensity along the path of travel of internal wave events. This work is ongoing and will result in a PhD thesis for Sagers in the next FY. Related SW06 analysis work that was completed last year was published. [16]

In preparation for future sea tests, we are building a towable and ocean bottom deployable version of the combustive sound source (CSS). Firing CSS in open water is becoming more difficult due to environmental regulations limiting sound levels in the water, even for this source, which is intended to replace SUS. We conducted an engineering test this spring at HiTest, which is a former rock quarry in central Virginia (no source level limits there). We also conducted an ocean test of the bottom mounted version of CSS along with Miller and Potty at University of Rhode Island. The latter deployment is intended to study ocean bottom interface waves for the investigation of sediment shear properties. A picture of the deployment is shown in Fig. 9, and an example of the interface wave data is shown in Fig. 10.

Objective 3—Future Sea Test Planning:
The PI serves as co-chief scientist (with David Knobles) for the Sediment Characterization Experiment, an upcoming ONR-sponsored shallow water sea test to be fielded in 2013–14. This duty includes attending and participation in several workshops held at ASA meetings and stand-alone workshops in April in Austin, and in May in Arlington.

Objective 4—3-D Inversion for Sound Speed and Temperature:
We are developing a 3-D inversion scheme for water column sound speed profiles with applications to acoustic remote sensing for both ocean acoustics and ocean flow modeling. The approach utilizes distributed source and receivers. The method is being developed and tested using simulated acoustic data based on simulated ocean temperature data (see Fig. 11). The inversion scheme is up and running (see Fig. 11) and optimization is underway. We participated in MOMAX 2011 with Frisk and Becker as a means to obtain real data for use in this inversion scheme.

Finally, a full listing of all grant-related activities is shown in the Fiscal Year Publications section below.

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 [17] correctly predicts the porosity dependency of high frequency sound speed in water saturated sand. Low frequency (53–2000 Hz) attenuation data [10] from SW06 are also well described by Biot-Stoll and clearly follow the low frequency limiting slope of frequency squared. We are continuing our efforts to get ever-more-broadband and more accurate laboratory measurements with an increased understanding of the measurement uncertainties.

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

TRANSITIONS

This PI received another $225k in the current fiscal year from the Naval Oceanographic Office for further development of the combustive sound source (CSS) as a replacement for explosives in ocean surveys. The PI received a DURIP award ($257.5k) to develop the CSS for use in ocean acoustics experiments. 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 FY09, 10 and 11. This PI continued a project originally started in 2009, funded by Shell Oil, to use bubbles to reduce the radiated noise from offshore drilling operations. Much of this PI's experience with bubbles was due to a project previously funded by ONR and also due to the current grant. This PI also leveraged previous OA funding to win a grant on the Basic Research Challenge Fish Acoustics program.

RELATED PROJECTS

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

SAX04: Sediment Acoustics Experiment 2004

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

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

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GRANT-RELATED PUBLICATIONS THIS FISCAL YEAR

Archival Journal Papers

[1] C.J. Wilson, P.S. Wilson, C.A. Greene, and K.H. Dunton, "Seagrass leaves in 3-D: Using computed tomography and low-frequency acoustics to investigate the material properties of seagrass tissue," *Journal of Experimental Marine Biology and Ecology* **385**, pp. 128-134 (2010).
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HONORS/AWARDS/PRIZES

Our paper on sediment sound speed as a function of frequency and porosity [13] was the second-most-downloaded paper in JASA in April 2011.

http://asadl.org/jasa/most_downloaded?month=4&year=2011

FIGURES

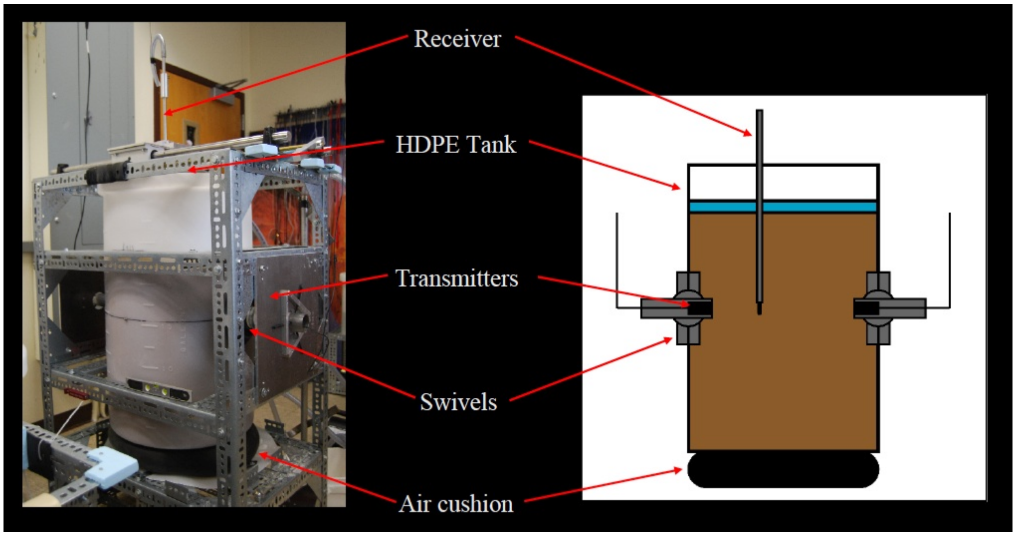

Fig. 1. The new time-of-flight sound speed and attenuation apparatus for water saturated sediment measurements is shown. It allows for direct absolute measurement of sound speed and attenuation with minimized measurement error.

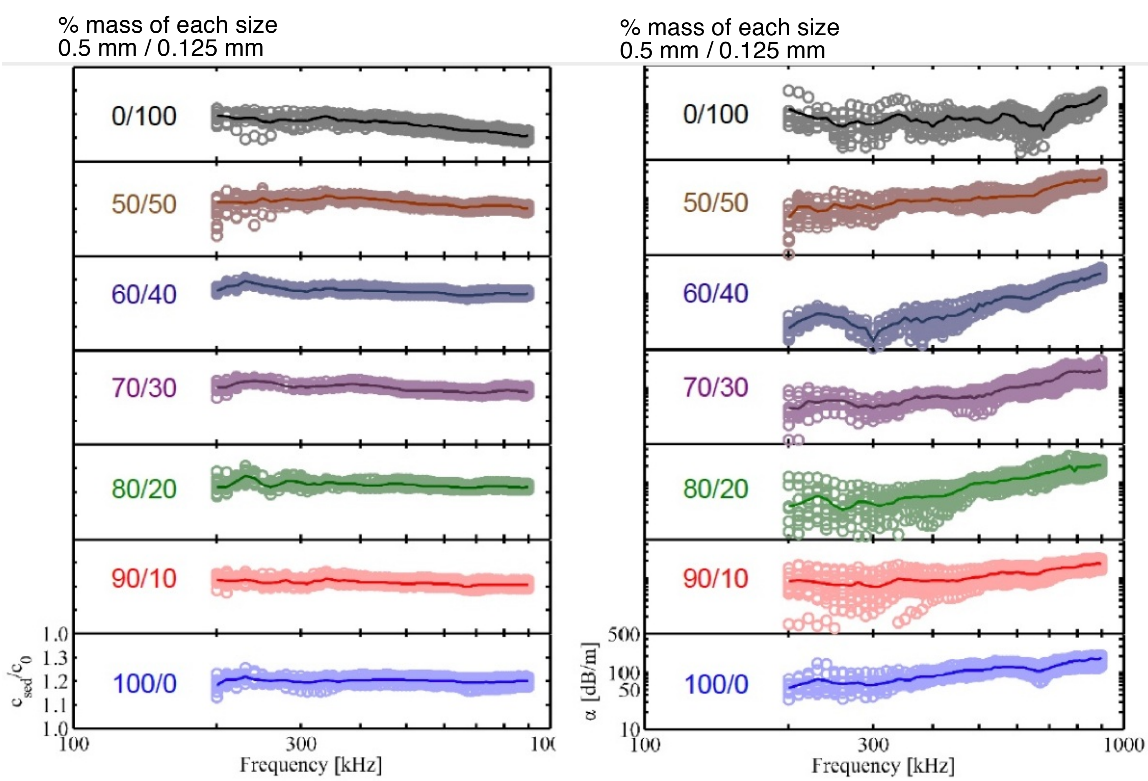

Fig. 2. An overview of sound speed (left) and attenuation measurements (right), as a function of frequency in monodisperse and bi-modal distributions of glass beads. The sizes used were 0.5 mm and 0.125 mm diameter spherical beads. The numbers on the left side of each column represent the % mass of each bead size within each sediment case. For example, 0/100 represents 0 % of the 0.5 mm beads and 100 % of the 0.125 mm beads by weight. Similarly, 50/50 represents 50 % of the 0.5 mm beads and 50 % of the 0.125 mm beads by weight.

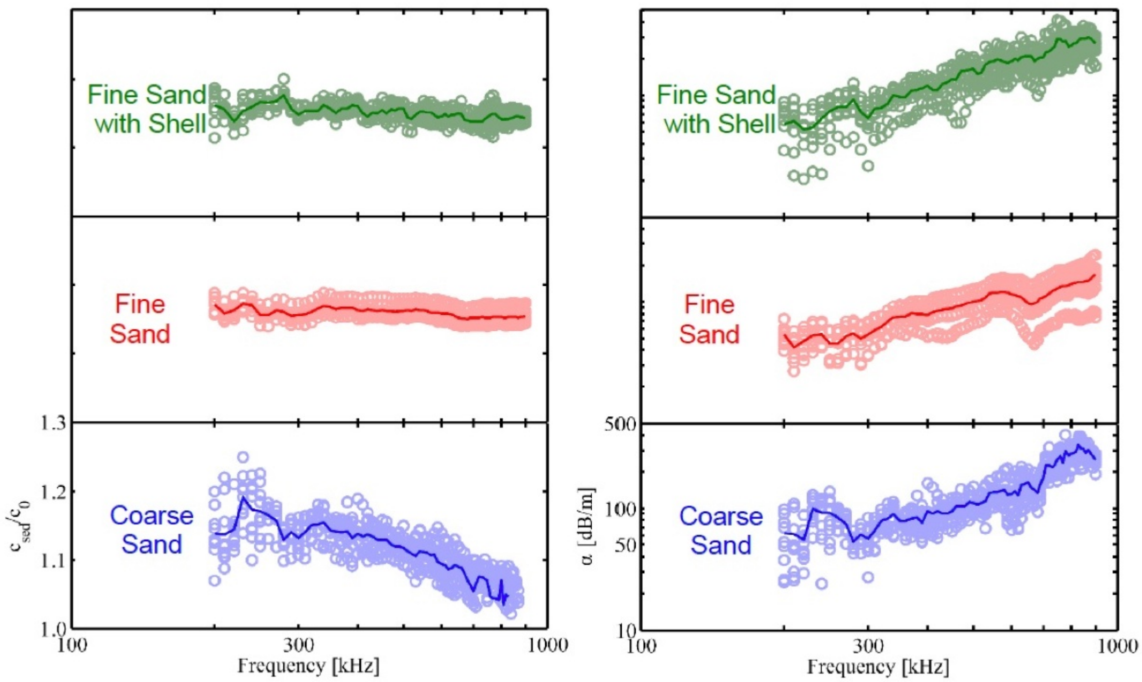

Fig. 3. An overview of sound speed (left) and attenuation measurements (right), as a function of frequency in course and fine sands, and fine sands with shell hash.

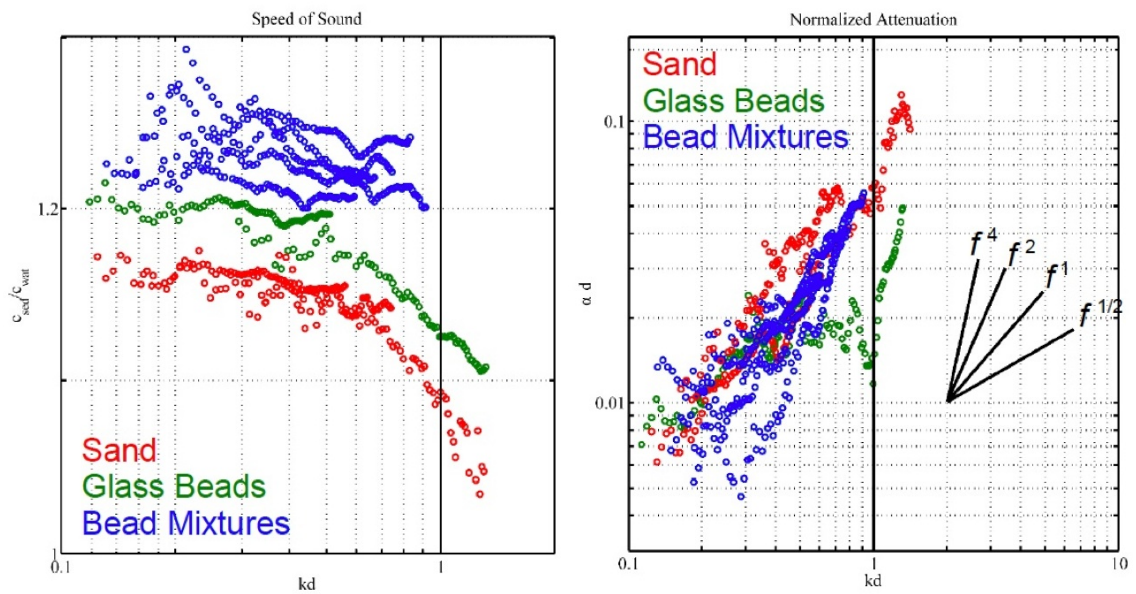

Fig. 4. A combined view of all the data from the three-previous figures, plotted normalized by *kd* on the horizontal axis where *k* is the wave number and *d* is the mean grain diameter for each sample.

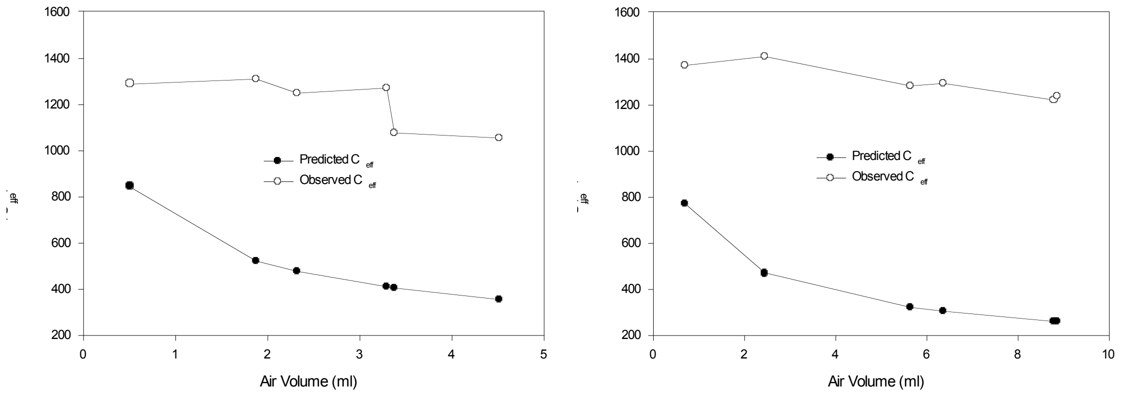

Fig. 5. Measured low frequency (Wood limit) sound speeds (m/s) as a function of internal kelp air volume, within an artificial forest of two species of kelp, *Macrocystis pyrifera* (left) and *Egregia menziessi* (right). The lines with open circles are the measurements. The lines with solid circles are the predicted sound speed based on measured kelp air content and Wood's Equation. As we found with sea grass, the acoustic properties are controlled by tissue acoustic properties as well as air content, and Wood's Equation alone is insufficient to predict the sound speed within a kelp forest.

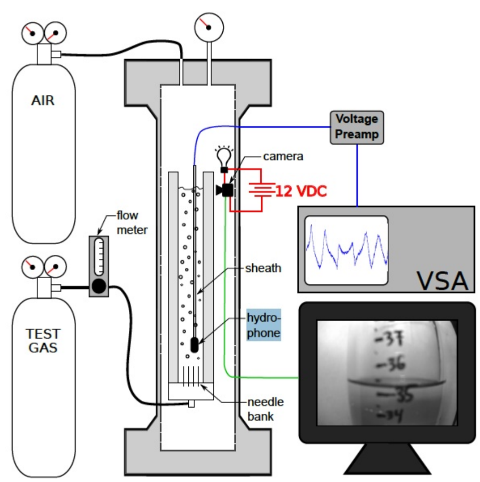

Fig. 6. Apparatus to simulate ocean bottom conditions through temperature and pressure control and to measure the acoustic properties of materials in such conditions using the resonator method. This was used to investigate bubbly liquids at elevated hydrostatic pressures.

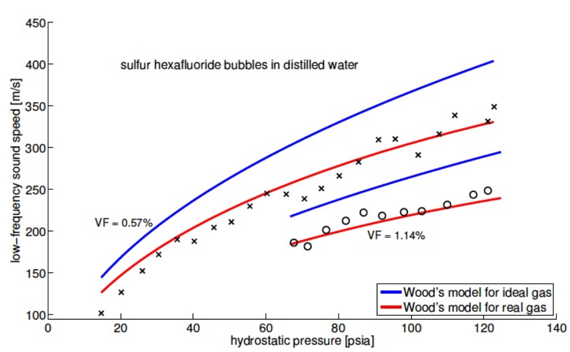

Fig. 7. Sound speed measurements in air bubbles (left) and sulfer hexaflouride (right) as a function of hydrostatic pressure. Blue lines are model predictions assuming the gas behaves as ideal. Red lines are for model predictions assuming the gases behave as real gases.

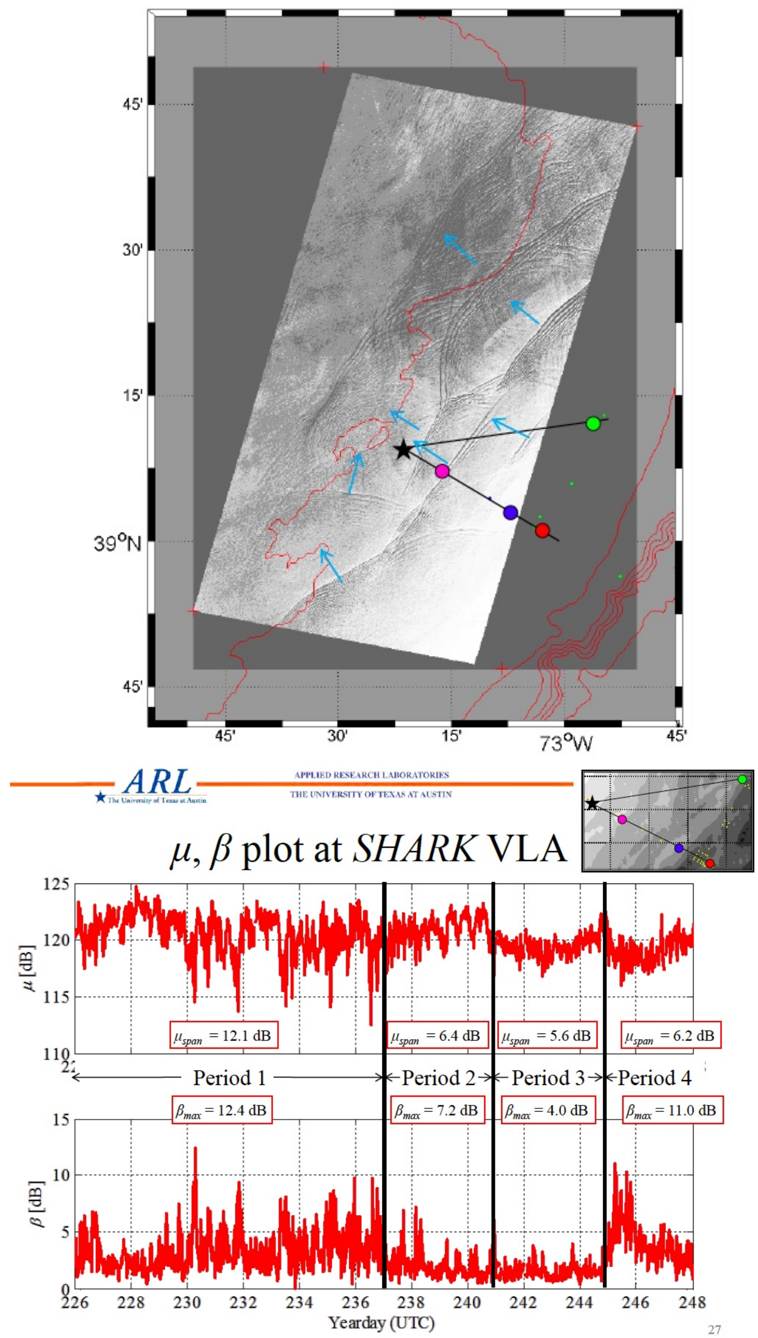

Fig. 8. SW06 SARS imagery of internal wave activity as it relates to SWAMI moorings and various acoustic paths (upper plot). The lower plot is the variability of mean μ and standard deviation β of the acoustic intensity along the path from the purple to the red dot in the upper plot. The four periods illustrated in the lower plot correspond to four distinct bouts of internal wave activity.

Fig. 9. Engineering test of URI geophone sled (being deployed) and the bottom mounted CSS (partially visible as frame) in Narragansett Bay, Rhode Island AUG 2011.

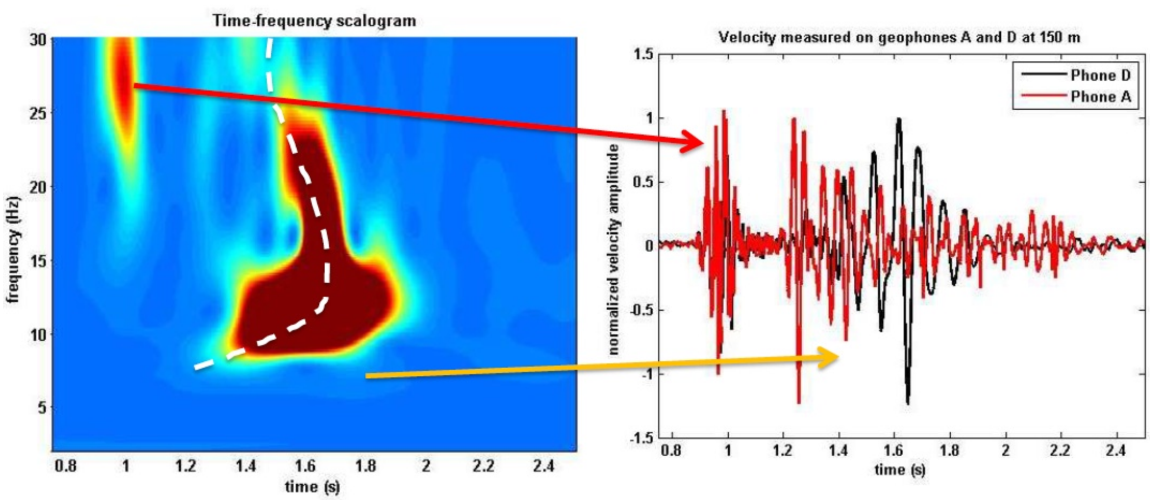

Fig. 10. Time domain (right) and joint time-frequency domain (left) representations of vertical geophone signals obtained in the Narragansett Bay Engineering Test. [Figure courtesy Potty and Miller.]

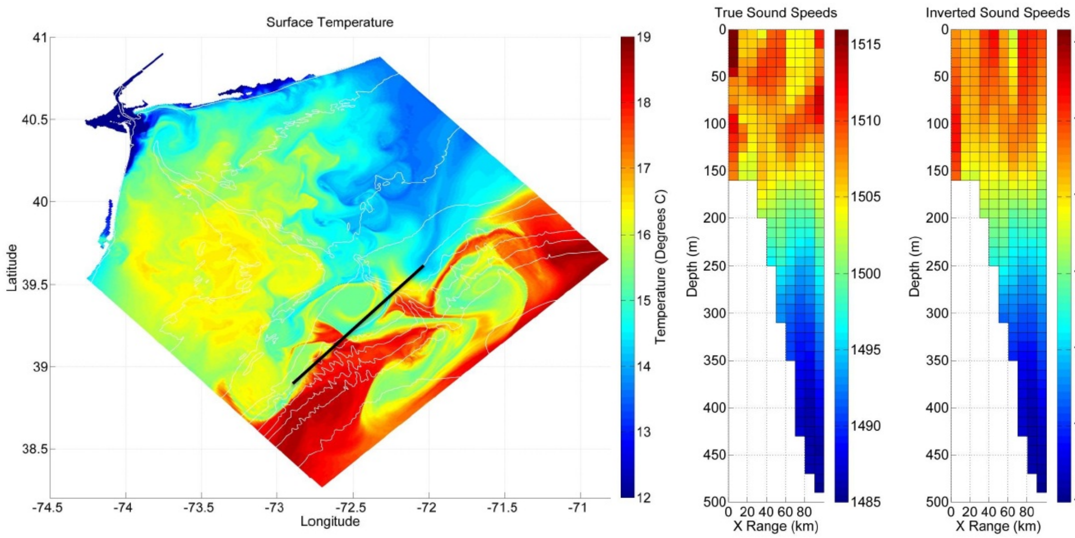

Fig. 11. Simulated ocean temperature field near the SW06 site (left). Only surface temperatures are shown (with the color scale) but full water column temperatures are known. The black line represents an acoustic path over which the inversion scheme was run. On the right, the true sound speed profiles along the black line are shown. On the far right, our inversion results are shown. Good agreement between true and inverted sound speeds was obtained.