The Physics of Sound Scattering From, and Attenuation Through, Compliant Bubbly Mixtures and Saturated Laboratory Sediments

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Grant Numbers: N00014-97-1-0425
http://www.bu.edu/eng/

LONG-TERM GOALS

The goal of this research is to acquire a quantitative understanding, leading to predictive models, of the broader aspects of linear and nonlinear sound scattering, transmission and coherency in oceanic sediments and bubbly mixtures pertinent to the shallow-water acoustics. Of particular interest is the delineation of different regimes of behavior as a function of frequency, bubble size distribution, flow characteristics and volume fraction, and sediment properties. In all cases, we focus on lower-frequency behavior for which the effective medium approximation is valid.

OBJECTIVES

An objective specific to this project is the extension of the theory of sound transmission and coherency in bubbly liquids to derive attenuation characteristics for both small amplitude (linear response) and large amplitude (nonlinear response) forcing, ultimately incorporating the effects of contaminating surface-active solutes. A second objective is the development of a unique laboratory capability for the measurement of the frequency-dependent complex acoustic impedance of, scattering from, and the coherency of propagation through well-characterized bubble ensembles *for frequencies spanning the individual bubble resonance frequencies*. Characterization implies the precise knowledge of the space- and time-dependent bubble density and size distribution. A third objective is the development of a laboratory capability for the measurement of the frequency-dependent complex acoustic impedance of saturated and partially saturated laboratory sediments, particularly in the frequency range extending from a few hundred Hertz to 10 kHz.

APPROACH

Our approach involves a balance between theory, analytical modeling and experiments to predict and measure propagation, scattering, and coherency characteristics. The dynamics of a single bubble for both small and large amplitude forcing and is treated numerically using the Keller formulation for

Report Documentation Page				*Form Approved* *OMB No. 0704-0188*	
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1. REPORT DATE **30 SEP 2003**		2. REPORT TYPE		3. DATES COVERED **00-00-2003 to 00-00-2003**	
4. TITLE AND SUBTITLE **The Physics of Sound Scattering From, and Attenuation Through, Compliant Bubbly Mixtures and Saturated Laboratory Sediments**				5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Dept. of Aerospace and Mechanical Engineering, ,Boston University 110 Cummington Street,,Boston,,MA,02215**				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT **The goal of this research is to acquire a quantitative understanding, leading to predictive models, of the broader aspects of linear and nonlinear sound scattering, transmission and coherency in oceanic sediments and bubbly mixtures pertinent to the shallow-water acoustics. Of particular interest is the delineation of different regimes of behavior as a function of frequency, bubble size distribution, flow characteristics and volume fraction, and sediment properties. In all cases, we focus on lower-frequency behavior for which the effective medium approximation is valid.**					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

bubble dynamics in a Newtonian viscous fluid. Attributes of bubble behavior (mainly damping and resonance response) can be quantified and incorporated into a comprehensive description of sound propagation, scattering and coherency by extending the Wood-Foldy-Morse theories.

Laboratory experiments in bubbly liquids cover three fronts of activity. FY02-03 efforts focused on the measurement of the complex surface impedance of bubble distributions terminating a sound-hard impedance tube over frequencies ranging from well below to well above bubble resonance. From this, the frequency dependent sound speed and attenuation was inferred. The bubbly medium was also characterized optically using a stereo microscope and acoustically using a standing wave apparatus to determine void fraction and the low frequency Wood's limit. From this, the frequency-dependent phase velocity and attenuation of the bubbly medium is computed. The direct comparison of measured and computed dispersion curves permitted us to verify the measurement scheme and/or refine the models. We believe this approach is particularly powerful when applied to hard-to-measure situations such as high void fraction flows and bubbles trapped in sediments.

Experiments were also focused on scattering from bubble assemblages of known geometry (bubbly cylinders and spheres) and void fraction. The objective was to determine whether or not low-frequency scattering from bubbly assemblages can be explained without resorting to complex single-bubble and multiple scattering models.

The third experimental thrust for FY02-03 was the use of optical scattering to measure the dynamic response of single bubbles suspended in a viscoelastic holding medium (xanthan gum). This material has been used extensively for experiments in which bubbles distributions are "frozen" in space for purposes of facilitating detailed study. Laser scattering provides a non-invasive measure of the instantaneous bubble radius as a function of time and driving frequency. This yields the frequency response for acoustically driven bubbles for comparison with Newtonian viscous theory and (eventually) bubble dynamics models based on non-Newtonian fluid rheology – all for frequencies spanning the bubble resonance and all in the absence of any boundaries.

In addition to the ongoing bubble work, we initiated a new study: modeling and measurement of the low frequency acoustical properties of laboratory sediments. The acoustical descriptors of interest are the sediment complex acoustic impedance, sound speed, and attenuation for frequencies ranging from around 10 kHz down to (eventually) as few hundred Hertz. The idea is that, in this frequency range, the sediment behaves like an effective medium and can be characterized by a limited number of bulk parameters. However, before we can proceed with building a model, we require a mass of quality experimental data upon which to base inferences and test this hypothesis.

The experimental apparatus used for sediment characterization employed a modified version of the impedance tube used for bubbly liquids experiments, where the sample holder was filled with a saturated sediment rather than bubbly water. Direct measurement (yielding complex impedance) and inversion (yielding sound speed and attenuation) proceeded along the same lines. This effort, which was envisioned as a proof of concept in FY03, was funded by a supplemental ONR OAS grant.

The two PI's (Carey and Roy) shared the task of project management and guidance. Five grad students, three of whom graduated in the project period, work on a variety of tasks. Preston Wilson (PhD 2002) spearheaded the bubble acoustics work and the sediment acoustics proof of concept experiments. Ryan McCormick (MS 2002) was in charge of the single-bubble experiments. Eun-Joo

Park (MS 2003) assisted Wilson with the sediment work. The two students who continue to work on the project, Jason Holmes (PhD) and Jed Wilbur (MS), are working to make the impedance tube apparatus field deployable.

WORK COMPLETED

In FY02-03, laboratory experiments were conducted to explore the acoustic properties of well-characterized assemblages of bubbly fluid, to measure the resonance response of individual bubbles, and to measure the frequency depending acoustic impedance of saturated laboratory sediments.

Measurements of bubbly liquid properties by impedance tube

Using the water filled impedance tube apparatus, we were able to measure the frequency dependent impedance of a bubbly termination and process the data to yield frequency dependent sound speed and attenuation. The measurements spanned the resonance frequency of the individual bubbles (order 5 kHz) and were obtained at moderately high void fractions (order 10^{-4}). Representative data, shown in Fig. 1, exhibits good agreement with model predictions.

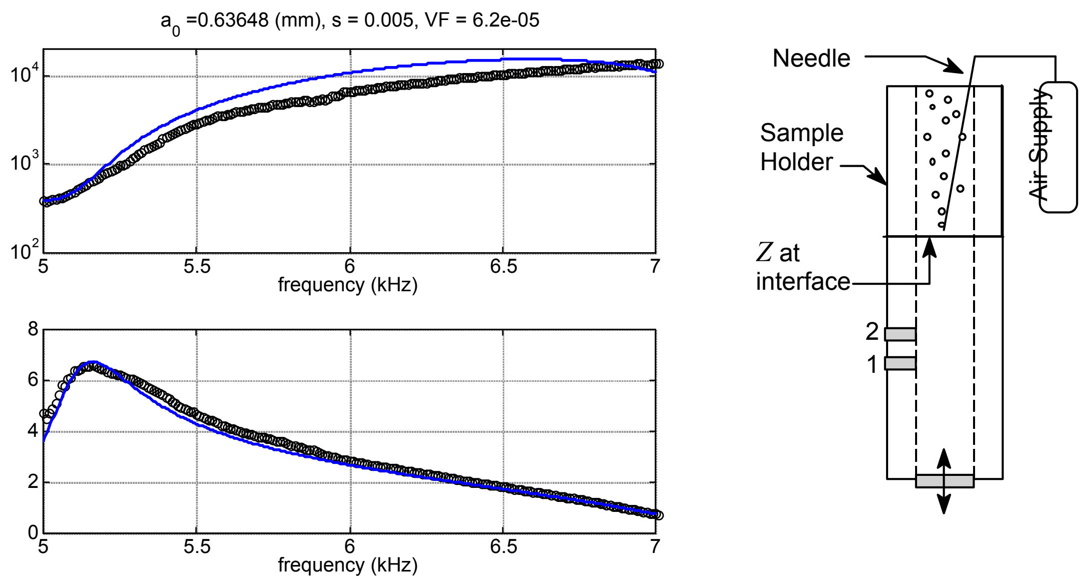

Figure 1. The measured (dots) and predicted (solid lines) phase speed (upper plot in m/sec) and attenuation (lower plot in dB/cm) for propagation in a bubble-filled test section. The bubble size mean value, standard deviation, and void fraction are indicated.

One advantage of the method is we can obtain the frequency-dependent impedance curves in less than 5 seconds, and thus can monitor the fluctuations in the bubble acoustic properties as the bubbles are formed. We determined that, although it is reasonable to think in terms of a steady state condition, the fluctuations in both sound speed and attenuation can be significant about this steady mean. When one is reporting average values obtained from oceanic measurements obtained in a dynamic setting, the choice of sample size can dramatically impact what one measures.

Acoustic backscatter from well-characterized bubbly assemblages

Using the Acoustic Test Facility at NUWC, we measured the frequency-dependent backscatter from bubbly spheres and cylinders, and applied an effective medium model to quantitatively explain the results. The spherical targets consisted of voided polyurethane spheres and plastic pipettes bulbs filled with bubbly xanthan gum; both targets were on the order of 1-cm in diameter. The cylindrical target was a 3-m long, 1.25-in inner diameter Tygon tube through which bubbly water was circulated. An EDO 515-250H projector was driven with short tone bursts (order 5 cycles with cosine taper) over frequencies ranging from 5 kHz to 20 kHz, depending on the target under study. Measured and predicted results for scattering from the tubular target are shown in Fig. 2., where the predictions are based on classical scattering theory (the standard partial wave solution) and the fluid in the scatterer was modeled as a uniform effective medium with reduced sound speed and enhanced attenuation. In all cases, the resonance frequencies of the bubbles comprising the scattering bodies were greater than the frequency of the incident wave, thus we were operating in the Wood limit.

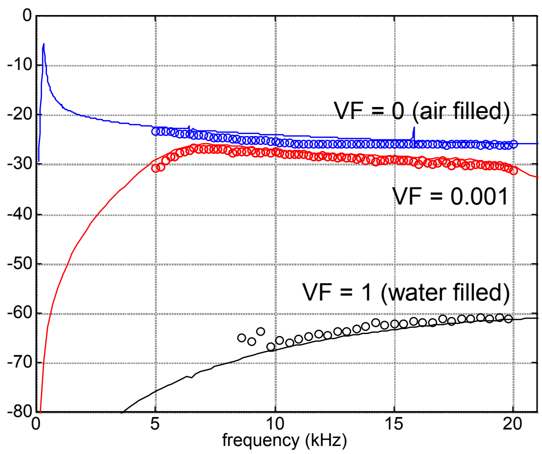

Figure 2. Acoustic backscatter echo level (in dB re an arbitrary reference) from a 1.25-in diameter bubbly filled tube. The bubbles are all smaller than resonance size at 10 kHz. The solid lines are predictions from classical scattering theory, assuming an effective medium for the bubbly fluid. Note the dramatic increase in backscatter echo level with the addition of only 1 part per thousand for free gas.

Dynamical response of individual bubbles suspended in a polymer gel

Using a viscoelastic gel as a holding medium, we successfully measured the linear resonance response of individual bubbles of varying sizes (250 – 500 µm radius), where the equilibrium bubble sizes were measured *in situ* via video microscopy. The peak response frequency compared favorably with predictions using the Minneart equation. This was repeated for bubbles of different size and from the Q of the resonance we derived the size dependent damping coefficient at resonance, which compared well with predictions from standard free-bubble models. Not only was this the first time the resonance response of a single bubble, removed from boundaries, has been measured, it demonstrated that shear thinning in the polymer gel makes it behave very much like water in the frequency range of interest. With this apparatus, we intend to initiate a suite of high-resolution studies of how small groups of bubbles can interact when exposed to low-frequency sound.

Measurement of sediment acoustic properties by impedance tube

This effort was initiated in FY03 as a proof of concept experiment in which we modified the impedance tube apparatus to make it suitable to measuring sediment properties. It also involved collaboration with Dr. Kerry Commander at CSS Panama City, who provided supplemental funding for travel and deployment. The modified apparatus took on two manifestations. First, we took the standard water filled tube equipped with wall mounted hydrophones, added an acoustically transparent Mylar window at the interface between the top of the propagation tube and the bottom of the test section, and carefully filled the test section with a saturated sand sediment sample. The measurement procedure was identical to the bubbly liquid experiments and data was obtained yielding the complex impedance of the sample for frequencies ranging from 5 kHz to 9 kHz. (The upper limit is set by the tube diameter and the lower limit is set by the source transducer response characteristics.) Given a suitable model for the sample holder acoustics, we were able to derive the frequency dependent sound speed and attenuation over the same frequency range.

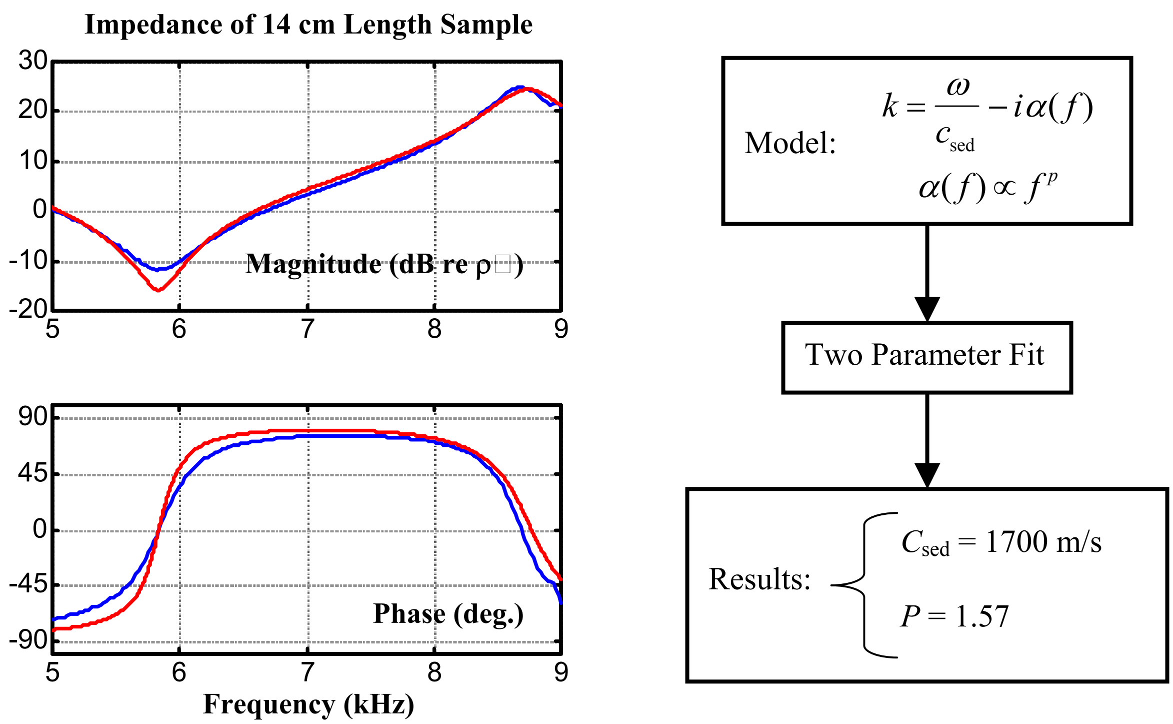

Figure 3. The measured (blue) and modeled (red) complex acoustic impedance of water saturated coarse sane from the Gulf of Mexico. The model is a 2-parameter fit where the sample holder is modeled as a 1-d waveguide and the sediment sound speed is assumed to obey a power law.

The second apparatus was designed with the sample holder at the bottom of the tube (thereby removing the need for a window) and a mechanically scanned hydrophone to sample the field (thereby greatly simplified calibration). The apparatus was transported down to CSS/Panama City to measure the properties of sediment samples removed from the Gulf of Mexico. The measured complex acoustic impedance exhibited the resonance characteristics of the sample holder, which was modeled as a fixed-length, 1-D waveguide. (See Fig. 3 for a representative data set.) With this model, and assuming a power law dependence on sound speed, it was possible to infer sound speed and attenuation over the frequency range of interest. Results exhibited reasonable agreement with model predictions, however, the attenuation values did appear to be somewhat elevated. We believe that this is due to added loss mechanisms at the wall of the tube that are not accounted for in the model. We are currently modifying the apparatus to support large tank and *in situ* measurements that do not employ a small-diameter sample holder.

RESULTS

The following tasks were either completed or significantly advanced during the reporting period. Details on the progress made in each task are given above. Below is a brief summary.

1. The impedance tube apparatus was used to measure the complex acoustic impedance of bubbly flows, and with this data we inferred the frequency dependent sound speed and attenuation of the bubbly mixture. Results compared well with models, however, we have yet to obtain data at the very high void fractions of interest (order 1%).

2. Working at the NUWC Underwater Test Facility, we successfully measured acoustic backscatter from well-characterized bubbly assemblages. Results compared well with simple models that treat the targets as classical scatterers consisting of effective media. We did not consider the role of individual bubbles, given that sub-resonant bubble sizes employed.

3. Using a novel technique for stabilizing a bubble – a viscoelastic polymer gel – we measured the frequency dependent response of an acoustically driven bubble across the resonance regime. Results compared very well with predictions using a Newtonian viscous model. We believe that this will be an extremely useful tool for studying in detail the interactions of a small numbers of bubbles when exposed to sound (i.e. bubble-bubble interactions, coupling, etc.).

4. Using a modified version of the impedance tube apparatus, we demonstrated that it is possible to measure the frequency-dependent impedance of saturated sediments in the laboratory setting. This instrument is amenable to low-frequency (sub kilohertz) measurements in a confined space. From the impedance, we infer frequency-dependent sound speed and attenuation given a viable propagation model of the test sample. This apparatus is currently be modified for *in situ* measurements and will be deployed in the field, given adequate funding to cover engineering design and fabrication costs.

IMPACT/APPLICATIONS

That bubble clouds can be driven to pulsate collectively is important to any assessment of scattering and attenuation from oceanic bubble clouds and layers. This research is important to understanding high frequency shallow water noise, propagation, mine hunting sonar systems, high power acoustic MCM arrays, and wake homing torpedoes. Furthermore, the acoustical measurement of bubble populations and circulation patterns depends on the physics of multiple scattering and absorption in bubbly mixtures. The persistence of micro-bubbles in the shallow water column is the limiting factor determining the resolution of sonar systems and needs to be quantified.

As for the sediment work, knowledge of the frequency dependent attenuation and sound speed is critical input to shallow water propagation and bottom interaction models. There is a paucity of data in the 1-10 kHz range, which are the frequencies targeted in this effort. In addition, the utility of popular poro-elastic models (Biot model) is compromised by the fact that too many un-measurable parameters are required to run the model. With data obtained in this study, we hope to develop simplified predictive models, applicable to the lower frequencies, in which the sediment is treated as a uniform viscoelastic medium. Finally, the next phase instrument development will be to create an apparatus for measuring in situ sediment properties at relatively shallow depths (less than 50 meters). With this capability, we hope to alleviate the scarcity of quality data in this critical frequency range.

RELATED PROJECTS

1. A collaboration with K. Commander of CSS and K. Williams of APL/UW involving the use of the impedance tube to measure sediment acoustics below 10 kHz is ongoing.

2. An ongoing collaboration with WHOI (Dr. J. Lynch) and RPI (Prof. W. Siegmann) provides for intensive numerical studies coupled with the planning and conduct of at-sea experiments in the 0.1 to 10 kHz range. This has enabled BU grad students to be Guest Students at WHOI.

PUBLICATIONS

Note: Because an annual report was not submitted to ONR for FY02, we include all publications and presentations for this grant for the period FY02 and FY03.

Wilson, P.S., Roy, R.A., and Carey, W.M., “An improved water-filled impedance tube,” J. Acoust. Soc. Am. 113, 3245-3252, 2003. [published refereed]

Wilson, P.S., Sound Propagation and Scattering in Bubbly Liquids, Ph.D. Dissertation, Department of Aerospace and Mechanical Engineering, Boston University, Boston, MA 2002. [published refereed]

McCormick, R.D., Experimental Investigation of Linear Bubble Dynamics in a Viscoelastic Xanthan Gel, M.S. Thesis, Department of Aerospace and Mechanical Engineering, Boston University, Boston, MA 2002. [published refereed]

Park, E.-J., Acoustic Characterization of Saturated Sediments using a Thick-Walled, Water-Filled Impedance Tube, M.S. Thesis, Department of Aerospace and Mechanical Engineering, Boston University, Boston, MA 2002. [published refereed]

W. Carey, P. Cable, W. Siegmann, J. Lynch and I. Rozenfeld, " Measurement of Sound Transmission and Signal Gain in the Complex Strait of Korea," IEEE Jour. of Oceanic Eng., Volume 27, No. 4, October 2002. [published refereed]

Rozenfeld , W. Carey, et al, " Modeling and Analysis of Sound Transmission in the Strait Of Korea", IEEE Journal of Ocean Engineering, Volume 26, No. 4 October 2001. [published refereed]

Roy, R.A.., Wilson, P.S. and Carey, W.M., “Some new experimental insights into the acoustics of bubbly liquids,” in Proceedings of the 17th International Congress on Acoustics, 2001. [published]

Carey, W.M. and Roy, R.A.., “Radiation and scattering from micro-bubble clouds,” in Proceedings of the 17th International Congress on Acoustics, Plenary and Invited paper,2001. [published]

R.A. Roy, W.M. Carey, P.S. Wilson, “The production and scattering of low-frequency sound by bubbly assemblages” To be presented at the 6th International Conference on Theoretical and Computational Acoustics, Honolulu, HI, August 2003. [invited presentation]

Roy, R.A.., Wilson, P.S., McCormick, R.D., Park, E.J. and Carey, W.M., "The acoustics of bubbles and bubbly assemblages: a suite of laboratory studies," J. Acoust. Soc. Am. 111(5 pt. 2), 2345 (2002). [invited presentation]

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(4 pt. 2), 2318 (2003). [presentation]

P.S. Wilson, E.J. Park, R.A. Roy, and W.M. Carey, "The measurement of acoustic dispersion in loosely consolidated, saturated sediments using a water-filled impedance tube," J. Acoust. Soc. Am. 112(5 pt. 2), 2363 (2002). [presentation]

P.S. Wilson, R.A. Roy, and W.M. Carey, "Measurements of the time-dependent attenuation in a non-stationary bubble distribution," J. Acoust. Soc. Am. 111(5 pt. 2), 2346 (2002). [presentation]

P.S. Wilson, R.D. McCormick, E.J. Park, R.A. Roy and W.M. Carey, "Broad band acoustic scattering from a bubbly-liquid filled compliant cylinder with known bubble population statistics," J. Acoust. Soc. Am. 110(5 pt. 2), 2778 (2001). [presentation]

R.D. McCormick and R.A. Roy, "Measurements of the frequency- and size-dependent response of single, acoustically driven bubbles suspended in a polymer gel," J. Acoust. Soc. Am. 110(5 pt. 2), 2733 (2001). [presentation]

HONORS/AWARDS/PRIZES

Preston Wilson was awarded the John H. and Helen Carey Fitzgerald award as the top graduate student in the Department of Aerospace and Mechanical Engineering, Boston University.

Ronald Roy was elected to the Technical Council of the Acoustical Society of America and was named Editor in Chief of Acoustic Research Letters On Line .

William M. Carey was named Associate Editor for Underwater Acoustics for the Journal of the Acoustical Society of America and is the Editor Emeritus Of the IEEE Journal of Oceanic Engineering and an elected member of the OES Advisory Committee.

W. Carey and R. Roy were invited to give a Plenary Paper at the 17th ICA.

W. Carey was asked to Chair the NRLS Peer Review Panel and R. Roy was a member of the NRLN Peer Review Panel. W. Carey was chosen to be the Environmental Acoustics' Session Chairman of The ONR LRAPP Convocation.