The Effects of Sediment Properties on Low Frequency Acoustic Propagation

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LONG-TERM GOALS

Our work focuses on understanding the frequency and depth dependence of compressional wave attenuation and developing new inversion schemes for shear wave properties. Our initial investigations have indicated that water-borne acoustic arrival properties such as their Airy Phase are sensitive to sediment shear properties. Our major emphasis this year has been to develop and test inversion schemes for simultaneous estimation of compressional and shear properties.

The long term goals of our research are to:

- Improve inversion schemes for the estimation of sediment geoacoustic properties using low frequency broadband acoustic signals at short and long ranges.
- Continue fine-tuning our Shear Measurement System, recently developed under a DURIP grant, for short-range interface/Scholte wave-based inversions for shear properties.
- Design, build and test the proposed Interface Wave Sediment Profiler (iWASP) system. This DURIP project was awarded recently and work on this project is expected to start soon.
- Adapt our long range sediment tomography technique for compressional and shear wave speeds, and attenuation profiles utilizing the broadband Combustive Sound Source (CSS) developed at the Applied Research Laboratories (ARL), University of Texas.

OBJECTIVES

We are pursuing the long term goals listed above by executing the objectives listed below.

A. Engineering tests: A shear measurement system has been developed and tested at URI as part of a DURIP grant. This geophone array based system will be prepared for deployment at the New England Mud patch during the Seabed Characterization Experiment. Modeling studies are in progress to design the Scholte wave experiment taking into account the unique nature of the sediment. Design, building and testing of the iWASP system will also be carried out in time for deployment at the NE Mud patch in 2017.

B. Signal processing: We continue to explore new signal processing techniques in order to extract the arrival times in our long-range sediment tomography technique and Scholte wave approach.

C. Modeling: Development of a forward model that can incorporate elastic properties and account for the natural layering in the sediments is an important objective of our study. In addition we are also undertaking studies on the mode conversion in range dependent environments. The topics of research can be summarized as follows:

a. Scholte wave dispersion modeling using Dynamic Stiffness method, Finite element modeling (in collaboration with ARL-UT (Marcia Isakson) and Finite Difference method.

b. Developing mathematical methods for modeling mode conversions in range-dependent environments. This work is carried out by Charles White as part of his PhD dissertation research.

D. Measurements and inversions: One of the major objectives of the study is to design and implement inversion schemes to estimate sediment geoacoustic properties. The tasks associated with this objective are summarized as follows:

a. Develop inversion schemes for speed and attenuation of compressional and shear waves using acoustic and Scholte wave data.

b. Deploy the Shear Measurement System in field experiments in preparation for the ONR seabed characterization experiment in the New England Mud Patch in 2017.

c. Develop high resolution (near seabed) inversion for sediment properties using interface wave techniques. The iWASP system will provide the data for this inversion.

E. Experiment design

We also propose a task to assist ONR and other PIs in designing a new shallow water experiment. A site has been identified in the New England Mud Patch which is close to the Shelfbreak Primer Experimental site. The PIs will participate in the planning workshops and contribute to the science objectives of the seabed interaction experiment.

APPROACH

A shear measurement system consisting of geophone/hydrophone array and WHOI-SHRU data acquisition system designed, developed and tested as part of a DURIP grant. Data were collected during three field tests so far which are being used to develop a scheme to estimate shear properties. Efficient inversion approaches are being developed for this purpose. Application of recent signal processing techniques is being pursued for improving the time-frequency analysis of the broadband data for better mode identification and extraction of modal arrival data for long range inversions. A new Interface Wave Sediment Profiler (iWASP) will be designed, developed and tested as part of another DURIP grant.

WORK COMPLETED

Former graduate student, Jennifer Giard, designed and performed a field test in Davisville Basin in Narragansett Bay, RI as part of her Master’s thesis study. Estimation of shear properties of the bottom using Scholte wave data is also being pursued currently. Current PhD student Charles White is focusing on the mode conversion effects in range dependent environments. Graduate student Chris Norton built a ‘sand box’ to perform high-resolution surface wave inversions. The PIs are preparing for the upcoming Seabed Experiment. Gopu Potty participated in the first leg of the seabed survey on board R/V Sharp in July-August, 2015.

RESULTS

A. Time delay estimation of Scholte wave arrivals

One of the problems encountered while processing the Scholte wave data is the effect of higher order modes. Often it becomes hard to identify and separate out the multiple modes when they are present. This could result in incorrect estimation of phase velocities. Empirical Mode Decomposition based techniques (Huang, et al., 1971) was used to explore the possibility of identifying higher order modes. We used Scholte wave data acquired during the Davisville, RI test (Giard, et al., 2013) to investigate this possibility. The EMD is a time domain method to decompose any a signal into a finite number of basis functions, which are derived from the signal (Huang, et al., 1971). These components are known as intrinsic mode functions (IMFs).

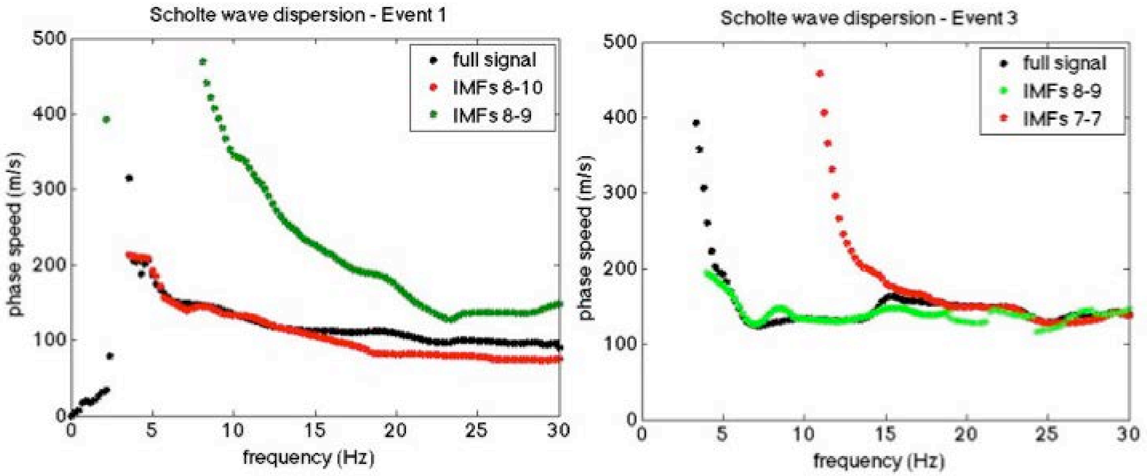

Figure 1. Phase velocity dispersion calculated using original data (black) and intrinsic modes (red and green) for two source events. The intrinsic mode based processing captures the higher modes in both events.

Arrival time difference on the two geophones can be calculated based on the phase difference extracted from cross-spectral density. Figure 1 shows the phase velocities calculated at different frequencies using the arrival time difference and known spacing of geophones. Phase velocities calculated using the entire time series from the two geophones for two source events are shown as black lines in the left and right panels. This traditional processing was able to extract the fundamental mode. But processing using the decomposed empirical modes (shown in red and green lines) was able to extract a higher mode on addition to the fundamental. The higher order modes provide additional information that is very useful for inversions if they can be successfully modeled using a forward model.

B. Shear Measurement System based on interface wave dispersion:

a. **Shallow water test in Davisville, RI:** A test of URI's Shear Measurement System was completed on February 5, 2013 in the Davisville Basin in Rhode Island (Giard, et al., 2013). The inversion scheme employed to invert the dispersion curve data into shear speed profiles provided results consistent with the range of shear speed values estimated from the boring logs at the Davisville site (Giard, et al., 2013). In addition to the shear wave speeds, we have also estimated shear wave attenuation. This inversion is based on spectral ratio technique (Broadhead, et al., 1994). We used the spectral ratio method to obtain estimates of the dimensionless parameter Q, which is inversely proportional to attenuation. This approach provides a depth and range averaged estimate of attenuation of shear waves. Figure 2 shows the estimates of shear wave attenuation obtained using the Davisville data. Left panel shows the shear wave attenuation as a function of frequency. The right panel compares the estimated values against the very limited published data on shear wave attenuation. The predictions from the Grain Shearing (GS) theory (Buckingham, 2014) are also shown in the figure as the black line. It can be seen from the figure that the estimated values fill in a data gap in the low frequency region. The inversions compare well with the GS predictions. Current work focuses on estimating depth dependent attenuation profiles using the Davisville data and providing model-data comparisons.

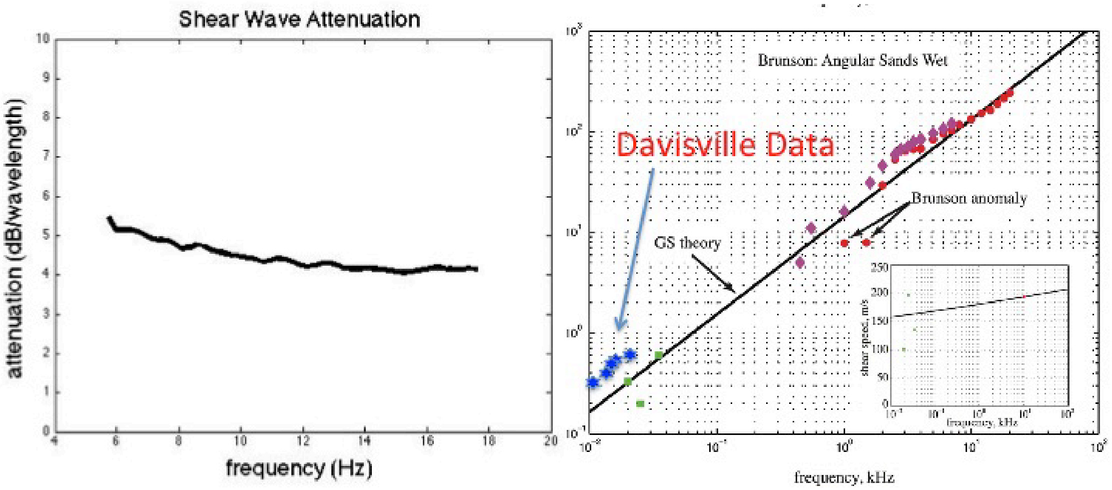

Figure 2. Shear wave attenuation estimated using the Davisville data (Left panel). Right panel compares the Davisville data with published data and GS theory.

b. Test on land – Gainer Dam, RI: The shear measurement system was deployed as part of a project that focused on the preliminary evaluation of the seismic performance of the Gainer Memorial dam in RI. The shear wave velocities were calculated from the Rayleigh surface wave velocities. The shear wave velocity obtained from the inversions predicted a loose layer of soil at a depth of approximately 21 meters (Figure 3) that corresponds to the soils composing the core trench (very loose sediment). This layer of loose soil was subsequently verified through Standard Penetrometer Test (SPT).

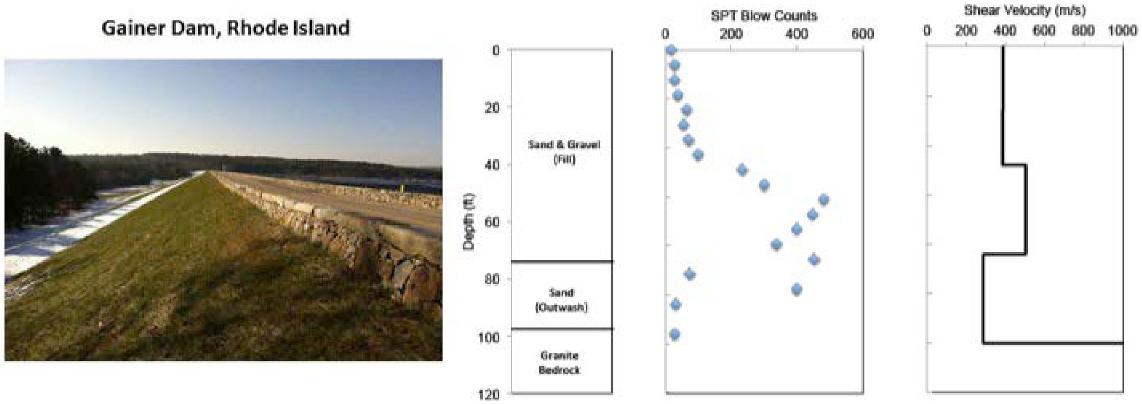

Figure 3. Shear wave profile of Gainer dam (shown in the left panel) calculated using the inversion (right panel) compared to Standard Penetration Test (SPT) results.

D. Modeling

Efforts are underway to develop better modeling tools to understand the wave propagation physics and for incorporation into inversion schemes. This work was part of graduate student Holly Clark's Masters work and we collaborated with Ralph Stephen (WHOI). Simulations using a Time Domain Finite Difference (TDFD) code developed by Ralf Stephen at WHOI were carried out for an environment similar to the Primer location. The water depth was assumed 100 meters. The bottom consisted of a low speed layer 12 meters thick with a compressional wave velocity of 1530 m/s, a shear velocity of 100m/s and a density of 1400kg/m^3. This was over a faster homogeneous half-space with a compressional velocity of 1700m/s, and a shear velocity of 500m/s, and a density of 1800kg/m^3. Figure 4 shows a snapshot of various wave types in the sediment layers at a specific time instant. The low velocity layer layer is from 100 m to 112 m. You can see the Scholte wave on both plots. There is also an evanescently generated shear wave just below the Scholte wave. This model in particular will prove to be very helpful in predicting expected results for acoustic tests in a muddy environment.

E. High Resolution Profiling of Ground Properties using Rayleigh Wave Dispersion

This project was funded by US Army Research Laboratory (Greg Fischer, POC). Our goal is to demonstrate the utility of Rayleigh wave dispersion for estimating the properties of the top 1 to 2 m of soil and/or pavement. A laboratory 'sand tank' was constructed and instrumented with accelerometer array to measure surface waves. The 'sand box' has dimensions 8ft x 4 ft x 2 ft and is filled and compacted with three layers of sediment with different shear speeds (soft 50 m/s, medium 100 m/s and hard 150 m/s). Bender elements were also inserted in the layers at different depths to measure shear speed. In addition, a laser was also used to measure the surface wave displacements for comparison with accelerometer measurements. The accelerometer measurements were used for our inversion technique to produce estimate of the shear speed in three layers of sediment and compared with bender element measurements. In Figure 5 top left panel shows the comparison of accelerometer and laser data. Bottom right panel shows the shear speeds values estimated by the bender elements. The bottom left panel shows the observed phase speed dispersion compared with model predictions based on the shear speed values shown in the bottom right panel. Graduate student Chris Norton presented this work at the Acoustical Society of America meeting in Pittsburgh and won the best student paper award.

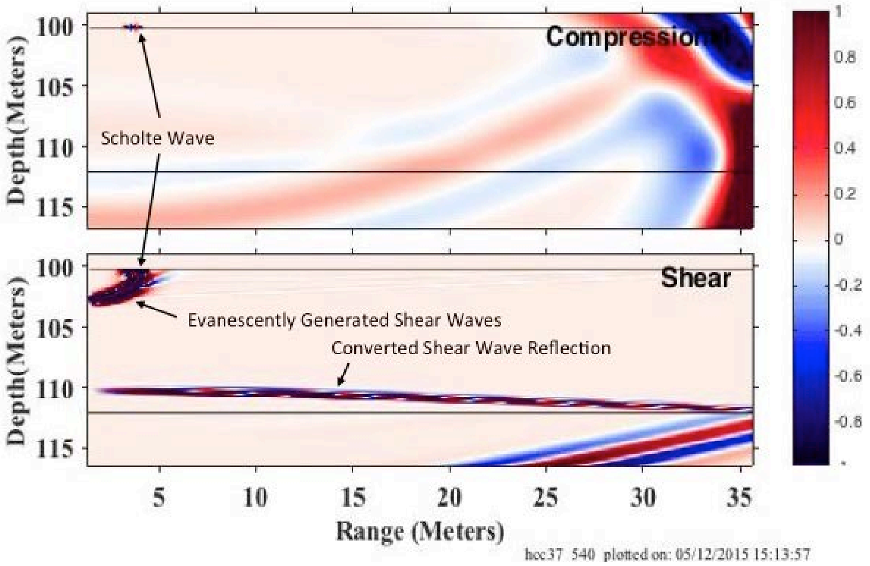

Figure 4. Snapshot of the propagating waves modeled for a slow sediment layer over a fast half-space. The Scholte wave can be seen in the compressional wave (top panel) and shear wave (bottom panel). There is also an evanescently generated shear wave just below the Scholte wave.

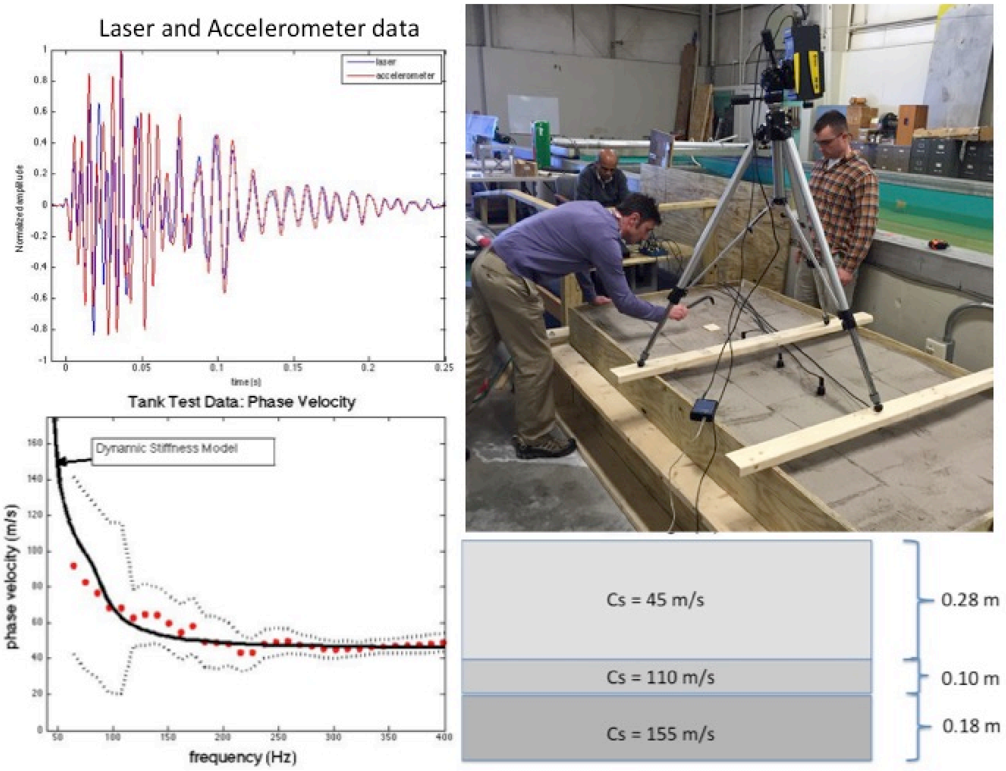

Figure 5. Results from the 'sand box' experiments. Bottom right panel shows the shear speed in the three layers obtained from the bender elements. Bottom left panel shows the observed (red dots) and modeled (black line) – using the shear speed values- phase speed dispersion. Top right panel shows the sand box with instrumentation including the laser. Top left panel shows the comparison of laser and accelerometer data.

D. Experimental designs for the Seabed Characterization Experiment.

We currently are designing experiments to measure geoacoustic properties in anticipation of the upcoming Seabed Characterization Experiment in the New England Mud Patch area. The 1996 Shelfbreak Primer experiment (Potty, et al., 2000) was conducted on the western edge of the 'mudpatch' as shown in Figure 6. The average thickness of the soft surface layer in the Primer experimental area is approximately 2 m (Twichell, et al., 1981). Acoustic (SUS charges), oceanographic (SeaSoar) and geotechnical (sediment cores) data were collected as part of the Primer experiment. Locations of the SUS charges, gravity cores and the Vertical Line Arrays are shown in Figure 6. The acoustic and geoacoustic data from the Primer experiment is being revisited and documented in preparation for the field study in the Mud Patch. A poster summarizing the Primer data will be presented at the Acoustic Society of America meeting in November, 2015. Preliminary modeling of Scholte wave dispersion modeling is being currently done using the Primer data and simulated Mud Patch data. The phase velocity of Scholte waves shown in the right panel of Figure 7 as modeled using the shear speed profile shown in the left panel. The red curves in both panels correspond to the Primer sediment properties (based on previous inversions). The black curves correspond to a scenario corresponding to a layer of mud with very low shear speed in the upper 8 m of sediment. The contrast in dispersion characteristics between these two scenarios is dramatic and will be carefully considered in the design of the Scholte wave experimental plan.

IMPACT/APPLICATIONS

The inversion scheme using explosive sources is suitable for rapid estimation of acoustic properties of sediments in shallow water. This method is cost effective as a single sonobuoy and air-deployed explosives can provide the data. Using multiple sources and receivers sediment properties would allow an area to be mapped. Scholte wave based methods are ideal for the estimation of shear speed in the bottom.

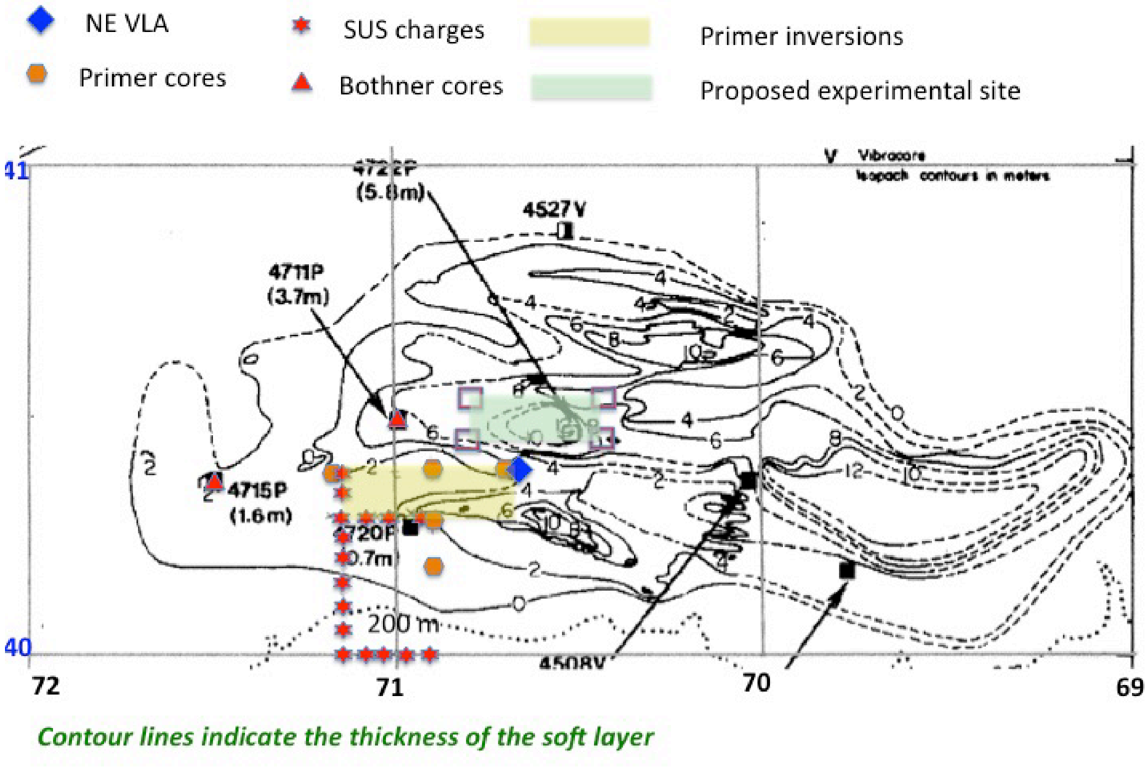

Figure 6. Shelf Break Primer Experiment site showing the locations of the broadband sources, vertical line array (NE VLA) and gravity cores. The yellow box indicates the region where geoacoustic inversions were performed and the green box shows the region where the proposed experiment is planned. The mud thickness contours from Twichell et al. (1981).

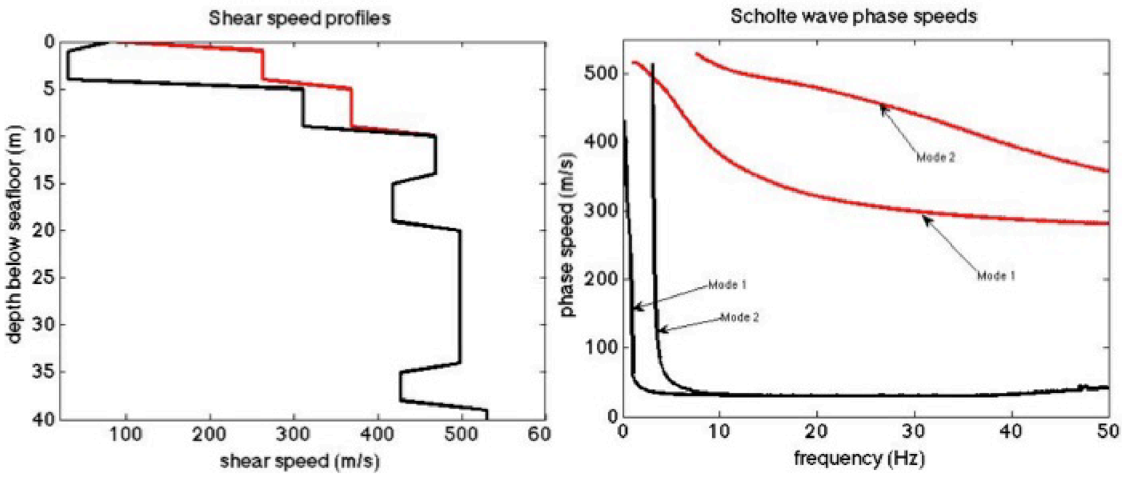

Figure 7. Phase velocity dispersion modeled using the Primer geoacoustic data (red curves) and simulated mud data (black curves). Shear speeds corresponding to the Primer and mud patch scenarios are shown in the left panel.

TRANSITIONS

The sediment parameters obtained by this inversion will compliment the forward modeling efforts. The sediment tomography technique is suitable for forward force deployment when rapid assessment of environmental characteristics is necessary. In addition to naval air ASW applications using sonobuoys and SUS charges, this technique would be compatible with Navy special operations involving autonomous vehicles.

RELATED PROJECTS

1. Title: **Interface Wave Sediment Profiler**
PIs: James H. Miller and Gopu R. Potty (URI)
Total Request: $ 337,443
Start Date: August 15, 2015
Duration: One year
Submitted to: DURIP -CFDA #12.300 (Office of Naval Research)
ONR Program Manager: Dr. Kyle M. Becker, Code 322 OA

Project Summary
Recently, there has been a revolution in the understanding of the role of the seafloor in acoustic transmission loss and sonar performance in littoral waters. In particular, a large part of the acoustic bottom loss and attenuation has been shown to be tightly correlated to the shear properties of the sediment. We propose to develop the Interface Wave Sediment Profiler (iWaSP) for the measurement of bottom properties such as shear speed and attenuation in the top 1-2 meters of a variety of sediment types (including mud) with a wideband, vibratory source and accelerometers with bandwidth up to 1 kHz. The Principal Investigators of this proposal have previously developed a measurement system based on Scholte wave dispersion to partially address this goal. A low frequency geophone receive array and data acquisition package was acquired under a previous DURIP grant for estimating the shear wave speed in shallow water sediments at deep depths with lower resolution. This system is capable of measuring interface waves of frequencies below 50 Hz and estimating the sediment properties down to 10s of meters with a depth resolution of the order of a meter in the near seafloor sediment layer. We have successfully tested this low-frequency system by deploying it in a few shallow water locations in Narragansett Bay. The proposed new system will complement the existing one since by using high frequency source and receivers to achieve higher resolution (10s of cm) in the near seafloor sediment layer (top 1-2 m). Both the existing and proposed new systems will be fully compatible and complementary. By deploying both the systems simultaneously we can infer shallow sediments with high resolution (using high frequencies) and deeper sediment layers (using low frequencies). In addition, the iWaSP system has the potential to be deployed on ice to measure the elastic and acoustic properties of the ice sheet. The same principles are being applied by the PIs to the measurement of soil properties on land.

The proposed new system includes an electronic vibratory source capable of generating interface waves in the seafloor at frequencies up to 1 kHz and a short line array of accelerometers with matching frequency response. A deployment system to house the source and extend the receive array will also be developed. The iWaSP system will be designed to provide adequate coupling between the receiver and the sediment and decouple the source-induced structural vibration from the receive array. The system has been designed to reduce the acoustic source level in the water below 160 dB re 1 µPa at 1 m and therefore minimize any effects on any marine mammals. The overall goal of the research using the proposed system is to understand the effects of these sediments properties on acoustic propagation and thereby improve the understanding of Navy sonar system performance in littoral waters. The frequency dependence of attenuation in the sediment is a subject of intensive investigations from a number of researchers and institutions. One of the key components of the attenuation is the conversion of acoustic energy into shear waves at interfaces including the seafloor. In addition, the iWaSP system provides the capability to measure the shear speed profile as well as the attenuation in the top few meters of a variety of bottom types including mud, silt, and sand. The system will have the bandwidth to measure interface wave speeds (and hence shear speed profiles) from 100 m/s typical of muds to 500 m/s typical of hard sands. The depth resolution of the profile is expected to be in the range of a few centimeters. The deployment and mooring system will allow for the effective coupling between the sediments and the source and sensors. The iWaSP deployment system design can be adapted to be effective in hard sediments such as sand and soft bottoms such as mud. We have partnered with Falmouth Scientific Inc. of Bourne, Massachusetts to develop the vibratory source and electronics and Woods Hole Oceanographic Institution to develop the deployment and recovery system including the cabling as well as the iWaSP Stinger to effectively deploy a linear array of accelerometers.

2. Title: **High Resolution Profiling of Ground Properties using Rayleigh Wave Dispersion**
PIs: James H. Miller**,** Gopu R. Potty**,** Aaron Bradshaw**,** Christopher D. P. Baxter (URI)
Total Request: $ 85,000
Start Date: October 1, 2015
Duration: One year
Submitted to: US Army Research Laboratory
ARL Program Manager: Dr. Greg Fischer, Code RDRL-SES-P
Project is starting this year and involves field tests on land of Interface Wave Sediment Profiler "stinger" recently awarded by the DURIP program for deployment of accelerometers with no penetration enabling the highest possible resolution in URI Interface Wave Test Facility, highway testbeds, and other locations. We will fabricate a new set of layers for the Interface Wave Test Facility including clay layer. This set of layers and their properties will be designed and installed in coordination with the Army Research Laboratory.

3. Title: **Noise Measurements during Block Island Wind Farm Construction**
PIs: James H. Miller **and** Gopu R. Potty
Total Request: $ 85,000
Start Date: August 1, 2015
Duration: One year
Submitted to: HDR, Inc. (BOEM prime)
BOEM Program Manager: Dr. Mary Boatman

The University of Rhode Island (URI) is measuring the underwater acoustic pressure and particle motion at sites as near to the piling events The pressure and particle motion are being measured at the seafloor using the URI geophysical sled equipped with an OYO Geospace Sea Array Gimbaled 3-D Geophone deployed 5 meters from the sled and its data acquired by a Wood Hole Oceanographic Institution (WHOI) Several Hydrophone Receive Unit (SHRU) Data Acquisition System. WHOI prepared the SHRU data acquisition system and also designed and built mooring equipment for the in-water measurement system. URI has deployed a 4-hydrophone vertical array of hydrophones at a range of 750 meters from piling driving events. HTI-94-SSQ type hydrophones are used for this measurement and the data acquisition system is a WHOI SHRU. Hydrophone spacing is 5 meters with the lowest hydrophone just above the seafloor. Transect measurements of the acoustic field from as close to the pile driving event out to a range of 30 km (or the 120 dB re 1 μPa rms level, which ever is less) using a towed hydrophone array are being made using a Hydroscience 8 hydrophone towed array deployed from the URI Research Vessel Shanna Rose for a number of piling driving events. Marine Acoustics, Inc. (MAI) will operate the towed array and data acquisition system.

4. Title: **Remote Sensing of Sub-Surface Structure of Extraterrestrial Bodies using Laser Doppler Velocimetry Measurements of Rayleigh Waves**
PIs: James H. Miller, Gopu R. Potty, and Tao Wei
Total Request: $175,965
Start Date: August 1, 2015
Duration: Three years
Submitted to: NASA EPSCOR
RI Space Grant Program Manager: Dr. Peter Schultz (Brown U.)

We plan to measure Rayleigh waves using laser Doppler vibrometers with application to the estimation of the elastic medium properties of the substructures of a planetary body or satellite. Rayleigh waves are vertically-polarized propagating waves that are trapped at the interface between an elastic medium and a vacuum like Europa (or low density atmosphere such as Earth's or Titan's). These waves can propagate large distance because their amplitudes decay primarily as one over square root of range as opposed to compressional (P) and shear (S) waves that decay as one over range. These waves are the cause of much damage due seismic activity on Earth. Impactors on the moons and rocky planets can also excite Rayleigh waves. It is reasonable to assume that these waves can propagate in ice sheets on Europa. Interface waves at the seabed are called Scholte waves and those waves at the interface of two elastic media are called Stonely waves. The presence of these features implies that the surface is being churned by the underlying liquid water and the surface of the Europan ice sheet most likely supports these interface waves spreading from these lenticulae and ridges as they are formed.

The dispersion of the speed of Rayleigh waves (often referred to as P-SV waves) as a function of frequency is dependent on the underlying vertical profile of elastic medium properties such as the shear modulus/speed. A number of models are available to estimate the Rayleigh wave dispersion given the elastic properties of the medium. A number of techniques have been developed for the estimation of the vertical shear speed given measurements of Rayleigh wave dispersion from explosions, impacts and other energetic sources using these models.

Measurements of Rayleigh waves have traditionally been carried out using geophones at low frequencies and accelerometers at mid- to high frequencies. Recently, we have investigated the use of laser Doppler vibrometers (LDV) for the measurement of Rayleigh wave motion. The laser vibrometers use the Doppler shift of reflector motion to infer velocity in the direction of the beam.

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HONORS/ AWARDS/ PRIZES

Gopu Potty is serving as one of the Associated Editors for IEEE Journal of Oceanic Engineering since July, 2011.

Gopu Potty will chair a session at the Acoustical Society of America Jacksonville, FL meeting to be held in Nov. 2015.

Graduate student Chris Norton won the students paper award (AO) for his paper: "Laboratory and field measurements of Rayleigh waves" co-authored with the PIs at the Pittsburgh meeting of the Acoustical Society of America (2015).

Gopu Potty is serving as the Acoustical Oceanography representative to the ASA Committee on Standards (ASACOS)

Gopu Potty is serving on the International Advisory Committee and Technical Committee of the 2015 International Symposium on Ocean Electronics, India, 17-19, November, 2015.

James H. Miller served as President of the Acoustical Society of America in 2013-2014.

James H. Miller is serving on the ASA Foundation Board of Directors for the term of 2015-2018.

FarSounder, Inc. of Warwick, RI, co-founded by **James H. Miller**, was been selected to be honored with the 2015 Tibbetts Award for Innovative and Outstanding Contribution to the Small Business Innovation Research (SBIR) Program.

James H. Miller and **Gopu R. Potty** were co-chairs of the 167th Meeting of the Acoustical Society of America, May 5-9, 2014, Providence, Rhode Island.

James H. Miller served as Deputy Chief Scientist and Department Head at the NATO Centre for Maritime Research and Experimentation in La Spezia, Italy from June, 2011 to August 2013.