

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.
- 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 propose to pursue the long term goals listed above by executing the objectives listed below.

A. Engineering tests: A shear measurement system is recently being developed and tested at URI as part of a DURIP grant. Additional sensors will be integrated into this system and further engineering tests will be conducted to make the system ready for deployment during future ONR field tests. The tasks associated with this objective can be summarized as follows:

- a. Conduct a number of engineering tests on land and in the shallow waters of Narragansett Bay of the URI Shear Measurement System.
- b. Enhance the capability of the system by integrating and testing 3-axis geophones.
- c. Test the SHRU receiving system with both hydrophones and geophones.

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. Following tasks will be part of this objective:

- a. Adapt new signal processing algorithms (warping transform¹ and modified S-transform²) for time-frequency analyses for more accurate extraction of modal arrival times and frequencies especially near Airy frequencies.
- b. Continue the development of techniques for identifying surface wave arrivals on both the vertical axis and 3-axis geophones.

C. Modeling: Development of a forward model which can incorporate elastic properties is an important objective of our study. We have used a simple model developed by Chapman and Godin³ to predict the Scholte wave arrivals for an ocean bottom assuming power-law variation of shear speed as a function of depth. This fast and simple model does not account for the natural layering in the sediments and we plan to:

- a. Extend the investigation into shear effects using layered bottoms using models based on dynamic stiffness methods. Finite element modeling also will be explored in collaboration with ARL-UT (Marcia Isakson).
- b. Develop an inversion scheme to estimate shear profile using a suitable model identified in task (a).

D. Measurements and inversions: One of the major objectives of the study is to design and implement inversion schemes to estimate sediment geoacoustic properties. Existing long range sediment tomography technique for compressional wave speed estimation and the new short range shear wave speed estimation using Scholte wave data will be pursued. The tasks associated with this objective are summarized as follows:

- a. Develop inversion schemes for compressional and shear profiles using Scholte wave data.
- b. Deploy the Shear Measurement System in field experiments in preparation for the ONR seabed characterization experiment in the Gulf of Mexico.

E. Experiment design

We also propose a task to assist ONR and other PIs in designing a new shallow water experiment. A number of possible sites, water depths, and sediment types will be considered. 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 was designed and developed 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.

WORK COMPLETED

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. She extended the work initiated by another

graduate student, Jeannette Greene, who performed limited testing of a shear measurement system. Estimation of shear properties of the bottom using Scholte wave data is also being pursued currently. PhD student Hui-Kwan Kim is focusing on finite element modeling of wave propagation. Another graduate student, Edwards Richards, focused on the impact of environmental uncertainty on Adjoint based inversions. Graduate student George Dossot has completed his Ph. D dissertation and is currently preparing manuscripts based on this work for publication. Some of the results from these investigations are highlighted below. The PIs also participated in the Seabed Experiment planning meeting held during the Kansas City ASA meeting in 22-26, October, 2012.

RESULTS

Some of the results of work completed during last year are summarized in the following sections.

A. Adjoint based inversion

The adjoint inversion method has been used to measure both the range independent ocean sound speed environment and acoustic bottom properties. Graduate student, Edwards Richards, explored the limits of environmental conditions under which the adjoint method can be expected to converge to the correct result. Adjoint inversions were performed in this study using synthetic acoustic data created using glider based sound speed measurements, which was carried out by the NATO Centre for Maritime Research and Experimentation (CMRE) in a marine region off the western coast of the Gulf of Taranto, Italy. The test setup used in the simulation study is shown in Figure 1 (left panel) with two hypothetical arrays at 4 km and 6 km. The convergence results of simulation study are shown in Figure 1, which demonstrate the strong dependence of the performance of the adjoint inversion on range. In the 4 km case the RMSE error of the all inversions was comparable to the mean RMSE of these inversions. In the 6 km transmission case there are several very significant outliers, in some cases reaching one standard deviation of scaled RMSE. This heuristic error criterion implies that 6 km is at the limit of the viability of the adjoint inversion method.

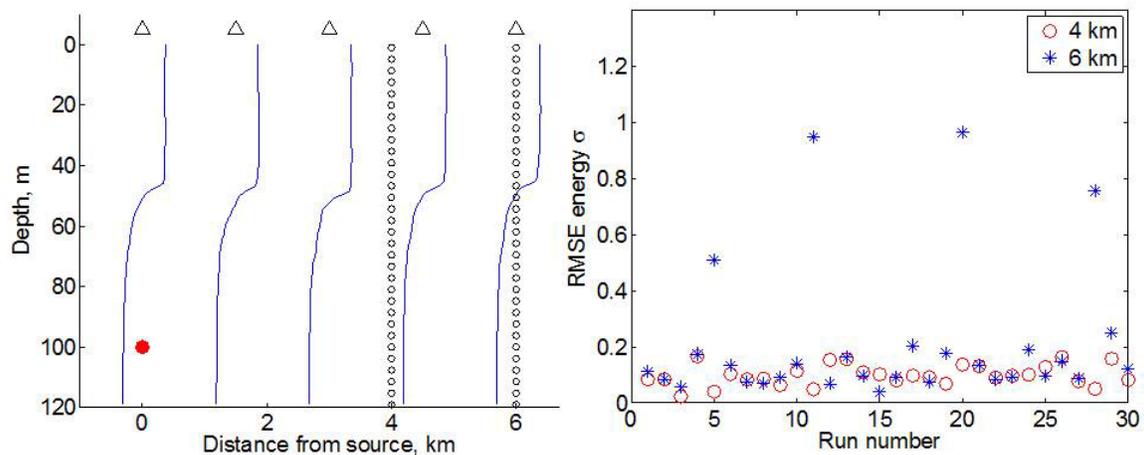


Figure 1. Basic numerical simulation setup (left panel). The source is deployed at range 0 and a depth of 100 m, shown as a red dot. The location of each sound speed profile is designated by a triangle along the top horizontal axis. Each circle at the range of 4 and 6 km designates an element in a 32 element array. Right panel shows the comparison of inversion results with increasing range.

B. Time-frequency analysis techniques

Long range sediment tomography inversion technique requires accurate estimation of the arrival times of acoustic normal modes. The modal arrival times are calculated from the time-frequency analysis of broadband acoustic data collected on a single hydrophone. Taking advantage of some of the recent developments, dispersion based short time Fourier transform (DSTFT) and warping transform techniques were used for the time-frequency analysis, in recent times. The time-frequency diagrams shown in Figure 2 were generated using the warping transform approach which is described in detail by Bonnel and Chapman¹. This warping function transforms the modal components to monotonies at the modal cut-off frequencies. For any mode m the procedure to create a dispersion diagram consists of warping the time series, filtering out the warped mode, and un-warping this mode. The steps involved in creating the time frequency diagrams are illustrated using CSS data from the SW-06 experiment in Figure 2. We plan to apply this technique to broad band signals (both hydrophone and geophone data) to improve mode identification and thereby extract the modal data more accurately.

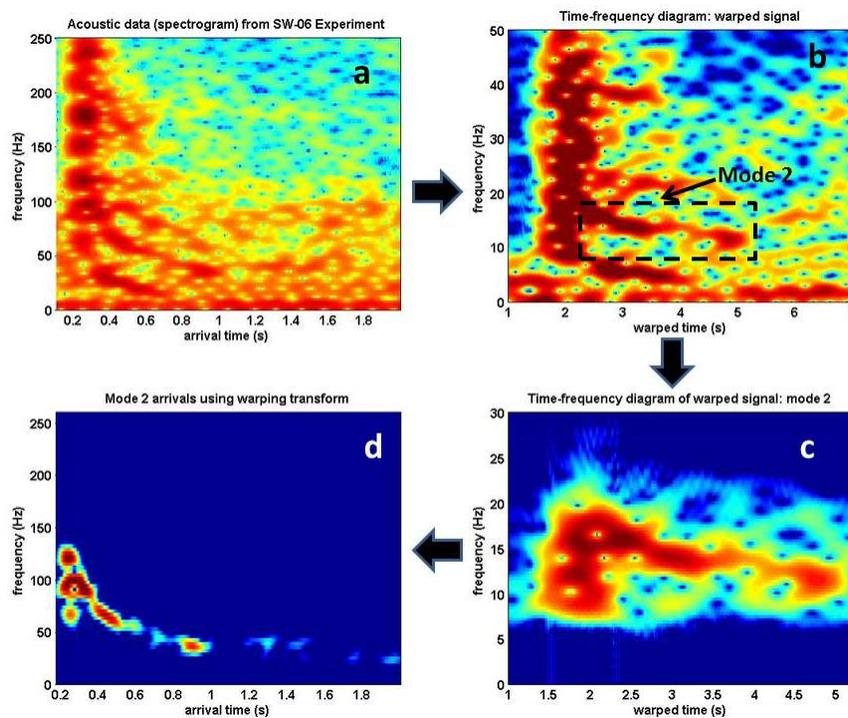


Figure 2. *The different steps involved in the time-frequency analysis using warping transform approach. (a) The Short Time Fourier Transform (STFT) of the original signal. (b) The STFT of the warped signal. The x-axis is the warped time. The acoustic modal arrivals are now seen as tonals. (c) band pass filtered mode 2 arrivals in the warped domain. (d) Mode 2 arrivals in the actual time (x-axis) after inverse warping.*

C. Shear Measurement System based on interface wave dispersion:

We have acquired a geophone/hydrophone array under a DURIP grant (*Seafloor Shear Measurement Using Interface Waves*, Miller and Potty PIs) capable of collecting interface wave data. Using the dispersion characteristics of the interface wave data we plan to invert for shear wave speed. A test of URI's Shear Measurement System was completed on February 5, 2013 in the Davisville Basin in Rhode Island using a 114 kg weight impacting the bottom. The array was deployed twice over boring

locations (BH-15 and BH-8). We used three different correlation relationships to convert the reported N-values from the borings to a shear speed profile. The components of the shear measurement system and the locations of the array and weight drops for both deployments relative to the borings are shown in Fig.3. The composite dispersion curves calculated using multiple geophone pairs are shown in Fig. 4. These averaged dispersion curves were then run through the inversion scheme to determine the best fit power-law shear speed profile. The inverted shear speed profiles were then compared to the range of shear speed values estimated from the blow counts contained in borings BH-15 (Figure 4). The theoretical dispersion curve calculated using the inverted shear speed profiles was compared to the data as shown in Figure 4.

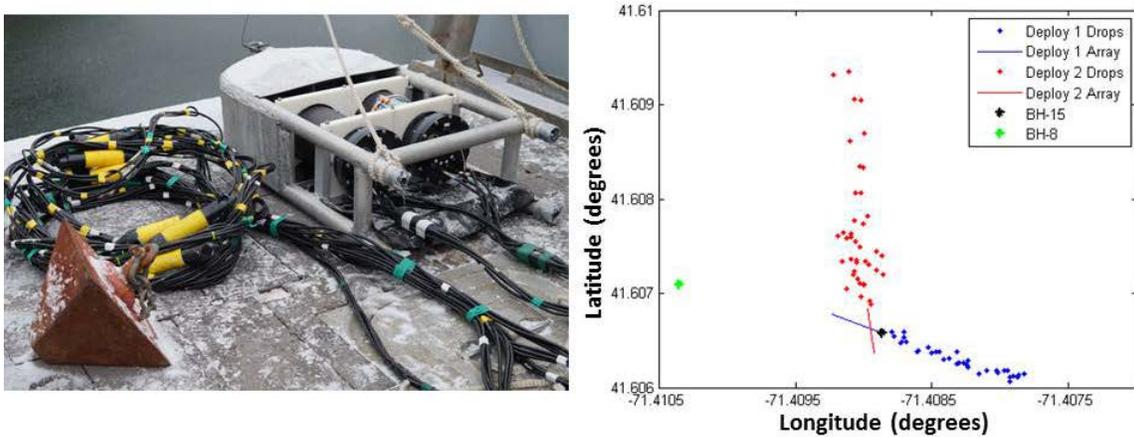


Figure 3: The sled with the SHRUs (left panel) on the deck of R/V Shanna Rose ready to be deployed during the sea test at Davisville, RI. The geophone array and the weight can also be seen in the picture. Right panel shows the locations of the geophone array and the weight drops for deployment 1 (in blue) and deployment 2 (in red).

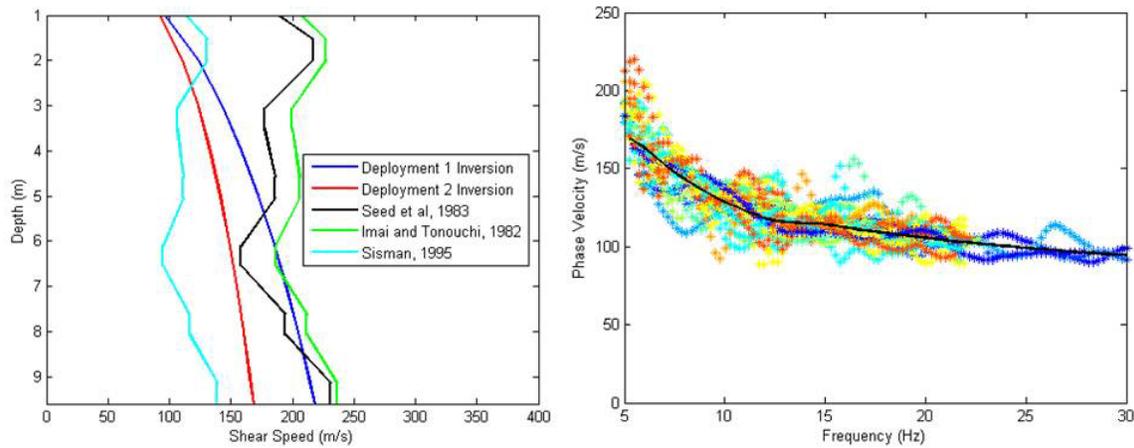


Figure 4: Comparison of the shear speed profiles (left panel) estimated for Deployment 1 and Deployment 2 at the Davisville site with the range of shear speed values estimated from the SPT blow counts (using three different methods) contained in boring log BH-15. Right panel shows the theoretical dispersion (black line) calculated using Godin-Chapman model for the inverted shear speed profile compared with the data. The different geophone pairs are represented by the different colors.

D. Modeling

Efforts are underway to develop better modeling tools to understand the wave propagation physics and for incorporation into inversion schemes. The focus in this effort is mainly to model the interface wave propagation and also to model near source propagation. An interface wave propagation model based on dynamic stiffness matrix approach was developed and validated. Near source propagation was also modeled using Finite Element approach (Kim). This work is summarized here.

a. Dynamic stiffness matrix approach: In the new model based on the dynamic stiffness matrix approach, the dispersion relationship for the Scholte wave has been computed from the global stiffness matrix K_{total} of the water over layered bottom system. The sediment is assumed elastic in this analysis and the dynamic stiffness matrix of the complete bottom (K_{total}) is obtained by assembling the stiffness matrices of the individual sediment layers and the bottom half space. The model was validated by comparing the output of the model with results from Rauch⁴ for a shallow water waveguide with layered bottom. Fig. 5 shows the output of the present model with Rauch's results. The agreement between Rauch's results and output of the present model is very good.

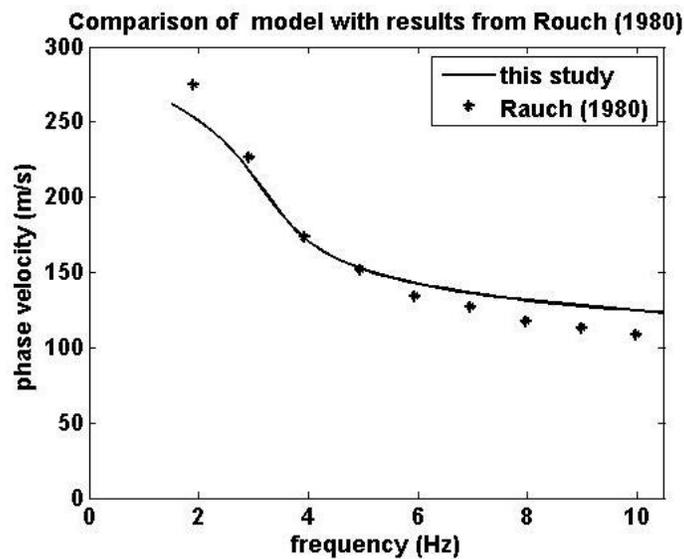


Figure 5. Comparison of the present model with results from Rauch⁴. The bottom model used in the model consists of four layers of sediment above the half-space. The properties of the sediment used in the model calculation are from Rauch⁴.

b. Finite Element modeling:

This study was carried out in the context of radiation of acoustic waves due to impact pile driving. To simulate offshore impact pile driving noise, a commercial Finite Element (FE) code, (Abaqus 6.11) and a standard underwater acoustic propagation model (Monterey-Miami Parabolic Equation (MMPE) model) have been used. We used the FE code to model the harmonic response of the pile and to calculate the acoustic pressure amplitude on the surface of the pile due to impact loading. The complex acoustic pressure amplitudes were used as a starting field at corresponding frequencies for the MMPE propagation model. The analysis was carried out in 26 m of water and 20.8 m of sediment. The length and radius of the pile are 46.8 m and 1.8 m respectively in this model. An example of the FE output is shown in Figure 6 and it is compared to the finite difference modeling done by Stephen⁵.

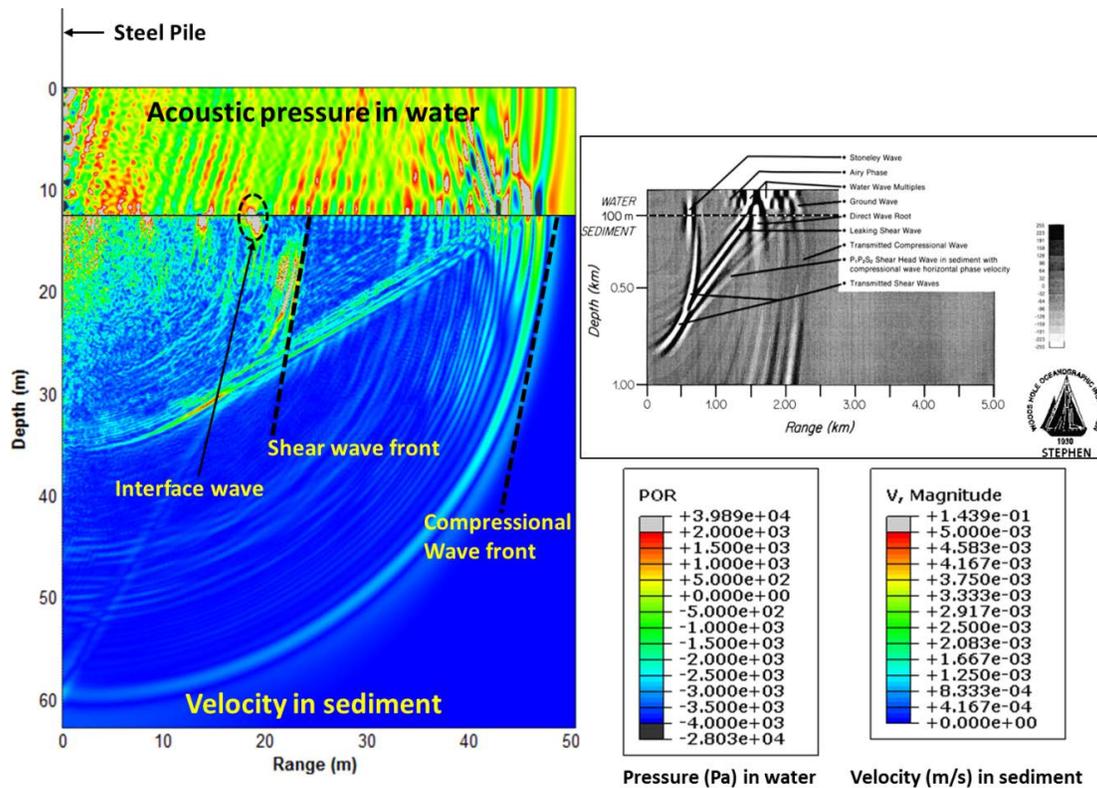


Figure 6: The acoustic pressure in the water column (0 to 26 meters depth), and the particle velocity in the bottom to a range of 50 meters. On the right is a comparison to the finite difference modeling of Stephen⁵.

E. Re-calibration of blast sensors used in confined rock removal during the Columbia River Channel Improvement Project

The PIs are currently advising a group of senior undergraduate students in the Re-calibration of blast sensors used in confined rock removal during the Columbia River Channel Improvement Project. This project is to support the Pacific Northwest National Laboratory, Sequim, WA and United States Army Corps of Engineers, Portland OR in their effort to validate the data acquired during the blasting operations using blast sensors and hydrophones. This effort will properly re-calibrate the data which could then be used to investigate the effects of blasting on fish and marine mammals.

F. CMRE research results

One of the PIs (Miller) took a leave of absence from the University of Rhode Island at the NATO Centre for Maritime Research and Experimentation from June 2011 to August 2013. One technical accomplishment of note was on the project entitled “Glider Acoustic Sensing of Sediments (GLASS).” Two sea trials were conducted during the period, one in 2012 off the Versilian Coast in the Mediterranean Sea and one in 2013 conducted in the Gulf of Mexico off Panama City. The concept involved the estimation of sea floor sediment properties using ambient noise measured on an array mounted to an underwater vehicle. The sensors employed and mounted on the eFOLAGA autonomous underwater vehicle were the compact tetrahedral and vertical hydrophone array. Figure 7 shows preliminary results from the 2012 experiment in which the AUV was mounted on a frame directly above the seafloor.

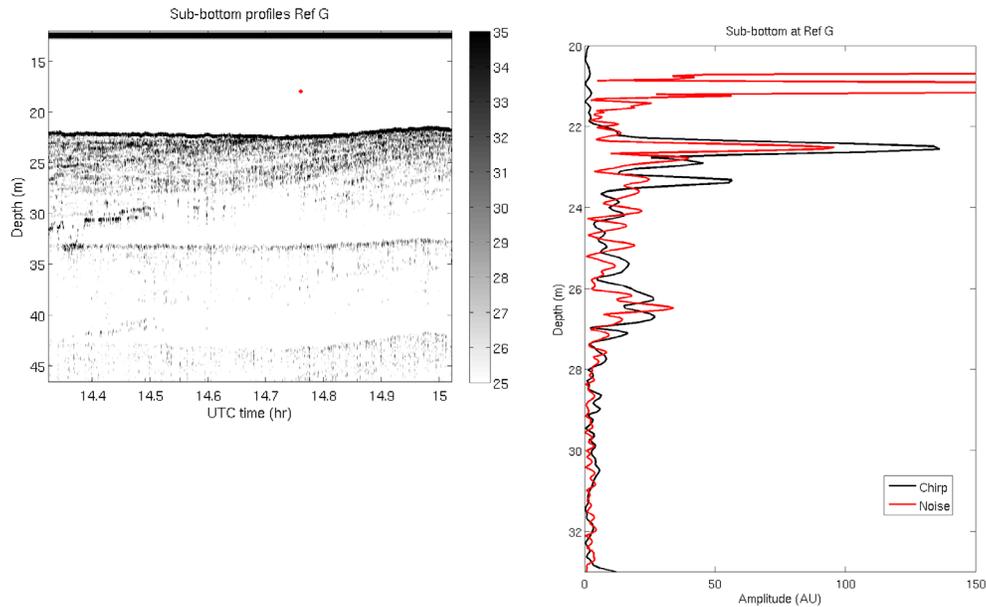


Figure 7. On the left is the sub-bottom profile results from a chirp sonar for the seafloor off the Versilian Coast in the Mediterranean Sea. On the right is the sub-bottom profile inferred from ambient noise as measured on the vertical array mounted in the AUV.

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.

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

None

REFERENCES

1. I. Tolstoy, "Dispersive properties of a fluid layer overlying a semi-infinite elastic solid," Bulletin of the Seismological Society of America, 44(3), 1954.
2. Bonnel, Chapman, "Geoacoustic inversion in a dispersive waveguide using warping operators," J. Acoust. Soc. Am. 130 (2), 2011.

3. D. M. F. Chapman and O. A. Godin, "Dispersion of interface waves in sediments with power-law shear speed profiles. II. Experimental observations and seismo-acoustic inversions," *J. Acoust. Soc. Am.* 110 (4), 1908-1916, 2001.
4. D. Rauch, "Seismic interface waves in coastal waters: A review," SACLANT ASW Research Centre, Tech. Rep., 1980.
5. R. A. Stephen, "Head waves, diving waves, and interface waves at the seafloor," *J. Acoust. Soc. Am.*, vol. 118, no. 3, pp. 1968-1969, 2005.

PUBLICATIONS

1. Crocker, S. E.; Miller, J. H.; Potty, G. R.; Osler, J. C.; Hines, P. C., "Nonlinear Inversion of Acoustic Scalar and Vector Field Transfer Functions," *IEEE J. Ocean. Eng.*, 37(4), 589-605, 2012, [refereed].
2. James H. Miller, Gopu R. Potty and Hui-Kwan Kim, "Pile driving pressure and particle velocity at the seabed: Quantifying effects on crustaceans and groundfish," in *Effects of Noise on Aquatic Life II*, eds. Popper, Arthur and Hawkins, Anthony, Springer, 2014 [to be published, refereed].
3. Giard, J., Potty, G. R., Miller, J. H., and Baxter, C. D. P., "Validation of an Inversion Scheme for Shear Wave Speed using Scholte Wave Dispersion," *OCEANS 2013*, September 23-26, San Diego, USA, (2013) [accepted, refereed].
4. Richards, E and Potty, G. R., "Range Limitations on Acoustic Adjoint Inversions," *OCEANS 2013*, September 23-26, San Diego, USA, (2013) [accepted, refereed].
5. Potty, G. R and Miller, J. H., "Application of Time Frequency Analysis Techniques for Long Range Sediment Tomography," *IEEE 2013 Underwater Acoustic Signal Processing Workshop (UASP-2013)*, October 16-18, Rhode Island, USA, (2013) [accepted]
6. Potty, G. R., and Miller, J. H., "Efficient use of a priori data in sediment tomography through the use of null space," *Proceedings of the International Symposium on Ocean Electronics (SYMPOL)*, October 23-25, Kochi, India, [accepted, refereed].
7. Sanjana, M. C., Latha, G., and Potty, G.R., "Sensitivity Analysis of model parameters in geoacoustic inversion," *Proceedings of the International Symposium on Ocean Electronics (SYMPOL)*, October 23-25, Kochi, India, [accepted, refereed].
8. O'Rielly, C., Grilli, A., and Potty, G., "Micrositing optimization of the Block Island Windfarm, RI, USA," *Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering (ASME)*, Nantes, France, June 9-14, OMAE2013-10191, (2013) [refereed].
9. Gopu R. Potty and James H. Miller, "Measurement and Modeling of Scholte Wave Dispersion in Coastal Waters," *Advances in Ocean Acoustics, Proceedings of 3rd International Conference on Ocean Acoustics (OA2012)*, Beijing, China, J. Simmen, Z. Li, and J-X Zhou eds., AIP Conference Proceedings, 1495, 500-507, 2012, [refereed].
10. Potty, G. R., Greene, J., Miller, J. H., and Baxter, C. D. P., "From Geoacoustics to Geotechnics: Extracting soil parameters using acoustic methods," *Proceedings of Indian Geotechnical Conference*, December 13-15, India, 215-218, 2012, [refereed].

11. Scheifele, P. M., Clark, J. G., Sonstrom, K., Kim, H., Potty, G. R., Miller, J. H., and Gaglione, E., "Ballroom Music Spillover into a Beluga Whale Aquarium Exhibit," *Advances in Acoustics and Vibration*, 2012 (doi:10.1155/2012/402130) [refereed].
12. O'Rielly, C., Grilli, A., and Potty, G., "Offshore Wind Farm Siting using a Genetic Algorithm," *Proceedings of the International Conference on Green Technologies-ICGT12, India, Dec 18-20*, DOI: 10.1109/ICGT.2012.6477974, 208 – 214, (2012) [refereed].
13. Annette Renee Grilli, Malcolm Spaulding, Christopher O'Reilly, Gopu Potty, "Offshore Wind Farm Macro and Micro Siting Protocol Application to Rhode Island," *Coastal Engineering Proceedings*, 1(33), doi:10.9753/icce.v33, (2012)
14. S. M. Reilly, G. Potty, M. Goodrich, "Sonar Propagation Modeling using Hybrid Gaussian Beams in Spherical/Time Coordinates," *Journal of Computational Acoustics*, 2012 [submitted, under revision].
15. Gopu R. Potty, James H. Miller, and Marcia Isakson, "Measurement and modeling of Scholte waves in shallow water (A)," *J. Acoust. Soc. Am.* **132**, 2093 (2012).
16. Charles E. White, Cathy A. Clark, and Gopu Potty, "Mode coupling due to bathymetric variation (A)," *J. Acoust. Soc. Am.* **132**, 1943 (2012).
17. Peter L. Nielsen, Martin Siderius, Jim Miller, Steven Crocker, and Jennifer Giard, "Seabed characterization using ambient noise and compact arrays on an autonomous underwater vehicle," *POMA 19*, 070030 (2013).
18. John Gebbie, Martin Siderius, Peter L. Nielsen, James H. Miller, Steven Crocker, and Jennifer Giard, "Small boat localization using adaptive three-dimensional beamforming on a tetrahedral and vertical line array," *POMA 19*, 070072 (2013).
19. Gopu R. Potty and James H. Miller "Time frequency analysis techniques for long range sediment tomography," *POMA 19*, 055074 (2013).
20. Huikwan Kim, James H. Miller, and Gopu R. Potty, "Predicting underwater radiated noise levels due to the first offshore wind turbine installation in the U.S.," *POMA 19*, 040067 (2013).
21. Edward Richards and Gopu R. Potty, "Acoustic interface treatment with an adjoint operator for linear range-dependent ocean index of refraction inversions," *POMA 19*, 070078 (2013).
22. Under Sea Modeling Library (USML), C++ software for sonar modeling and simulation, Ocean Acoustics Library, (<http://oalib.hlsresearch.com/>), 2012.
23. Jennifer Giard, An inversion scheme for shear wave speed using Scholte wave dispersion, Thesis (M.S.)--University of Rhode Island, 2013.
24. Edwards Richards, Effect of the Acoustic Environment on Adjoint Sound Speed Inversions, Thesis (M.S.)--University of Rhode Island, 2013.

HONORS/AWARDS/PRIZES

James Miller is serving as the President of the Acoustical Society of America. His one year term continues up to the Providence meeting in 2014.

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

James Miller and Gopu Potty are co-chairs of the Acoustical Society of America Providence, RI meeting to be held in 2014.

Gopu Potty was elected Fellow of the Acoustical Society of America “*for contributions to ocean acoustic inversion methods in shallow water.*”

Gopu Potty is coordinated the U.S. vote on new ISO/TC 43/SC 3 document - **N20 - ISO/NP 18406** “**Underwater acoustics – Measurement of radiated noise form marine pile driving**” on behalf of US TAG for ISO/TC 43/SC 3.

Gopu Potty was nominated 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 2011 International Symposium on Ocean Electronics, India, 16-18, October 23-25, 2013.

Gopu Potty served on the Technical Committee of the **International Conference on Green Technologies-ICGT12**, (Jointly organized by Mar Baselios College of Engineering and Technology and University of Dayton), India, Dec 18-20, 2012.

Huikwan Kim won the Student Paper Award (1st prize) at the Hong Kong Meeting of the Acoustical Society of America (2012) for his presentation “Long range propagation modeling of offshore wind turbine noise using finite element and parabolic equation models”. This paper was co-authored by Gopu R. Potty, James H. Miller, Kevin B. Smith, and Georges Dossot.