Estimation of Ocean and Seabed Parameters and Processes Using Low Frequency Acoustic Signals

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LONG-TERM GOALS

The long term goals of our research are to:

- Understand, model and exploit the acoustic propagation physics in shallow water in the presence of ocean fronts and internal waves. This goal conforms to the major theme of the Shallow Water 06 experiment i.e. 3-D acoustic effects. The effects of oceanographic variability such as frontal meander, and internal solitary waves on 3-D acoustic reflection and refraction will be investigated.
- Improve inversion schemes for the estimation of sediment geoacoustic properties using low frequency broadband acoustic signals. The existing inversion method has been shown to successfully map compressional wave speed. The new work will focus on understanding the frequency and depth dependence of compressional wave attenuation and develop new inversion schemes for shear wave properties. We hypothesize that water-borne acoustic arrival properties such as their Airy Phase are sensitive to sediment shear properties.

OBJECTIVES

We are proposing to address our goals with a series of objectives:

A. Characterize 3-D acoustic variability due to internal waves and fronts.

The tasks associated with this objective are:

1. **Data analysis:** Acoustic signals transmitted from the R/V Sharp in the Shallow Water 06 Experiment at various ranges and angles to the WHOI Shark Array and Single Hydrophone Receive Units (SHRU) will be analyzed.
2. **Calculate various intensity metrics:** Different intensity metrics will be calculated, including scintillation Index (SI), integrated energy over the depth of the array and over the duration of the acoustic signal, temporally integrated energy over the duration of the acoustic signal on a single hydrophone, single hydrophone intensity observations.

3. **Modeling:** A number of representative events will be modeled with and without the sound-speed profile of the measured internal wave in order to explore and compare the effects of the internal wave on acoustic propagation and intensity variability with measurements.

B. Long Range Sediment Tomography using Combustive Sound Sources (CSS)

The tasks associated with the long range sediment tomography objective are:

1. **Investigate the effect of shear on compressional wave dispersion**: Effect of shear on the modal dispersion was investigated. Estimates of shear wave velocity can be made based on this analysis.
2. **Develop new inversion techniques for shear properties**: A new inversion scheme is being developed to estimate shear properties of the sediment using interface wave dispersion. The instrumentation and other assets (including horizontal bottom-mounted geophone array) required for this task were recently acquired under the DURIP program.
3. **Finite Element Modeling of wave propagation**: Doctoral student, Hui-Kwan Kim, is modeling wave propagation within short ranges.

APPROACH

The PIs (James Miller and Gopu Potty) took part in the SW-06 on the R/V Knorr and participated in the CSS deployments. Effect of shear on modal dispersion was studied using the Shelfbreak Primer data. SW06 data are used to investigate for the evidence of intensity fluctuations associated with internal wave interaction with acoustics. Modeling using a 3-D propagation code (3D PE) was also carried out to confirm these intensity fluctuations. 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 two field tests which are being used to develop a scheme to estimate shear properties.

WORK COMPLETED

The data from SW-06 have been analyzed and preliminary results have already been presented at ASA meetings. Graduate student George Dossot has completed the analysis of the data from R/V Sharp transmissions received on the WHOI- Shark VLA and has modeled the propagation to include the effect of internal waves using a 3D Parabolic Equation code and 3D Kraken. He has completed his Ph. D dissertation and is currently preparing manuscripts based on this work for publication. He worked in close collaboration with Dr. Mohsen Badiey (University of Delaware), Kevin Smith (Naval Postgraduate School), Dr. James F. Lynch and Dr. Y.-T. Lin (Woods Hole Oceanographic Institution). Another graduate student, Jeannette Greene, designed and performed limited testing of a shear measurement system as part of her Master's thesis work. Another full-scale sea test was conducted in collaboration with ARL, UT (Preston Wilson, PI) in August, 2011 in Narragansett Bay and off Block Island. PhD student Hui-Kwan Kim is focusing on finite element modeling of wave propagation. Estimation of shear properties of the bottom using Scholte wave data is also being pursued currently.

RESULTS

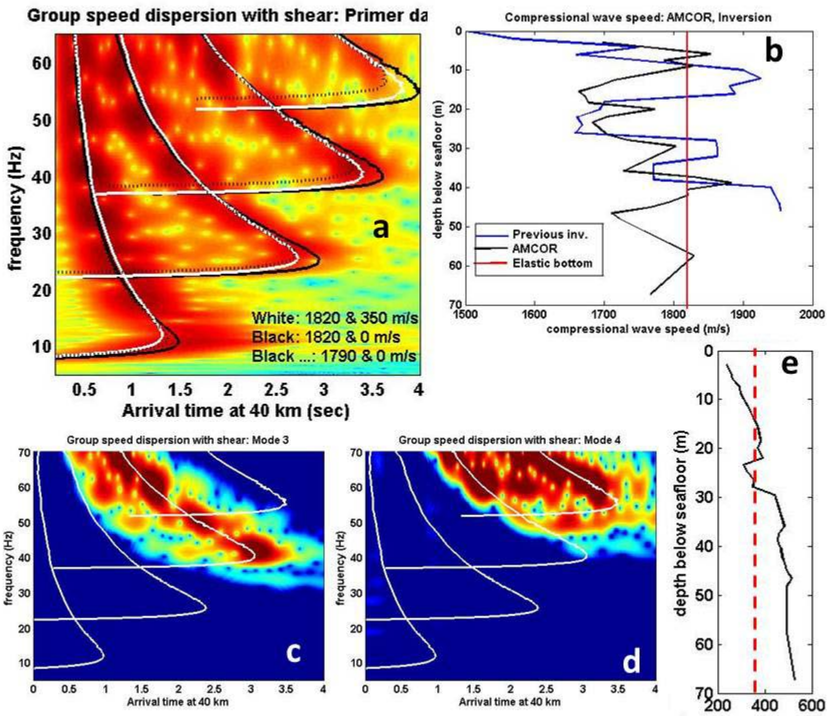

Figure 1: Panel (a) shows the calculated and observed modal arrival times. The continuous white lines are the modal arrival times calculated for a half space elastic sediment model with a compressional speed of 1820 m/s and a shear speed of 350 m/s. The broken black lines indicate that neglecting shear will have to be compensated by reducing the compressional wave speed to 1790 m/s. Panel (b) shows the compressional wave speeds in the sediment obtained by previous inversions and core data compared with the present estimate (1820 m/s). Panels (c) and (d) shows the theoretical group speeds (white lines) calculated using the half space model compared with mode 3 and mode 4 data. These time-frequency diagram were produced using the warping transform approach. Panel (e) compares the estimated shear speed (350 m/s) with shear speed computed using core data.

1. Acoustic variability in the presence of internal waves

Georges Dossot, as part of his doctoral dissertation research, examined the extreme variations of acoustic signals in the presence of internal waves. Specifically, we focused upon the intensity fluctuations of acoustic transmissions made by the R/V Sharp during the Shallow Water 2006 (SW06) experiment. This work has been completed and the results are being documented for publication in Journal of Acoustical Society of America.

1. Effect of shear on the modal dispersion:

We have been investigating the effect of shear on the modal propagation and attenuation using data from the Shelfbreak Primer (1996) data. We used a simple elastic half space sediment model and followed the approach introduced by Tolstoy[1] to calculate the theoretical model dispersion. We iteratively adjusted the shear speed and eventually matched the observed dispersion reasonably well as shown in Figure 1 (data from Primer experiment). Panel (a) in Figure 1 shows the calculated and observed modal arrival times at a range of 40 km. The continuous white lines are the modal arrival times calculated for a half space elastic sediment model with a compressional speed of 1820 m/s and a shear speed of 350 m/s. The effect of shear is more pronounced in the frequency region where the group velocity is a minimum (Airy phase region). The theoretical curves seem to agree with the data especially near the Airy phase for modes 1 and 2. The black lines are the arrival times assuming no shear in the sediment. It can be seen that addition of shear makes the modes to arrive earlier. Neglecting shear can be compensated by adjusting the compressional wave speed (broken black lines). By reducing the compressional wave speed to 1790 m/s good match is obtained at lower order modes but it is hard to match the data across higher and lower modes simultaneously as can be seen in the figure. Panel (b) shows the compressional wave speeds in the sediment obtained by previous inversions and core data compared with the present estimate (1820 m/s). The core data correspond to compressional (panel b) and shear speed (panel e) estimates using AMCOR 6012 data.

Panels (c) and (d) in Figure 1 shows the modes 3 and 4 compared with theoretical predictions based on a half-space sediment model with a shear speed of 350 m/s. The time-frequency diagrams shown in these figures were generated using the warping transform approach which is described in detail by Bonnel and Chapman[2]. The warping operator transforms a signal (x(t)) into a warped signal (y(t)) using the warping function w(t) as follows[2]:

$$y(t) = \sqrt{|w'(t)|}\,x[w(t)]$$

The square root term $\sqrt{|w'(t)|}$ ensures conservation of energy in the original and warped domains. Based on an ideal isovelocity waveguide with pressure release upper boundary and rigid bottom, the warping function can be defined as[2]:

$$w(t) = \sqrt{t^2 + \left(\frac{r}{c_w}\right)^2}$$

Here c_w is the sound speed in the water column and r is the range. This warping function transforms the modal components to monotones at the modal cut-off frequencies. For any mode m the procedure to create a dispersion diagram (as shown in figures 1c and 1d) can be summarized as follows:

1. Warp the time series using w(t)
2. Filter out the warped mode m.
3. In the time domain, un-wrap the mode using $w^{-1}(t)$.

The theoretical dispersion curves for the elastic bottom compare well with the data as shown in Figure 1c and 1d.

4. **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. We have conducted two field tests and planning to perform more engineering tests this fall.

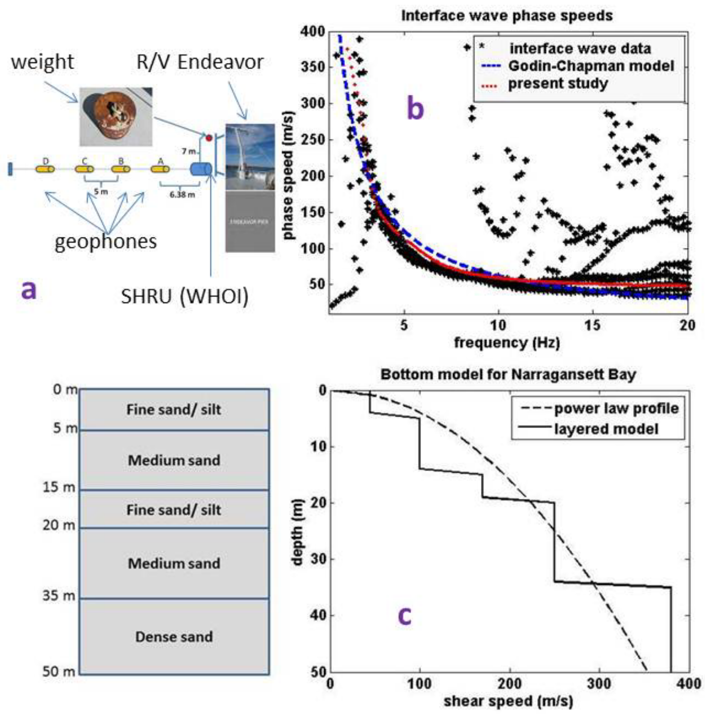

Figure 3: Phase velocity estimates (in black dots) from all possible geophone-event pairs (panel b). The experimental geometry for the Scholte wave data collection is shown in panel a. The continuous lines are theoretical group and phase velocity curves calculated using the Chapman-Godin approach (blue) and dynamic stiffness method (red). Panel c shows the shear wave speed profile (layered model for dynamic stiffness method and power law profile for Chapman- Godin model) used to calculate the theoretical group and phase speed curves. The layered sediment model is based on the sediment layers assumed (based on published data) for the location (shown to the left of panel c).

The first seabed test, using some of the components of the shear measurement system, was conducted north of the R/V Endeavor Pier in the Narragansett Bay Campus of the University of Rhode Island on March, 2011. One SHRU and a four geophone array were deployed off the stern of R/V Endeavor in approximately 6 m of water. The geophones were properly placed, with a spacing of 5 m underwater, with the help of divers. The layout is shown in Figure 2(a). A 300 lbs weight was released from just below the surface of the water off the stern of R/V Endeavor using the ship's capstan. Data were collected by repeating the weight drops ten times.

The signals received on the four geophones were used to calculate the phase velocity as a function of frequency. Phase difference calculated from the cross spectral density between signals from a geophone pairs is used to calculate the phase speeds. The phase speeds calculated using all the possible event-geophone pairs are shown in Figure 2 (black asterisks in panel b). A model to predict the Scholte wave phase speed dispersion based on the dynamic stiffness method was developed recently. This model will be described in the next section. Phase speed dispersion is also calculated assuming a power law variation of shear speed in the sediment. A model developed by Chapman and Godin is then used to model the phase speed dispersion. The phase speeds calculated theoretically based on Chapman- Godin approach[3] and the new dynamic stiffness model is overlaid on the data in the figure 1(b). The theoretical phase and group velocity curves shown in panel b of Figure 2 have been calculated based on a shear wave speed profile shown in panel c. The layered model was used in the dynamic stiffness method and power law profile was input to the Chapman- Godin model. The layered sediment model is based on the sediment layers assumed (based on published data) for the location (shown to the left of panel c).

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 stiffness contribution of water layer was also included in the global stiffness matrix. The characteristic equation relating the phase velocities to the frequencies can be obtained by setting the determinant of K_{total} to zero.

$$\det[K_{total}] = 0$$

The model described above was successfully validated by comparing with published results.

Another full-scale sea test was conducted during 22-25, August 2011 in Narragansett Bay and off Block Island, RI. We accomplished three days of testing of the geophone array and the Combustive Sound Source (Preston Wilson, ARL, UT Texas) which were deployed by R/V Shanna Rose. We are currently processing the data from the test and use the Scholte wave data to invert for the shear properties of the bottom using the method adopted in our earlier test.

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. 3-D propagation effects are important to naval applications as it can cause fluctuation in the acoustic field of the order of 5 to 10 dB. The understanding of the causes of these large fluctuations in transmission loss will aid their possible exploitation in ASW.

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

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HONORS/AWARDS/PRIZES

James Miller has been elected as the President of the Acoustical Society of America. His one year term starts at the end of the Montreal meeting on June 7, 2013.

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

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

Gopu Potty is coordinating 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 served on the International Advisory Committee and Technical Committee of the 2011 International Symposium on Ocean Electronics, India, 16-18, November, 2011.

Gopu Potty is serving 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.