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. Improve our long range sediment tomography technique for compressional wave speed and attenuation profiles and utilize a new broadband Combustive Sound Source (CSS) developed at the Applied Research Laboratories (ARL), University of Texas. 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. We hope to validate this hypothesis over the next period of investigation.

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) are being 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

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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.

   PhD student Georges Dossot carried out on this study as part of his dissertation topic. We worked in close collaboration with Dr. Mohsen Badiey (University of Delaware), Dr. James F. Lynch and Dr. Y.-T. Lin (Woods Hole Oceanographic Institution).

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

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

1. **Compressional wave speed and attenuation inversion using SW06 data**: Combustive Sound Sources (CSS) provide a promising broadband impulsive sound source which can be used for inversions of bottom properties. CSS were deployed during the SW06 experiment from R/V Knorr and we performed inversions for sediment compressional wave speeds and attenuations.
2. **Attenuation as a function of depth and frequency**: A variation on our technique provides a profile of attenuation as function of depth and acoustic frequency. This task enables us to explore the depth variation of attenuation in addition to its variation with frequency.
3. **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.
4. **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.

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. The CSS data, collected on the WHOI Single Hydrophone Receive Unit (SHRU) and the SWAMI 52 VLA, were used to perform inversions for sediment properties. The inversions were performed using the long range sediment tomography technique developed earlier (Potty et al, 2000). Effect of shear on modal dispersion was studied using the Shelfbreak Primer data collected in 1996. Graduate student George Dossot also participated in the experiments in the R/V Sharp. Transmissions from the R/V Sharp were 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) is being done to confirm these intensity fluctuations.

WORK COMPLETED

The data from SW-06 is being analyzed and preliminary results have already been presented at ASA meetings. A JASA- EL article has been published based on our inversions using Combustive Sound Sources (CSS). Graduate student George Dossot has been working on the data from R/V Sharp transmissions received on the WHOI- Shark VLA. He has completed the analysis of the data and has made significant progress in modeling the propagation to include the effect of internal waves using a 3D Parabolic Equation code and 3D Kraken. We are currently preparing manuscripts based on these results.

RESULTS

1. Acoustic variability in the presence of internal waves

Georges Dossot, as part of his doctoral dissertation research, has been examining the extreme variations of acoustic signals in the presence of internal waves. Specifically, we focus upon the intensity fluctuations of acoustic transmissions made by the R/V Sharp during the Shallow Water 2006 (SW06) experiment. Our ongoing research in this area involves close collaboration with the University of Delaware, The Woods Hole Oceanographic Institution, and the Naval Postgraduate School. Internal waves are known to cause extreme fades and intensifications of acoustic signals that pass through (or near) them depending on the angle between the propagating internal wave and the source-receiver pair. We are most interested in acoustic signals that pass parallel (or nearly parallel) to the internal wave front because this configuration leads to a "ramping" of acoustic intensity which anticipates the arrival of the internal wave.

The R/V Sharp experienced over fifty internal wave events while participating in the SW06 experiment. Throughout the experiment, the R/V Sharp transmitted broadband acoustic signals using a J15 acoustic source at various angles in relation to the WHOI receiving arrays. This experimental configuration was purposefully done in order to examine the angle relationship between the source-receiver path and propagating internal waves. Environmental sensors aboard the R/V Sharp and on the deployed moorings were investigated for each event to determine the size and structure of the internal wave. These events were catalogued in a web-based archive and organized in a manner which prioritized promising datasets for acoustic analysis.

Data analysis prior to FY11 showed that several of the R/V Sharp's datasets yielded significant ramping of acoustic signals in anticipation of an approaching internal wave, and additional fluctuations as the wave packet passed. The ramping phenomenon can be attributed to a three-dimensional version of the Lloyd's Mirror effect; which causes acoustic signals to refract off the approaching internal wave front, resulting in multiple arrivals (and signal intensification) at the receiver. The fluctuations due to the passing wave packet can be attributed to a combined interference pattern due to two primary causes. Firstly, as an internal wave soliton passes over the source-receiver path, a large shadow zone can occur, spreading the energy outwards. Secondly, as a wave packet passes, "ducting" can occur which traps the signal between solitons, and yields extreme signal intensification.

Our efforts over the past year have focused on modeling the sound field to better understand the phenomena we believe to be taking place. We have worked closely with the Naval Postgraduate School to enhance (and make use of) the three-dimensional Miami-Monterey Parabolic Equation (MMPE) code. By implementing a customized three-dimensional sound-speed profile, we have accurately modeled the trends apparent in Event 44. Repeated model runs have simulated the time dependence of the approaching internal wave and replicated the intensity fluctuations that we have seen in the measured data.

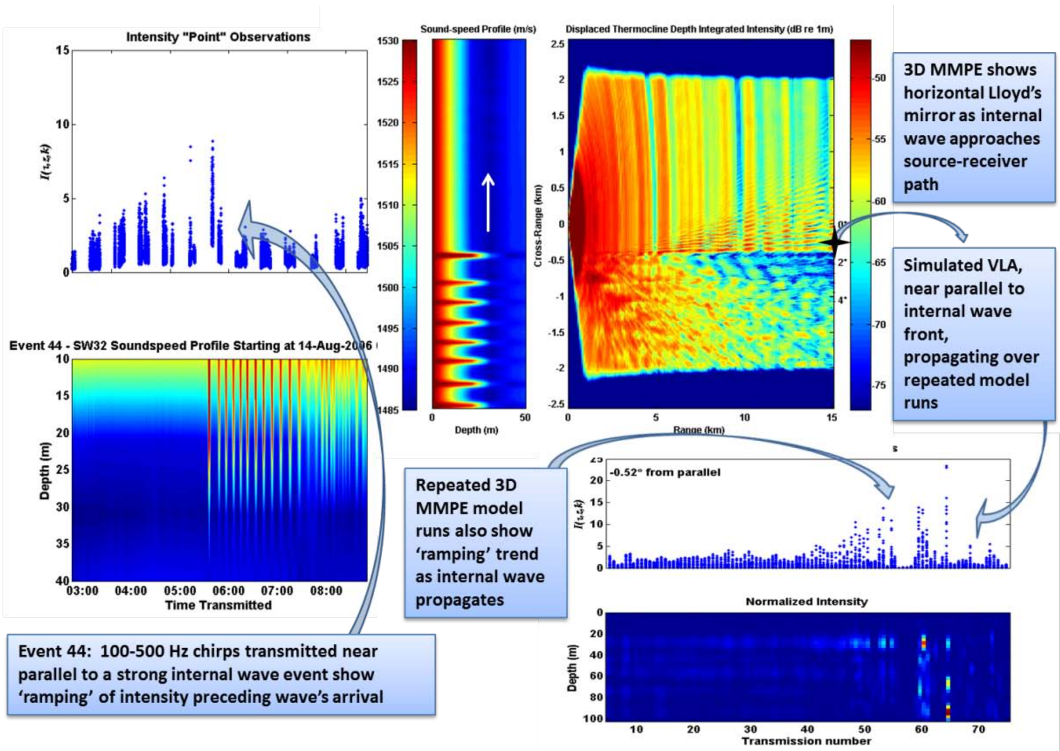

Figure 1: Measured normalized intensity values arriving at the WHOI VLA versus arrival time (top left); corresponding environmental mooring sound speed versus time and distance (bottom left and top middle); depth integrated energy of the MMPE field showing horizontal refraction due to the approaching internal wave (top right); repeated MMPE runs showing evidence of refraction, ducting, and anti-ducting (bottom right).

Figure 1 shows a comparison of the modeled and measured data for internal wave Event 44. Measured intensity values of R/V Sharp transmissions received by the WHOI VLA are shown on the top left. The corresponding measured sound speed profile from an environmental mooring directly between the source and receiver is shown (versus time) below these intensity measurements on the bottom left, and also shown as the modeled sound speed input (versus distance) in the top middle. The top right figure shows the depth integrated energy of a single MMPE run before the internal wave arrives at the source. In this instance, horizontal refraction is easily seen. Repeated model runs simulated the internal wave's progress over time – allowing us to model the VLA in different locations. The bottom right figure shows modeled intensity fluctuations if the VLA were situated one-half degree off-parallel from the approaching internal wave. At this angle, both ramping before the wave's arrival and fluctuations due to the passing soliton packet are evident. At angles above one degree we have found that fluctuations due to refraction tend to dominate more than fluctuations due to the passing soliton field, which we believe is a significant result.

2. Geoacoustic inversions

Geoacoustic inversions are being carried out using data from Combustive Sound Sources (CSS). These sources were deployed by ARL- UT from R/V Knorr and acoustic data received at the WHOI-Single Hydrophone Receive Units (SHRU) and SWAMI-52 vertical line array are used for the inversions. The inversions were carried out using our modal dispersion based long range sediment tomography technique (Potty et al, 2000).

Compressional wave attenuation inversions were also carried out using our technique based on modal amplitude ratios (Potty et al., 2003). Figure 2 shows the results of the compressional wave speed and attenuation inversion. Left panel shows the compressional wave estimates calculated using the SWAMI-52 vertical line array data compared with our earlier inversions using the SHRU data (Potty et.al., 2008). The two inversions correspond to different acoustic propagation paths. Right panel shows the compressional wave attenuation calculated using the SWAMI-52 data. The black stars represent shallower sediments whereas the red stars correspond to deeper sediments. The frequency exponents are 1.86 and 1.89 for deep and shallow sediments respectively. Inversions compare well with earlier (Primer) inversions. Frequency exponent agrees with Holmes et al. (JASA-EL;2007) value of 1.8 +/- 0.2.

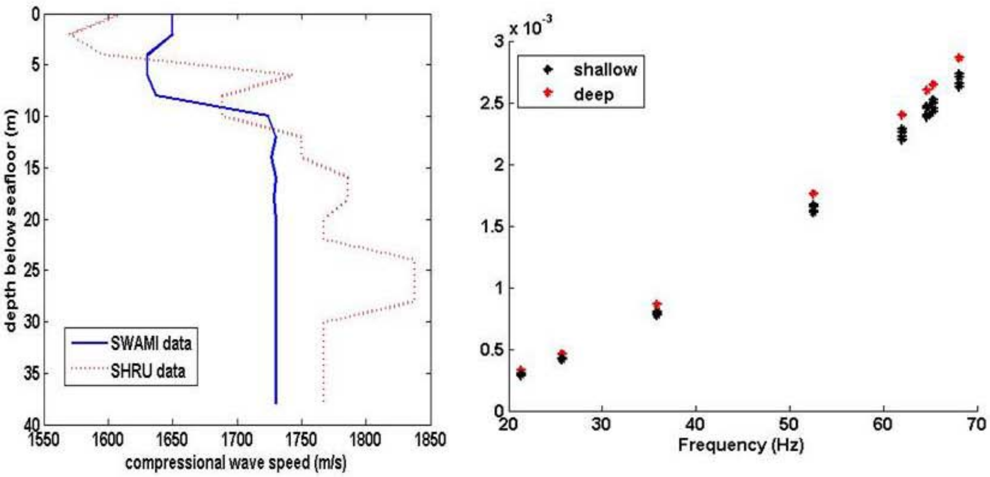

Figure 2: Left panel shows the compressional wave estimates calculated using the SWAMI-52 vertical line array data compared with our earlier inversions using the SHRU data (Potty et.al., 2008). Right panel shows the compressional wave attenuation calculated using the SWAMI-52 data. The black stars represent shallower sediments whereas the red stars correspond to deeper sediments. The frequency exponents are 1.86 and 1.89 for deep and shallow sediments respectively.

3. Effect of shear on the modal dispersion:

There has been renewed interest in understanding the effect of shear on compressional wave propagation, especially attenuation. The role of shear conversion in modifying the frequency dependence of attenuation has been the subject of some recent publications. We have tried to investigate the effect of shear on the modal propagation and attenuation. We used data from Shelfbreak Primer experiment to investigate the shear effects. This data has excellent signal to noise ratio and the modal arrival time structure is rich with six to seven well separated modes. We used a simple elastic half space sediment model and followed the approach introduced by Tolstoy to calculate the theoretical model dispersion. We iteratively adjusted the shear speed and eventually matched the observed dispersion reasonably well as shown in Figure 3.

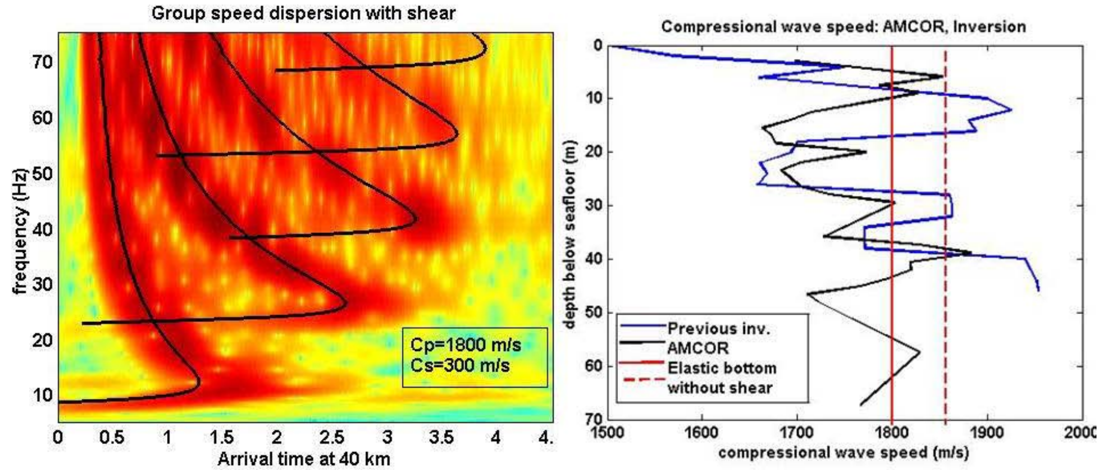

Figure 3: Left panel in Figure 3 shows the calculated and observed modal arrival times. The continuous black lines are the modal arrival times calculated for a half space elastic sediment model with a compressional speed of 1800 m/s and a shear speed of 300 m/s. The right panel shows our previous inversion (Potty et al. 2000) and core data (AMCOR-6012) compared with this value of 1800 m/s. The dashed line corresponds to a half space model with no shear.

Left panel in Figure 3 shows the calculated and observed modal arrival times. The continuous black lines are the modal arrival times calculated for a half space elastic sediment model with a compressional speed of 1800 m/s and a shear speed of 300 m/s. The right panel shows our previous inversion (Potty et al. 2000) and core data (AMCOR-6012) compared with this value of 1800 m/s. The dashed line corresponds to a half space model with no shear. We also observed that the inclusion of shear increases the travel time of the modes and the effect is pronounced near the Airy phase. We also found that higher modes are affected more than the lower order ones.

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 propose to invert for shear wave speed. A mobile version of the CSS could be used to generate the interface waves. The array consists of two Several Hydrophone Receive Units (SHRUs) built by WHOI each having 4 channels. An array consisting of geophones and hydrophones will be mated to this data collection system. Tests are planned in the near future using the Combustive Sound Source (CSS) developed at ARL-UT (Preston Wilson). One of our graduate student, Jeannette Greene, has been involved in the design and testing of this system including the sled which will house the data collection system.

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. 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.

REFERENCES

1. Potty, G., Miller, J.H., Lynch, J.F., and Smith, K.B. (2000). " Tomographic mapping of sediments in shallow water," J. Acoust. Soc. Am., 108(3), 973-986.
2. G. R. Potty, J. H. Miller, and J. F. Lynch, "Inversion for sediment geoacoustic properties at the New England Bight," J. Acoust. Soc. Am. 114, 1874-1887 (2003).
3. Potty, G., Miller, J. H., and Lynch, J. F., Newhall, A., Wilson, P., "Geoacoustic inversions using combustive sound source signals," J. Acoust. Soc. Am. 124 EL146 (2008).
4. I. Tolstoy, "Dispersive properties of a fluid layer overlying a semi-infinite elastic solid," Bulletin of the Seismological Society of America, 44(3), 1954.
5. J. D. Holmes, W. M. Carey, S. M. Dediu, and W. L. Siegmann, "Nonlinear frequency-dependent attenuation in sandy sediments," J. Acoust. Soc. Am. 121, EL218 (2007).

REFEREED PUBLICATIONS

1. Gopu R. Potty and James Miller, "Geoacoustic Inversions using Combustive Sound Source Data from Shallow Water- 2006 Experiment," Proceedings of the International Symposium on Ocean Electronics (SYMPOL), 100-105, 2009.
2. Gopu R. Potty, "Ocean Acidification: Implications to Underwater Acoustics," Proceedings of the International Symposium on Ocean Electronics (SYMPOL), 106-109, 2009.
3. Gopu R. Potty and James H. Miller, "Long Range Sediment Tomography in the East China Sea," in *Shallow Water Acoustics,* J. Simmen, E. S. Livingston, J-X Zhou and F-H Li eds., AIP Conference Proceedings, 255-261, 2010.

OTHER PUBLICATIONS

1. Gopu R. Potty and James H. Miller, "Time-frequency analysis techniques for long range sediment tomography," J. Acoust. Soc. Am. 126 2207 (2009).
2. James Miller, Gopu R. Potty, et al. " Environmental assessment of offshore wind power generation near Rhode Island: Acoustic and electromagnetic effects on marine animals," J. Acoust. Soc. Am. 126 2272 (2009).

3. Georges A. Dossot, James H. Miller, Gopu R. Potty, Mohsen Badiey, James F. Lynch, Ying-Tsong Lin, Arthur E. Newhall, and Kevin B. Smith, “Modeling intensity fluctuations of acoustic transmissions from the Research Vessel Sharp during Shallow Water 2006,” J. Acoust. Soc. Am. 126 2304 (2009).
4. James H. Miller , Georges A. Dossot and Gopu R. Potty, “Intensity fluctuations of acoustic transmissions due to internal waves in shallow water,” INDO – US Workshop on Shallow Water Acoustics, National Institute of Oceanography, Goa, India, February 3 - 4, 2010.
5. Gopu R. Potty and James Miller, “Long Range Sediment Tomography for shallow water geoacoustic properties,” INDO – US Workshop on Shallow Water Acoustics, National Institute of Oceanography, Goa, India, February 3 - 4, 2010.
6. Gopu R. Potty and James H. Miller, “Studies on the effect of shear on compressional wave attenuation,” J. Acoust. Soc. Am. 127 1937 (2010).
7. Georges A. Dossot, James H. Miller, Gopu R. Potty, James F. Lynch, Ying-Tsong Lin, Mohsen Badiey, and Kevin, B. Smith, “Three dimensional parabolic equation modeling of an internal wave event during Shallow Water 2006,” J. Acoust. Soc. Am. 127 1786 (2010).
8. James H. Miller, Gopu R. Potty, Kathleen Vigness Raposa, David Casagrande, Lisa A. Miller, Jeffrey A. Nystuen, and Peter M. Scheifele, “Assessment of the acoustic effects on marine animals by an offshore wind farm,” J. Acoust. Soc. Am. 127 1755 (2010).
9. James H. Miller, Gopu R. Potty, Kathleen Vigness Raposa, David Casagrande, Lisa A. Miller, Jeffrey A. Nystuen, and Peter M. Scheifele, “Environmental assessment of offshore wind power generation: Effect on a noise budget,” Second International Conference on the Effects of Noise on Aquatic life, Cork, Ireland, August 15-20, 2010.
10. Georges A. Dossot, Kevin B. Smith, James H. Miller, Gopu. R. Potty, Mohsen Badiey, James F. Lynch, “Comparison of modeled and measured intensity fluctuations due to a strong nonlinear internal wave event,” European Conference on Underwater Acoustics (ECUA 2010), Istambul, Turkey, 5-9 July, 2010.
11. Gopu R. Potty, James H. Miller,” Studies on the effect of shear on compressional wave attenuation,” European Conference on Underwater Acoustics (ECUA 2010), Istambul, Turkey, 5-9 July, 2010.

HONORS/ AWARDS/ PRIZES

James Miller and Gopu Potty participated in the First INDO – US Workshop on Shallow Water Acoustics, National Institute of Oceanography, Goa, India, February 3 - 4, 2010.

James H. Miller and Gopu Potty visited Indian Institute of Technology, Delhi and James Miller gave a talk titled “Intensity fluctuations of acoustic transmissions due to internal waves in shallow water” February, 01, 2010.

Gopu Potty visited Indian Institute of Technology, Chennai and gave a talk titled “Recent Ocean Acoustics Research ” May, 11, 2010.

Gopu Potty was nominated to the Advisory Committee and Technical Program Committee of the International Symposium on Ocean Electronics organized by the Cochin University of Science and Technology in Cochin, India (November, 2010).