Geoacoustic Inversion Using the Vector Field

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Award #: N000141010WX20956

LONG-TERM GOALS

This research is being conducted under the Ocean Acoustics Graduate Traineeship / Special Research Award program. The first year of this award was FY10. The goal of this research is the study of new geoacoustic inverse methods using the information in the acoustic vector field. The fundamental question addressed by this effort is whether knowledge of the vector field can improve estimates for seabed properties as quantified by their *a posteriori* probability distributions and resolutions relative to approaches based solely on the scalar field.

OBJECTIVES

The overall objective of this work is to pose new geoacoustic inverse problems utilizing the acoustic vector field and to study their performance. Specific research questions include the following:

- What opportunity does knowledge of the acoustic vector field provide for the estimation of sediment geoacoustic properties via numerical inversion?
- How does inversion performance vary when different acoustic parameters such as impedance and intensity are used to support the estimates?
- Does knowledge of the vector field improve the convergence rate relative to methods based solely on the acoustic scalar field?
- Does knowledge of the vector field result in a different or improved estimate for the sediment properties? Does knowledge of the vector field reduce the solution variance?

APPROACH

It is postulated that information in the vector field can be exploited to improve the convergence rate, reduce the solution variance and/or improve the resolution of geoacoustic parameters estimated via non-linear inversion. This postulate is being tested by evaluating the performance of inversions conducted in two different experimental settings; one involving measurements at a point, the other using data collected as the source-receiver range varies continuously. The relative performance of inversions based on the specific acoustic impedance and on the acoustic intensity is also being compared with inversions using only the scalar field. Thus, this research is exploring the value that the acoustic vector field represents for non-linear inversion in two distinctly different experiments, using two different vector acoustic quantities. In all cases, the expected performance will be quantified using simulated data. These expectations will then be verified using acoustic data collected during experiments at sea.

Sediment Acoustics Experiment 2004 (SAX04)
This component of the research is investigating the development and performance of a new approach to geoacoustic inversion based on the experimental setting of SAX04.[1] The data on which the inversion is based were provided by four Wilcox Research TV001 acoustic vector sensors as shown in Figure 1. Two of the sensors were suspended above the seabed, and two were buried. The sensors were arranged in a vertical line directly beneath an acoustic projector in about 18 meters of water. All (available) acoustic data were collected at normal incidence. Gated continuous wave signals were transmitted into the seabed at a variety of frequencies, using two different pulse widths.

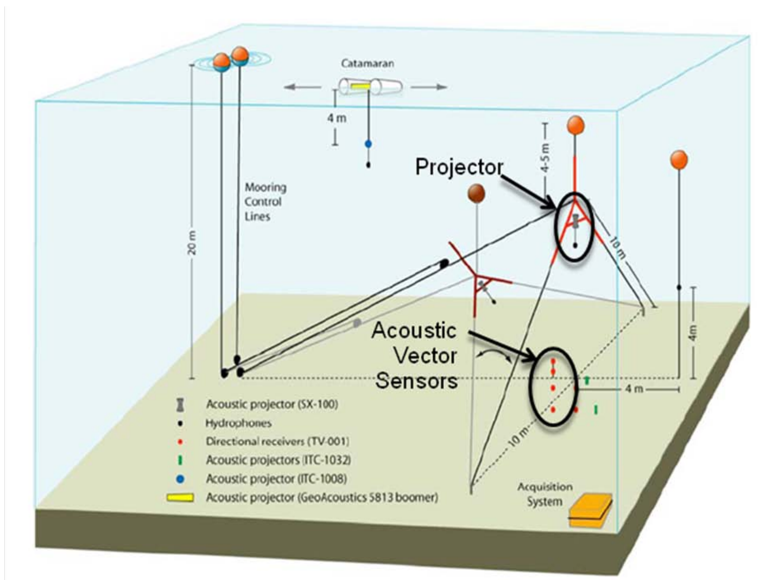

Figure 1: SAX-04 Experiment Setup

Two different vector acoustic quantities are being used to support the inversion for the purpose of comparing the performance of each. In the first version, the process inverts for the geoacoustic properties of the bottom using the specific acoustic impedance observed at the vector sensors. The impedance based inversion has the advantage of requiring relatively little information about the source signal. The complex impedance is computed from the observed data using the ratio of the Fourier transformed pressure and velocity signals. The forward model arrives at the predicted impedance as the ratio of the pressure and velocity transfer functions. There is no need to specify the source spectrum. Therefore, this approach has the potential to provide enhanced robustness in the event of contaminated or absent data for the source signal. However, because the spectrum of the acoustic particle velocity and transfer function both appear in the denominator of the impedance, there is the potential for quite large variations in the acoustic impedance at frequencies characterized by small (or vanishing) acoustic particle velocity in the vicinity of reflecting boundaries. Large excursions in the observed or predicted impedance have the potential to degrade performance of the inversion.

Intensity based inversion eliminates the potential for the large excursions associated with a vanishing acoustic particle velocity. However, the square of the Fourier transformed source signal is required by the forward model to predict the acoustic intensity at the vector sensor locations. This creates the potential for an additional source of error in the event that the source reference signal used to compute the source spectrum is noisy, contaminated by the presence of reflecting boundaries or altogether absent.

The performance of these two approaches to vector field inversion of the SAX04 data set will be compared for both simulated and real data using the *a posteriori* probability distributions and associated resolutions of the parameter estimates. In addition, the performance will be compared to inversions computed using only the hydrophone channels of the acoustic vector sensors.

Block Island Sound, Ocean Special Area Management Plan (SAMP) Experiment
The second approach follows the more traditional route of collecting acoustic data in shallow water (35 m) as the source-receiver separation was varied from about 20 meters to two kilometers. Frisk and Lynch [2] developed a method to characterize the shallow water wave guide by Hankel transformation of the pressure amplitude and phase versus range for a continuous wave signal. This part of the study is evaluating whether extension of their approach to include the acoustic intensity can improve on the variance and resolution of the estimated parameters relative to inversion using only the scalar field.

To support validation of the proposed inversion method, an experiment was conducted in Block Island Sound in conjunction with acoustic transmission loss measurements performed by the State of Rhode Island. The measurements were conducted as part of Rhode Island's SAMP program associated with the construction of an offshore wind project in state waters. [3,12] A short vertical receiving array consisting of two USRD H52 hydrophones and one Wilcoxon-Research TV001 acoustic vector sensor was built. The array was deployed vertically in 35 meters of water while a low frequency continuous wave acoustic source (operated by the State of Rhode Island) was towed over the longitudinal axis of a submerged glacial lake bed located to the northwest of Block Island as shown in Figure 2.

The experiment successfully collected acoustic data, including particle acceleration measurements, for source-receiver separations ranging from about 20 meters to two kilometers. Figure 3 shows transmission loss measurements computed from two hydrophones at depths of 9 and 21 meters. [3] This data set will support the validation of new inverse methods that extend on the Hankel transform based inversion of Frisk and Lynch. In addition, the data set will support a direct comparison of inversions performed using the acoustic vector field to that using only the scalar field.

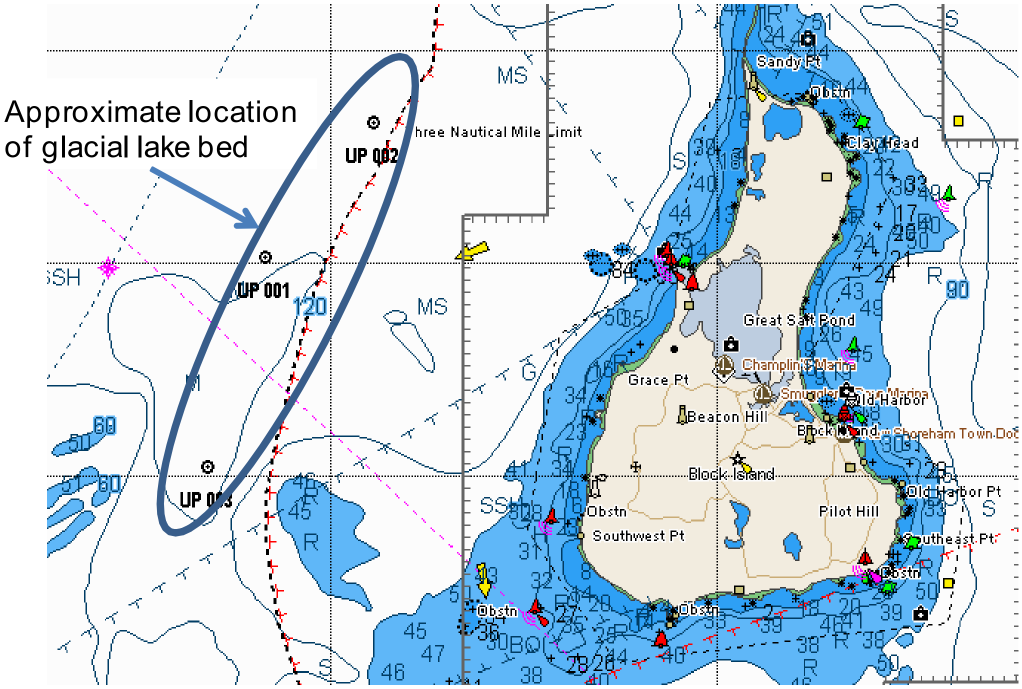

Figure 2: Target Geoacoustic Feature

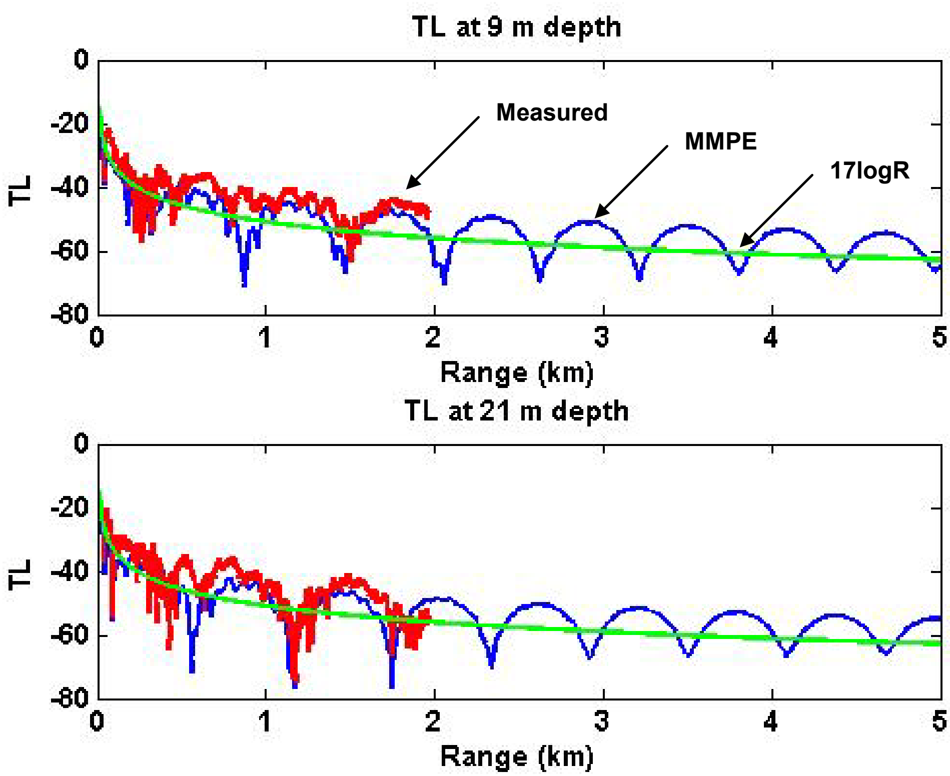

Figure 3: Block Island Sound Transmission Loss

In all cases, a genetic algorithm (GA) based on differential evolution (DE) is used to perform the inversions. [4,5] This approach was selected due to its demonstrated robust performance and scalability for execution in a parallel computing environment. [6] Since the objective of this study is to quantify the value that knowledge of the acoustic vector field represents for geoacoustic inversion, the same algorithm (using the same set of tuning parameters) is being used throughout the study.

WORK COMPLETED

Components of this work that were completed prior to this Special Research Award include:

- Implemented a non-linear global optimization code in a parallel computing environment
- Processed vertical incidence vector sensor data (SAX04)
- Developed an impedance based inverse method for a fluid bottom (SAX04)
- Designed and built a three element hybrid vertical array (SAMP)
- Collected data for the Block Island Sound transmission loss measurement (SAMP)

Inversion studies for the SAX04 data set were the focus of the FY10 effort. Inversion results were obtained using the impedance based method. The data consisted of short duration acoustic waveforms transmitted at normal incidence. A fluid bottom was assumed. A significant part of this effort was focused on the processing of data collected by the vector sensors that were suspended above the seafloor. Concerns about the influence of the sensor buoyancy, and potentially other effects, resulting from burial of the vector sensors suggested that initial efforts should focus on the "easy" case of a neutrally buoyant vector sensor mounted in a compliant suspension.

Following these initial studies, processing of the buried sensor data commenced. Previous investigators had tacitly assumed that the velocity of the buried vector sensor was equal to the local acoustic particle velocity [7] (as is typically assumed for water-borne vector sensor processing). During the course of this work, it was discovered that the influence of the sediment on the dynamic response of the buried vector sensors could not be neglected. First, the buried sensors were not neutrally buoyant, thus the magnitude of the complex sensitivity was effectively changed by the act of burial. Attempts to improve the inversion result by incorporating the difference between the sensor and sediment densities into the forward model were not successful. [13]

The second factor considered was that the buried vector sensor was subjected to viscoelastic restoring forces when driven by the time varying velocity field. Osler showed that a suspension resonance, within the test band, was predicted for the sensors buried at the SAX04 test site. [7]

The forward model was further improved to incorporate the transfer function between the local acoustic particle velocity and the velocity of the sensor case that resulted from the density and the viscoelastic properties of the sediment. Among the simplifications in the approach was the treatment of the sensor case as spherical. [7,8] This simplification was necessary because closed form solutions for the radiation impedance of spherical end capped cylinders (as used for the SAX04 experiment) do not exist. Refinement of the transfer function estimation to include the treatment of non-spherical sensor cases will be the subject of future effort.

RESULTS

Initial parameter estimates based on data from the two suspended sensors were completed. [13] A relatively simple, five layer model with constant properties was employed. A fluid bottom was assumed. As shown in Figure 4, a minimum normalized error of about 0.14 was achieved following more than 20,000 function evaluations. The panel at right shows both the observed and predicted impedance for the best estimate of the seabed.

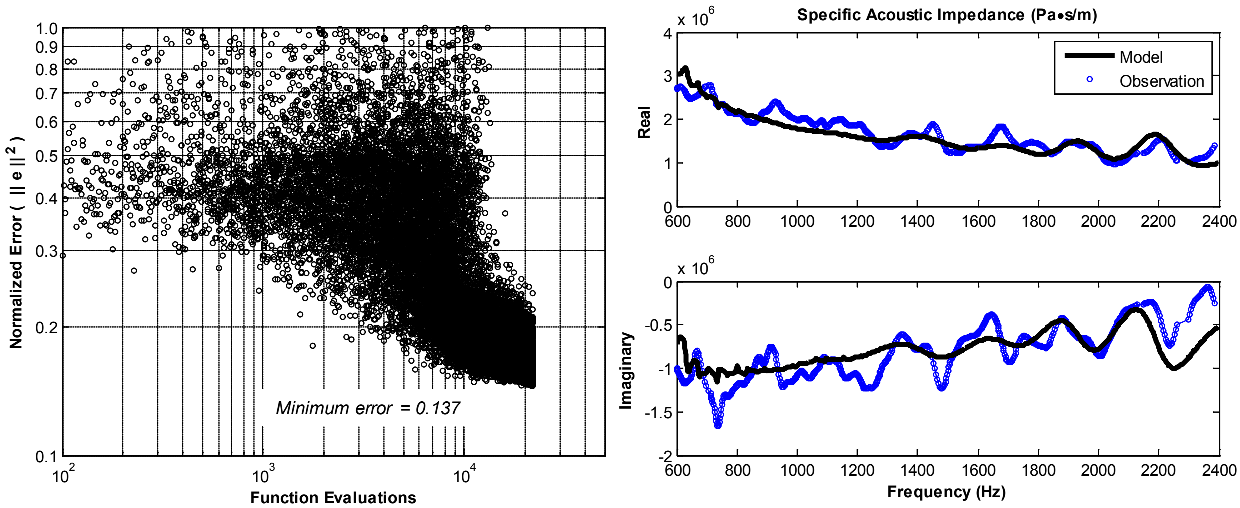

Figure 4: SAX-04 Inversion Performance

Initial results from this inversion study are provided as Table 1. As shown in the table, the result suggests a simplified depiction of the bottom attained by reducing the thickness of layers three and four to the minimum allowed by the run time parameters (1cm). Thus the bottom was estimated as a 27cm layer overlying a pair of lower impedance layers with total estimated thickness of about 3.2 meters. An acoustic half-space beginning at a depth of about 3.5 meters had a characteristic impedance that was consistent with course sand. [9]

Table 1: SAX-04 Inversion Result

Layer	Thickness (meter)	Impedance (ρ c)
One	0.27	2.79×10^6
Two	1.90	2.39×10^6
Three	0.01	2.86×10^6
Four	0.01	3.92×10^6
Five	1.32	2.18×10^6
Half Space	Inf	3.74×10^6

The reasons for the low impedance of the surface layers are unknown, but may be related to disturbance during the passage of Hurricane Ivan (Category 4) six weeks before the acoustic data was collected. [10] A simple half space model was not sufficient to explain the complexity of data collected at the same site. A shallow, low impedance layer has been suggested. [7]

Work to incorporate the suspension dynamics of the buried sensor into the forward model was also begun. In many applications, the acoustic vector sensor is assumed to have a sensitivity that is both purely real (zero phase response) and constant across some bandwidth. However, the actual performance is often characterized by a complex, frequency dependent sensitivity that includes a significant contribution from the suspension associated with the sensor mount. In some cases, an in-band suspension resonance exists. This is generally an undesirable outcome for acoustic vector sensor based systems.

In geoacoustic inverse studies, the velocity transfer function for the buried vector sensor carries information about the medium in which the sensor is buried. The dynamic behavior of the buried sensor is a function of the sensor's mass properties, the sediment density, complex compression modulus and complex shear modulus. Similar work in biomedical applications has developed successful approaches for the estimation of the viscoelastic properties of tissue based on the response of embedded calcifications excited by ultrasonic wave fields. [11] Given that the velocity transfer function for the buried vector sensor is a function of geoacoustic properties of interest, there is an opportunity to improve the quality of inversion for these parameters similar to approaches taken in biomedical applications.

Figure 5 shows a result of a sensitivity study conducted using the SAX04 data set. The panel at left illustrates the objective function value for all instances of the forward model. The panel at right illustrates the sensitivity of the objective function to the shear wave speed in the vicinity of the optimum solution. In both instances, the sensitivity of the impedance based inversion method to the shear wave speed in the sediment was demonstrated. Figure 6 illustrates the a posteriori probability distribution for shear wave speed estimate based on these early efforts.

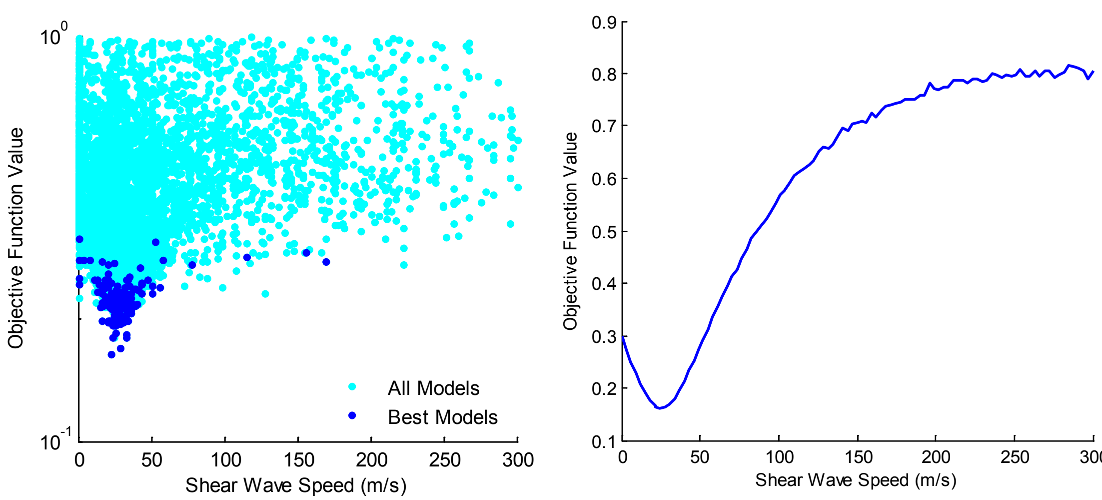

Figure 5: Inversion Sensitivity to Shear Wave Speed

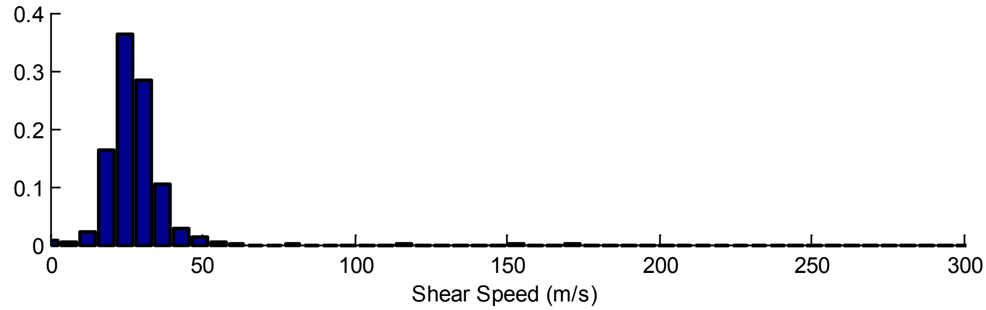

Figure 6: Shear Wave Speed Probability Distribution

IMPACT/APPLICATIONS

Information contained in the acoustic vector field is being used to develop new inverse methods for estimation of sea bed geoacoustic properties. Significant progress was made toward the development of methods to invert the observed specific acoustic impedance for geoacoustic properties of the sea bed. Additional work to compare the impedance and intensity based inverse methods is planned for FY11. Ultimately, these results may lead to novel inverse methods for the estimation of seabed geoacoustic properties with improved solution variance and resolution.

RELATED PROJECTS

On-going work to develop methods for the precision calibration of acoustic vector sensor systems is being conducted. In addition to improvements in the measurement of the complex sensitivity in the acoustic far field [14], new measurement methods applicable in the acoustic near field have been developed. Among the innovations in this work was the implementation of self correcting algorithms that detect, track and correct for certain measurement errors encountered during data post-processing. [15]

REFERENCES

1. Osler, J.C., “Cruise Report SAX04”, Defense Research & Development Canada, Atlantic Technical Report, 2004.

2. Frisk, G.V. and Lynch J.F., “Shallow water waveguide characterization using the Hankel transform”, J. Acoust, Soc. Am. 76, 205-216, 1984.

3. Miller, J.H., Potty, G.P., Raposa, V.P., Cassagrande, D., Miller, L., Nystuen, J.A., and Scheifele, P.M, “Assessment of the acoustic effects on marine animals by an offshore wind farm”, J. Acoust. Soc. Am. 127, 1755, 2010.

4. Storn, R., and Price, K.V., “Differential evolution – a simple and efficient heuristic for global optimization over continuous spaces”, Journal of Global Optimization 11, 341-349, 1997.

5. Price, K.V., Storn, R.M., and Lampinen, J.A., Differential Evolution: A Practical Approach to Global Optimization, Springer-Verlag, 2005.

6. Chakraborty, U.K. (editor), Advances in Differential Evolution, Springer-Verlag, 2008.

7. Osler, J.C., Chapman D.M.F., Hines, P.C. Dooley, G.P. and Lyons, A.P., "Measurement and modeling of seabed particle motion using buried vector sensors", IEEE J. Ocean. Eng. 35, 516-537, 2010.

8. Oestrieicher, H.L., "Field and impedance of an oscillating sphere in a viscoelastic medium with an application to biophysics", J. Acoust. Soc. Am. 23, 707-714, 1951.

9. Hamilton, E.L. "Geoacoustic modeling of the seafloor", Journal of the Acoustical Society of America, Vol. 68, pp 1313-1340 (1980).

10. Guza, R.T. and O'Reilly, W., "Attenuation of Ocean Waves by Ripples on the Seafloor", Scripps Institution of Oceanography, Technical Report, 2007.

11. Catheline, S., Gennisson, J.L., Delon, G., Fink., M., Sinkus, R., Abouelkaram, S. and Culioli, J., "Measurement of viscoelastic properties of homogeneous soft solid using transient elastography: An inverse problem approach", J. Acoust. Soc. Am. 116, 3734-3741, 2004.

PUBLICATIONS

12. Miller, J.H., Potty, G.P., Raposa, V.P., Cassagrande, D., Miller, L., Crocker, S.E., Tyce, R., Preston, J., Roderick, B., Nystuen, J.A., and Scheifele, P.M., "Environmental assessment of offshore wind power generation near Rhode Island: Acoustic and electromagnetic effects on marine animals", J. Acoust. Soc. Am. 126, 2272, 2010. [published]

13. Crocker, S.E., Miller, J.H., Hines, P.C., and Osler, J.C., "On the use of acoustic particle motion in geoacoustic inversion," J. Acoust. Soc. Am. 125, 2747, 2009. [published]

14. Crocker, S.E., Straw, T.B., Richards, R.T., "Calibration and characterization of a vector sensor towed array", USN J. Und. Wtr. Acoust. 60, 337-403, 2010 (Invited). [published, refereed]

15. Crocker, S.E., "A self-correcting method to calibrate acoustic vector sensors in the acoustic nearfield", NUWC-NPT Tech Memo 10-056, 2010.