Measurement and Analysis of High-Frequency Scattering Statistics And Sound Speed Dispersion

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LONG-TERM GOALS

The long-term goal of the present high-frequency scattering statistics work is to link the high-frequency reverberation envelope distribution to measurable seafloor geoacoustic properties in conjunction with sonar system parameters (such as frequency and resolution cell size), providing the foundation necessary for solving several problems related to the detection of targets in non-Rayleigh clutter. A direct link between system and environmental parameters via scattering models to the statistical distribution of reverberation will allow: performance prediction for different systems based on seafloor properties, extrapolation of performance to other system/bandwidths, and optimization of system parameters such as frequency/bandwidth to the local environment.

The long-term goal of the sound speed measurement initiative is to contribute to the assessment of different physical models for porous media to be assessed and evaluated based on the unique sound speed dispersions that they predict. This knowledge concerning the most suitable physical model for the seabed, and its limitations, can be used to improve the performance of mine hunting sonar systems.

OBJECTIVES

The objectives of the high-frequency scattering statistics project are to

(1) collect and use experimental data determine the primary environmental properties that can influence the frequency and range dependence of amplitude distributions obtained with high-frequency acoustic systems (e.g. synthetic aperture sonar) in shallow water;

(2) develop and use high-frequency scattering models together with collected ground truth to determine the scattering properties of patchy seafloors;

(3) test current models or develop models where none exist which link environmental parameters and system characteristics to predict scattered amplitude statistics as a function of frequency and range for complex environments.

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14. ABSTRACT
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The objectives of the sound speed dispersion work are to participate in the component of the SAX04 experiments dealing with the speed of sound in a surficial layer of sand. In particular:

1) experimental concepts will be developed and implemented to measure the anticipated sound speed dispersion from approximately 500 to 10,000 Hz,

2), vector sensor array data will be collected and analyzed as part of the SAX04 sea-trial, and

3) numerical model simulations will be developed and compared with experimental data.

APPROACH

Work has been conducted recently at the Applied Research Laboratory – Penn State University (ARL-PSU) to model high-frequency scattered amplitude statistics from seafloors with discrete scatterers as well as those with patches of differing scattering properties. What is lacking are experimental studies designed to link these models of amplitude statistics to scattering models in order to improve predictive capabilities for high-frequency acoustic systems operating in shallow water areas that have spatially heterogeneous seafloors. High-frequency seafloor scattering data will be analyzed from several high-frequency experiments which took place over the last three years which were part of a Joint Research Project (JRP) between the NATO Undersea Research Centre (NURC) and ARL-PSU and the SAX04 experiment off of Ft. Walton Beach Florida. These experiments provide data for examining the connections with environmental factors (geological/biological patchiness) and for exploring the dependence of clutter on system characteristics such as frequency or bandwidth. A variety of areas with complicated bottom properties are included in the study areas. The diversity of sites allows an excellent opportunity to examine the statistics of scattering from a wide variety of extreme seafloor environments in terms of acoustic clutter. Ground truth consisting of a combination of video and high-resolution side scan and multibeam sonar can be used for estimating heterogeneity of seafloor properties. A digital stereo photogrammetry system will provide estimate roughness properties of seafloor patches. Synthetic aperture sonar data collected from a rippled sandy seabed by APL/UW on their rail facility as part the SAX04 sediment acoustics experiment in fall 2004 will be analyzed to examine the dependence of resolution on the scattering statistics as well as frequency and the propagation environment.

Experimental concepts were developed (in collaboration with Dr. John Osler and Dr. Paul Hines of Defense Research and Development Canada, DRDC) to measure the sound speed dispersion during the SAX04 experiment. The experimental geometry was developed with the goal of being able to make several complementary measurements of sound speed, and an effort is being made to quantify potential sources of uncertainty in each of the measurement approaches. A combination of vector and pressure receivers will deployed during the SAX04 experiment in October, 2004. These will permit measurements of sound speed by: (a) measuring the angle of refraction of energy into the seabed; (b) measuring the time of flight between buried receivers; (c) measuring reflection loss in the water column through a wide range of angles; (d) measuring the impedance of the seabed.

WORK COMPLETED

1) Scattering statistics: As part of 2004 U.S. Office of Naval Research sponsored SAX04, SAS experiments took place about 1 km offshore in water about 17 m (55 ft) deep in the Gulf of Mexico

south of Fort Walton Beach, Florida. A bottom mounted rail/mobile tower system was deployed by Applied Physics Laboratory scientists to carry out scattering strength and SAS measurements. The SAS data examined so far were collected over five frequency bands spanning the range from 2 to 100 kHz. Ripples on the sandy bottom can be seen in portions of the image formed from a 60-100 kHz transmitted waveform. Preliminary statistical analysis has been performed on these data showing agreement with predictions of the relationship between bandwidth and the shape parameter of the *K* distribution based on the model of Abraham and Lyons (2002). Simulations of the effect of the propagation on the statistics as a function of range based on the work of Abraham and Lyons (2004a) was found to match measured values.

2) Sound speed dispersion: As part of the SAX04 experiment, a combination of vector and pressure receivers was employed to make sound speed measurements. These data are currently being analyzed to estimate sound speed dispersion by:

(a) measuring the angle of refraction of energy into the seabed;

(b) measuring the time of flight between buried receivers;

(c) inversion of ship noise attenuation data via Kramers-Kronig inversion;

(d) measuring reflection loss in the water column. Initial results show significant dispersion in the sandy sediments off Ft. Walton Beach, Florida.

RESULTS

Figure 1 shows an example of the type of SAS images studied. Ratios of *K* distribution shape parameter estimates at a given range were formed for each bandwidth ratio (i.e. at bandwidth ratios of 2 kHz/4 kHz, 2 kHz/16 kHz, etc.). The means of these ratios at each bandwidth ratio are plotted in Fig. 2. In this figure an inverse dependence of shape parameter on bandwidth is clearly evident. The model of Abraham and Lyons (2002), based on a finite number of scatterers, gives insight into how the PDF of the SAS image data changes as a function of sonar system parameters such as transmit waveform bandwidth. Because the shape parameter can be related to the number of contributing scatterers, it will be linearly related to the sonar system resolution (shown as the solid line on Fig 2).

The data presented in Figure 3 display a trend toward higher shape parameters (i.e., toward a Rayleigh distribution) with increasing range. Preliminary analysis based on the results of Abraham and Lyons (2004b) indicates that, with respect to array processing, the statistics are most strongly dependent on the beamwidth of the array. Thus, when SAS processing results in constant cross-range resolution with range, the beamforming is not expected to significantly alter the statistics even though many more pings are used at longer ranges. A more likely explanation may be found in accounting for the effects of multipath propagation (Abraham and Lyons, 2004a). Simulation of the effect of propagation on the shape parameter is shown as the solid red line in Figure 3. The earlier travel-times have less or no multipath arrivals while the later travel-times do, leading to more scatterers contributing to reverberation and therefore a higher K-distribution shape parameter.

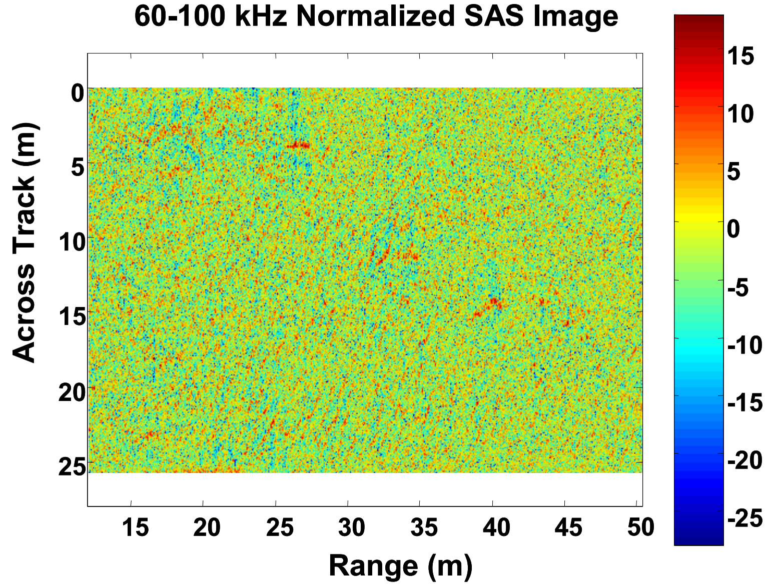

Figure 1. Example of normalized synthetic aperture sonar image. Ripples and possible targets can be seen in this image.

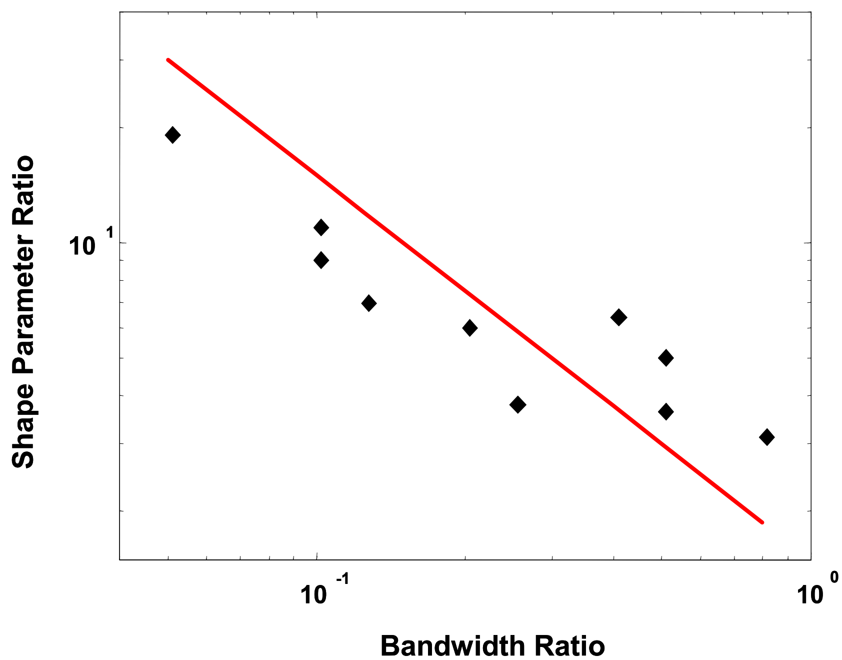

Figure 2. Mean of shape parameter ratio estimates at a given bandwidth ratio (symbols) along with a line indicating the inverse relationship between shape parameter and bandwidth (red line).

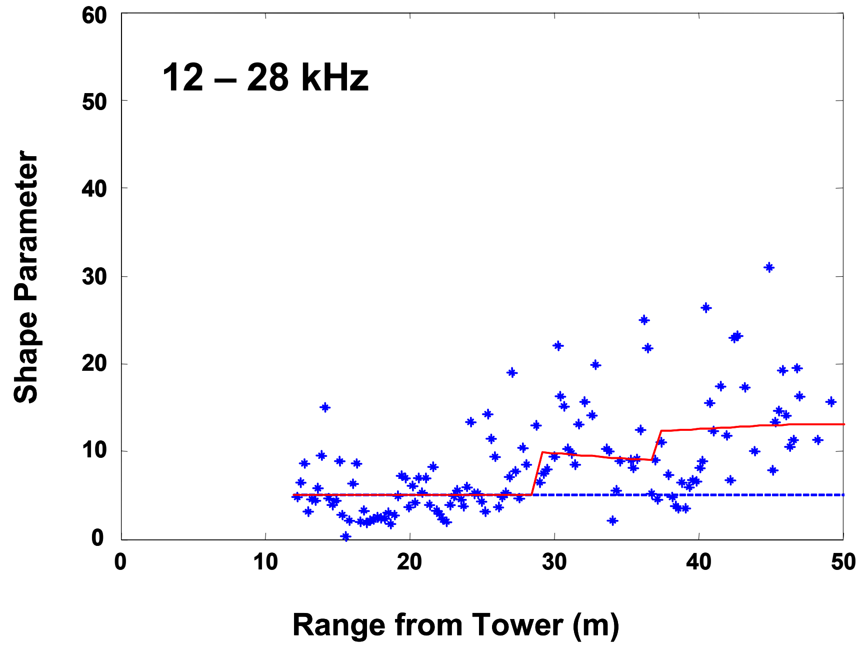

Figure 3. Comparisons of reverberation statistics with simulations including multipath (red line).

Figure 4 illustrates the geometry of the ship noise measurements along with the different refracted arrival paths for ship noise 'seen' in the sediment by the directional sensors assuming sound speed dispersion. The data set analyzed in this paper consists of recordings on three accelerometer channels and the pressure channels housed in the TV-001 vector sensors buried in approximately 0.5 and 1 m of sediment and a nearby sensor lying on the sediment interface. The pressure and acceleration data were filtered into 1024 sub-bands using a discrete Fourier transform (DFT). Using the time series of the pressure and the acceleration components, the arrival angle of acoustic energy as a function of frequency can easily be determined from the magnitudes of the y- and z-components of the intensity spectrum (Lyons, et al., 2005). Figure 5 displays the measured incident grazing angle as a function of frequency. A trend can be seen toward less refraction at lower frequencies, corresponding to an assumed lowering of the sediment sound speed with frequency. Sound speed ratios determined from the measured angles of Figure 5 with the assumption of plane waves incident at the water-sediment interface are shown in the bottom graph on the figure. Also shown on the figure are predictions based on the effective density fluid model (EDFM) using SAX99 parameter inputs (green line) and a phenomenological model (blue line) which obeys the Kramers-Kronig relationship (given by the equation shown on the figure).

The top graph of Figure 6 shows measurements of sediment attenuation using ship noise as a sound source. Classic Kramers-Kronig methods of determining dispersion from attenuation required knowledge of attenuation over all frequencies, which can never be achieved in realistic experimental work. By applying the theory of linearity and causality to an acoustic system, and assuming that the derivative of the attenuation coefficient and the phase velocity do not change rapidly over the frequency bandwidth of interest, an equation can be derived that enables one to calculate the dispersion from the local attenuation. It should be noted that this equation will yield information on the shape of the dispersion curve and not absolute levels. Levels would have to be set using overlapping data from a method that does yield absolute values (such as the time-of-flight measurements discussed in Hines, 2005). Inversion results using measured attenuation data are shown in the bottom graph of Figure 6.

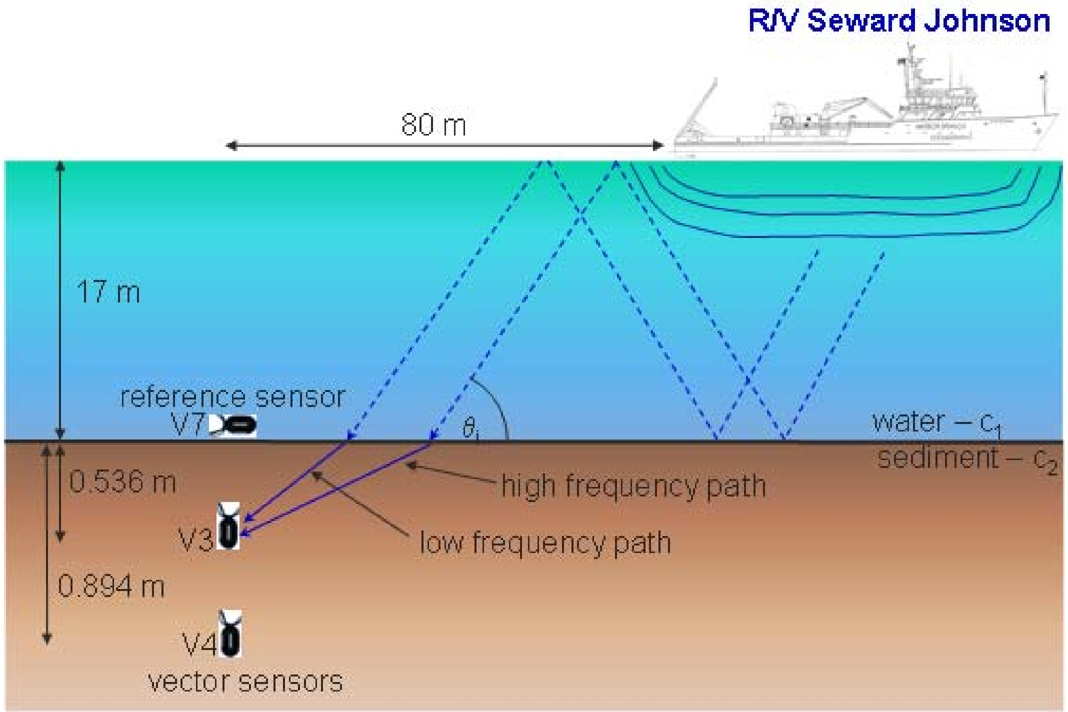

Figure 4. Geometry of vector sensor field with respect to the moored RV Seward Johnson showing dominant arrival path of ship noise at the vector sensor array.

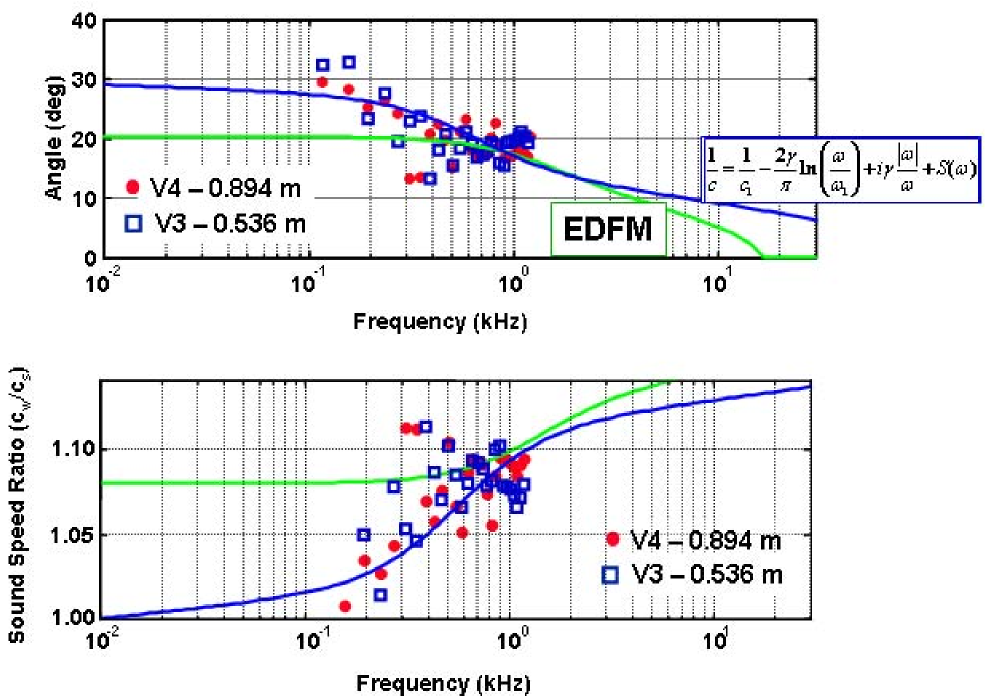

Figure 5. Top: Measurements of the angle of the intensity vector estimated using the pressure and acceleration channels of a buried vector sensor (symbols) shown with predictions of the refracted angle (solid lines). Bottom: Sound speed ratios determined from the measured arrival angles.

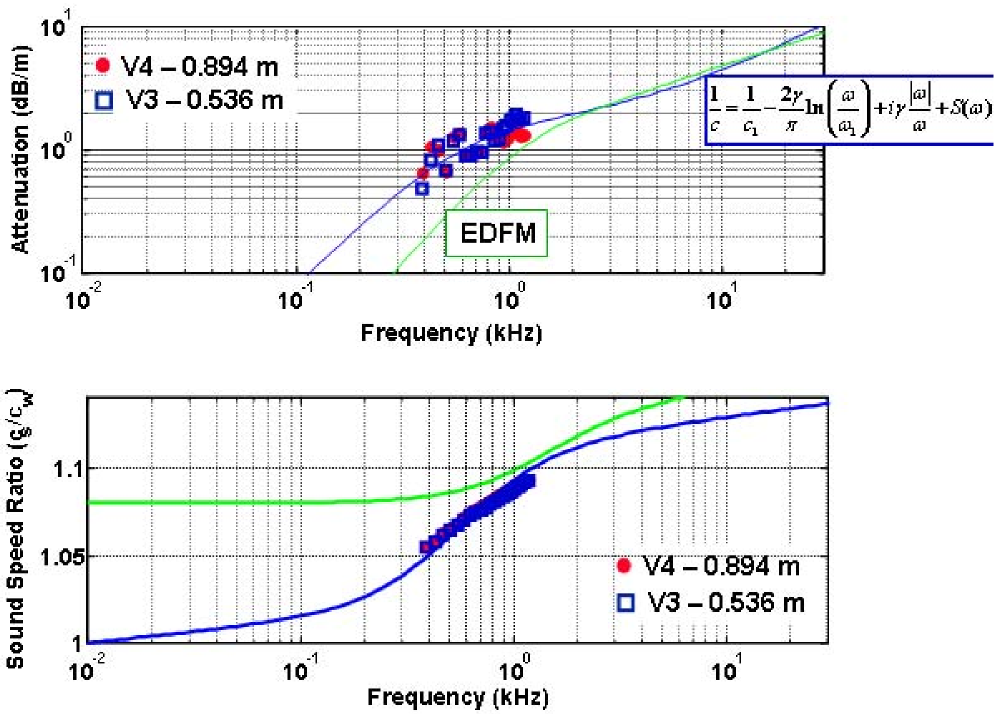

Figure 6. Top: Measurements of attenuation in the sediment (symbols). Also shown is the predicted attenuation (solid lines). Bottom: Dispersion estimated by applying an approximate form of the Kramers-Kronig relation to the measured attenuation data.

IMPACT/APPLICATIONS

The scattering statistics research is providing an improved understanding of the link between environmental parameters and system factors in causing clutter, as well as models and methods for characterizing, predicting and mitigating clutter. This study is leading to methods for modeling and predicting acoustic clutter that may be used to minimize the negative impact of clutter on detection and classification of targets on or near the seafloor in shallow water. Knowledge gained will help in the development of reverberation simulation tools, adaptive systems for sonar clutter reduction and rapid environmental assessment techniques for estimating the strength of clutter for a given area.

The study of the frequency dependence of sediment sound speed has implications for the operation of sonar systems and methods used by the Navy. This study will lead to a greater understanding of dispersion in marine sediments and improved methods for modeling dispersion. Immediate potential impacts could be increasing coverage rates of mine hunting sonar by optimizing the frequencies used. Prediction of the coverage rates of mine hunting sonar could also be improved with knowledge of the seafloor environment.

TRANSITIONS

The statistical models of clutter that have been explored and developed are being quickly incorporated into the ARL-PSU Technology Requirements Model (TRM), a high fidelity, physics-based digital simulator. Discussions are also under way to include models into simulations of Synthetic Aperture Sonar being developed by APL-UW. These models will allow efficient simulation of false alarms and false targets for many different scenarios for which experimental data do not exist.

RELATED PROJECTS

A related ONR project (Grant N00014-03-1-0245) is Characterizing and Modeling the Torpedo Clutter Environment managed by David Drumheller, code 333. Items were purchased for this project under a DURIP (Grant N00014-04-1-0445).

REFERENCES

Abraham, D.A. and A.P. Lyons, 2002, Novel Physical Interpretations of K-distributed Reverberation, IEEE J. Ocean. Eng., 27, 800-813.

Abraham, D.A. and A.P. Lyons, 2004a, Simulation of Non-Rayleigh Reverberation and Clutter, IEEE J. Ocean. Eng., 29, 347-362.

Abraham, D.A. and A.P. Lyons, 2004b, Non-Rayleigh Reverberation Modeling for Arrays, Proceedings of the Institute of Acoustics, 26.

Lyons, A.P., J.C. Osler, P.C. Hines, D.M.F. Chapman, 2005, Estimating Sound Speed Dispersion Using Ship Noise, In Underwater Acoustic Measurements: Technologies and Results, Heraklion, Crete, Greece, eds. John S. Papadakis and Leif Bjorno.

Hines, P.C., J.C. Osler, and J. Scrutton, A.P. Lyons, 2005, Time-of-flight measurements of Acoustic wave Speed in sandy sediments from 0.6 – 20 kHz, In Proceedings of Boundary Influence in High Frequency, Shallow Water Acoustics, Bath, UK, ed. Nicholas Pace. [published]

PUBLICATIONS

Lyons, A.P. and E. Pouliquen, 2004, Advances in High-Resolution Seafloor Characterization in Support of High-Frequency Underwater Acoustics Studies: Techniques and Examples, Meas. Sci. and Tech., 15, R59-R72. [published, refereed]

Lyons, A.P., 2005, On the Potential Impact of Shell Fragment Distributions on High-Frequency Seafloor Backscatter, IEEE J. Ocean. Eng., 30, July, 2005. [in press, refereed]

Lyons, A.P., S.F. Johnson, D.A. Abraham, and K.L. Williams, 2005, Statistical Analysis of Synthetic Aperture Sonar Reverberation, In Proceedings of Boundary Influence in High Frequency, Shallow Water Acoustics, Bath, UK, ed. Nicholas Pace. [published]

Osler, J.C., A.P. Lyons, P.C. Hines and D.M.F. Chapman, 2005, In Situ Assessment of the Orientation and Performance of Buried Directional Receivers for Use in Sediment Acoustic Studies, In Proceedings of Boundary Influence in High Frequency, Shallow Water Acoustics, Bath, UK, ed. Nicholas Pace. [published]

Johnson, S.F., A.P. Lyons, D. A. Abraham, E. Pouliquen, L. Pautet, Bandwidth Dependence of High-Frequency Seafloor Backscatter Statistics, Boundary influence in high frequency, shallow water acoustics, University of Bath, UK, 5-9 Sept 2005. [published]

Hines, P.C., J.C. Osler, and J. Scrutton, A.P. Lyons, 2005, Time-of-flight measurements of Acoustic wave Speed in sandy sediments from 0.6 – 20 kHz, In Proceedings of Boundary Influence in High Frequency, Shallow Water Acoustics, Bath, UK, ed. Nicholas Pace. [published]

Lyons, A.P., J.C. Osler, P.C. Hines, D.M.F. Chapman, 2005, Estimating Sound Speed Dispersion Using Ship Noise, In Underwater Acoustic Measurements: Technologies and Results, Heraklion, Crete, Greece, eds. John S. Papadakis and Leif Bjorno. [published]

Briggs, K.B., A.P. Lyons, E. Pouliquen, L.A. Mayer, and M.D. Richardson, 2005, Seafloor Roughness, Sediment Grain Size and Temporal Stability, In Underwater Acoustic Measurements: Technologies and Results, Heraklion, Crete, Greece, eds. John S. Papadakis and Leif Bjorno. [published]

Osler, J.C., A.P. Lyons, P.C. Hines, J. Scrutton, E. Pouliquen, D. Jones, D.M.F. Chapman, M. O'Connor, D. Caldwell, M. MacKenzie, I.B. Haya, and D. Nesbitt, 2005, Measuring Sound Speed Dispersion at Mid to Low Frequency in Sandy Sediments: An Overview of Complementary Experimental Techniques Developed for SAX04, In Underwater Acoustic Measurements: Technologies and Results, Heraklion, Crete, Greece, eds. John S. Papadakis and Leif Bjorno. [published]

Osler, J.C., A.P. Lyons, and P.C. Hines, 2005, Using Snell's Law to Measure Sound Speed Dispersion, In Underwater Acoustic Measurements: Technologies and Results, Heraklion, Crete, eds. John S. Papadakis and Leif Bjorno. [published]

Hines, P.C., J.C. Osler, I.B. Haya, and A.P. Lyons, 2005, Measuring the Acoustic Wave Speed in Sandy Sediment Using Buried Sources and Receivers, In Underwater Acoustic Measurements: Technologies and Results, Heraklion, Crete, Greece, eds. John S. Papadakis and Leif Bjorno. [published]