

Statistics of High Frequency Acoustic Boundary Scattering and Vector Ambient Noise Fields

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LONG-TERM GOALS

The long-term goal of the present high-frequency scattering statistics work is to examine the links between environmental parameters of shallow water boundaries and the statistics of high frequency, broadband acoustic fields using a combination of at-sea measurements, ground truth and theoretical modeling. The influence of the properties of the boundaries to the scattered envelope statistics and noise fields will be examined in detail. The proposed project is designed to (1) examine experimental acoustic data to determine how environmental properties (e.g. roughness or bubble clouds) influence statistical distributions obtained with broadband, acoustic systems in shallow water including SAS, AComms and vector sensor systems; (2) test current models or develop models where none exist which link measured environmental parameters (e.g. roughness, bubble distributions) and system characteristics (e.g. bandwidth, frequency) to predict these statistics in realistic shallow-water ocean environments. The proposed effort will lead to methods for modeling and predicting properties that may be used to minimize the negative impact of the environment on: 1) detection and classification of targets on or near the seafloor in shallow water; 2) AComms equalization algorithms; and 3) processing of data taken with vector sensor arrays.

OBJECTIVES

The importance of the present work lies in the ability to link scattered envelope distributions to measurable environmental properties such as seafloor patch size composition or sea surface roughness. In conjunction with sonar system parameters, this link will provide the foundation necessary for solving several important problems related to the SAS detection of targets and AComms fading statistics. The direct link between system and environmental parameters via scattering models to the statistical distributions will allow: performance prediction for different systems based on environmental properties, extrapolation of performance to other system/bandwidths, and optimization of system parameters such as frequency/bandwidth to the local environment. Concisely the project objectives are:

1. Through analysis of experimental data and modeling, determine the frequency, bandwidth and grazing angle dependence of seafloor and sea surface scattered amplitude distributions observed in high-frequency sonar systems operating in shallow water.

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2. Using ground truth and scattering models, develop methods for predicting the effects on current and future high bandwidth sonar systems.
3. Define an adaptive strategy to a given environment for mitigating the effects if the environment on sonar systems.
4. Collect vector ambient noise data using vector sensor in a variety of environmental conditions.

APPROACH

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 are lacking. This research program will attempt to characterize the frequency and grazing angle dependence of clutter in the output of high-frequency sonar systems operating in shallow water and link this statistical characterization of returns to the environment through models which will aid in the prediction of environmental effects on future MCM acoustic systems. These goals will be achieved through a combination of at-sea measurements and modeling primarily at frequencies between 3 and 300 kHz. Experimental acoustic data sets will consist of high-frequency narrow and broadband single beam collected as part of a Joint Research Project (JRP) with the NATO Undersea Research Centre (NURC), multi-beam data collected recently by ARL at Seneca Lake, as well as Synthetic Aperture Sonar (SAS) on a rail data that has been collected by the Applied Physics Lab–University of Washington (APL-UW) as part of the SAX04 experiment.

In order to measure vector ambient noise fields, two orthogonal arrays of vector sensors will be deployed within the shallow water environment of AUTECH, Andros Island for a long term study of the acoustic intensity as related to weather and waves. The long deployment period (months) will also allow for multiple opportunities to gather data sets on isolated AUTECH vessel traffic (harbor security) as well as to investigate the ability to utilize surface generated noise to study the geo-acoustic characteristics of the ocean bottom. Deployment at AUTECH is unique in that there is no local industry, commercial traffic or significant sources of anthropogenic ambient noise in the 50Hz to 5kHz region thereby allowing this study to provide baseline performance information on the natural characteristics of acoustic intensity fields in shallow water.

WORK COMPLETED

A predictive model for the statistical distribution of clutter resulting from scattering from two different contributing seafloor types within the same resolution cell was developed and compared with high-frequency acoustic scattering data collected with NURC at Elba Island. The seafloors were modeled as being comprised of a finite number of homogeneous scattering patches (in contrast to the more traditional asymptotic derivation of the K-distribution) on a background (the area around the scattering patches) that was assumed to produce a Gaussian scattered return. In the statistical model, the impact of the relative scattering properties on the angle or frequency dependence of scattered PDFs can be naturally included. Predictions of the effective shape parameter of the K-distribution made using the model with realistic input parameters for several example seafloor descriptions were compared with estimates of the shape parameter obtained from the NURC data. The strength of the developed framework is that any number of different scattering mechanisms can be accommodated and the individual component scattering models can be changed as they improve. In conjunction with sonar

system parameters, such as beamwidth, bandwidth, frequency and grazing angle, the clutter envelope distribution can be linked to measurable geo-acoustic properties.

The impact of propagation on reverberation statistics through modeling, simulation, and data analysis of high-resolution Synthetic Aperture Sonar data was also examined by my Ph.D. student Shawn Johnson. The K-distribution shape parameter was used to represent the reverberation statistics with large values indicating a trend toward Rayleigh-distributed reverberation. Prior to this work, research on the effects of multipath on reverberation statistics had been limited to theoretical studies predicting that multipath serves to make reverberation statistics more Rayleigh-like and experimental data analysis that did not conclusively demonstrate the effect without potentially confounding effects. Modeling and simulation of the SAX04 experiment configuration, sonar system, and local environment predicted a significant increase in the K-distribution shape parameter at the time of arrival of a vertically arriving multipath. Analysis of the SAX04 data illustrated a small shape parameter (on the order of 2) during times when the direct path dominated and a clear and significant increase in the shape parameter at the time of arrival of the fathometer-like multipath. The modeling elucidated a requirement that the sonar system configuration and environment must act together to cause the multipath and direct-path power levels to be within approximately 10 dB of each other for multipath to have a significant impact on the reverberation statistics.

In conjunction with Dave Deveau of NUWC (also my Ph.D. student), planning and initial preparation has begun for collecting vector ambient noise field data with ARL's Wilcoxon TV-001 vector sensors during the next fiscal year. Hardware has been shipped from Penn State to AUTC. Electro-optical cable will be used to bring the signals to shore. The PVC frame that will house the vector sensors has been designed and is being fabricated. A single unit of this frame was tested at NUWC's Dodge Pond calibration facility in August to measure the effects of the frame and mounting on sensor performance.

RESULTS

Fig. 1 shows a plot of the effective shape parameter versus grazing angle predicted by the model for three sample cases. For all three cases, an average density of scatterers of $3/\text{m}^2$ was used to produce the results shown in the figure. The average scattering patch sizes used were 0.2 m^2 for the rock/sand seafloor combination, 0.15 m^2 for live *Posidonia*/sand, and 0.1 m^2 for dead sand/dead seagrass. For estimating the size of the resolution cell on the seafloor used for calculating the model results presented in Fig. 4, the beamwidth at the center frequency of the chirp is used and a bandwidth of 1 kHz. As noted before, owing to the difficulties involved in quantitatively estimating the model parameters of patch size and density during the experiment, these were left as free parameters in the following model results. The size and density values chosen, however, are not unrealistic. For the sediment grain sizes and depths of the Elba Island experimental site, ripples have wavelengths of approximately 20 cm (Lyons, et al., 2002), so that the scales used for dead *P. Oceanica* patches residing in the ripple troughs were close to the expected values. Video confirmed that rocky areas consisted of exposed rock or individual rocks of approximately the size used as input for the model.

Fairly obvious in Fig. 1 is the strong angular dependence seen in the shape parameter estimates. This dependence comes about for several reasons. The general shape parameter increase at low grazing angles, and to a small extent at high angles, for all the examples shown is due to the expanding size of the resolution cell. As the density of scatterers, the transmit/receive beamwidth, and the height above the seafloor are the same for all cases, the different levels seen in the shape parameter for the three

bottom type combinations are due to the difference in scattered power from the scattering patches and surrounding background sediment. This difference is a function of both the individual scattering strength differences between the scattering patch and background and the average patch size. The live Posidonia example has relative scattered powers between scattering patch and background that are similar yielding larger values of the shape parameter (more Rayleigh-like PDFs). The kink in the curve near the critical angle coincides with the portion of the scattering strength curves where the levels for the sand and Posidonia are closest. The rocky seafloor example had large differences in scattering strength and comparatively large scatterers relative to the other two examples, yielding the lowest shape parameters. The dead Posidonia seagrass case had the largest background area and stronger differences in scattering strength, a combination giving shape parameters between the other two.

Fig. 2 displays a comparison between predicted and measured effective shape parameter versus bandwidth at 20° grazing angle for all three bottom types, exhibiting a particularly good fit in the mid-range of bandwidths. The higher variability of the data at the lowest bandwidths arises from the difficulty in estimating the shape parameter when the number of patches is large (as occurs at lower bandwidths). As previously mentioned, the disparity at the higher bandwidths might arise from over-resolution of the patches (note that the down-range resolution of 0.25 m at 3 kHz is on the order of that observed for the patches in the video data) or from an as yet not understood effect of a bandwidth dependent array beamwidth.

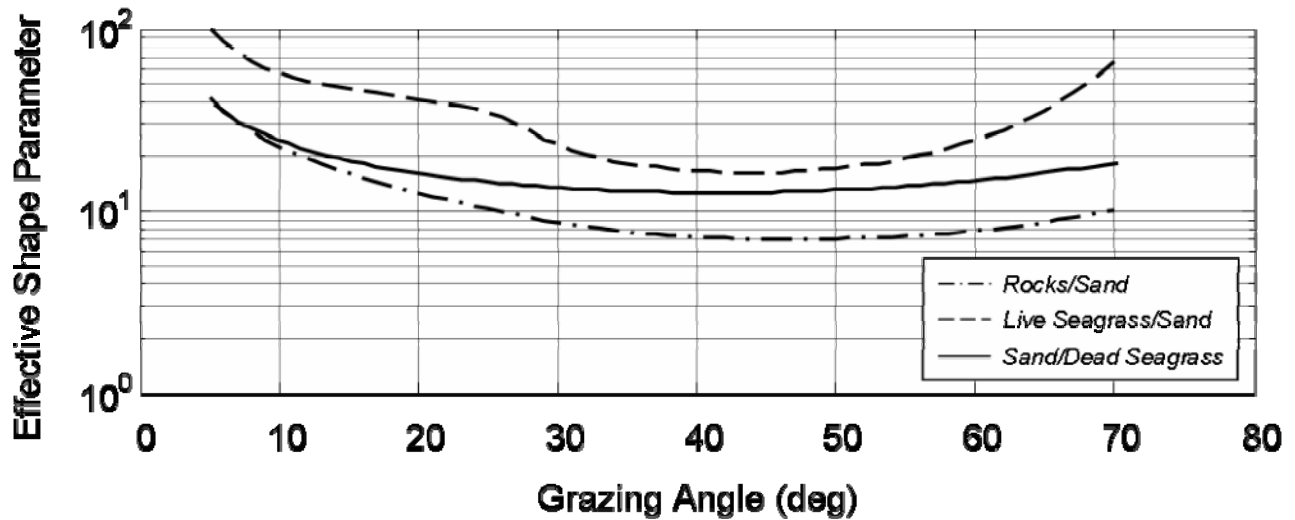


Figure 1. Model curves of effective K-distribution shape parameter versus grazing angle for three example combinations of bottom types. Parameter values are given in the text

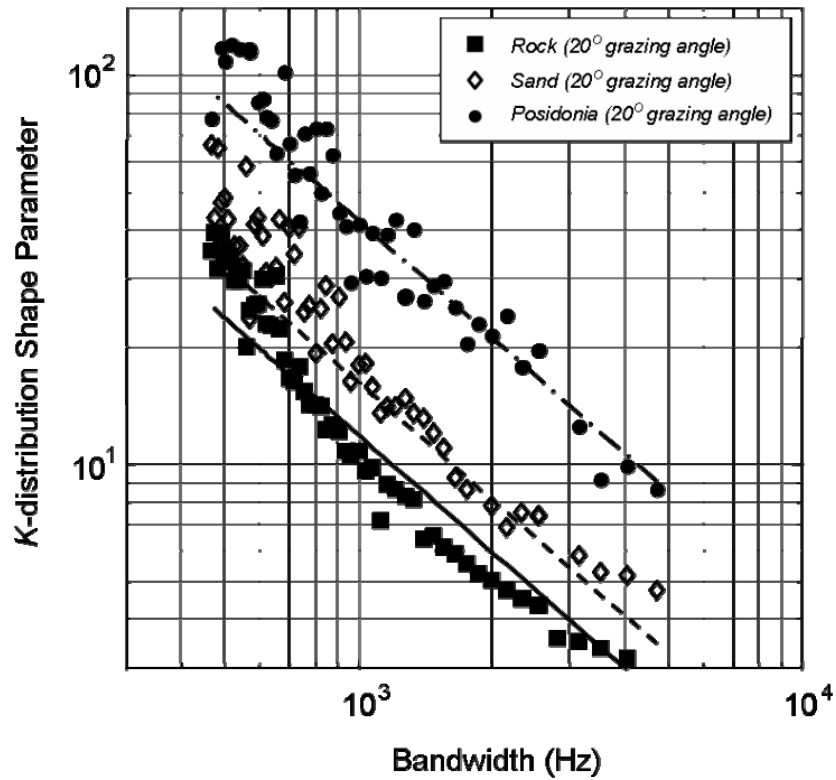


Figure 2. Overlay of 20° grazing angle data and model results of effective K-distribution shape parameter as a function of bandwidth.

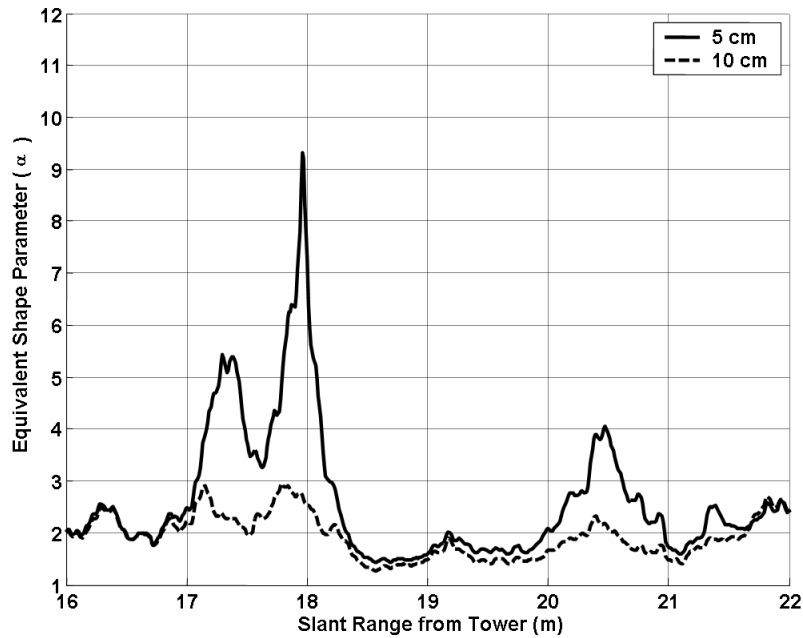


Figure 3. Equivalent K-distribution shape parameter vs. range for a 5 cm (solid) and 10 cm (dashed) vertical aperture receiver. Notice the strong impact on shape parameter at water depth of 18m, and structure multipath from tower/rail structure and other experimental equipment at 17.3 and 20.5 m for the 5 cm receiver, while the 10 cm receiver is minimally affected.

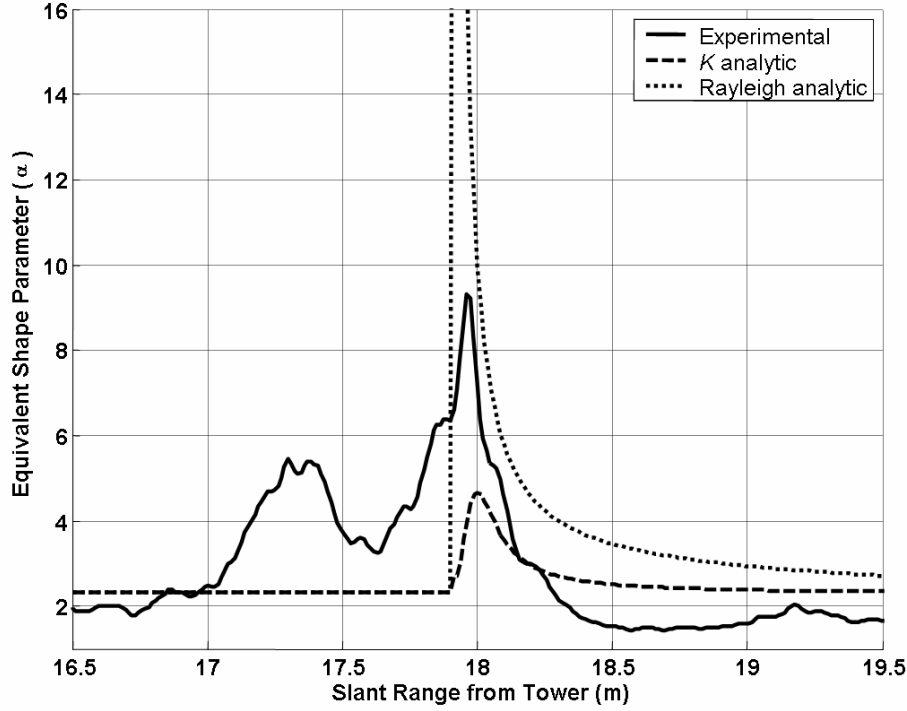


Figure 4. Comparison of 5 cm vertical aperture experimental data (solid) to the two bounding cases of Rayleigh (dotted) and K-distribution (dashed) PDF multipath.

For the SAS multipath work, a method-of-moments estimator was used to estimate a the K-distribution shape parameter as a function of range. A sliding window was used on the data to increase sample size in an attempt to minimize variance without unduly sacrificing spatial resolution (approximately 27,500 points covering 0.32 m). As seen in Fig. 3, the near vertical multipaths at 17.9 m range results in the anticipated increase in the shape parameter for the 5 cm vertical aperture receiver. Also visible in Fig. 3 is a slight increase in the shape parameter at 20.5 m arising from scattering off the electronics package, which was approximately 2.5 m below the receivers. A greater increase in shape parameter is seen at 17.3 m as a result of other tower/rail structure reflections. In contrast, negligible impact on shape parameter estimates due to multipath is seen for the data collected with the 10 cm receiver, which has a vertical beam pattern with a narrower main lobe and therefore rejects more off-axis reverberation than the smaller aperture. However, this tight beam pattern also reduces the useable range of the transducer for a fixed mounting angle.

A comparison of the model result to the experimental data for the 5-cm vertical receiver is shown in Fig. 4 for the region in range around the fathometer-like multipath (the 10-cm receiver was minimally affected by the fathometer-like multipath). The two analytical models (K-distributed direct path with either Rayleigh-distributed or K-distributed multipath) bound the experimental data, with the K-distributed multipath model underestimating, and the Rayleigh multipath model overestimating the increase in shape parameter. The most significant deviations in Fig. 4 occur around 17.3 m with the experimental data showing slightly higher shape parameter values, and at 18.5 m with slightly lower values, than modeled. As mentioned previously, the former is attributable to reflections from experimental apparatus that are not included in the propagation modeling. The latter may arise from

inaccuracies in the backscatter strength modeling leading to a slower roll-off of the multipath than actually occurs, in combination with range-dependant bottom composition of experimental data. Ripple structure is slightly more pronounced and can cause heavier-tailed reverberation from the direct path, effectively decreasing the effective shape parameter in spite of the presence of multipath (~ 1.5 at 18.5 m compared with the base value of 2.32 used in the modeling). This highlights a fundamental limitation to the modeling and analysis presented: there is an implicit assumption that the base shape parameter () of the seafloor backscattering is known (in the model evaluation it was estimated from a region solely containing direct-path reverberation).

For the planned vector sensor work, the arrays will be formed into a ‘T’ shape and mounted on a tripod assembly (Fig. 5). The PVC will be allowed to flood and kept small enough in diameter thus providing acoustic transparency at these frequencies. The sensors will be placed at $\lambda/2$ spacing at 3 kHz or approximately 25 cm . Each sensor will move independently while supported by a cradle of springs a very low stiffness to produce a resonance under 10 Hz. The sensor system will be deployed at a height of 2 meters off the bottom. The cables that run from the vector sensors are sufficiently long to allow the data acquisition system to be placed approximately 60 ft away from the tripod to minimize its interference as a bottom scatter. A single 2000 m length of armored electro-optical cable will be run from a shore termination building to the array deployment location (Fig. 6). The assembly will be placed in a nominal 15-20 meter water depth.

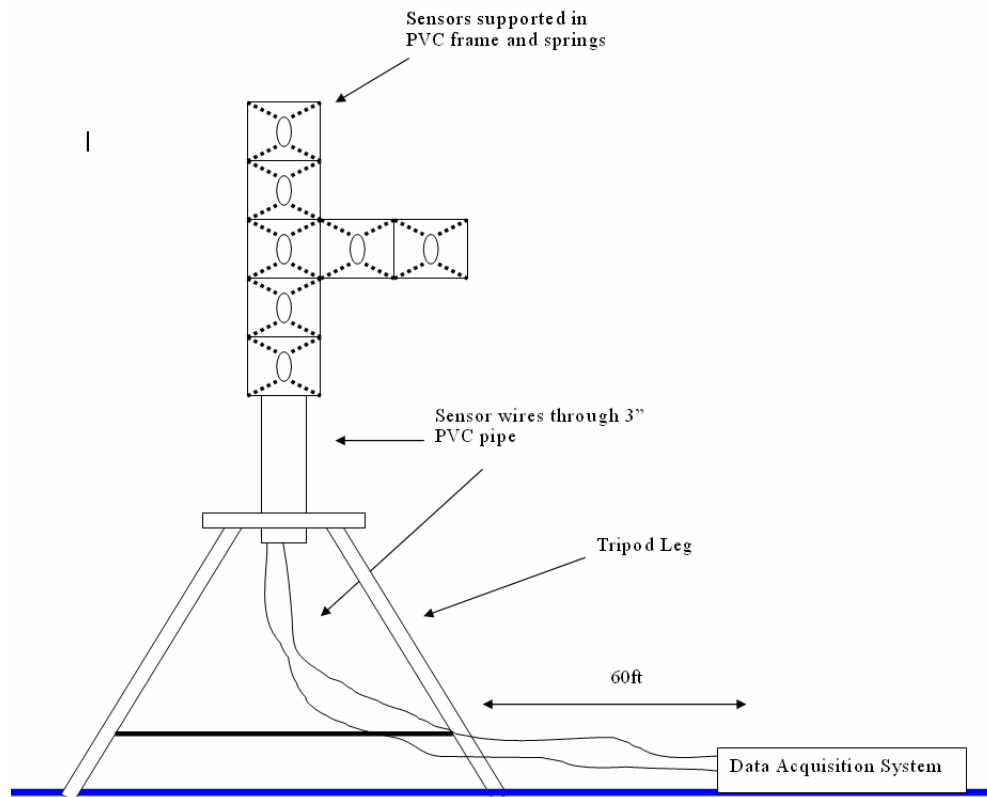


Figure 5. Vector sensor deployment frame.



Figure 6. Sensor cable deployment track.

IMPACT/APPLICATIONS

The scattering statistics research is providing an improved understanding of the link between environmental parameters and system factors in causing 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 vector noise fields has implications for the operation of future vector sensor sonar systems and methods used by the Navy. This study will lead to improved methods for modeling vector field of ambient noise.

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. Vector sensor ambient noise studies will yield guidance for future navy using arrays of these type of sensors.

RELATED PROJECTS

A related ONR project (Grant N00014-06-1-0245) 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).

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