Statistical Evaluation of 80 kHz Shallow-Water Seafloor Reverberation

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Abstract

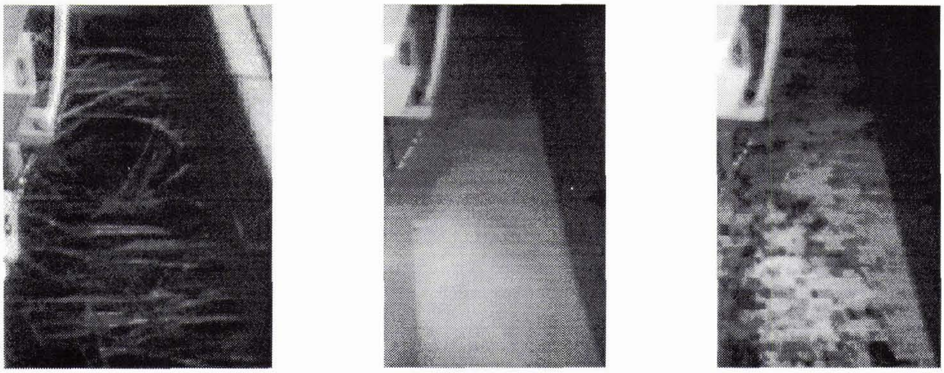
In this work a comparison is presented between 80 kHz reverberation statistics obtained at shallow water sites around Sardinia and Sicily. The data include measurements from several distinct bottom provinces, including sites with Posidonia Oceanica sea grass and sites covered with live shellfish. The reverberation statistics did not always exhibit a Rayleigh probability distribution function (PDF), but exhibited statistical distrubutions with longer tails. Several more appropriate models of reverberation PDF were examined in order to better describe the measured amplitude distributions. The Rayleigh mixture and the K models were found to be the most robust in describing the observed data.

1. Introduction

The detection and identification of objects on the seafloor is made more difficult by seafloor reverberation. While the problem of understanding and predicting high-frequency background reverberation level or mean energy scattered per unit area of the sea bed has received considerable attention, studies of high frequency reverberation statistics are relatively scarce. Of these studies, many have dealt with scattering from more or less homogenous seafloors in terms of bottom type [1, 2, 3]. Most shallow water areas, however, will not be homogeneous but will have patchiness in space and time, which is often a result of biology. An example of spatial inhomogeneity are shellfish which often do not exist uniformly on the seabed but are distributed in clumps of varying density. The motion of seagrass due to swell or currents causes a constantly changing number of scattering sites which can be thought of as time varying patchiness. Clutter is the acoustic expression of the non-uniformity of these types of seafloor environment.

When the effective numbers of scatters in the resolution cell of a sonar is large enough, the amplitude distribution is expected to be Rayleigh as the central limit theorem holds resulting in gaussian in-phase and quadrature components of the received signal. The changes in density of scatterers commonly found in shallow water suggests that this model might not always be appropriate especially when the area ensonified by the transmit and receive beam patterns is not large enough to encompass enough of the patches of differing scatter density. More general distributions for addressing amplitude statistics of scattering from heterogeneous seafloors are the Weibull, K, and Rayleigh mixture distributions each of which has the Rayleigh distribution as a submember. The K distribution, used to succesfully describe the statistics of radar sea surface clutter [4, 5], can be described as being the product of two components; a rapidly fluctuating Rayleigh (or 'speckle') distributed component and a chi distributed component. The physical interpretation is that the Rayleigh distributed component is from many scatterers that are modulated by large scale (time varying) structure. The Rayleigh mixture model [6] is a combination of Rayleigh random variables with each component having its own power. This distribution can be thought of as describing scattering from two (or more) different types of materials in a manner similar to that put forward by Crowther [7].

This paper presents acoustic data collected at 80 kHz at shallow water sites around Sardinia and Sicily. Fifteen sites were examined and results from seven of the sites are presented in terms of system independent site characterization. The sites studied included a variety of bottom types, including sites with *Posidonia Oceanica* sea grass and sites covered with live shellfish. Examples of three of the types of seafloor studied are shown in the video stills seen in Figure 1. The diversity of sites studied allowed an excellent opportunity to examine the statistics of reverberation from a wide variety of seafloor environments. Results of statistical analysis are cast in terms of mean power value or backscattering coefficient as well as analysis of the amplitude statistics. Rayleigh, Weibull, K, and 3-component Rayleigh mixture PDFs are compared to measured data and a non-parametric test is used to describe the goodness of fit between modeled and measured amplitude distributions.



(a) Posidonia covered sand bottom - station RR06

(b) Sand bottom - station RR12

(c) Shell covered sand bottom - station RR13

Figure 1: Examples of the nonhomogeneous nature of sand seafloors.

2. Data Analysis

The 80 kHz acoustic system used in this study has been fully characterized against reference hydrophones at the SACLANT Undersea Research Centre to quantify source level and beam pattern. System gains were measured while at sea. Using the transducer calibration value (pressure to voltage transfer function), processing gain and system gains, the absolute received levels at the hydrophone were recovered from the recorded data. In order to get quantitative seafloor information out of the received level, three effects that may modify the sound pressure level as the pulse travels from the source to seafloor and back to the receiver have been taken into account. These three factors are the effects of the beam pattern, transmisssion loss, including both spherical spreading and absorption, and equivalent ensonified area. With the above described components, seafloor backscattering strength as a function of time can easily be calculated using an inverted form of the sonar equation with a knowledge of the source level, transducer calibration and logging calibration. The backscattering strength as a function of grazing angle can then be obtained from knowledge of the transducer height and the sound speed of the sea water. In data processing only grazing angles within the $3dB$ down points of the one-way beam pattern were considered.

From each experimental site, returns from 200 $1ms$ pulses at each of four tilt angles (measured relative to the main beam axis) were analyzed. The 20 degree beamwidth of the transducer allowed scattering strength measurements versus grazing angle to be taken with these four tilt angles (for most sites the range of grazing angles from which data were obtained was from 10° to 80°. Every 15th data point of scattering curve was used for the amplitude statistics study as correlation analysis determined these to be independent. Data at each grazing angle were normalized by the mean power of 200 pings in order to remove grazing angle dependence. Data was grouped in 20 degree grazing angle bins, to increase the number of data points for statistical analysis. Amplitude data was tested for stationarity using the Mann-Whitney test as in [2, 3]. For a two tailed test at 95% confidence, values less than 1.96 and greater than -1.96 are considered to be from the same distribution. Data that fell out of this range was excluded from the analysis. The top graph of Figure 2 shows an example of the normalized amplitude for 200 pings in a 20 degree grazing angle bin, while the bottom two graphs illustrate the Mann-Whitney results for comparisons of groups of 20 pings and comparisons between grazing angle respectively. Rayleigh, Weibull, K, and Rayleigh mixture distributions were compared to the experimental PDFs. Fitting the model distributions to the experimental results entailed estimating the parameters of each of the candidate CDFs. Maximum likelihood estimates obtained using an iterative algorithm [8] were used for the parameters of the Weibull

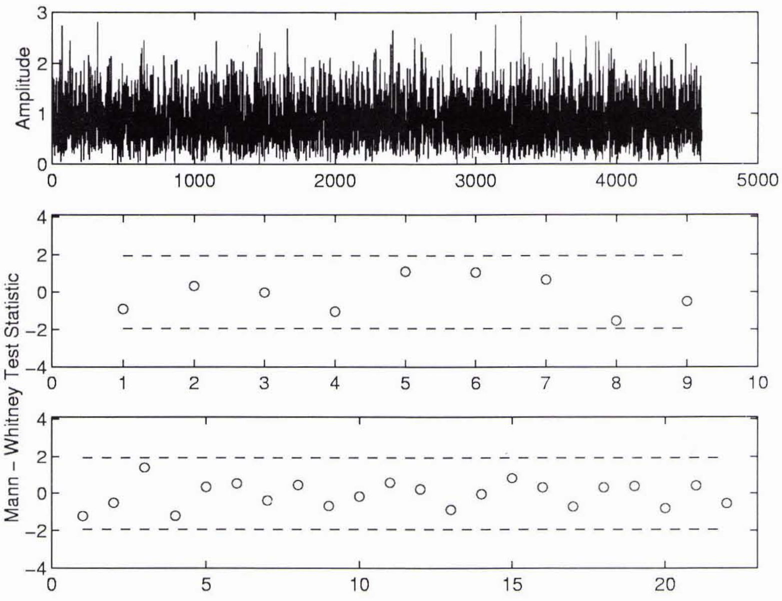


Figure 2: Sample results from the Mann - Whitney stationarity test

distribution, method of moments estimates were used for the parameters of the K distribution, matching the mean and variance, and for the Rayleigh mixture model the maximum likelihood parameter estimates were obtained using the expectation-maximization (EM) algorithm [9].

Backscattering strength resulting from the inversion described above from four sites is shown in the top graphs of Figures 3 - 6. Because all system dependent factors, as well as measurement geometry effects (including spreading loss and absorption) and the ensonified area contribution have been removed from the original raw data, the resulting inverted values represent the true quantitative acoustic response of the seafloor (backscattering strength.) Thus, in the graphs, quantitatively correct values indicate the different scattering properties of the three sites. The general patterns of the curves for the measurement sites are consistent with values reported near this frequency in that they approach a maximum as they near normal incidence, fall off to a nearly constant level over a wide range of grazing angles, then decrease at low grazing angles. In some of our sites the signal to noise ratio is too low to give reliable scattering strength estimates at the smallest grazing angles as seen by figure 3. The shellfish covered site had extremely high levels of backscatter at 80 kHz as did the posidonia covered site. Surprisingly the sand and mud sites shown in these examples had similar levels of backscattering, suggesting that absolute level is not sufficient to separate different bottom types.

Also shown in Figures 3 - 6 are visual examples of the the experimentally observed reverberation PDFs along with the fitted models. The non-Rayleigh nature of the distribution is easily seen in the high grazing angle shellfish, posidonia, and sand data. The distributions tend to Rayleigh at lower grazing angles. A simple explanation for this effect is that as a consequence of the height of the transducer remaining constant the resolution cell of the sonar will increase at the smaller grazing angles. More patches of seafloor are included in the beam at low grazing angle which drives the amplitude distribution toward Rayleigh as the central limit becomes valid. Chotiros [1] has discussed similar effects of the resolution cell (receive beamwidth). A quantitative table of goodness of fit of the observed data to each of the model distributions will be shown in the next section.

3. Results

To evaluate the flexibility and accuracy of the models in representing the reverberation from the different seafloor types, the Kolmogorov-Smirnoff (K-S) test statistic p-values were used to compare real data to model distributions [10]. These values provide a measure of the goodness of fit between the model distributions and the observed distributions. Results are presented for each of seven sites and are grouped in terms of grazing angle. Table 1 shows bottom type, average scattering level, and K-S p-values for the 60° to 80° grazing angle, Table 2 for 40° to

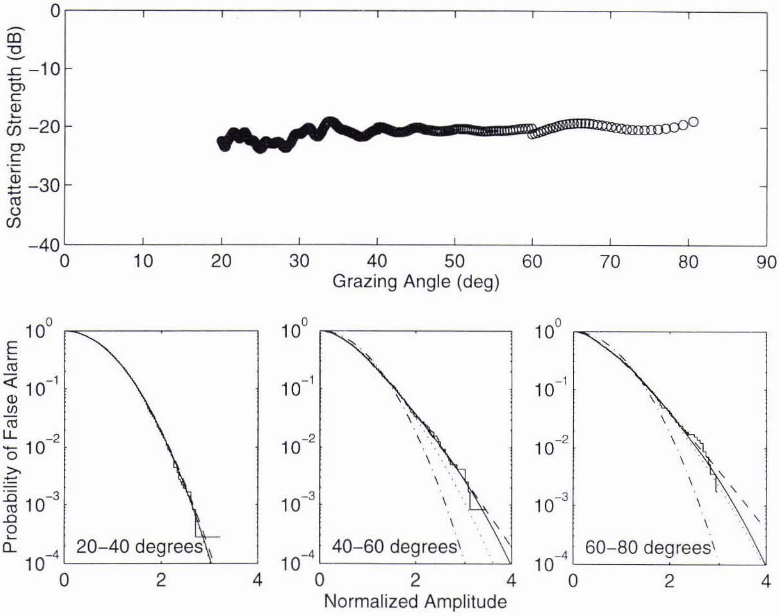


Figure 3: Posidonia statistics - station RR06. The dashed-dotted line is the Rayleigh distibution, the dotted is the Weibull, the dashed is the K, and the solid is the Rayleigh mixture

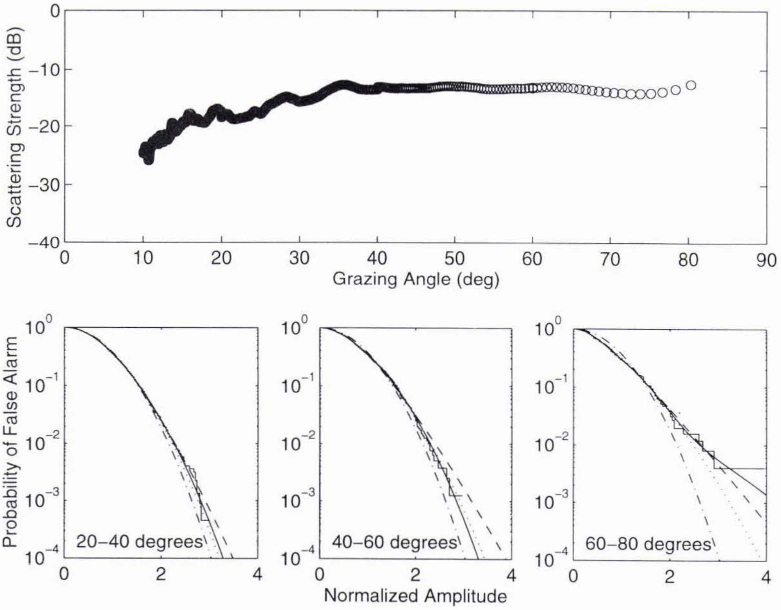


Figure 4: Shellfish statistics - station RR13. Line types as in Figure 3

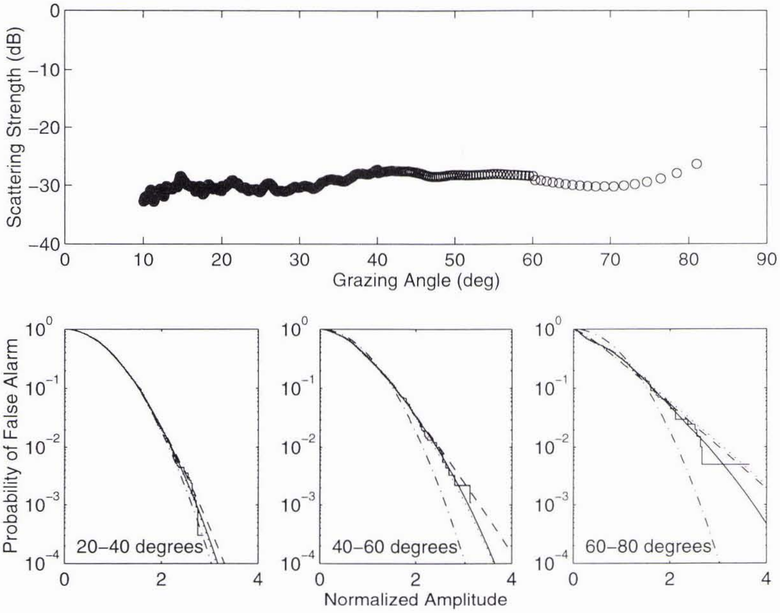


Figure 5: Sand statistics - Station RR12. Line types as in Figure 3

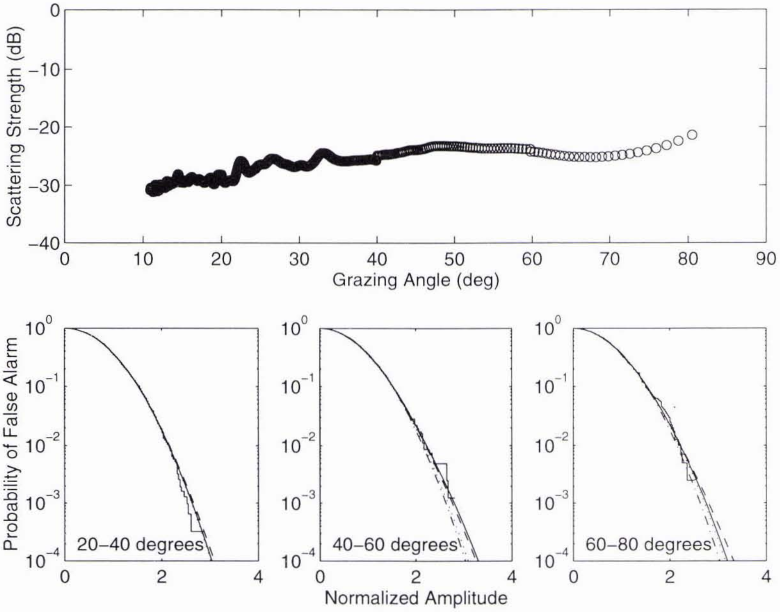


Figure 6: Mud statistics - station RR09. Line types as in Figure 3

60° grazing angle, Table 3 for 20° to 40° grazing angle, and Table 4 for 10° to 20° grazing angle. Any p-values above 0.7 are shown in bold to highlight the best fits to observed data. Quantitative agreement is seen with the qualitative assesment of the last section. The highest grazing angles are usually not well described by the Rayleigh distribution. The Weibull, Rayleigh mixture, and K distributions all do a better job of matching the observed distribution than a standard Rayleigh. The fact that this is true is obvious as each of the other distributions has more parameters to tweak to fit the data. The Rayleigh mixture and K distributional models are more robust in fitting the observed data and work over the entire range of grazing angles (resolution cell size). The scattering levels are not generally separable by bottom type. In general the muds give the lowest scattering level, the sands give medium scattering level, and the shellfish and posidonia covered bottoms give the highest levels.

4. Conclusions

Rayleigh PDFs were often found to not be accurate descriptors of the shallow water 80 kHz reverberation analyzed, especially at high grazing angles. This more than likely is due to the number of patches of differing scatter density or strength included in the sonar resolution cell at a given grazing angle. Rayleigh Mixture or K distributions are the best in fitting the observed distributions over all bottom types at high grazing angles and, as these contain the Rayleigh distribution as a submember, also work very well at low angles. A 3-component Rayleigh mixture model was used in this analysis but could be expanded easily to more to include more components which would allow it to fit almost any distribution.

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Table 1: Results for selected sites and for 60°-80° grazing angle. Values over 0.7 are given in bold.

Station	*Bottom Type*	*Scattering Level*	*Rayleigh*	*Weibull*	*Rayleigh Mixture*	*K*
RR06	posidonia covered sand	-20.0 dB	1.04×10^{-9}	0.667	**0.983**	**0.933**
RR09	mud	-23.5 dB	**0.902**	**0.986**	**0.998**	**0.999**
RR10	coarse sand/shell hash	-20.4 dB	**0.818**	**0.843**	**0.818**	**0.747**
RR11	coarse sand/shell hash	-23.0 dB	**0.992**	**0.999**	**0.997**	**0.999**
RR12	medium sand	-28.9 dB	3.42×10^{-12}	0.543	**0.977**	0.123
RR13	shell covered sand	-13.8 dB	1.57×10^{-4}	0.440	**0.850**	**0.802**
RR16	mud	-25.7 dB	0.026	0.473	**0.999**	**0.875**

Table 2: Results for selected sites and for 40°-60° grazing angle.

Station	*Bottom Type*	*Scattering Level*	*Rayleigh*	*Weibull*	*Rayleigh Mixture*	*K*
RR06	posidonia covered sand	-21.0 dB	1.28×10^{-7}	0.367	**0.989**	**0.996**
RR09	mud	-23.8 dB	**0.827**	**0.979**	**0.999**	**0.999**
RR10	coarse sand/shell hash	-21.2 dB	**0.978**	**0.853**	**0.978**	**0.984**
RR11	coarse sand/shell hash	-24.4 dB	**0.953**	**0.941**	**0.953**	**0.969**
RR12	medium sand	-28.2 dB	4.25×10^{-4}	**0.716**	**0.881**	0.615
RR13	shell covered sand	-13.5 dB	0.002	0.508	**0.963**	**0.866**
RR16	mud	-25.4 dB	0.246	**0.785**	**0.951**	**0.965**

Table 3: Results for selected sites and for 20°-40° grazing angle.

Station	*Bottom Type*	*Scattering Level*	*Rayleigh*	*Weibull*	*Rayleigh Mixture*	*K*
RR06	posidonia covered sand	-21.8 dB	**0.955**	**0.982**	**0.955**	**0.794**
RR09	mud	-27.0 dB	**0.941**	**0.886**	**0.941**	**0.974**
RR10	coarse sand/shell hash	-23.7 dB	**0.803**	**0.983**	**0.952**	**0.980**
RR11	coarse sand/shell hash	-26.1 dB	**0.812**	**0.871**	**0.986**	**0.885**
RR12	medium sand	-29.5 dB	0.070	**0.927**	0.616	**0.749**
RR13	shell covered sand	-16.2 dB	0.014	0.328	**0.888**	**0.863**
RR16	mud	-26.2 dB	**0.888**	**0.924**	**0.888**	**0.877**

Table 4: Results for selected sites and for 10°-20° grazing angle.

Station	*Bottom Type*	*Scattering Level*	*Rayleigh*	*Weibull*	*Rayleigh Mixture*	*K*
RR09	mud	-30.1 dB	**0.995**	**0.999**	**0.995**	**0.875**
RR10	coarse sand/shell hash	-24.7 dB	**0.970**	**0.997**	**0.999**	**0998.**
RR12	medium sand	-29.0 dB	0.204	**0.915**	**0.902**	**0.912**
RR13	shell covered sand	-21.1 dB	**0.939**	**0.999**	**0.968**	**0.992**