2aUW7. Comparison of statistics of controlled source tones and single ship noise in the deep ocean

Brianne Baxa*, Gerald D'Spain, Peter Worcester, Matthew A. Dzieciuch, Kevin Heaney, James Mercer and Arthur Baggeroer

*Corresponding author's address: Scripps Institution of Oceanography, UC San Diego, San Diego, CA 92037, bmoskovitz@gmail.com

The deep ocean experiment, PhilSea09, was conducted April-May, 2009, in the central part of the northern Philippine Sea (22d N, 126d E). During one period in the experiment, the R/V Melville was station-keeping 35 km from the Distributed Vertical Line Array (DVLA) while seven tones, from 79 Hz to 535 Hz, were transmitted from a controlled source suspended below the ship. Recordings on the 1000-m section of the DVLA centered on the surface conjugate depth at 5026 m were dominated by the noise of this ship in certain frequency bands, and also the controlled source tones at the transmitted frequencies. Using non-parametric statistical tests, the complex statistics of the spectral envelope at the tone frequencies are compared to the statistics of those for the nearby ship-noise-dominated frequency bins. When the controlled source tone dominates, the statistics are Gaussian, and the statistics of the tones differ from those of the nearby noise at the 5% level of significance by the Kolmogorov-Smirnov two-sample test. Both the tones and shipping noise travel approximately the same path to the DVLA, so these differences in the received field statistics represent differences in the statistical properties of these two acoustic sources themselves, not of the environment.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

A variety of sources contribute to ambient noise in the ocean. In different frequency ranges, ambient noise may be dominated for example by wind, seismic activity, marine mammal sounds, air gun signals, and shipping noise. A Gaussian distribution is typically assumed when statistical properties of these sounds are used. The probability density function of ambient ocean noise is assumed to be Gaussian by invoking the Central Limit theorem [1][2][3][4]. The Central Limit Theorem states that the sum of an infinite number of independent, identically distributed random variables will have a distribution that tends towards a Gaussian distribution. When ambient noise is dominated by an individual ship, it has already been noted that the statistics are non-Gaussian [5]. Aside from the fact that a single source is present, the resulting statistics may also be due to the nature of the source or the environmental factors along the propagation paths. This paper identifies differences in statistics of noise from a station-keeping ship and from concurrently received controlled source tones sent from the same ship.

The experimental setup allows analysis of the statistics of a stationary ship and single frequency tones that travel the approximate same path to a fixed vertical array 35 km from the sources. Because the sound travels along the same path, the environmental effects on the statistics are approximately the same, and any differences in the statistical properties of the ship signal and source tones are likely due to the mechanical forces driving the individual sources themselves.

Non-parametric statistical tests are used in this paper based on the work of Jobst and Adams [6]. Tests such as the Kolmogorov-Smirnov 1 and 2 sample test, and the Lilliefors test are used to categorize the spectral envelope of the time series. Using non-parametric tests, no prior knowledge of the data is needed, and no assumptions are made to perform the tests.

This paper compares the statistics of a single ship to the statistics of controlled source tones. Description of the Experiment describes the setup of the experiment conducted in the Northern Philippine Sea. A description of the statistical tests and data processing is presented in Description of Statistical Tests and Data Processing. The Results and Discussion section describes the results for the statistics of a single ship, the controlled source tones, and a comparison of the two. Conclusions are presented in the last section.

DESCRIPTION OF THE EXPERIMENT

The deep ocean experiment, PhilSea09, was conducted April-May, 2009, in the central part of the northern Philippine Sea.

Distributed Vertical Line Array

The Distributed Vertical Line Array (DVLA) was moored on the ocean bottom in 5530 m deep water at 21°21.8987N, 126°01.02451E. The two sections on the DVLA were composed of the axial section spanning the sound channel axis, and the deep section. The deep 1000-m section of the DVLA was composed of 30 hydrophone elements, with the upper 10 elements spaced 90 m apart (equal to half-wavelength at 8.3 Hz) and the deepest 20 elements spaced 5 m apart (half-wavelength at 150 Hz). The top element was at a depth of 4285 m, and the array spanned the conjugate depth at around 5000 m. Data collected were sampled at 1953.125 samples per second. The array recorded primarily four types of sounds not purposefully created as part of the experiment: wind noise, ship noise, airgun signals, and earthquake T-phases.
Experiment Setup

The time period selected for this study was when the R/V Melville was station-keeping 35 km northeast of the DVLA at 21.67N, 126.12E. At a range of 35 km, the R/V Melville is at a distance of 1/2 convergence zone from the DVLA. With the Melville at this range, the dominant source recorded on the lower section of the DVLA is the Melville itself.

During the first 30 min time period, the J-15 source was suspended 60 m below the Melville. It created a seven tone signal with frequencies at 79 Hz, 100 Hz, 135 Hz, 198 Hz, 355 Hz, 405 Hz, and 535 Hz. Focus centered on the results of the first four tones due to their high signal-to-noise ratios (SNR). Tone data were taken from the center frequency bin. Ship noise data were taken four frequency bins above and below the tone bin. Spectral analysis verified that no significant energy from the tone was present in these bins.

Description of Statistical Tests and Data Processing

This section describes the statistical tests and data processing performed on the data. The noise field is analyzed for time stationarity and normality using the Kolmogorov-Smirnov two-sample test (KS2), and Lilliefors Test respectively. The statistical tests were run on the data from each element in the array. Procedure follows that of Jobst and Adams [6].

For the thirty min segment of interest, an 8192 point FFT was taken with a Kaiser Bessel window, $\alpha = 2.5$, with 50% overlap. Statistics are computed on the complex spectral envelopes of each element.

The KS2 test for stationarity compares the cumulative distribution function (CDF) of the first half of the data, to the last half of the data. The maximum value of the absolute difference of the CDFs is the test statistic. The null hypothesis is that the data belong to the same distribution. The hypothesis that the data samples are normally distributed is tested using the Lilliefors test. The Lilliefors test is a two-sided goodness-of-fit test suitable when a fully-specified null distribution is unknown and its parameters must be estimated from the data. This test was chosen over the Kolmororov-Smirnov one-sample test (KS1) because the KS1 test requires the null distribution to be completely specified. The process is similar to the KS2 test in that it takes the maximum value of the absolute difference of the CDF of the sample data and compares it to the CDF of a normally distributed sample with the same mean and variance as the data. The null hypothesis is that the data comes from a Gaussian distribution. The p value for each test is also calculated. The p value is the probability of obtaining a test statistic. The lower the p-value, the more likely one is to reject the null hypothesis.

In addition to these non-parametric tests, a derivative of the KS2 test was used. To compare the statistics of the controlled source tone frequency bin to the nearby frequency bin on shipping noise, the CDF of the controlled source tone data was compared to a CDF of the shipping noise data, and the maximum absolute difference between these two CDFs was the test statistic. The null hypothesis is that the two data sets belong to the same continuous distribution.

Results and Discussion

Statistics of a Single Ship and Controlled Source Tone at 35 km

Statistical tests for stationarity and Gaussianity were run on the first 30 min time period. Over the first 15 minutes, the received level of ship noise was higher than the last 15 minutes. The KS2 test was run to compare the CDF of the first five minutes to each consecutive five minute segment. From these results, the ship noise was stationary over the first 15-min time period. With the first fifteen minutes of data, the Lilliefors test was performed. The upper plot
The upper plot shows the results of the Lilliefors test for Gaussianity from 0 to 200 Hz on the first 15 minutes of data when ship noise was dominant. The coloring is the probability of accepting the null hypothesis that the distribution is Gaussian. Therefore, dark blue coloring indicates areas where the distributions are highly unlikely to be Gaussian. The lower plot shows the received sound pressure level as a function of depth and frequency during the same 15 minutes of data.

![Figure 1](image_url)

**Figure 1**: The upper plot shows the results of the Lilliefors test for Gaussianity from 0 to 200 Hz on the first 15 minutes of data when ship noise was dominant. The coloring is the probability of accepting the null hypothesis that the distribution is Gaussian. Therefore, dark blue coloring indicates areas where the distributions are highly unlikely to be Gaussian. The lower plot shows the received sound pressure level as a function of depth and frequency during the same 15 minutes of data.

in Fig. 1 shows the results of the Lilliefors test over frequency and depth. The probability of accepting the null hypothesis from 0 to 0.5 is colored from dark blue to red. From the range of 10 to 80 Hz, the spectral envelope is highly unlikely to be Gaussian. These results are in agreement with Brockett [5] who found that single ship noise was non-Gaussian. From 80 Hz to about 115 Hz, one is unable to reject the null hypothesis based on the Lilliefors test. This frequency band and period correspond to a lower received level. It appears that this frequency band may be dominated by wind noise as opposed to the single ship noise. From the Central Limit Theorem, the wind noise follows a Gaussian distribution because there is an infinite number of identically distributed sources that contribute to the sound field. From about 115 to 160 Hz, the results indicate a non-Gaussian distribution. This frequency band corresponds to a higher spectral level between 4500 and 4700 m depth which is likely due to focusing phenomenon of the ship signal.

Knowing that the distributions from 10 to 80 Hz are non-Gaussian, histograms of the data at a given frequency and depth were generated to describe the probability density function. At frequency bins of 10, 30 and 50 Hz, the histograms of the spectral envelope of the received field were analyzed along the DVLA. Distributions were found to have a higher kurtosis (i.e., are peakier) than that of a Gaussian distribution. Similar results can be seen with single ship noise in Baggeroer [7]. The Pearson's VII distribution is a symmetric distribution with a kurtosis greater than that of a normal distribution, and was fit to the histograms. The formula for the
Figure 2: This figure shows histograms of the received field for the 15 min of data, at a depth of 5185 m. The middle plot is the histogram of the 135 Hz tone data, whereas the upper and lower plots show the nearby noise bins below and above the tone bin, respectively. The red line shows a Gaussian distribution with sample mean and variance. The green line shows a Pearson VII distribution with the sample kurtosis. The probability density function is as follows with $\gamma$ being the sample kurtosis (minus 3 to normalize):

$$p(x) = \frac{1}{{\alpha B(m - \frac{3}{2}, m)}} \left[ 1 + \left( \frac{x - \lambda}{\alpha} \right)^2 \right]^{-m}$$

$$\alpha = \sigma \sqrt{2m - 3}, m = \frac{5}{2} + \frac{3}{\gamma}$$

For the non-Gaussian distributions, the Pearson VII is a better fit than the Gaussian distribution.

Histograms of ship noise and tones were plotted for single elements at various depths and frequencies. Figure 2 shows histograms of the data for an element at 5185 m depth at three frequency bins around the 135 Hz controlled source tone. The upper plot is a histogram of the ship noise data four frequency bins lower than the center frequency of 135 Hz. The center plot is the frequency bin containing the controlled source tone, and the lower plot is the ship noise data four frequency bins above the center frequency. The Pearson VII distribution is superimposed on each histogram using the sample kurtosis (in green). The normal distribution is superimposed in red. In the frequency range when ship noise is dominant, the distributions are non-Gaussian, with symmetric distributions that are peakier than Gaussian. The received level of the ship noise around 135 Hz at 5185 m is fairly low, so a combination of ship noise and wind noise likely contributes at this depth and frequency. The histograms show a non-Gaussian distribution with higher kurtosis for these data (Fig. 2).

The middle plot of Fig. 2 shows the distribution of the 135 Hz controlled source tone. The distribution follows a Gaussian distribution which is confirmed by the Lilliefors test (Fig. 3). The controlled source tone has a distinctly different distribution than the neighboring ship/wind noise.

The statistical tests were conducted for the controlled source tones at 79 Hz, 100 Hz, 135 Hz, and 198 Hz. The Lilliefors test shows that the distributions for controlled source tones are
**FIGURE 3**: Lilliefors test for Gaussianity on ship sound and 100 Hz tone in the upper plot and ship sound and 135 Hz tone for the first 15 min of data in plot B. Statistics for real values on the spectral envelope are plotted as circles, and for imaginary values as squares. The probability of accepting the null hypothesis that the distribution is Gaussian is plotted along the horizontal axis from 0 to 0.5.
FIGURE 4: Using the Kolmogorov-Smirnov two-sample test, the CDFs of the controlled source tones and noise were compared. The left plot compares the tonal bins and noise four bins below the tone, and the right compares the tonal bin to the noise four bins above the tone. The probability plotted is the likelihood of accepting the null hypothesis that the distributions are from the same underlying continuous distribution. Red points depict SNR greater than 9 dB, magenta points are SNR between 5 and 9 dB, and green points are SNR less than 5 dB.

unable to reject the null hypothesis (Fig. 3).

Comparison of Single Ship and Signal using KS2 test

In order to determine whether the statistics of the ship noise and controlled source tones were the same, a comparison of the single ship noise and controlled source tones was done using the KS2 test. The CDF of the ship noise was compared to that of the tone for shipping noise above and below the tone. The results are grouped according to the SNR. The SNR was calculated by finding the difference in received level in decibels from the tonal bin to the noise bin four bins away. In Fig. 4, SNR greater than 9 is plotted in red, SNR between 5 and 9 is plotted in magenta, SNR between 1 and 5 plotted in green, and SNR less than 1 plotted in blue. Figure 4 plots the probability of accepting the null hypothesis that the distributions are from the same continuous distribution. For frequency bins with high SNR, the distributions are statistically different than those dominated by ship noise. This difference must be due to the difference in source properties. The propagation paths of the noise from the single ship and the tones coming from a source submerged below the ship are very similar. The ship-dominated noise statistics may differ from those of the controlled source because the ship acts as a spatially distributed source.

The two frequency bins above and below the tone were also compared. This test was unable to reject the null hypothesis, so the distributions likely came from the same continuous distribution.

CONCLUSIONS

The sounds of a single stationary ship and controlled source tones sent from the same ship travel the approximate same path to a fixed vertical array. Differences of the statistics of these data are most likely due to the differences of the mechanics of the sources themselves.

When ship noise is dominant below 80 Hz, distributions of the ship noise are seen to be non-Gaussian, with symmetric, peakier distributions. Different frequency bands are dominated by different sources, and those bands where wind is dominant are Gaussian distributed. From
115 to 160 Hz, another mode of ship noise dominates the received levels. Again, these distributions are non-Gaussian.

The statistics of the controlled source tones are Gaussian distributed, and differ from the neighboring noise frequency bins using the KS2 sample test. The difference between these distributions cannot be due to the path the sound emanating from the source travels, but must be due to some source mechanisms. What still needs to be understood is why the statistics of the controlled source tones differ from the statistics of the stationary ship. Future work will help answer this question.

ACKNOWLEDGMENTS

The authors would like to thank Stephen Lynch and Sean McPeak, both formerly of the Marine Physical Laboratory, Scripps Institution of Oceanography (MPL/SIO), Keith von der Heydt (Woods Hole Oceanographic Institution), and Kyle Becker at the Applied Research Laboratories, Penn State for their assistance in collecting the PhilSea09 data set. The captains and crews of the R/V Melville and R/V Kilo Moana were critical to the overall success of this experiment. Additional at-sea assistance was provided by Rex Andrew (Applied Physics Laboratory, University of Washington) and Jim Murray at OASIS. Initial processing of the DVLA data was performed by Heidi Batchelor and Galina Rovner at MPL/SIO. This research is supported by the Office of Naval Research, both through the Applied Research Laboratory program and Code 322(OA)).

REFERENCES


