Deep Water Ambient Noise and Mode Processing

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LONG-TERM GOALS

The broad goals of this research are to characterize deep ocean noise processes, to analyze mode propagation in the deep water channel, and to implement acoustic tomography using mode signals.

OBJECTIVES

The primary focus of this project is the analysis of data from the Philippine Sea (PhilSea) experiments in 2009-2011. Data from previous ONR-sponsored deep water experiments may also be analyzed. The specific objectives of the project are: 1) to characterize the ambient noise in the PhilSea data set using spectral analysis and to compare the results to those for other deep water data sets; 2) to analyze the acoustic modes in the ambient noise and moored source data sets acquired in the PhilSea experiments; 3) to implement tomographic inversions using mode signals from the PhilSea experiments.

APPROACH

As described in the proposal, this three-year project is divided into five main tasks. Since the start of the project in March 2012 we have focused on the first two tasks: 1) Strum Characterization and Removal and 2) Deep Water Noise Analysis. The following paragraphs provide an overview of these tasks.

During the PhilSea experiments, a Distributed Vertical Line Array (DVLA) recorded transmissions from the moored tomography sources. In 2009 the DVLA also recorded segments of ambient sound during time periods when the tomography sources were not transmitting. In our previous work we showed that the DVLA data set contains a significant cable strum component. The first task of this project is to characterize the array strum and develop signal processing tools to remove it. Based on our previous results, the strum lies within a low-dimensional subspace defined by the eigenvectors of the spatial covariance matrix. This suggests that adaptive array processing techniques can be used to isolate the strum components. Dominant Mode Rejection, developed by Abraham and Owsley [1], is one approach that may be particularly useful for this application. It is designed to null out the largest

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interferers, which are defined by the eigenvectors associated with the largest eigenvalues. We will explore how well DMR can cancel the strum while leaving the ambient noise and other signals of interest unaffected. Other adaptive processing methods may also be considered.

The second task of this project is to analyze deep ocean noise in the PhilSea and SPICEX data sets. SPICEX took place in the North Pacific during 2004-2005. Both PhilSea and SPICEX used large aperture vertical arrays to sample the water column. Measurements of the vertical structure of ocean noise are important for understanding noise generation and propagation and for designing sonar signal processing systems. One research question of great importance to the Navy is how to characterize the noise below the critical depth. Gaul et al.'s analysis of the Church Opal data set showed that noise levels decreased substantially (on the order of 20 dB) below the critical depth [5]. This project will explore whether the ambient noise at the PhilSea and SPICEX sites obeys similar behavior. In addition to investigating noise level as a function of depth, this project will also consider the wind dependence and vertical directionality of the noise in these two experiments.

Prof. Kathleen Wage of George Mason University is the principal investigator for this project. Mr. Mehdi Farrokhrooz is a graduate student working on the project.

WORK COMPLETED

Since the start of this award in mid-March 2012, we presented one conference paper, and worked on three journal articles to be submitted to the Journal of the Acoustical Society of America (JASA) in fall 2012. The conference paper, authored by Wage, Buck, Dzieciuch, and Worcester, analyzes data recorded during the 2010 Philippine Sea experiment. Specifically, the paper focuses on using the loud low-frequency strum signals recorded by the DVLA to test an adaptive beamforming algorithm. The strum lies within a low-dimensional subspace spanned by the first few eigenvectors of the spatial covariance matrix. The Dominant Mode Rejection beamformer [1] is designed to remove the strum by placing notches in the direction of the strum components. The conference paper compares the measured notch depth for the PhilSea data to model predictions described in a companion paper by Buck and Wage [2].

One journal article was submitted for the upcoming JASA special issue on deep water ocean acoustics. The article by Chandrayadula, Wage, Worcester, Dzieciuch, Mercer, Andrew, and Howe [3] describes a statistical model for low mode signals propagating through internal waves and uses that model to design improved travel time estimators. It analyzes data from the Long Range Ocean Acoustic Propagation Experiment (LOAPEX). Two other articles are in preparation. Farrokhrooz, Wage, Dzieciuch, and Worcester are preparing an article analyzing the ambient noise received on the VLAs deployed during SPICEX. Wage, Dzieciuch, and Worcester are analyzing the ambient noise receptions recorded during the PhilSea09 experiment. As a part of the ambient noise analysis, we prepared a memorandum describing how to calibrate the measurements made with the SPICEX and PhilSea09 recording systems in order to present results in terms of absolute sound pressure levels [7].

RESULTS

The following paragraphs present a few key results derived from the analysis of ambient noise recorded during SPICEX. Data for the experiment are calibrated to provide absolute noise levels. The calibration accounts for the sensitivity of the hydrophone and the frequency response of the front-end recording system (amplifiers, signal conditioning filters, and the analog-to-digital converter). Since the SPICEX arrays span a large portion of the water column, it is important to correct for the depth-dependent hydrophone sensitivity. Analysis of calibration data for the High Tech hydrophones indicates that the depth dependence can be modeled using a linear fit to the logarithm of the sensitivity.

SPICEX used two equally-spaced vertical line arrays (VLAs) deployed a few kilometers apart. The first array contained 40 elements spanning 1400 meters around the sound channel axis. The second array consisted of three 20-element subarrays spanning the critical depth. The middle subarray failed, leaving the 20 elements above and 20 elements below the average critical depth. The element spacing for both VLAs was 35 m. The VLAs were designed to receive transmissions from several sources. This ambient noise study focuses on the receptions from the moored tomography sources. Since the tomography source transmissions lie in the 200-300 Hz frequency band, ambient noise can be measured outside this band. The data set consists of more than 2000 receptions recorded by the arrays during 2004-2005. Each reception lasted 135 seconds, and the sampling rate was 1000 Hz.

The ambient noise data is analyzed using the standard averaged-periodogram approach developed by Welch [8]. Each 135-second reception was divided into 2-second blocks with 50% overlap. A Hamming window was used to taper the temporal Fourier transform. With these parameters, the frequency resolution of the spectra is approximately 1 Hz. Fig. 1 shows the median of the ambient noise received on both arrays for six frequencies: 15, 35, 50, 80, 120, and 200 Hz. The plot indicates that the shipping noise (50 Hz band) decreases approximately 6 dB between the sound channel axis and the deepest hydrophone, located below the critical depth. The observed drop below the critical depth in the SPICEX data is significantly less than the 20 dB reported by Gaul [5]. A probable reason for this difference is related to the bathymetry of the two experimental sites. Gaul's Church Opal measurements were taken at a site south of the Moonless Mountains, whereas the SPICEX site is located farther north. In a 1990 paper, Shooter et al. show how bathymetric features such as the Moonless Mountains can substantially reduce the distant shipping noise received on a deep array [6]. It is also worth noting other important differences between Gaul's data set and the SPICEX data. Gaul's data was acquired over a 10-day period, whereas the SPICEX data includes receptions over an entire year.

Fig. 2 shows the median ambient noise spectra up to 200 Hz for three depths (the center of the axial VLA, and the centers of the two subarrays on the SPICEX deep VLA). The plots illustrate how the spectra vary with surface wind speed. As expected based on Wenz's earlier work [9], wind has a very strong effect on the noise above 100 Hz. The wind data set used for these calculations is from the European Centre for Medium-Range Weather Forecasts [4].

A unique aspect of the SPICEX data set is that it contains measurements over one year that facilitate the analysis of seasonal variations in ambient noise. As an example, consider Fig. 3, which shows the median noise levels at 50 Hz as a function of depth for two months in 2004. The plot shows linear fits to the data in each subarray, in addition to the median data points. For the axial subarray and upper subarray on the deep VLA, the slope is essentially the same in June and November, but the offset changes. For the deepest subarray (below the critical depth), the slope changes significantly between the two months. Further analysis indicates that the change in slope is related to two factors. First, the critical depth changes with time, as the surface temperature changes. Second, the average surface wind changes over time. While wind is not the dominant source of noise at 50 Hz, it can have a measurable effect. Additional analysis of these effects is ongoing.

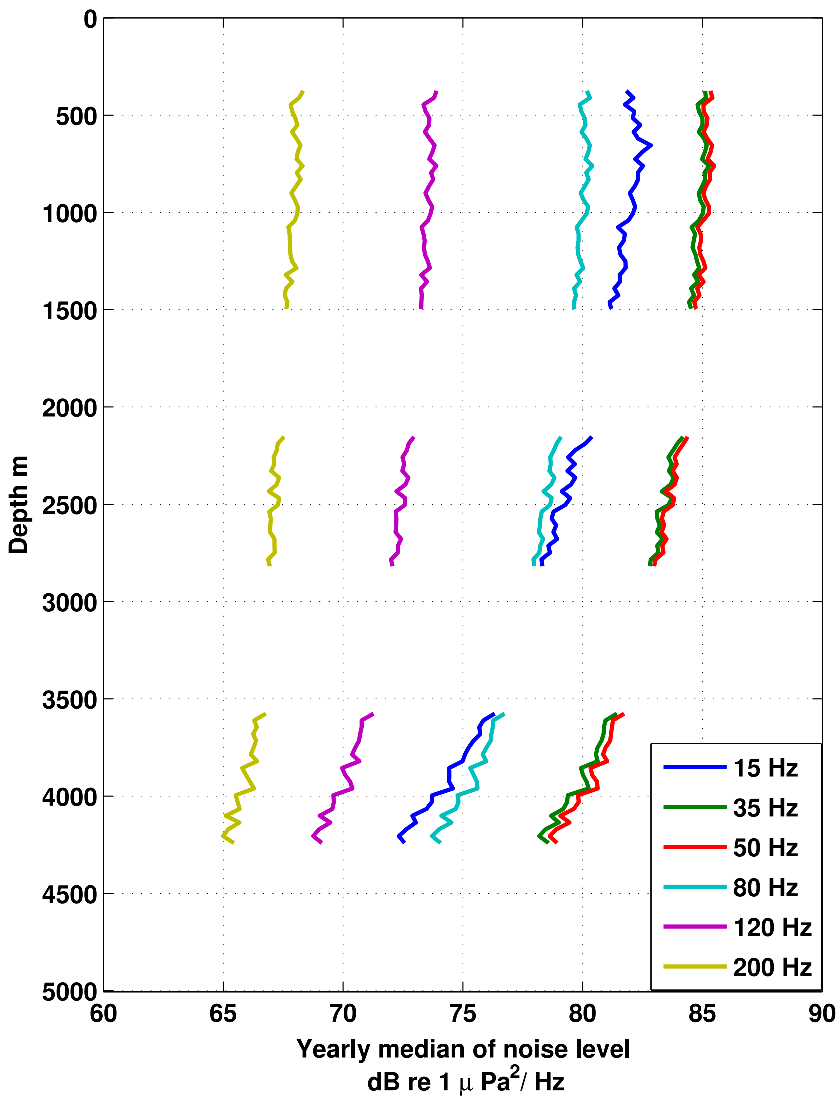

Figure 1: Median noise level as a function of depth for the year-long SPICEX data set. The lines show the results for six frequencies: 15, 35, 50, 80, 120 and 200 Hz. SPICEX included two vertical arrays, one array centered on the sound channel axis, and a deep array spanning the critical depth. One segment of the deep array failed, leaving a gap in the measurements. This plot indicates an approximately 6 dB decrease of shipping noise (at 50 Hz) between the sound channel axis and the deepest hydrophone, which lies below the critical depth.

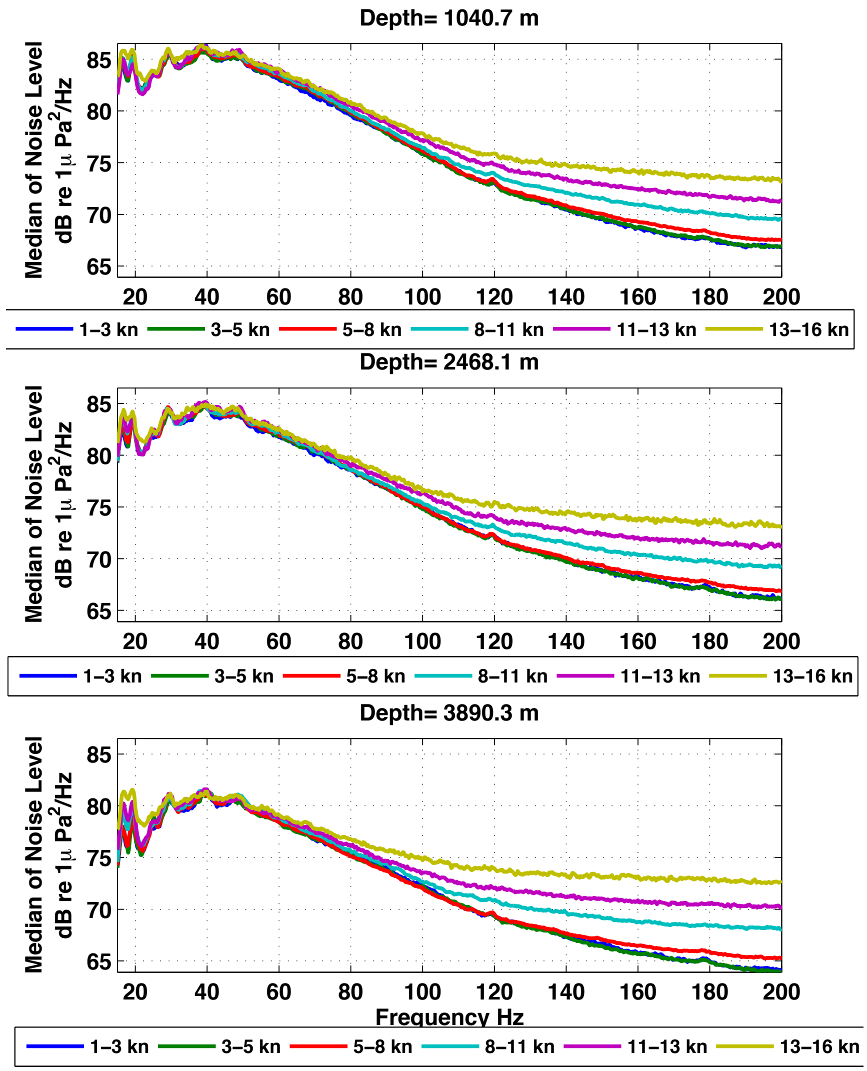

Figure 2: Median ambient noise spectra for three depths: 1041 m, 2468 m, and 3890 m. Each plot shows six curves, corresponding to the median spectra for different wind speeds: 1-3, 3-5, 5-8, 8-11, 11-13, and 13-16 knots. The wind data used for these results is from the European Centre for Medium-Range Weather Forecasts. These plots show that the noise depends primarily on wind for frequencies higher than 100 Hz, as predicted by Wenz [9].

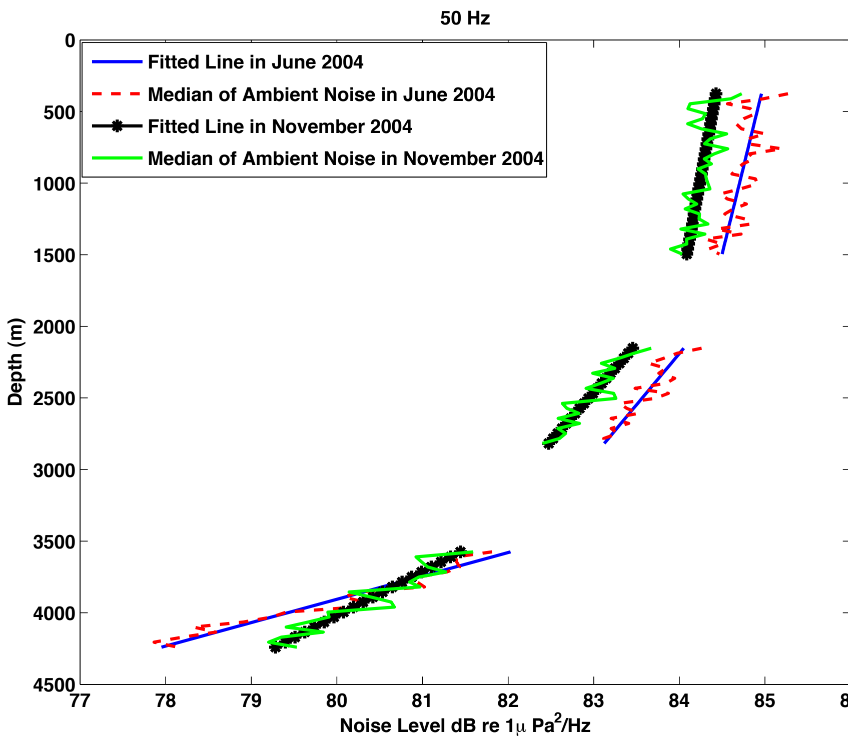

Figure 3: Median noise as a function of depth measured by the SPICEX arrays in June 2004 and November 2004. Results are shown for the 50 Hz bin. In addition to the median data points, the plot also shows a linear fit to the measurements for each subarray. The lines show how the mean levels and the slopes vary for June and November.

A similar analysis of ambient noise is being done for the PhilSea09 and PhilSea10 data sets. A comparison of the SPICEX and PhilSea noise results has been submitted for presentation at the International Congress on Acoustics scheduled for June 2013.

IMPACT/APPLICATIONS

This project is relevant to the Navy for several important reasons. First, the PhilSea experiments provide a unique set of high quality ocean noise measurements that quantify the reduction in ambient noise below the critical depth and facilitate the analysis of vertical directionality. Understanding deep ocean noise characteristics is required to accurately predict the performance of bottom-mounted arrays and to improve the design of adaptive array processing algorithms. Second, the 150-element vertical array deployed in the PhilSea10 experiment was designed to sample a large set of acoustic modes, facilitating an investigation of the effects of mesoscale and internal waves on deep water mode propagation. The analysis from this experiment will be valuable in refining statistical propagation models for dynamic environments such as the Philippine Sea. Finally, the tomographic component of this project will provide valuable insights about the PhilSea environment and will be an opportunity to adapt and improve existing mode tomography methods. In addition to investigating tomographic inversions for the controlled sources, this project will also consider using ambient noise to invert for the normal modes of the channel. Ambient noise inversions offer the possibility that a processor could be "tuned" to the environment using an automated noise analysis procedure, providing improved performance without requiring additional sensors (*e.g.*, thermistors) on an array.

RELATED PROJECTS

The Philippine Sea experiments involved researchers from a number of institutions. The PI is collaborating with Peter Worcester and Matthew Dzieciuch (SIO) on the analysis of the Philippine Sea data set. She is also continuing her collaboration with Tarun Chandrayadula, a graduate of George Mason University who is currently a postdoctoral fellow at the Naval Postgraduate School.

The PI has another ONR project funded by Code 321 that is related to this award. The Code 321 project is titled Random Matrix Theory (RMT) for Adaptive Beamforming (N00014-12-1-0048). The RMT project is using some of the Philippine Sea data for testing adaptive beamformers. The RMT analysis focuses on sonar signal processing issues, rather than propagation, ambient noise, or tomography. The project described in this report may benefit from the results of the RMT project, but there is no direct overlap in research tasks.

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PUBLICATIONS

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T. K. Chandrayadula, K. E. Wage, P. F. Worcester, M. A. Dzieciuch, J. A. Mercer, R. K. Andrew, and B. M. Howe, "Reduced rank models for travel time estimation of low mode pulses," submitted to Journal of the Acoustical Society of America. [submitted to refereed journal]