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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 is also being 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

Since the start of the project in March 2012 we have focused primarily on 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 interferers,

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which are defined by the eigenvectors associated with the largest eigenvalues. We are exploring how well DMR can cancel the strum while leaving the ambient noise and other signals of interest unaffected.

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 [6]. This project is investigating 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 is considering 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 published two journal articles in FY13 and one refereed conference paper in FY12. The two journal articles were published in the October 2013 special issue on deep water ocean acoustics in the Journal of the Acoustical Society of America (JASA). The first of these articles, by Chandrayadula, Worcester, Dzieciuch, Mercer, Andrew, and Howe, describes a statistical model for low mode signals propagating through internal waves and uses that model to design improved travel time estimators [3]. It analyzes data from the Long Range Ocean Acoustic Propagation Experiment (LOAPEX). The second article by Worcester et al. summarizes the Philippine Sea experiments in 2009-2013 [14].

The conference paper published in FY12 [11] 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].

In addition to the papers described above, we developed new results on deep ocean ambient noise. We are analyzing noise data from both the SPICEX and Philippine Sea experiments. We have compared the depth-dependent noise characteristics with prior measurements and examined the seasonal dependence of the noise. The following section describes the results in more detail. We presented some of this work at the International Congress on Acoustics in June 2013 [12] and the Acoustical Society of America meetings in December 2013 [4] and May 2014 [5]. Two journal articles are currently in preparation. 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 [10].

RESULTS

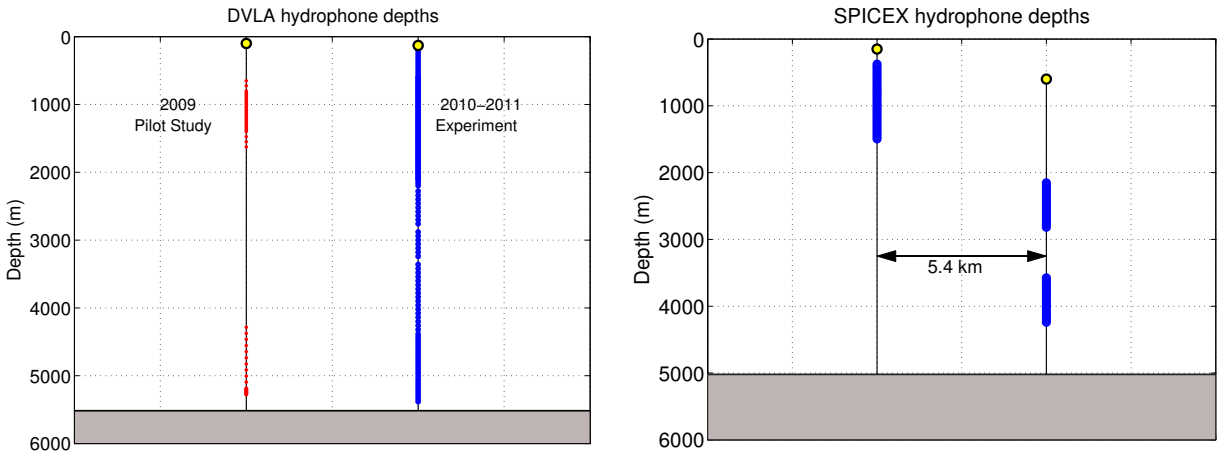
This section describes several results of the ambient noise analysis of the Philippine Sea and SPICEX data sets. Both the PhilSea09 pilot study and the SPICE experiment included an axial array and a deep array. In both cases the deep array had hydrophones above and below the conjugate depth. The year-long PhilSea10 experiment used a 150-element array spanning the water column (approximately 5 km). Figure 1 shows the hydrophone depths for the arrays deployed in the PhilSea and SPICE experiments. Ambient noise data in all of these experiments is analyzed using standard averaged-periodogram methods [13]. The data is calibrated to account for the responses of the hydrophones and the recording system [10]. The ambient noise measurements described below are displayed in terms of absolute sound pressure levels.

Figure 2 shows the calibrated spectra for two hydrophones in the PhilSea09 array. The hydrophones are near the sound channel axis (1050 m) and below the conjugate depth (5280 m). The plot shows the median (solid lines) along with the 90th and 10th percentiles (dashed lines above and below the median). The data set consists of the 155 second ambient noise recordings made during the month-long experiment. The sample rate for these receptions is 1953.125 Hz. Fig. 2 illustrates several key points. First, there is an obvious drop in ambient levels below the conjugate depth for frequencies below 130 Hz. The drop is between 6 and 7 dB for frequencies in the shipping band (around 50 Hz). For frequencies above 130 Hz, the median noise measured at the two hydrophones is approximately equal. Fig. 2 also shows the impact of cable strum on the low frequency noise measurements made with the axial subarray. Noise from strum dominates the median spectrum below 20 Hz and the 90th percentile spectrum below 40 Hz.

Figure 3 shows the wind dependence of the ambient noise measurements for the same two hydrophones. The wind data is from the European Centre for Medium-Range Weather Forecasts (ECMWF). The frequency at which wind dependence becomes apparent varies with depth. At 1050 m, the plot shows that the spectrum above 110 Hz depends on wind speed. At 5280 m, the plot shows a dependence on wind speed starting at slightly lower frequencies, around 105 Hz. According to Urick, the noise in bands dominated by wind at the sea surface follows the Knudsen spectra, and the slope is typically -5 to -6 dB octave [9]. This is approximately true for the measured spectra at 1050 m. The slope of the spectra measured at the deep hydrophone is somewhat different, as might be expected since the measurement is farther away from the sea surface where the noise is generated.

Figure 4 shows the depth dependence of the ambient noise measured during the PhilSea10 experiment. These plots show the 10th, 50th, and 90th percentiles computed from a year's worth of data for two frequencies: 50 Hz and 350 Hz. The measured levels towards the top of the array are corrupted by cable strum. The strum is most evident in the top 1000 m at 50 Hz. At 350 Hz, the strum is primarily confined to the upper 500 m. Fig. 4 illustrates the depth dependence of noise in the shipping band (50 Hz). Median noise levels decrease approximately 7 dB below the conjugate depth at 50 Hz. At 350 Hz, the noise is dominated by wind and the noise levels are approximately constant with depth. Fig. 5 shows that the average drop in noise level below the conjugate depth remains stable over time. The plot shows the daily median noise levels for the year-long experimental period. The average drop is 6.9 dB. There are no obvious seasonal trends in the data.

The SPICE experiment provided an opportunity to study the depth dependence of ambient noise in the North Pacific. Figure 6 compares the depth profile of the shipping noise at 50 Hz measured during SPICEX with the noise measured during earlier North Pacific experiments by Morris [7] and Gaul [6].



(a) PhilSea vertical line arrays

(b) SPICEX vertical line arrays

Figure 1: Hydrophone depths of the vertical line arrays deployed in the PhilSea09, PhilSea10, and SPICE experiments. The PhilSea09 array has 60 elements in two subarrays, one spanning the sound channel axis and the other spanning the critical depth. The PhilSea10 array has 150 elements spanning the entire water column. The SPICE experiment deployed two vertical line arrays, approximately 5.4. km apart. The first array had 40 hydrophones spanning the sound channel axis. The second array had two 20-hydrophone subarrays (a third subarray in the middle failed).

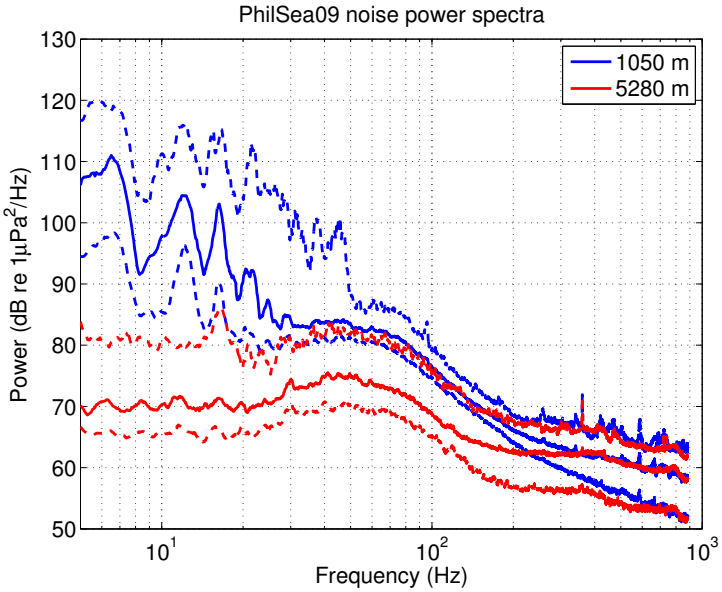
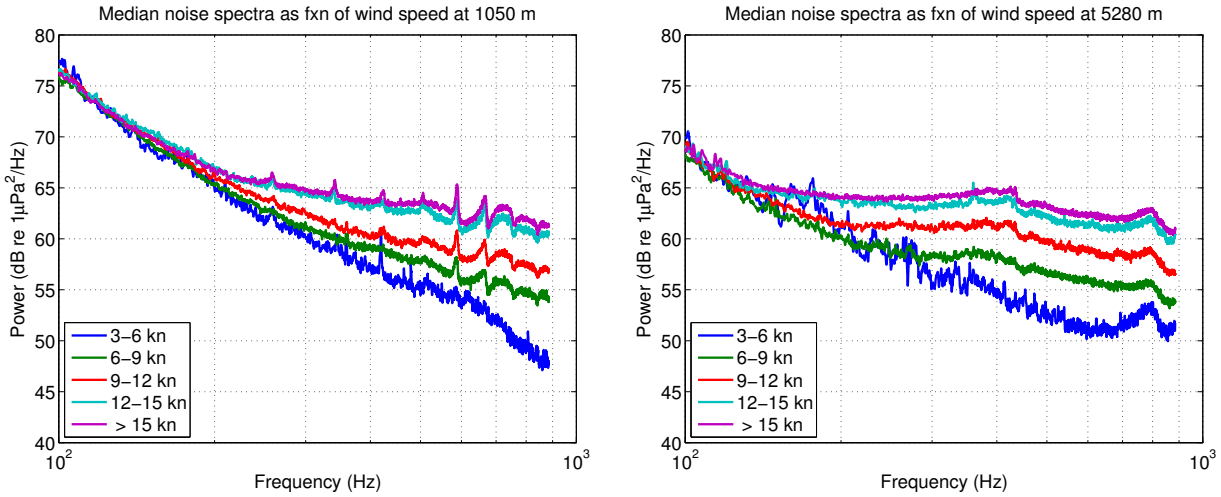


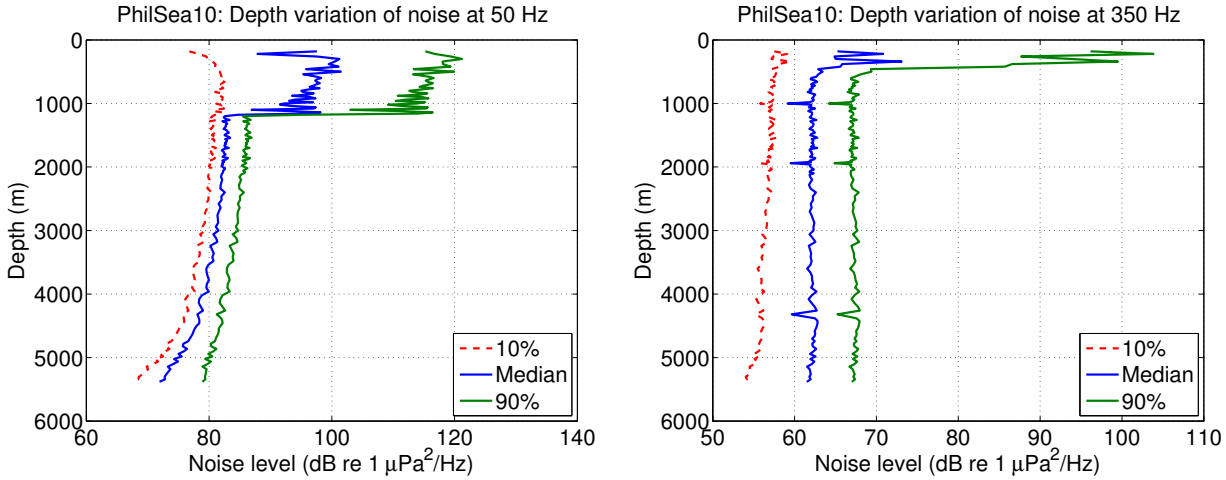
Figure 2: Calibrated spectra from the PhilSea09 experiment. The plot shows data for two hydrophones at depths of 1050 m (near the sound channel axis) and 5280 m (below the conjugate depth). The solid lines are the median and the dashed lines above and below the median indicate the 90th and 10th percentiles, respectively. The plot shows the drop in ambient noise below the conjugate depth. It also highlights the impact of array strum in the upper part of the array on the low-frequency ambient noise measurements. The median is dominated by strum below 20 Hz and the 90th percentile is dominated by the strum signal below 40 Hz.



(a) Noise spectra at 1050 m

(b) Noise spectra at 5280 m

Figure 3: Calibrated noise spectra as a function of wind speed measured during PhilSea09. The wind data is from the European Centre for Medium-Range Weather Forecasts. Results are shown for two hydrophone depths: 1050 m and 5280 m. At 1050 m noise appears to be a function of wind speed for frequencies above 110 Hz. At 5280 m, the wind speed dependence is obvious for frequencies above 105 Hz.



(a) Noise at 50 Hz

(b) Noise at 350 Hz

Figure 4: Ambient noise as a function of depth measured by the water-column-spanning vertical line array deployed in the Philsea10 experiment. Results are shown for two frequencies: 50 Hz and 350 Hz. The solid blue lines show the median levels for the year-long data set and the dashed red and solid green lines show the 10th and 90th percentiles, respectively. The high levels in the median and 90th percentiles in upper part of the array are due to cable strum. The plots illustrate that noise levels in the shipping band (around 50 Hz) are depth-dependent, whereas noise levels in the wind-dominated band (around 350 Hz) are approximately depth-independent. At 50 Hz, median noise levels decrease approximately 7 dB below the conjugate depth.

The three noise profiles all decrease with depth, and the decrease is particularly sharp below the conjugate depth. The profiles for SPICEX and the Morris experiment are approximately equal above the conjugate depth, which is remarkable given the 31-year gap between the experiments. Below the conjugate depth, SPICEX and Morris' experiment have comparable slopes, whereas the Church Opal experiment shows a much sharper decrease. This supports Shooter et al.'s hypothesis that the Moonless Mountains shielded the Church Opal site from noise generated in the shipping lanes located primarily to the north of that underwater range [8]. The shipping noise in SPICEX and Morris' experiment may be higher since it is not blocked by a similar bathymetric feature. There are still open research questions about the vertical structure of ambient noise in deep water, particularly in the 20-100 Hz band associated with shipping noise. Work with the PhilSea and SPICEX data sets is ongoing.

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 finished a postdoctoral fellowship at the Naval Postgraduate School and has recently started a faculty position at IIT Madras.

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.

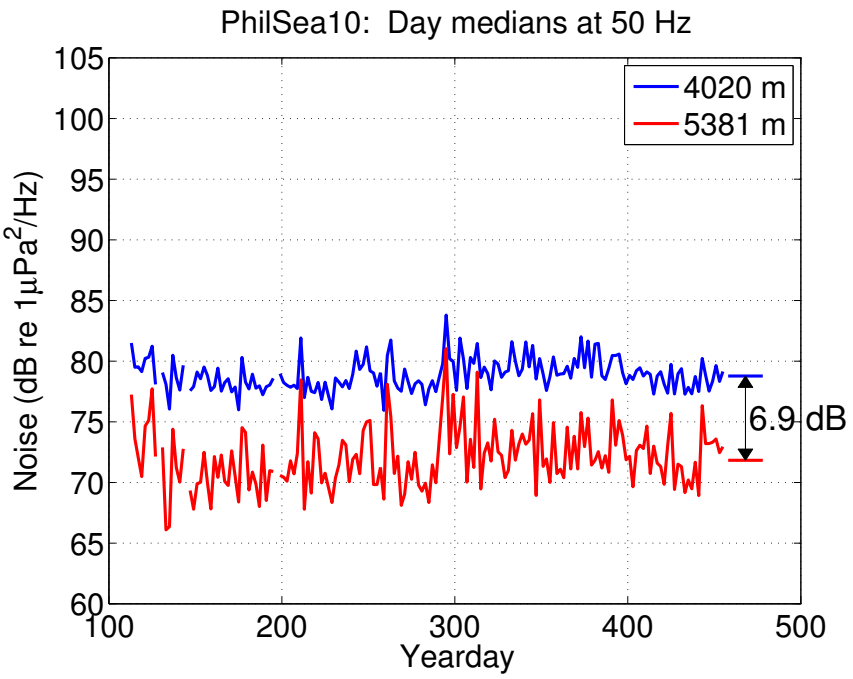
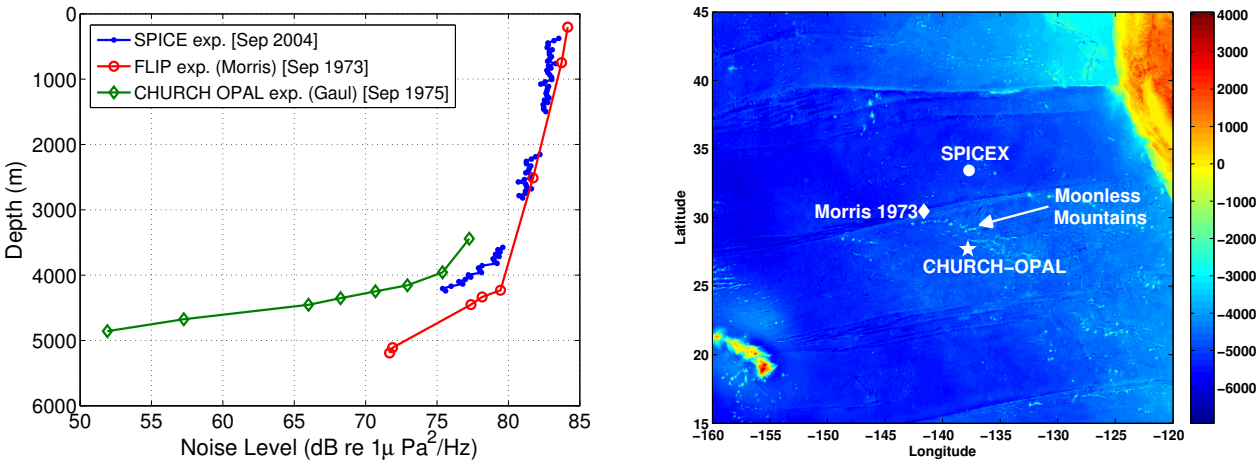


Figure 5: Median noise levels at 50 Hz as a function of time measured during the PhilSea10 experiment. The results show the daily median levels measured by hydrophones located at 4020 m and 5381 m. On average there is a 6.9 dB drop in level between these two hydrophones. This drop is stable over time and the plot does not reveal any strong seasonal trends.



(a) Ambient noise at 50 Hz in the North Pacific

(b) Location of the measurements

Figure 6: Decrease of ambient noise below the conjugate depth for three experiments in the North Pacific. The CHURCH OPAL experiment reported by Gaul et al. [6] shows a dramatic decrease, while the SPICEX measurements and the FLIP experiment by Morris [7] indicate more modest reductions.

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