Propagation and Ambient Noise Studies for Ocean Acoustics Applications

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LONG-TERM GOALS

The purpose of this research is to study the characteristics of the low and mid frequency ocean ambient noise field with the long term goal of exploiting the noise field for physics based processing methods that improve sonar system performance.

OBJECTIVES

Ocean ambient noise has been studied for decades. Much of the interest has been on determining the impact of noise on sonar performance. In this context, noise has generally been considered a nuisance and the research focus has been on methods to measure and predict ocean noise. In this project, the emphasis has been shifted to how ocean noise can be exploited. Results over the past several years have shown that breaking wave noise can be used for remote sensing the environment. There are several advantages to passive remote sensing including simple measurement requirements and the minimal environmental impact.

Advancements in the noise-based remote sensing methodologies will be described in this annual report. In particular, one of the techniques being investigated uses noise as a type of passive fathometer or sub-bottom profiler and another uses noise to estimate the seabed reflectivity (i.e., bottom loss). Both techniques lead to better characterization of the seabed. Knowing the seabed properties is important to predict sound propagation in the ocean (and therefore predicting sonar system performance). Eventually, these methods can lead to new surveying techniques that might be used to update the Low Frequency Bottom Loss (LFBL) or High Frequency Bottom Loss (HFBL) databases. LFBL and HFBL are databases that the Naval Oceanographic Office (NAVO) maintains and updates and are used for sonar performance prediction as part of the navy's tactical decision aids.

APPROACH

The majority of the effort on this project has been on improving our understanding of two methods that use ocean ambient noise for remote sensing the seabed. The first method uses the idea of coherent noise processing and is referred to as passive fathometer processing [Siderius *et al,* 2006]. This year, the practical supergain method [Cox *et al*] has been applied to the passive fathometer processing. The initial results are described here with additional details given in publication [1]. The second method

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uses noise intensity (or incoherent processing) to estimate bottom reflectivity at angles from 0 to 90 degrees (i.e., bottom loss) [Harrison and Simons]. On this topic the effort was primarily on analyzing how adaptive beamforming methods could be used for this application and some of the drawbacks. The research has been theoretical, numerical and experimental and results are described in publication [2].

SUPERGAIN PROCESSING FOR SEABED IMAGING

The interest is in imaging the seabed using the passive fathometer method where the noise directly overhead a vertical hydrophone array is the effective signal and all other sources are contaminating noise [Siderius *et al,* 2006, Siderius *et al,* 2010]. For this application, a vertical array is essential to form up-looking and down-looking beams, which are cross-correlated. In the original passive fathometer formulation conventional (i.e., delay and sum) beamforming was used to form the up- and down-looking (endfire) beams. Subsequent analysis showed there to be substantial contamination to the seabed image due to competing noise sources coming from directions other than endfire. This noise enters the passive fathometer process because the beamforming is not perfect and endfire beams contain sidelobes, which allow noise from other directions into the beamformer output. Further, the conventional beams can be relatively large in the endfire directions especially at the low frequencies where the array length may be only a fraction of a wavelength. Using array shading helps with the sidelobes but increases the mainlobe. Only a limited region containing noise sources coming from the endfire direction contribute to the coherent components of the noise cross-correlation, therefore, some control over the size of the endfire beams is desired in the processing.

To mitigate the beamwidth problem as well as to minimize sidelobe contamination adaptive processing was introduced [4]. Adaptive processing, in theory, should address these issues and provide optimal complex array weighting for gain and sidelobe suppression. However, in practice, there are several drawbacks to adaptive methods. First, they are known to be highly sensitive to random errors. For example, these can be errors in the actual versus assumed hydrophone locations (e.g., due to tilting or sagging of the array). Second, the adaptive processing requires inversion of the measured cross-spectral density matrix (CSDM). The inversion not only requires adequate data averaging but also usually requires diagonal loading for stability. The diagonal loading is equivalent to adding white noise to the CSDM and choosing the ideal amount of white noise is an additional complication. In spite of these difficulties, the adaptive methods showed a marked improvement on certain data sets. But, in some cases it may not be possible to overcome random errors or the required averaging may pose serious limitations. For example, if the seabed or array motion is changing rapidly the averaging may be better applied after the beamforming rather than before to allow for time alignment of data.

The concept of supergain [2] is explored for the passive noise seabed-imaging problem and compared to the theoretically optimal adaptive methods. Supergain uses delay and sum beamforming but with performance that is nearly the same as adaptive methods. Therefore, it does not suffer from the drawbacks associated with adaptive methods. The supergain technique uses simple array shading to suppress sidelobes and oversteering past endfire to limit beamwidth size.

While adaptive methods give the theoretically optimal complex weights, for steering in the endfire directions practical supergain produces nearly optimal results by simply applying array shading and oversteering to the delay and sum beamforming. Using this approach avoids the pitfalls of adaptive processing while maintaining the performance. It also has the advantage of allowing the averaging to be done after beamforming since the data cross-spectral density matrix is not used to construct the beamforming weights as is required for adaptive processing.

Supergain uses beamforming in spatial frequency rather than grazing angle (sometimes referred to as $k-\omega$ beamforming but here $k-f$ is used where $f=\omega/2\pi$. The $k-f$ beamforming is performed by taking a Discrete Fourier Transform (DFT) over the array elements. The spatial frequency, or wavenumber is bounded according to, $-\pi/d \le k \le \pi/d$ where d is the hydrophone separation. However, propagating acoustic waves are bounded by the slowest speed a wave can physically propagate (i.e., $c \approx 1500$ m/s) which corresponds to a wavenumber magnitude of $|k|=\omega/c$. Inside the region $|k| \le \omega/c$ is the so-called visible space since outside this region there are no propagating acoustic waves.

To illustrate, first consider beamforming on typical ocean noise which is shown in Fig. 1 This is data taken in the Mediterranean Sea (also analyzed in Siderius, *et al* 2010) and has frequency band of 20-4000 Hz, sampling frequency is 12 kHz, the vertical array has 32 equally spaced hydrophones with spacing d = 0.18 m. Panel (a) shows the vertical directionality of the noise field using conventional delay and sum beamforming as a function of frequency and grazing angle. The grazing angles range from $+90°$ to $-90°$. Horizontally arriving sound corresponds to $0°$ and upward steered beams with positive angles are towards the sea-surface while negative beams are towards the seabed ($+90°$ is directly above the array and $-90°$ is directly below the array). A 32-point Taylor window was used for shading the array.

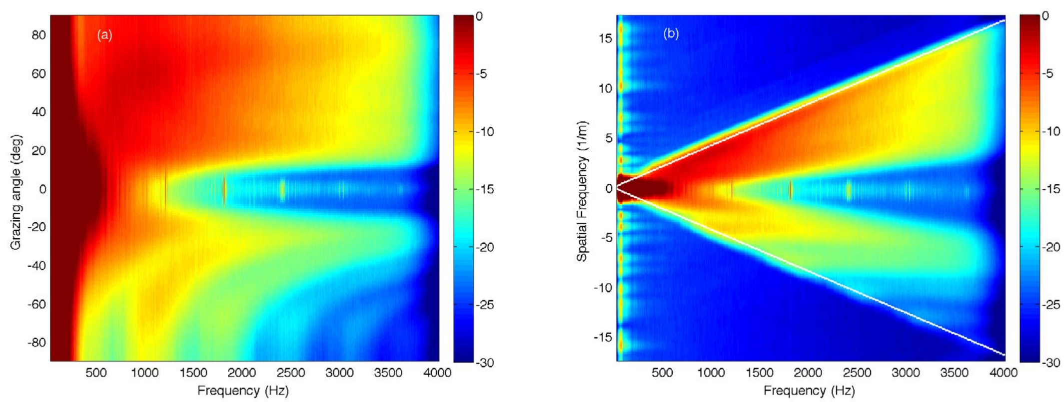

Figure 1: Vertical directionality of ocean noise using delay and sum beamforming on a vertical hydrophone array. Panel (a) on the left shows beam output as a function of frequency and grazing angle. Positive angles are towards the sea-surface and negative angles are pointed towards the seabed. Panel (b) on the right is also delay and sum beamformer output of the same data using a Discrete Fourier Transform. The beam output is a function of frequency and wavenumber. White lines show the locations that correspond to the visible region with grazing angles between $\pm 90°$, which corresponds to the angular region covered in panel (a).

To illustrate DFT beamforming used for supergain, the same data was processed again as a function of spatial frequency rather than grazing angle. This was performed by taking a Discrete Fourier Transform (DFT) over the 32 array elements. The DFT beamforming results are shown in panel (b) of

Fig. 1. Zero padding was used to extend the DFT from 32 to 256 points. The solid white lines correspond to the endfire directions, and form a V region inside which grazing angles between $\pm 90^{\circ}$ fall. This region is the so-called visible space where the spatial frequencies correspond to sound speeds equal to or greater than the ocean sound speed *c*. Outside the V is beyond the visible space and corresponds to slow waves that travel at sound speeds less than *c*. In principle, if these slow waves existed they would not represent propagating sound but some other type of signal such as mechanical waves due to array strum. However, for properly functioning arrays this region has no propagating sound and therefore shows very low beam outputs as evident in Fig. 1. Note, that some of these non-propagating signals are present at the lowest frequencies and may, in fact, indicate some low frequency mechanical signals on the array.

For noise imaging of the seabed, only the endfire beams are used and these are cross-correlated. One of the factors that degrade results is the interference from noise sources other than endfire. This can be seen in Fig. 1 where equally high intensity sound can be seen coming from most of the positive angular directions. These high levels will enter the cross-correlations through the beam sidelobes. If aggressive array shading is used, these sidelobes can be greatly suppressed, however, this is at the high price of widening the main lobes, which are already large in the endfire directions.

The practical supergain approach consists of array shading to suppress sidelobes and mild oversteering to limit the effective size of endfire beamwidths. That is, the effect of the wider main lobe is reduced by steering the beam out of the visible space past endfire; effectively narrowing the beamwidth. The sidelobes were suppressed using a 32-point Hanning window. To oversteer, the time delay applied to the array m^{th} hydrophone element was, $\tau_m = (1+\beta)md/c$ where β is a small positive constant, which was used to oversteer the array. For the example that will be presented in the results section, the array was oversteered by 7 points in the 256-point DFT.

WORK COMPLETED

An initial application of the supergain approach was applied to data previously analyzed with adaptive beamforming. This is reported in publication [1] and results are summarized in the next section.

RESULTS

A comparison can be made between imaging the seabed using conventional delay and sum, adaptive, and practical supergain processing. This is shown for data collected in the Mediterranean (same array parameters as indicated previously) in Fig. 2. In panel (a) are the conventional beamforming results and in panel (b) the adaptive processing. Each time trace is a vertical line of the image and is formed using 90 seconds of averaging time. The horizontal axis is file number that corresponds to range since the array was drifting over the seabed. The vertical axis is distance to the seabed and sub-bottom layers (two way travel time is actually measured but is converted to distance using sound speed of 1500~m/s). In panel (c) are the supergain results. The supergain beamforming weights do not depend on the data so these are formed independently from the data. For comparison, here the data were beamformed after the same 90 second averaging time as done for the conventional and adaptive processing. However, essentially the same results were found by beamforming and cross-correlating after just 10 seconds of averaging for the CSDM followed by additional averaging after beamforming (for a total of 90 seconds). It may be possible to do most of the averaging after beamforming but the advantages of pre-beamforming averaging versus post-beamforming averaging have not been studied in detail.

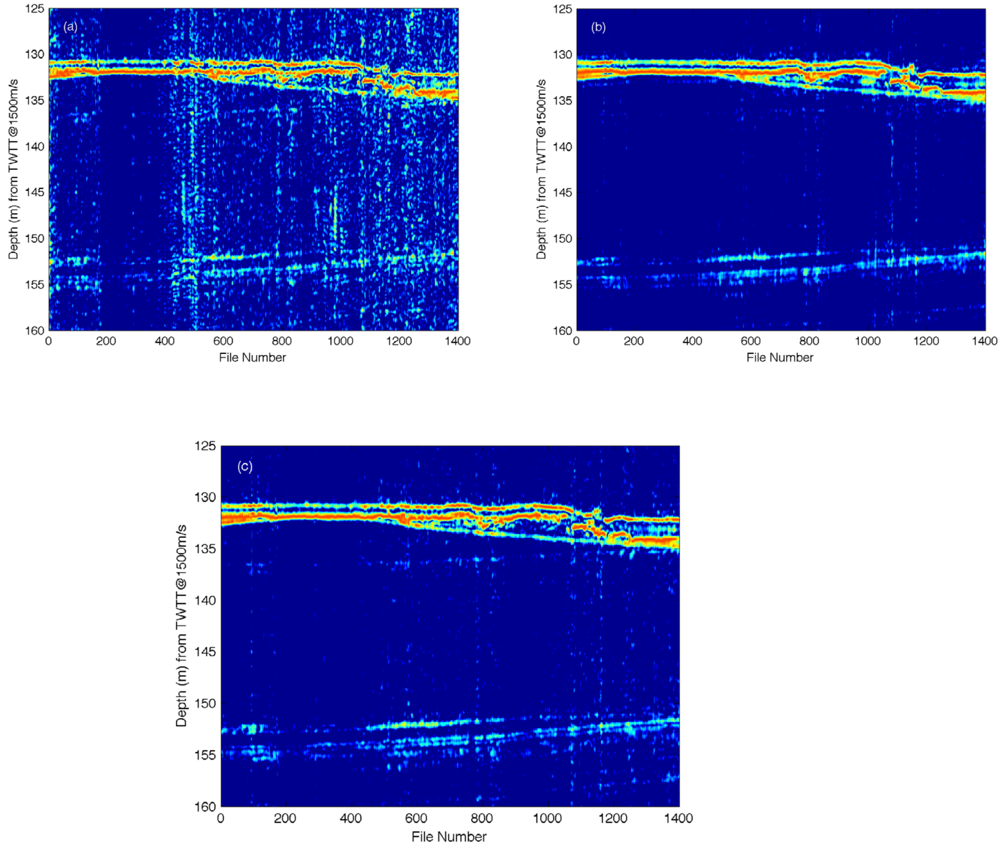

Figure 2: Panel (a) in the upper left shows the conventional beamforming results, panel (b) in the upper right the adaptive beamforming and panel (c) in the lower panel is the supergain results. The horizontal axis is equivalent to range as the array drifted over the seabed. The vertical axis is the beam cross-correlation output and colors show location of seabed reflections. The water-seabed interface (bathymetry) is the first line that appears at a depth of around 130~m. The conventional results are the poorest and the supergain results are about the same as the adaptive results.

IMPACT/APPLICATIONS

This work may have a significant impact on several Navy sonar systems (e.g., ASW, MCM, underwater acoustic communications). Knowing the seabed properties will improve at-sea situational awareness by being able to accurately predict acoustic propagation. And, because this is a passive method it can be designed into a system used for covert activities, low power applications and can be used even in environmentally restricted areas.

TRANSITIONS

None at this time.

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