Ocean Ambient Noise Studies for Shallow and Deep Water Environments

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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

Research over the past several years has shown that breaking wave noise can be used for remote sensing of the environment. There are several advantages to passive remote sensing including simple measurement requirements and minimal environmental impact. While 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 project, the emphasis has been shifted to how ocean noise can be exploited to improve sonar performance and performance prediction.

In this report, recent work will be described that improves estimates of the seabed bottom loss derived from measurements of ambient noise. Knowing the seabed properties is important to predict sound propagation in the ocean (and therefore predicting sonar system performance). These methods will lead to new surveying techniques that can 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

Seabed bottom loss is an important quantity for predicting transmission loss (TL) in the ocean. There have been a variety of methods developed over the years to estimate bottom loss but a simple one was introduced by Harrison and Simons [Harrison 2002] and uses vertically beamformed measurements of ocean ambient noise. This takes a ratio between averaged noise signals coming from the direction of the seabed with those coming from the surface. The ratio reveals the losses due to interaction with the seabed, which by definition, is the bottom loss. One of the advantages of this technique is that it produces bottom loss directly without requiring data inversion schemes. This measured bottom loss can subsequently be used directly in propagation models to predict TL. In theory, the bottom loss can be estimated exactly using this method but this would require perfect beamforming and averaging which implies an infinitely long hydrophone array (i.e., infinitely narrow beams) as well as infinite averaging time. With finite hydrophone arrays, the bottom loss estimate is somewhat smoothed out due to beam widths. This smoothing of the bottom loss estimate is generally undesirable as it can shift the location of the critical angle or if the seabed is layered, can significantly reduce the level of interference fringes. When this estimated bottom loss is used directly in propagation models this smoothing can create errors in transmission loss estimates. It can also create errors if the estimated bottom loss is used in an inversion scheme to estimate geo-acoustic properties of the seabed.

In the work completed this year, the Toeplitz (or approximately Toeplitz) property of the ambient noise cross-spectral-density matrix (CSDM) is used to reduce the degree of smoothing caused by the finite beams. This Toeplitz property simply implies that the noise spatial coherence depends only on the distance between hydrophones and not their absolute position in the water column. Exploiting this property essentially provides higher resolution beamforming by making the array appear larger than the physical dimension. That is, the processing creates a kind of synthetic array, which is similar to increasing the size of the array. For surface generated ocean noise, the CSDM is theoretically expected to be approximately Toeplitz as discussed in Buckingham [Buckingham 1980], as long as the array is not too near the boundaries. For practical measurements at frequencies of interest the array can be expected to be several wavelengths from the boundaries so the CSDMs are expected to be Toeplitz (assuming surface wave noise such as that from wind is being measured) and the techniques described here should provide higher resolution bottom loss estimates. Simulations are used to generate CSDMs and demonstrate the processing. Although the CSDMs are only approximately Toeplitz this is sufficient to improve the bottom loss estimates.

Typical data processing for the noise coherence starts by transforming measured time series data to the frequency domain followed by averaging to estimate the CSDM. The hydrophone data for each channel at angular frequency ω, are written as a column vector $\mathbf{p} = [p_1, p_2, \ldots, p_M]^T$ for the M hydrophones (T indicates transpose operation). Each entry is determined through a discrete Fourier transform (DFT) of an ambient noise time series measured on each channel, $p_m(\omega) = F\{p_m(t)\}$. The number of points in the DFT processing will be referred to as the snapshot size. A single snapshot of the CSDM $\tilde{\mathbf{C}}_n$ is formed as the outer product of the data vector,

$$\tilde{\mathbf{C}}_n = \mathbf{p}\mathbf{p}^H$$

where H indicates conjugate transpose operation. Multiple snapshots (N) can be averaged to better estimate the CSDM $\mathbf{C}_n$,

$$\mathbf{C} = \frac{1}{N}\sum_{n=1}^{N}\tilde{\mathbf{C}}_n$$

The Toeplitz CSDM implies the terms down each of the super- and sub- diagonals as well as the main diagonal are the same. While making this Toeplitz assumption may not seem obvious, in words it asserts that the coherence function depends only on the hydrophone separation and not the absolute position of the hydrophones in the water column. For surface generated noise Buckingham noted this many years ago as long as the frequency is high enough to support around 10 or more modes and the hydrophones are not too close to the boundaries [Buckingham 1980]. Harrison derived an expression for this distance from the boundary and for a somewhat typical critical angle of 20 degrees and 3 kHz this distance is about 1 m [Harrison 1996].

In Siderius et al (Publication 5, 2012), this methodology is described using a DFT formulation as well as the original methodology from the paper by Harrison and Simons [Harrison 2002]. Here, only the original methodology is described where beamforming is used to divide downward steered by upward steered beams. To beamform, each channel is multiplied by a complex weight to properly delay (phase shift) before summing all channels together. The weight for the m^{th} hydrophone steered at angle θ is written $w_m = e^{-im(\omega/c)\Delta z \sin\theta}$, for plane waves arriving at grazing angle θ between the hydrophones separated by distance Δz with sound speed c. Therefore, a beam steered at angle θ is $b(\theta) = \mathbf{w}(\theta)\mathbf{p}$. The beam power is $B(\theta) = b(\theta)b(\theta)^*$ (* indicates conjugation) which is,

$$B(\theta) = \left[\mathbf{w}^H(\theta)\mathbf{p}\right]\left[\mathbf{w}^H(\theta)\mathbf{p}\right]^* = \mathbf{w}^H\mathbf{C}\mathbf{w}$$

According to the original derivation by Harrison and Simons, the bottom power reflection coefficient is estimated by dividing beams steered towards the seabed by beams steered towards the surface,

$$R(\theta) = B(-\theta)/B(\theta).$$

To envision this new synthetic array processing consider a CSDM with just 3 hydrophones (for simplicity). The coherences are denoted c_{11} between hydrophone 1 and itself, c_{12} between hydrophones 1 and 2 and so on to form the CSDM. Further, the coherence between hydrophones 2 and 1 is the conjugate of 1 and 2, $c_{21} = c_{12}^*$ That is, by definition a CSDM matrix is always Hermitian but it is not necessarily Toeplitz (e.g., when not from surface noise but from a signal). Below, the matrix shown is the most general form of a CSDM,

$$\mathbf{C} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{12}^* & c_{22} & c_{23} \\ c_{13}^* & c_{23}^* & c_{33} \end{pmatrix}$$

If the CSDM is also Toeplitz, then the CSDM is given by the matrix below,

$$\mathbf{C} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{12}^* & c_{11} & c_{12} \\ c_{13}^* & c_{12}^* & c_{11} \end{pmatrix}$$

This shows the Toeplitz CSDM consists of just 3 complex numbers (and conjugates). This is compared with 6 complex numbers for the general CSDM (and conjugates). Next, consider synthetically adding 3 imaginary hydrophones vertically below the original 3 (total of 6 hydrophones). Lacking any additional information, a general CSDM is constructed from just the three real hydrophones and most of the entries in the 6×6 CSDM would be unknown as shown below,

$$
\mathbf{C}=\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12}^{*} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13}^{*} & c_{23}^{*} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}
$$

However, if it is known that the CSDM is Toeplitz, it implies the CSDM is,

$$
\mathbf{C}=\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12}^{*} & c_{11} & c_{12} & c_{13} & 0 & 0 \\ c_{13}^{*} & c_{12}^{*} & c_{11} & c_{12} & c_{13} & 0 \\ 0 & c_{13}^{*} & c_{12}^{*} & c_{11} & c_{12} & c_{13} \\ 0 & 0 & c_{13}^{*} & c_{12}^{*} & c_{11} & c_{12} \\ 0 & 0 & 0 & c_{13}^{*} & c_{12}^{*} & c_{11} \end{pmatrix}
$$

Where here, zeroes are entered for the unknown numbers in the CSDM. This implies that if the CSDM has no special properties, adding additional synthetic hydrophones does nothing. However, if Toeplitz, as expected with surface generated ambient noise, then synthesizing additional hydrophones allows a larger CSDM to be constructed with most entries non-zero. This new, larger CSDM can be beamformed and bottom loss estimated in the same way as a CSDM with only real hydrophones. This same methodology can be used on arrays of sizes larger than 3 hydrophones and will be applied in the next section to simulated data on a 32-element array. In theory this could be extended to construct even larger synthetic arrays (CSDMs) but the effect may be diminished as the number of unknown entries becomes too large.

WORK COMPLETED

The work this year developed a way to improve bottom loss estimates from ambient noise by exploiting the inherent property that surface generated noise spatial coherence mainly depends on the distance between hydrophones and not their absolute position in the water column. This implies the noise cross-spectral density matrix is Toeplitz. With this property, additional entries in the cross-spectral density matrix can be added and this, effectively, creates synthetic hydrophones on an array. Simulations with a full wave model are shown in the results section and these include refraction and absorption losses. These results demonstrate how this processing can improve vertical beamforming resolution of the noise field. This leads to improvements in the resolution of bottom loss estimates that use vertical ambient noise directionality.

Also completed this year was an invited review paper on ocean ambient noise that was presented at and has been submitted for publication for the Third International Conference on Underwater Acoustics. This invited paper is, “Thirty years of progress in applications and modeling of ocean ambient noise” and is co-authored by Michael J. Buckingham. This review paper on ocean ambient noise was one of several given at the conference summarizing thirty years of progress in different underwater acoustics topics.

RESULTS

A simulated noise coherence function is generated using the full wave ocean noise model OASN [Schmidt 2004]. OASN is part of the OASES acoustic propagation package that numerically implements a full wave solution producing a CSDM for surface noise in a horizontally stratified media using a spectral integration technique [Kuperman 1980, Jensen 2011]. OASES is used since it includes refraction and absorption effects. It has also previously been shown that OASN compares extremely well with measured ocean noise data. For these simulations, the acoustic frequency is 3500 Hz and the water depth is 200 m. The sound speed in the water column is 1500 m/s from the surface to 50 m depth and then is linearly downward refracting to 1490 m/s at the seabed. The seabed has a 0.75 m layer over a half-space. The layer has sound speed of 1550 m/s, density of 1.5 g/cm^3 and attenuation of 0.2 dB/wavelength. The infinite half-space below has sound speed of 1600 m/s, density of 2.0 g/cm^3 and attenuation of 0.15 dB/wavelength. The 0.75 m layer gives rise to interference in the bottom reflection loss, which is also apparent in the beamformer output.

For the simulations OASN produces a noise CSDM of size 32×32 from a 32 element vertical array with the top hydrophone of the array located at a depth of 180 m with hydrophones spacing of Δz = 0.1875 m such that the total array length is L = 5.8125 m. Figure 1 shows the conventional beamforming on the 32×32 CSDM as a dashed line. Also shown as a gray line is the conventional beamforming on the synthetic array using the Toeplitz property to synthesize a size 64×64 CSDM. The solid gray line shows more depth in the nulls, which is an effect of the higher resolution. Since OASN is a full wave model the output CSDM is only approximately Toeplitz (e.g., due to effects such as slight differences in absorption terms along the array). The new synthetic CSDM is formed by first averaging terms along diagonals as described previously to get the array elements of the coherence function (from the original size 32×32 CSDM). This coherence function can then be expanded into a 64×64 CSDM by placing terms of along super- and sub-diagonals of the CSDM and zeros where terms cannot be filled in.

The previously determined beam outputs are used to estimate the bottom loss (BL). Results are compared for the BL using beamformer output from the original data contained in the 32×32CSDM with results using beamformer output on the synthetic CSDM of size 64×64. These are both compared with the ground-truth bottom loss (exact solution can be determined in several ways, see for example, [Jensen 2011]). Figure 2 shows the results. The black solid line is the true BL, the dashed black line is the conventional computation with the CSDM of size 32×32. The gray line is the synthetic array data with size 64×64 CSDM. Taking the mean squared error (on the log scale) between the true bottom loss and the two estimates gives a result that the synthetic array approach (gray line) has about half the error (0.7 dB) as the original (black dashed line) error (1.4 dB).

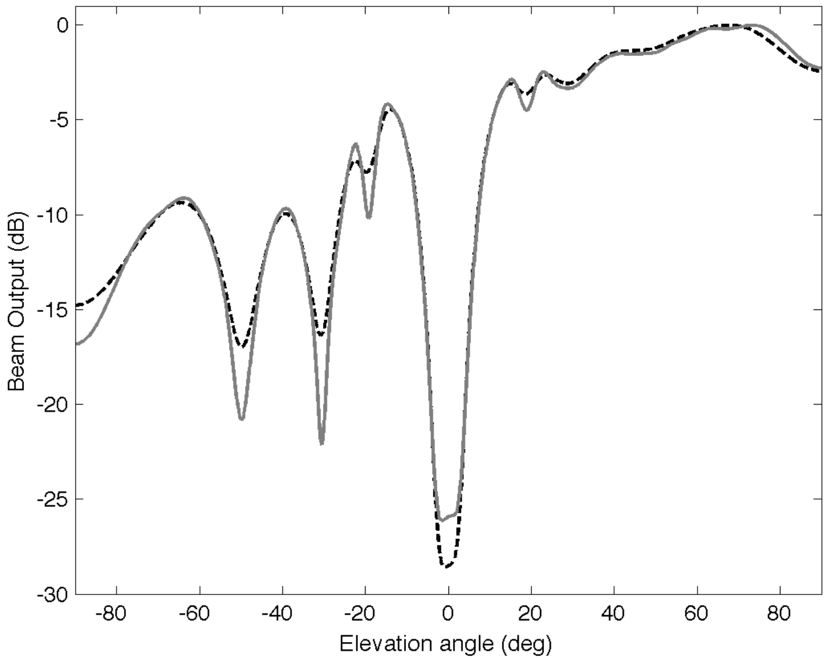

Figure 1: Beamformer output using data from 32-element array. The solid gray line uses the synthetic array approach with size 64×64 CSDM and yields deeper nulls in the beamformer output compared to the dashed black line, which is the standard beamformer with CSDM of size 32×32.

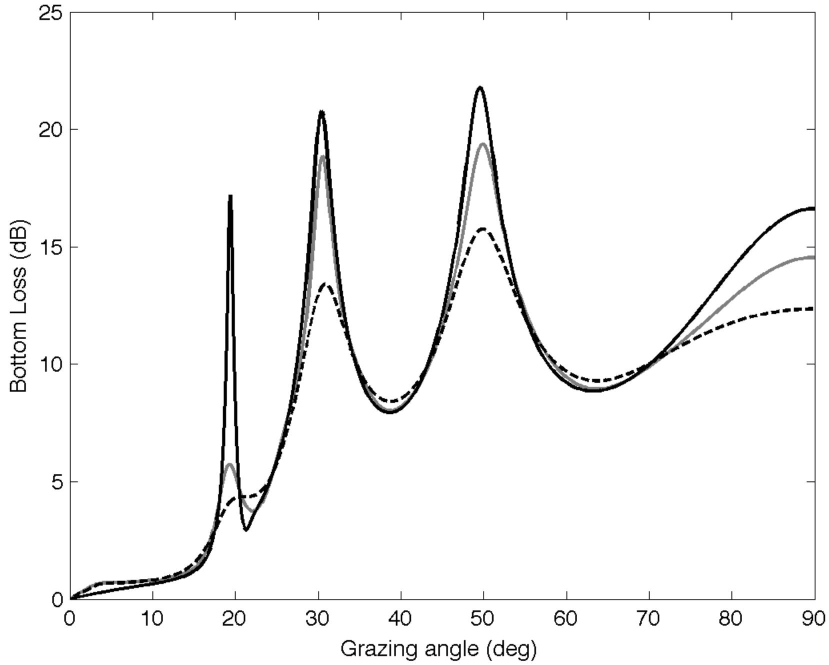

Figure 2: Black solid line is the true bottom loss; the dashed black line uses the standard beamforming with CSDM of size 32×32 to estimate bottom loss from ambient noise. The gray line is the synthetic array that produces a CSDM with size 64×64 to estimate bottom loss. The gray line is closer to the ground truth both from visual inspection and as measured by a mean-squared error estimate.

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.

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