OPTIMUM SPACE-TIME FILTER PERFORMANCE USING A REALISTIC NOISE MODEL OF THE AMBIENT ENVIRONMENT

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Abstract: To evaluate the reliability of underwater acoustic communication systems, it is typically assumed that the noise at the receiver follows a white Gaussian noise distribution. In this work, a space-time underwater acoustic noise model in the 100-10 kHz frequency band is used to estimate the performance of a multi-hydrophone receiver in a coherent communication system. The objective is to reliably transmit in a shallow water environment a frame of information over a narrow band centered around 2 kHz.

A space-time ambient noise model developed in this work is intended to represent shallow water environments, and includes the effects of shipping noise, surface motion, and turbulent flow. The model also includes the effect of correlation as a function of vertical position. The space-time noise coherence in a vertical array of hydrophones is extracted over the bandwidth of interest using a shallow water model. To validate the noise model, it is compared with real measurements of ambient noise taken near the Halifax Harbour. A 5-element vertical line array is deployed, in a shallow environment. Interestingly, it is found that the noise is generally isotropic.

To evaluate the communication link performance, the signal of interest is modelled in software. The signal contribution at the input of the receiver is added to the measured noise signal. A minimum mean square error (MMSE) adaptive space-time equalizer is used to obtain optimal weights. Because the noise contains a space-time signature, it is found that detection reliability relies on the ability of the filter to separate the two signals.

Keywords: Ambient Noise, Spatial Coherence, Optimum Combiner
1. INTRODUCTION

Underwater acoustic communication reliability is sensitive to the channel conditions, particularly in shallow water environments. To reduce sensitivity, an array can be used at the receiver to improve the signal-to-noise ratio. While uncorrelated additive noise is often assumed in the design of communication systems, the array gain depends on the correlation of the noise at each element.

In this work, a discrete-time wideband ambient noise model using stochastic processes will be described to represent realistic noise conditions. The model combines the underwater noise P.S.D. [1], and spatial coherence [2] of ambient noise sources. An instantiation of the model will be realized for shallow environments from derivations proposed by [3]. It will be validated by comparing it with real measurements.

Also, an adaptive minimum mean square error (MMSE) equalizer will be used to mitigate the presence of noise and interference on a five-element vertical line array. Adaptive filters have been demonstrated to be a necessary element of the receiver. For example, in [4] a decision feedback equalizer is employed to combat severe multipath time-varying conditions. Also, in [5] a least mean square (LMS) algorithm with a variable step size was proposed to combat ambient noise with variable power. In the proposed work, a simple linear adaptive filter originally described in [6] is used to obtain the spatial weights that will minimize the mean square error between the transmit sequence and its estimate at the output of the spatial combiner. The structure of the filter is used to analyze the array gain in presence of ambient noise in a limited transmission bandwidth. The filter can easily be enhanced to a space-time equalizer to combat multipath arrival and frequency selectivity.

The rest of this paper is organized as follows: in Section 2, the space-time model will be described, in Section 3, the array gain is presented, and finally, in Section 4, the work will be summarized.

2. A SPACE-TIME NOISE MODEL

In this Section, a space-time noise model will be developed. In Section 2.1, a classification of noise sources is reviewed. The noise sources are classified depending on their spectral content, and an autoregressive filter is presented to model the transient behavior of noise. In Section, 2.2, well established space-time stochastic model is reviewed. The model is applied to assess the characteristics of ambient noise obtained during a measurement campaign taken near the Halifax Harbour.

2.1. A transient model of wideband noise

Ocean ambient noise is random in nature. Due to the randomness of ambient noise, studies have relied on stochastic approach in analyzing these noise sources. Urick in [1] characterized the spectrum of ambient noise into three bands. The power spectrum of ambient noise is found to have different integral power over different frequency band of interest. In this work, we assume that the noise in the band of interest will be dominated by volume noise which is largely dominated by an isotropic noise field.

A discrete-time model to generate a space-time noise sequence is estimated by an autoregressive model. First, to ensure stationarity of the process, a Dickey-Fuller test was run on of the noise data obtained from a sea-trial. Having established stationarity, an autoregressive (AR) model is described which characterizes the noise in time and space. From [7], a two-dimensional AR field is described by
\[ x(m,n) = \sum_{i=0}^{k_1} \sum_{j=0}^{k_2} a(i,j)x(m-i,n-j) + u(m,n) \] (1)

where \((k_1, k_2)\) represents the order of the model over spatial and time dimensions respectively, \(x(m,n)\) is the output of the process, and \(u(m,n)\) is the two-dimensional white noise input field \(N(0, \sigma_u^2)\). The coefficients \(a(i,j)\) which estimate the process are obtained from the Wiener-Hopf equation \(\vec{r} = R^{-1}\vec{a}\), where \(\vec{a}\) is a vector of all \(a(i,j)\) and \(\vec{r}\) is obtained from the observations of the process. The variance \(\sigma_u^2\) is obtained from \(\sigma_u^2 = r(0) - ar\). As described in [8], a better estimate of the process is obtained with higher orders of \(k_1, k_2\). To fully quantify the effect of noise on an acoustic array, the procedure described in [9] for signals with tunable correlation characteristic in time and space was used. The results of figure (1a) and (1b) represents the 2D cross-correlation as a function of space and time, obtained through simulation and data measurements respectively.

Figure (1a): 2D correlation from data measurements  Figure (1b): 2D correlation from an AR process

### 2.2. Characterization of ambient noise measurements

In this Section, well established models to characterize the shallow water models applicable for volume noise are reviewed, and the power spectral density (P.S.D) and the spatial coherence are analyzed to quantify the noise content at different points in space.

In [2], Cron and Sherman developed a space-time correlation function to model surface noise in the deep ocean. The authors assume a randomly propagating noise field with the same statistical properties for all noise sources, distributed over a sphere of radius \(r\), for a receiver lying just beneath the sea surface. Cox in [10] extended the earlier work by Cron and Sherman for homogeneous noise fields, composed of a superposition of uncorrelated plane waves, arriving at sensors with arbitrary orientation from different directions. To characterize the noise resemblance at two points in space, an important figure of merit has been recognized to be the spatial coherence \(\Gamma_{12}\), as a function of frequency. For a cross power spectral density, \(S_{12}\), a P.S.D. at point 1, \(S_{11}\), and a P.S.D at point 2, \(S_{22}\), the spatial coherence \(\Gamma_{12} = S_{12} / \sqrt{S_{11}S_{22}}\).

Ambient noise data was collected from the Halifax Harbour at a shallow water location with an approximate depth of 14 meters. The properties of the seabed in this region of the Harbour were
extracted from the existing data in [11] and [12]. The loss parameter $\delta = 2\alpha v_c \ln(10)/f 40\pi$, where $\alpha_v/f = 0.4556$ in $(dB/m/kHz)$. The sediment porosity $N = P_s(u_s + 2\Delta/u_s + 4)$, where $u_s$ is defined as the grain size, $P_s$ is the packing factor of a random arrangement of surface spheres and $\Delta$ is the rms roughness measured about the mean surface of the grains.

The vertical line array consists of five hydrophones separated by $\lambda/2$. The power spectrum of the colored noise obtained from measurement is shown in figure (2a). The P.S.D of these noise sources closely compare with Urick’s equation for equivalent volume noise. To model shallow water conditions, a theoretical model presented by Deane and Buckingham in [13] for spatial coherence was validated against measurements, with the geo-acoustic parameters of the Harbour as input for the model.

The spatial coherence shown in Figure (2b) confirms that for local breaking waves, the cross-spectral density of the noise sources, at pairs of hydrophones may be decomposed into real and imaginary components. While the spatial coherence equation is applied for homogenous fluid sediment, the sediment values obtained from the data in [14] suggests that the percentage constitution of the bottom boundary of the experimental region is about 90% sand and 75% gravel which is generally described as a veneer. This explains the subtle deviation of the coherence function at frequency values greater than 3kHz.

![Figure 2a. Ambient Noise P.S.D](image1)

![Figure 2b. Comparison of coherence functions](image2)

![Figure 3. 2D noise autocorrelation at 10-minute time intervals](image3)
The 2D autocorrelation of the measured noise process is also analyzed over short window spans within a 10-minute interval. Note that for this analysis, the noise spectrum is limited to the 400 Hz bandwidth around the 2-kHz frequency of interest. Two consecutive windows are shown in Figure 3 as representative of the process. As can be observed, the ambient noise does contain multipath arrival, originating generally from broadside. The characteristics of this noise process will affect the communication performance as will be demonstrated in the next Section.

3. IMPACT ON THE COMMUNICATION PERFORMANCE

In this work, a digital filter is realized at the output of the spatial array to maximize reliability in presence of ambient noise. The system is steered electronically and an MMSE filter originally described by Winters in [6] is implemented. This objective of this filter is to maximize the signal to noise and interference ratio (SINR) at the output of the combiner.

To assess the array gain in controlled conditions, a data transmission frame \( x(t) \) is modelled in Matlab. The received signal vector at the VLA is \( r(t) = h x(t) + n(t) \). It is sampled at a rate on the order of 10.24 kHz. Binary information is modulated using phase shift keying and is up-converted at a center frequency of 2048 kHz. After pulse shaping, the waveform occupies a bandwidth of 400 Hz. To evaluate the effect of correlated noise, the signal arrives at the receiver at an impinging angle \( \phi \) with respect to the plane of the VLA, such that the channel vector with normalized amplitude is \( h = [\exp(j \pi \cos(\phi)) \ldots \exp(j(M-1)\pi \cos(\phi))] \) for \( \lambda/2 \) separation between elements.

The spatial filter combines the output of the VLA to form a signal estimation of the transmit signal \( \hat{x}(t) = w^T_v(t)r(t) \), where the optimum weights \( w_v(t) \) solve the popular Wiener-Hopf equation defined in [15] as \( w_v = R_v^{-1}p_v \). Note that \( R_v \) is the ambient noise covariance matrix \( R_v = E[nn^H] \) and \( p_v \) is the correlation vector between the desired sequence \( x(t) \) and the received vector \( y(t) \) such that \( p_v = E[x \cdot r] \).

![Figure 4. Spatial filter array gain as a function of angle of arrival](image)

In practice, an adaptive filter [15] is realized to train the filter coefficients and update the weights dynamically. A recursive least square algorithm is used to reduce convergence time. Also, to combat the effect of frequency selectivity, the spatial filter is enhanced with a time domain adaptive equalizer. The array gain of the MMSE filter is evaluated as a function of the impinging gain of the signal on the array. The performance of the adaptive MMSE filter is also compared to that of the theoretical performance of a fixed beamformer in presence of uncorrelated AWGN noise source. When the noise is not correlated in either space and time and the signal is fully correlated, it is expected that the SNR
gain at of the array is equal to $10\log n = 7.0\, dB$. However, when the impinging signal is received in presence of the ambient noise measured the performance is much better. This can be attributed to the fact that the noise is correlated in both space and time. In fact, the array performs best when the signal arrives from endfire with an array gain approximately equal to 14 dB, while the array gain is worst, at broadside, with an array gain slightly better than 8 dB. As can be observed, there is a significant benefit in implementing adaptively steered space-time filters to combat ambient noise, even in narrowband conditions.

4. CONCLUSION

In this paper, the impact of realistic ambient noise on the design of a communication receiver is analyzed. A 5-element vertical line array is deployed in shallow water, and the noise characteristics are extracted. Space-time correlation is demonstrated, and it is shown that the noise process follows a temporal variation. Finally, an MMSE space-time filter is compared to a fixed beamformer, and it is found that the performance is significantly improved over all angles of arrival.

REFERENCES


