Abstract—In passive sonar systems, knowledge of low-frequency shipping noise is significant for target detection performance. However, an accurate model for the shipping noise structure is difficult to obtain, because of the varying distributions of ships and complicated underwater environment. This work characterizes low-frequency distant shipping noise observed in deep water environments as a function of receiver depth and vertical arrival structure below the conjugate depth. Distant shipping noise is examined using a Monte Carlo simulation based on statistics derived from the Historical Temporal Shipping (HITS) database. Source levels and source depths of ships are assigned depending on the ship classification. The complex pressure field radiated from each interferer is computed using a normal mode propagation model, and the predicted values are summed coherently at each receiver location. Parameters for the ocean channel are chosen in agreement with the experimental observations, and sensitivity to exact parameters of the bottom sediment is explored. The depth dependence of the simulated shipping noise is in agreement with published experimental measurements. A Vertical Line Array (VLA) is used to produce vertical beams that isolate the surface interference from nearby targets. Simulation results quantifying the beamformer output as a function of ocean environment, receiver aperture, and frequency are presented for both conventional and adaptive beamformers. The results suggest a favorable detection performance of a target in the presence of distant shipping interferers and wind noise, by adaptive beamforming using diagonal loading with white noise gain constraint techniques.

I. INTRODUCTION

Research on low-frequency shipping noise structure for target detection in the ocean environment has both military and civilian applications [1]. Shipping noise dominates the total ambient noise field in the frequency band 50-300 Hz. In the deep ocean environment, distant shipping noise has broad peak around 30 Hz and quickly declines when the frequency reaches above 100 Hz [2].

Noise arising from shipping can be modeled as point sources at precise locations, or by shipping densities on a latitude and longitude grid [3]. The HITS database is a climatological global database of surface shipping density, and it can be used as an input to propagation models for the description of the levels and directional dependence of the low-frequency ambient noise as a function of time and location. A VLA is usually utilized to produce vertical beams to isolate the surface interference from nearby targets. Noise level received from the VLA at a specific position depends on the acoustic propagation conditions between the VLA and all the surface ships. Wind noise received by the VLA in the deep ocean environment normally has steep angles from the upward vertical [3].

To improve the performance of target detection in the presence of surface shipping noise and wind noise, it is necessary to characterize the ambient noise. In passive sonar, beamforming is utilized to extract the angular information in the form of beams. Conventional beamforming is inadequate because of its limited sidelobe rejection [4]. Therefore, adaptive beamforming is used to improve detection performance. Adaptive beamforming is typically based on the minimum variance distortionless response (MVDR) formulation [5]. The adaptive beamformer with MVDR can minimize output power in a desired look direction while preserving target energy. Mismatch loss results from incorrect steering vectors, and this is a major cause of performance degradation in adaptive beamformers. When the steering vector is perfectly known, adaptive beamforming can give high spatial resolution and good interference suppression. When the presumed steering vector and actual steering vector are different, adaptive beamformer would suppress signals and have poor interference rejection, which is called the self-nulling phenomenon. In this work, diagonal loading improves the robustness of the adaptive beamformer [6].

This paper deals with the vertical arrival structure of shipping noise and the detection of a passive sonar target in the presence of ambient noise. Section II provides simulation models including HITS database, ANDES noise model, source depth model, KRAKEN propagation model, and OASES wind noise model. These models were all used to calculate the ambient noise in the deep ocean environment. It also reviews the beamforming principles, including conventional beamforming and adaptive beamforming techniques. Section III presents Monte Carlo simulations of the surface shipping noise. The results are compared with published experimental measurements conducted by Gaul et al. in [7]. The ambient noise levels can be successfully modeled in complicated deep
water environments as shown by agreement with [7]. A VLA is used to indicate the vertical arrival structure of shipping noise and wind noise using passive sonar. The results from different beamforming methods show the effect of isolating the target from the ambient noise.

II. METHODS

A. Simulation Model

1) Historical Temporal Shipping (HITS) database:
The HITS density database [8] provides monthly global shipping densities for vessels divided into the following five types: super tankers, large tankers, tankers, merchant vessels, and fishing vessels. The monthly density is given in units of ships per 1000 square nautical miles (ships/1000 nm²). This can be used to estimate the expected number of ships in a particular area. Resolution of the database is given by cells of 5 nm × 5 nm, and the ship count is calculated by the product of the density and the area of the cell. Statistics for fishing vessels were collected in 1999 and they do not follow distinct shipping lanes because their locations depend upon the distribution of marine species. The data corresponding to all other ship types were collected in 1998, and show lanes of heavy traffic between ports.

In this paper, surface ship noise is examined with a Monte Carlo simulation based on statistics derived from the HITS database. Details of this process can be found in section II-B.

2) Noise Models and Source Depth:
The Ambient Noise Directionality Estimation System (ANDES) model developed in the early 1980s is used to assign the source level spectra, based only on the ship classification. The ship length or speed is not considered in the assignment of the source level. The source depth of each of the surface ships is assigned based on the ship draft, which is usually related to the ship length with a ratio of 1:20 [9]. In this paper, the ship length is estimated as the average length based on ship classification. Table I shows the source depths and source levels for different types of ships at the frequency of 50 Hz and 300 Hz.

<table>
<thead>
<tr>
<th>Ship Type</th>
<th>SD (m)</th>
<th>ANDES Source Level Model 50 Hz (dB)</th>
<th>300 Hz (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super Tanker</td>
<td>20</td>
<td>181.0</td>
<td>156.4</td>
</tr>
<tr>
<td>Large Tanker</td>
<td>13</td>
<td>177.0</td>
<td>152.4</td>
</tr>
<tr>
<td>Tanker</td>
<td>3</td>
<td>168.0</td>
<td>143.4</td>
</tr>
<tr>
<td>Merchant</td>
<td>8</td>
<td>159.0</td>
<td>134.4</td>
</tr>
<tr>
<td>Fishing</td>
<td>1.7</td>
<td>150.0</td>
<td>125.4</td>
</tr>
</tbody>
</table>

3) KRAKEN Propagation Model:
In this paper, surface ships are located many water depths away from the receiver. The acoustic pressure \( p(r, z) \) as a function of the position of interferers can be computed using the normal mode expansion [10] as

\[
p(r, z) = \frac{i}{\rho \sqrt{8\pi r}} e^{-i\pi/4} \sum_{m=1}^{M} \Psi_m(z_s) \Psi_m(z) e^{ik_{rm}r} / \sqrt{k_{rm}},
\]

where \( r \) is the source-receiver range and \( z \) is the depth of the receiver, \( \rho \) is the density of the water, and \( \Psi_m(z) \) is the \( m \)th mode function. \( z_s \) is the depth of the source and \( k_{rm} \) is the horizontal wave number. In (1), \( M \) is the total number of modes. Frequency dependency is included in the definition of wave number \( k_{rm} \).

KRAKEN normal mode program [10] is used to solve for the \( k_{rm} \) and \( \Psi_m \) by numerical methods. The inputs to the model are the sound speed profile (SSP), the characteristics of the seabed (density, sound speed, and sediment attenuation) and the depths of the source and receiver. The solution of (1) will be used in section III to calculate the pressure due to the target source and interferers.

4) OASES Wind Noise Model:
The OASES-OASN module [11] gives the seismo-acoustic field on arbitrary three-dimensional array of hydrophones and geophones in the presence of surface noise sources and discrete signal sources. This module uses the wave-number integration method to model the propagation of surface-generated ambient noise and provides simulated array responses. The input of the frequency dependant noise level at different wind speed is obtained from the Wenz’s curve [12]. The wind noise source level is dependant on the wind speed and frequency. Table II shows the relationship between sea state and source strength and wind speed at the frequency of 50 Hz.
27.7°N and 137.8°W respectively. The shipping density data extracted from HITS database are at the same month and same location but extend the range from 22°N to 32 °N and from -142°W to -127°W, which includes 21600 cells. Since HITS database only provides the density in a whole month instead of each moment in the month, a Poisson distribution is used to generate 5000 realizations, representing 5000 moments in the month. The mean in each cell for the Poisson distribution is determined by the ship count calculated from monthly shipping density data. One of the major purposes of the Church Opal experiment was to understand the nature of distant shipping noise in a deep water environment. In the Church Opal experiment, the majority of the ships are more than 400 km away, so the simulations in this paper only include ships outside the 400 km boundary (distant ships).

For each realization, each ship is assigned with a source depth and a source level according to the ship classification as shown in Table I. Fig. 1 gives the SSP at Church Opal [7].The channel axis, the critical depth and the ocean bottom depth are about 600 m, 4060 m and 4880 m respectively.

Bottom parameters for the ocean channel model are chosen in agreement with the experimental observations from Hamilton [13] and shown in Table III.

The complex pressure field radiated from each interferer is computed using KRAKEN and the predicted values are summed coherently at each receiver location. Wind noise calculated from the OASES model and Gaussian white noise are also included. The sensor device is a vertical linear array, which consists of equally spaced hydrophones with different spacings for different frequencies.

### Table II

<table>
<thead>
<tr>
<th>Sea State</th>
<th>Source Strength (dB)</th>
<th>Wind Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>4-6</td>
</tr>
<tr>
<td>3</td>
<td>59</td>
<td>11-16</td>
</tr>
<tr>
<td>6</td>
<td>68</td>
<td>28-33</td>
</tr>
</tbody>
</table>

### Table III

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>50</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom type</td>
<td>Rigid</td>
<td>Rigid</td>
</tr>
<tr>
<td>Sediment type</td>
<td>Silty clay</td>
<td>Silty clay</td>
</tr>
<tr>
<td>thickness (m)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>sound speed (m/s)</td>
<td>1508</td>
<td>1508</td>
</tr>
<tr>
<td>density (g/cm³)</td>
<td>1.344</td>
<td>1.344</td>
</tr>
<tr>
<td>$\alpha_p$ (dB/m)</td>
<td>0.005 to 0.009</td>
<td>0.03 to 0.054</td>
</tr>
</tbody>
</table>

### III. Simulation Results

Simulations were run at 50 and 300 Hz. The environmental parameters were set to represent Church Opal. Figure 2 shows the comparison between the statistics from HITS database and the generation from Monte Carlo realizations for large tankers in September. The shipping routes are clearly shown in Figure 2 which illustrates the lane-based representation in merchant distributions. The simulation results for fishing vessels, which are not shown in this paper, exhibit a uniform distribution.

Figure 3 shows the pressure field of a super tanker at Church Opal using KRAKEN Propagation Model. The 50 Hz source corresponding to the super tanker is at a depth of 20 m. The SSP is shown in Fig. 1, and the boundary conditions are shown in Table III. The ocean depth is 4880 m and the calculated range is 400 km. The simulation used 329 modes which include the waterborne modes, bottom-bounce modes and leaky modes [14].

Figure 4 demonstrates simulated noise level at different sea state using the OASES wind noise model. The frequency is 50 Hz. The source strength and wind speed for the different sea states are given in Table II.

#### A. Comparison of Simulated Results to Measurements

As introduced in Section II-B, the simulation for interferers only focus on distant shipping at a range larger than 400 km. The received level is affected by the ship distribution on the ocean and the vertical location of the receiver. In
Fig. 3. Transmission loss of a 50 Hz super tanker using KRAKEN propagation normal mode including 329 modes. The super tanker located at Church Opal has the depth of 20 m. The SSP and boundary conditions are given in the Figure 1 and Table III, respectively.

Fig. 4. Simulated noise level at different sea state at the frequency of 50 Hz. The source strength for these 3 sea states are 45 dB, 59 dB, and 68 dB respectively. Wind speeds are 4-6 knots, 11-16 knots and 28-33 knots respectively.

In order to analyze the effects of the receiver depth, Figure 5 shows the received level distribution from distant surface ships when the receiver is located at 50 m (near surface), 600 m (sound channel axis), 4060 m (critical depth), and 4850 m (near bottom), respectively. The ANDES model is used to determine the source level spectra and the source depth of each of the surface ships is assigned as described in Section II-A. KRAKEN is used to compute the complex pressure field radiated from each interferer. Comparison of these four depths shows that the received levels for the VLA located near the surface and at critical depth have a similar pattern. The received level near the bottom is the smallest.

In the Church Opal experiment, receivers were positioned well below the critical depth in order to examine noise attenuation with depth and separate the wind and the distant shipping components of the ambient noise. From the measurement, it is apparent that there is a depth dependence of the noise at phones in and below the critical depth. This observation could be quantitatively explained by the effects of bathymetric shielding and bottom attenuation of noise from distant shipping [15]. Figure 6 shows the simulated ambient noise structure as a function of depth at 50 Hz and 300 Hz. The wind noises correspond to 5 kn, 10 kn and 15 kn winds, respectively. The depth dependence of the simulated shipping noise is in agreement with the published experimental measurements, which suggest that the noise from distant shipping may be significantly reduced when measured on receivers below the critical depth. Furthermore, since the distant shipping noise arrives via shallow grazing angles, a Vertical Line Array (VLA) is used to produce vertical beams that isolate the surface interference from nearby targets.

In these simulations, parameters for the ocean channel model are chosen in agreement with the experimental observations, and sensitivity to exact parameters of the bottom sediment structure is explored. Figure 7 shows the dependency on bottom sediment layer at 50 Hz. The receiver is located 30 m above the ocean bottom, and the source depth is 10 m. The source to receiver ranges are 200 km, 800 km, 1500 km and 3000 km, respectively, and the bottom has a silty clay sediment. The figure shows that a significant sediment thickness effect occurs when the source-receiver range is about 200 km. This is because some of the energy penetrates into the sediment, and there is more transmission loss for a thicker layer. For the source-receiver range is much larger than 200 km, the transmission loss is dominated by lower order modes, the sediment thickness has less effect to the bottom transmission loss.

**IV. Beamforming and Directionality for VLA**

A beamformer is used to estimate the narrowband signal arriving from a desired direction in the presence of noise and interferers. For conventional beamforming, the output of an N-element array at frequency $f_0$ and direction $\Theta$ can be written as

$$P(f_0, \Theta) = \bar{v}^{H}(f_0, \Theta) \hat{K}(f_0, \Theta) \bar{v}(f_0, \Theta),$$

where $\bar{v}(f_0, \Theta)$ is the complex pressure at the $N$-th element of the array and $\hat{K}(f_0, \Theta)$ is a steering vector that includes the array's positions, and $\bar{v}^{H}$ denotes the Hermitian transpose.

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an adaptive beamformer, the output of an
from excessive target signal loss and peak migration [16]. For
forms conventional beamforming, even though it can suffer
about the ocean parameters, adaptive beamforming outper-
properties are well-known. However, when there is uncertainty
in an interference-free environment in which the channel
matrix. Conventional beamforming can perform very well
\hat{\mathbf{r}}(\mathbf{f}_0, \Theta) \hat{K}(\mathbf{f}_0, \Theta) \hat{\mathbf{w}}(\mathbf{f}_0, \Theta), \quad (3)
where \hat{\mathbf{w}}(\mathbf{f}_0, \Theta) is the \(N \times 1\) weight vector related to the
corresponding replica vector \(\mathbf{v}(\mathbf{f}_0, \Theta)\), and \(\hat{K}(\mathbf{f}_0, \mathbf{t}_0)\) is the
\(N \times N\) sample covariance matrix. To suppress the interference
sidelobes, the MVDR formulation is used. The weight vector
in (4) is given by [17]

\[ \hat{w}_v(\Theta) = \frac{\hat{K}^{-1} \hat{v}(\Theta)}{\hat{v}^H(\Theta) \hat{K}^{-1} \hat{v}(\Theta)}, \quad (4) \]

where \(\hat{K}\) is the sample covariance matrix. Assuming sufficient
snapshot support and uncorrelated sources, the covariance
matrices can be written in their asymptotic form as

\[ \hat{K} = \mathbf{K}_s + \mathbf{K}_i + \mathbf{K}_{\text{windnoise}} + \mathbf{K}_{\text{whitenoise}}, \quad (5) \]

with

\[ \mathbf{K}_s = \mathbf{x}_s \mathbf{x}_s^H, \quad (6) \]
\[ \mathbf{K}_i = \sum_{q=1}^{Q} \mathbf{K}_i(q) = \sum_{q=1}^{Q} \mathbf{x}_i(q) \mathbf{x}_i^H(q), \quad (7) \]
\[ \mathbf{K}_{\text{whitenoise}} = \sigma^2_n \mathbf{I}, \quad (8) \]

where \(\sigma^2_n\) is the output product of the input vector corresponding
to the signal receive from the target at the \(N\) elements of the
array. Similarly, \(\mathbf{K}_i(q)\) is the covariance corresponding to the
\(q\)th surface shipping interferer, and there are \(Q\) interferers
for each realization. The matrix \(\mathbf{K}_i\) is the summation of \(\mathbf{K}_i(q)\).
The matrix \(\mathbf{K}_{\text{windnoise}}\) is calculated by OASES model and
\(\mathbf{K}_{\text{whitenoise}}\) is the white noise matrix determined by white
noise power \(\sigma^2_n\).

The mismatch between the assumed signal and actual re-
ceived signal in complicated underwater environments can lead

Fig. 6. Simulated ambient noise levels as a function of depth at (a) 50 Hz and
(b) 300 Hz. Ambient noise includes surface distant shipping noise and wind
noise. The wind noises correspond to 5 kn, 10 kn and 15 kn, respectively.
VLA is located near the bottom from 3430 m to 4850 m.

Fig. 7. Computed bottom transmission loss as a function of silty clay
sediment thickness at 50 Hz. The receiver is located at the depth of 4850
m, which is 30 m above the bottom. The source depth is 10 m. The source
to receiver ranges are 200 km, 800 km, 1500 km and 3000 km, respecti-
vely. The bottom has a silty clay sediment.

where \(\Theta = (r, \phi, z)\) denotes the three-dimensional spatial
position in range, azimuth and depth, \(\hat{\mathbf{v}}(\mathbf{f}_0, \Theta)\) is the \(N \times 1\)
normalized weight vector which is called the replica vector
or steering vector, and the normalization achieves unity gain
on the target. \(\hat{K}(\mathbf{f}_0, \mathbf{t}_0)\) is the \(N \times N\) sample covariance
matrix. Conventional beamforming can perform very well
in an interference-free environment in which the channel
properties are well-known. However, when there is uncertainty
about the ocean parameters, adaptive beamforming outper-
forms conventional beamforming, even though it can suffer
from excessive target signal loss and peak migration [16]. For
an adaptive beamformer, the output of an \(N\)-element array at

\[ P(f_0, \Theta) = \hat{w}^H(\mathbf{f}_0, \Theta) \hat{K}(\mathbf{f}_0, \Theta) \hat{w}(\mathbf{f}_0, \Theta), \quad (3) \]
to signal cancellation and prevent the detection of the actual signal [18]. This paper implements diagonal loading of the covariance matrix using white noise gain constraint (WNGC) to reduce signal self-nulling. The weight vector is given by (9) [5].

\[
\hat{w}(\Theta) = \frac{(\hat{K} + \gamma I)^{-1} \hat{v}(\Theta)}{\hat{v}^H(\Theta)(\hat{K} + \gamma I)^{-1} \hat{v}(\Theta)},
\]

where \(I\) is the identity matrix, and \(\gamma\) is diagonal loading level which satisfies a specified WNG limit shown in (10).

\[
\frac{1}{\hat{w}^H \hat{w}} \geq WNG_{min}.
\]

The loading level could balance between a fully adaptive beamformer (\(\gamma = 0\)) and the conventional beamformer (\(\gamma = \infty\)). Therefore, the performance of diagonal loading can be varied remarkably and it is important to find an optimal loading level. A loading level which is 5-10 dB above the noise level is usually a good selection [19].

Since the distant shipping noise arrives via shallow grazing angles, a VLA is used to produce vertical beams that isolate the surface interference from nearby targets. In section III, simulation results quantifying the beamformer output as a function of ocean environment, receiver aperture, and frequency are presented for both conventional and adaptive beamformers.

A. Simulated Beamforming Results

The VLA is an array of 30 elements with spacing between elements of 5 m for 50 Hz and 2 m for 300 Hz, and is located near the ocean bottom. It is used to explore the application of conventional and adaptive array processing techniques on target detection in a deep ocean environment. The target is at 100 m depth and 5 km away. Interferers are distant ships,
and 5 kn wind noise calculated from OASES noise model is included. 20 dB white noise is assigned. The classification of source level of the target is shown in Table IV. To explore the impact of target strength, two different sounds levels are computed, denoted as “average” and “noisy” targets. The values for these two levels are taken from Urick [12] and adjusted by approximately 10 dB (his values represent broadband levels and are clearly historical, but they are used in a corrected form here in the absence of more representative values).

<table>
<thead>
<tr>
<th>TABLE IV</th>
<th>SOURCE LEVEL OF THE TARGET CLASSIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Quiet</td>
<td>105</td>
</tr>
<tr>
<td>Average</td>
<td>115</td>
</tr>
<tr>
<td>Noisy</td>
<td>137</td>
</tr>
</tbody>
</table>

Figure 8 shows the conventional beamforming with 45 dB Chebyshev taper at 50 Hz. Figure 9 displays the result using corresponding setup at 300 Hz. The target arrival angle is different from the distant shipping noise which is at 0 degrees and the wind noise which is between 60 to 90 degrees. The bottom bounce of the target is also detectable. The noisy target has better detection performance than the average one. At 50 Hz, the target arrival angle is approximately 45 degrees shown in the red line, and the target bottom bounce is at approximately -45 degrees. At 300 Hz, the target arrival angles are approximately 45 degrees and 60 degrees shown in the red line in Figure 9(b). It is interesting to note that the bottom bounce may prove a more robust detection path because it does not compete with the surface wind noise (as the direct target path does). However, the strength of the bottom bounce will depend on the bottom sediment properties.

Figure 10 shows the adaptive beamforming without diagonal loading. The frequency is 300 Hz. The target is at 5 km range, 100 m depth. Noise includes distant shipping noise, 5 kn wind noise and 20 dB white noise. (a) The source level of target is 100 dB (average source level) (b) The source level of target is 120 dB (noisy source level).

Figure 11. Adaptive beamforming with diagonal loading. The frequency is 300 Hz. The target is at 5 km range, 100 m depth. Noise includes distant shipping noise, 5 kn wind noise and 20 dB white noise. (a) The source level of target is 100 dB (average source level). Diagonal loading is 25 dB. (b) The source level of target is 120 dB (noisy source level). Diagonal loading is 25 dB.
loading at 300 Hz. The beamforming output narrow the beams of target and shipping noise. Figure 11 shows the adaptive beamforming with 25 dB diagonal loading at 300 Hz. The results suggest a favorable detection performance using adaptive beamforming implementing diagonal loading with white noise gain constraint techniques in the presence of distant shipping interferers and wind noise.

V. CONCLUSIONS

This paper has described a model of ambient noise in deep water channels to analyze the vertical arrival structure of shipping noise and detect the target from the ambient noise. Five thousand Monte Carlo simulations is used to obtain a close resemblance of the real data provided by HITS database. Parameters for the ocean channel model are chosen in agreement with the experimental observations. Sensitivity to exact parameters of the bottom sediment structure is explored. The depth dependence of the simulated shipping noise is in agreement with the published experimental measurements of Gaul et al. The results also suggest that the noise from distant shipping (range >400 km) may be significantly reduced when measured on receivers below the critical depth. The ambient noise model could calculate noise responses of arrays of hydrophones operating in complicated shipping and environmental conditions. It can be applied to predict directionalities and array responses in the deep ocean environment. Furthermore, the VLA produces vertical beams that isolate distant surface ship interference from nearby targets, since the distant shipping noise arrives via shallow grazing angles. Preliminary results suggest a favorable detection performance using adaptive beamforming implementing diagonal loading with white noise gain constraint techniques in the presence of distant shipping interferers and wind speed. The results also illustrate the complexity of the received signal structure from both the target and interference, with potentially strong contributions from bottom reflections appearing in the lower beams.

ACKNOWLEDGMENT

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REFERENCES