Modeling of wind induced ambient noise vertical directionality and its variation due to bottom characteristics in shallow Arabian Sea

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In underwater acoustics, knowledge regarding vertical structure of ambient noise has got lot of interest since it improves the design and performance of sonar systems. In this work the influence of ocean environment on wind induced vertical directionality of ambient noise has been analyzed using a model based on ray theory. Shallow water site off the Cochin coast at 30 m depth in Arabian Sea was chosen for studying the characteristics of vertical directionality. Variation of vertical directionality with respect to frequency, Sound speed profile and sediment properties were analyzed and the result clearly shows the importance of those environmental factors on directionality. Vertical directionality of summer and winter sound speed profiles was almost similar except for the broadside, where the effect of noise notch is prominent. Based on the difference in bottom reflectivity significant variation in intensity was observed for different sediment compositions. Variation of directionality with frequency clearly indicates the limitation of ray theory at low frequency. Finally the simulated directionality at different frequencies were compared with field measurements and the model results fits relatively well with the field data.

[Keywords: Ambient noise, shallow water, vertical directionality]

Introduction

Ambient noise in ocean is usually generated due to sources such as sea surface agitation, surface wave interaction, biological sources and ship traffic. Above all ambient noise induced by wind is predominantly considered in underwater acoustic systems since it is a primary contributor to the background sound in their operational limit. The spatial noise properties such as coherence and directionality are highly dependent on ocean environment and major factors in sonar signal processing. Vertical directionality of wind induced noise depends on sound source distribution and acoustic propagation environment. In shallow waters, ambient noise and its associated vertical directionality depend on bottom conditions and the strength of bottom interaction depends on the sound speed profile. Thus the wind induced ambient noise sensed by a vertical array can be used to extract sediment properties of the ocean environment. Due to the robustness in predictability, coherence and directionality are the major properties estimated, using ambient noise models.

A significant amount of research has been done for the estimation of coherence and directionality of ambient noise induced by wind. Cron and Sherman proposed an analytical model of ambient noise induced by wind based on ray theory. They considered that noises were generated from surface sheet of noise sources with dipole radiation pattern at the ocean surface. Kuperman and Ingenito developed a normal mode model for surface generated noise by assuming a stratified ocean environment. Harrison developed a ray based method for noise cross correlation between hydrophones which can include noise source as a sum of plane waves. Later Harrison extended the formula for coherence for range and azimuth dependent medium.

Measurement and characterization of ambient noise along east and west coast of India have been reported in recent years. Most recently, studies focusing on seabed characterization and modeling of ambient noise induced by wind along Indian continental shelf were reported. This study focuses on the dependence of vertical wind noise directionality on the acoustics propagation environments in shallow water regions off Cochin. For frequencies greater than several hundred hertz wind noise is largely due to noise generated by breaking waves. Generally wind induced noise dominates in the frequency range of 0.5-10kHz. Harrison’s formula for coherence based on ray theory has been used for the modeling of wind noise vertical directionality. The environmental
parameters that can be included in the model are sound speed profile, bottom geoacoustic properties in terms of bottom reflection coefficient, surface roughness in terms of surface reflection coefficient and volume attenuation\(^6\). Simulated results of directionality were compared with field measurements using a vertical array from shallow water site off the Cochin coast.

**Materials and Methods**

The major point in Harrison’ formulation for distributed sources is that the ray spreading from sources of noise is compensated by simultaneous increase in sources with surface area. The closed form solution used in the model for ambient noise cross correlation for a range independent environment can be written as\(^6\)

\[
C(d, \gamma) = 2\pi \int_0^{\pi/2} [1 - \sin \theta_s \sin \theta_b \exp(-a) + \sin \theta_s \sin \theta_b \exp(-b) - \sin \theta_s \sin \theta_b \exp(-c) - \sin \theta_s \sin \theta_b \exp(-d)] \\
\times \exp(ikd\cos \theta_s \cos \theta_b - kH \cos \theta_b) \, \mathrm{d} \theta_s \mathrm{d} \theta_b 
\]  

where \(d\) and \(\gamma\) represent the spacing and orientation between two receivers. \(\theta_s\) and \(\theta_b\) are surface and bottom ray angles related to the receiver angle \(\theta_r\) by Snell’s law. \(R_s(\theta_s)\) and \(R_b(\theta_b)\) are the plane wave reflection coefficients at surface and bottom respectively\(^13\). \(k\) is the wave number at the receivers and \(a\) is volume attenuation. \(s_c\) and \(s_p\) are the full and partial path length of the ray from source to receiver and can be estimated as

\[
s_c = (2H - h) / \sin((\theta_b + \theta_a)/2) \\
s_p = h / \sin((\theta_r + \theta_a)/2)
\]

where \(h\) and \(H\) are receiver and water column depths, respectively. Due to the dipole radiation pattern of wind generated noise the value of \(m\) is taken as 1 in simulations. Results are computed for unit source strength per unit area, as to estimate the dependence of various parameters on vertical directionality. Once the cross correlation between two receivers were obtained, cross spectral density matrix is created for an array of sensors. In order to obtain vertical directionality using conventional technique the beam power output in terms of frequency and steering angle can be written as\(^14\)

\[
B(\varphi, \omega) = w^\dagger p^\dagger (w^\dagger p)^\dagger = w^\dagger pp^\dagger w = w^\dagger C_\omega w
\]

where \(\dagger\) denote the conjugate transpose operation, \(w\) is the weight vector for steering angle \(\varphi\). \(p(\omega) = [p_1, p_2, \ldots, p_m]\) is the hydrophone data for each channel at angular frequency \(\omega\) for \(m\) number of hydrophones. \(C_\omega = pp^\dagger\) is the cross spectral density matrix. The steering angle \(\varphi = 0\) when array is steered towards broad side, \(\varphi > 0\) when steered towards surface and \(\varphi < 0\) when steered towards the bottom. For conventional beamforming the weight for the \(m^\text{th}\) hydrophone steered at an angle \(\varphi\) when the hydrophones separated by distance \(d\) is given as

\[
w_m = e^{-im(\omega/c)d \sin \varphi}
\]

where \(c\) is the sound speed and \(d\) is the spacing between hydrophones.

**Results and Discussion**

The study area off the Cochin coast is characterized by flat bottom covered with sediment composed of sand, silt, and clay. The water column depth is 30 m and the array was positioned around mid-water column. The results were estimated for uniform linear vertical array with 12 hydrophones with inter element spacing of 0.15 m. Vertical directionality for a frequency of 2.5 kHz is analyzed since the model is based on ray theory. Two types of sound speed profiles measured using a sound velocity probe during winter (December 2010) and summer (April 2011) were used in the model and are shown in Fig. 1. The sound speed profile measured during winter and summer was isovelocity and downward refracting respectively. The variations of vertical directionality for three types of sediments were investigated and the values of parameters are taken from Hamilton’s values for continental shelf environment\(^15\) and are given in table 1. Due to the unavailability of core sample the substrate layer was considered to be composed of coarse sand with acoustic properties taken from Hamilton’s geoacoustic model\(^15\).

Noise cross spectral density matrix at 2.5 kHz was estimated using equation (1) and final beamformed was obtained using equation (4) for winter and summer sound speed profiles. Geoacoustic properties of clay and coarse sand were used in the model for sediment and substrate layer. Sea surface is considered as totally reflecting since directionality is more sensitive to seabed geoacoustic properties. The variation in vertical directionality due to wind for
Table 1: Bottom parameters for three sediment types used in the model.

<table>
<thead>
<tr>
<th>Bottom type</th>
<th>Compressional speed (m/s)</th>
<th>Compressional attenuation (dB/wavelength)</th>
<th>Density (kg/m$^3$)</th>
<th>Shear Speed (m/s)</th>
<th>Shear attenuation (dB/wavelength)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment (clay, silt, fine sand)</td>
<td>1579</td>
<td>1</td>
<td>1596</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1615</td>
<td>0.8</td>
<td>1740</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1702</td>
<td>0.6</td>
<td>1856</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Substrate (coarse sand)</td>
<td>1836</td>
<td>0.4</td>
<td>2034</td>
<td>200</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Sediment layer thickness (0.5 m)

winter and summer sound speed profiles were shown in Fig. 2. Vertical angle of 90° represents noise directly coming from the surface and 0 degree corresponds to noise arrival from horizontal. As explained by Harrison for surface noise sources Noise notch, refracted surface reflected, surface bottom reflected path, direct path and high bottom loss paths were produced for summer sound speed profile(downward refracting)$^6$. Noise notch is produced due to the absence of surface generated noise arriving at the angles below direct path due to refraction of sound caused by variation in sound velocity. Small peaks in directionality correspond to the refracted surface reflected arrivals. Vertical directionality of winter and summer sound speed profiles was almost similar except for the broadside. When sound speed is constant along the water column, depth of the notch is almost filled due to the absence of refraction.

Dependence of vertical directionality on frequency was analyzed using simulated results and is shown in Fig. 3. Downward refracting sound speed profile with clayey sediment and coarse sand substrate was used for the generation of cross spectral density matrix. Surface generated noise interacting with bottom found to be increasingly attenuated with frequency. Vertical asymmetry in noise field distribution is observed due to downward refracting sound speed profile and soft sediment composition. Variation in intensity for bottom loss path at certain frequencies is due to the direct interaction of noise with substrate layer since the layer is thin compared to acoustic wavelength.

Fig. 4 shows the variation of vertical directionality for different sediment compositions such as clay, silt and fine sand. Cross spectral density matrix is created at 2.5 kHz for summer sound speed profile. Geo acoustic properties of coarse sand were taken for substrate layer and kept constant for the simulation of CSDM. The observed intensity in directionality shows increase as the sediment type changed from clay to fine sand due to strong reflection. The effects of critical angle in intensity of directionality for different sediment compositions were observed. Due to the difference in bottom reflectivity, intensity of clayey type at high angles (downward looking) were...
observed to be less compared to that of fine sand. The effect of sediment composition is observed to be negligible for broadside looking beams.

Comparison with field measurements

Time series ambient noise data were collected from shallow Arabian Sea (off Cochin) using a vertical linear array of 12 hydrophones with interelement spacing 0.15 m. In addition to ambient noise other environmental information such as wind speed, sediment samples and sound speed profile from the site were also collected (Fig. 1). Sediment samples collected from the site were subjected to sieve analysis and found to be composed of silt, clay and sand. As per Hamilton’s values for continental shelf environment compression sound speed= 1579 m/s, compressional attenuation= 0.8 dB/μ and density= 1596 kg/m³ were taken for the sediment layer. Based on geoacoustic inversion carried out on coherence function sediment layer thickness and acoustic parameters for infinite bottom half space were obtained. The sediment layer thickness is obtained as 0.3 m from the inversion results. The basement layer has sound speed of 1734 m/s, density of 1970 kg/m³ and attenuation of 0.45 dB/μ.

Based on the above geoacoustic values of sediment vertical directionality for summer profile at 2 and 2.5 kHz were estimated using the model and compared with the measured data and are shown in Fig. 5 (a, b). The properties of noise vertical directionality such as noise notch and surface bottom reflected path were accurately predicted by the model and the results are comparable with that of field measurements. Even though difference in intensity is observed at direct path and bottom reflected path (higher angles), the relative difference in level between these two regions were comparable between model and measurement.
Conclusion

In this work a modeling study was carried out to analyze the dependence of wind induced ambient noise vertical directionality on acoustic propagation environment for a shallow water site off Cochin. The ambient noise model used for the simulation of noise cross spectral density matrix was developed by Harrison based on ray theory. The model can be also used as a forward model for the inversion of geoacoustic parameters from ambient noise measurements. Based on simulated results, influence of vertical directionality on sound speed profile and different sediment compositions were analyzed. Variation of vertical directionality with respect to frequency and elevation angle clearly indicates the limitation of ray theory at low frequency. The lower limit of frequency where ray theory is applicable for the study area was found to be 510 Hz, based on the condition, $f > 10 \text{c/H}$. Simulated results of directionality were compared with field measurements from the same site and the field data compares well with model at broadside (lower angles). Relative difference in level for model between upward and downward looking beams at higher angles compares well with field measurement. This study clearly indicates the importance of bottom characteristics on wind induced vertical directionality at frequencies above several hundred hertz.

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References