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Wind induced ambient noise modelling and comparison with field measurements in Arabian Sea

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ABSTRACT

The present work focuses on modelling of wind induced ambient noise and comparison of noise properties with field measurements. Time series ambient noise data were taken from shallow waters of Arabian Sea, using a noise recording system consisting of a vertical array with twelve hydrophones. From the field measurements vertical coherence and noise spectral level were estimated and compared with the predictions from Harrison's formulas for coherence and noise level based on ray theory. Considering that the noise generated by the action of wind dominates in mid frequency range, this study concentrates on the band 0.2–5 kHz. Modelled results of both coherence and noise level compare well with field measurements. Moreover the simulated fluctuations in noise level with wind speed are in accordance with measured data. This is an initial attempt made to simulate noise properties in Arabian Sea and the model can be further used for geoacoustic inversion for extracting seabed parameters of the site.

1. Introduction

Ambient noise is generally considered as the unwanted background sound present in the ocean at a particular spot, where a measuring hydrophone is located. The information regarding ambient noise is one of the major input parameter required for the performance of both active and passive sonar, since it could diminish the performance. Wind, rain, marine life and ship traffic are the major sources of ambient noise in the Ocean. Above all, background sound induced by wind is considered as a predominant and constant source of noise in both deep and shallow water. Wind generated noise in shallow water sites are generally about 6–8 dB higher than that in deep water due to the environmental difference [1]. Even though ambient noise is considered as a nuisance, it contains information about the environment where it propagates. This makes it suitable for studying the medium through which it propagates as well as its boundaries. Extraction of sea bed geoacoustic properties using ambient noise is an active research field in underwater acoustics and several studies have been reported [2–4]. Earlier studies show that absolute noise level due to wind and rain depends on wind speed and rainfall rate in the vicinity of the receiver. Thus ocean ambient noise measured at a particular site can be used to figure out wind speed and rainfall rate [5,6].

Measurement of ambient noise for long period of time encounters difficulty considering sensor failure as a result of biological activities and natural calamities. Modelling is an alternative approach to characterize ambient noise field at a particular site. Ambient noise modelling is a complicated subject which includes the prediction of its spatial and temporal properties. Studies concentrating on this regard have started since 1960's and models based on different theories have been developed. An early analytical model of wind induced noise has been proposed by Cron and Sherman [7]. They considered directional noise from the surface without reflections from the seabed. Two seminal papers published in 1980's by Kuperman–Ingenito and Buckingham based on normal mode method provided the theoretical foundation for shallow water ambient noise modelling [8,9]. A detailed review of available ambient noise models were given by Hamson [10]. Harrison developed a formula for coherence based on ray theory and the model is known as CANARY (Coherence and Ambient Noise for ARraYs). Harrison's formula for coherence and noise level is applicable for a range independent ocean environment and later he extended it for a range dependent condition [11–13]. For surface distributed source such as wind CANARY assumes a dipole radiation pattern and the resultant coherence function for two receivers can be expressed in a single equation. Despite the fact that ambient noise studies are meager, measurement and characterization of ambient noise due to wind and shipping in shallow waters off the west and east coast of India have been reported as early as 2007 [14–16].

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In this work vertical coherence and noise spectral level were estimated from field measurements and compared with the simulated results from Harrison's ray based model [12]. Ambient noise data collected off the west coast of India at 30 m water depth during wind prevailing condition were used for comparison. The rest of the paper is organized as: Section 2 briefly introduces data collection methods and mathematical equations governing the ambient noise model. Comparison of modelled results such as vertical coherence and noise spectral level with field measurements is described in Section 3. Good agreement is achieved between the model and measured data in the Arabian Sea.

2. Measurements and processing methodology

2.1. Data collection

An automated subsurface noise recording system was developed and deployed at 30 m depth for time series measurements off the Cochin coast in Arabian Sea. Measurement system was deployed from April 2011 to June 2011 and the datasets measured during peak summer were used for analysis and comparison. Location of deployment and schematic of the noise measurement system are shown in Figs. 1a and 1b. Measurement system consists of data acquisition modules and a vertical linear array of 12 hydrophones with uniform sensor separation of 0.15 m. The omnidirectional hydrophones in the array are capable of measuring noise in the frequency range 0.1–8 kHz with a receiving sensitivity of −170 dB. Noise data were sampled at 50 kHz, recorded for 30 s with eight samples in a day at an interval of 3 h. In addition to ambient noise other environmental information's such as wind speed, sediment samples and sound speed profile from the site were also collected.

2.2. Model description

Harrison's ray based model for coherence has been used for the simulation of noise properties [12]. Model represents the result for cross correlation between two receivers in a single expression. For an array of receivers cross correlation matrix for different sensor combinations can be derived from that formula. Finally ambient noise properties such as coherence, vertical directionality and absolute level can be estimated. 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. The closed form solution used in the model for coherence between two receivers for a range independent environment can be written as [12]

$$\begin{aligned} C(d,\gamma) = 2\pi \int_0^{\pi/2} & [1 - R_s(\theta_s)R_b(\theta_b)\exp(-as_c)]^{-1} \\ & \times (\exp(ikd\sin\theta_r\sin\gamma)\exp(-as_p) \\ & + R_b(\theta_b)\exp(-ikd\sin\theta_r\sin\gamma)\exp(-a(s_c - s_p))) \\ & \times J_0(kd\cos\theta_r\cos\gamma)N(\theta_s)\cos\theta_r d\theta_r \end{aligned} \quad (1)$$

where d and γ represents the spacing and orientation between two receivers. θ_s and θ_b are surface and bottom ray angles related to the receiver angle θ_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. $N(\theta_s)$ is the function representing surface noise source spectral density with dipole radiation pattern. 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

$$s_c = (2H - h)/\sin((\theta_b + \theta_s/2)) \quad (2)$$

$$s_p = h/\sin((\theta_r + \theta_s/2)) \quad (3)$$

where h and H are receiver and water column depths, respectively. Equation for coherence gives absolute ambient noise level for a single hydrophone when the element spacing is set to zero.

$$\begin{aligned} C(d=0) = 2\pi \int_0^{\pi/2} & [1 - R_s(\theta_s)R_b(\theta_b)\exp(-as_c)]^{-1}(\exp(-as_p) \\ & + R_b(\theta_b)\exp(-a(s_c - s_p)))N(\theta_s)\cos\theta_r d\theta_r \end{aligned} \quad (4)$$

As an input to the model certain environmental information must be either known or estimated. Geoacoustic parameters were included in the model in terms of bottom reflection coefficient for a seabed which supports shear [17]. Surface reflection coefficient used in the model is based on Ainslie formula and is related to wind speed and frequency [18]. Volume attenuation is considered to be negligible since it has limited effect at shallow waters and lower frequencies [19]. The surface source spectrum level used in the model for wind induced noise is based on Kuperman–Ferla and Ainslie [20,21]. Based on the above environmental inputs, spatial coherence and ambient noise level were simulated and compared with field measurements.

3. Results and discussions

3.1. Vertical coherence

Coherence function represents the similarity between two time series signals and theoretically it is estimated from cross spectral density normalized by the product of individual power spectral densities. Measured coherence function is complex with both real and imaginary components where the presence of imaginary part implies asymmetry in the noise field along vertical. Spatial coherence due to wind induced ambient noise is a stable feature which depends on seabed geoacoustic parameters, sound speed profile and water column depth.

The sound speed profile measured using SVP from the site was downward refracting and shown in Fig. 2a. Sediment samples collected from the site were subjected to sieve analysis and found to be composed of silt, clay and sand. Seabed parameters for reflection loss estimation are taken from Hamilton's values for continental shelf environment as: compressional sound speed = 1579 m/s, shear speed = 55.2 m/s, compressional attenuation = 0.8 dB/γ and density = 1596 kg/m^3 respectively [17,22]. Shear attenuation is considered as negligible since water column sound speed is comparatively so much higher than that of shear speed. Estimated bottom reflection loss for the environment is shown in Fig. 2b and it is found to be comparatively higher due to soft sediment composition. Sea surface is considered as totally reflecting since noise coherence is more sensitive to seabed geoacoustic properties. Based on the above environmental inputs and receivers at mid water column with separation 0.75 m, vertical coherence is estimated using Eq. (1) for frequencies of 0.2–5 kHz.

In order to estimate the vertical coherence from field measurements first and sixth sensor of the array with separation 0.75 m is taken. Three consecutive data sets during wind prevailing conditions were used for the extraction of vertical coherence. Presence of imaginary component in coherence pattern confirms anisotropy in noise field along vertical direction. Comparison of coherence pattern for real and imaginary components between model and data (average) are shown in Fig. 3. Both real and imaginary parts of coherence function from data fits fairly well with the model. There are two dominant factors which contributes vertical asymmetry in noise field at this location. Firstly downward refracting sound speed profile which supports the downward propagation of locally generated noise and secondly soft sediment composition which absorbs most of the sound interacting with it.