TITLE

MODELLING THE VERTICAL COHERENCE OF THE SHALLOW WATER AMBIENT NOISE FIELD

Modelling the vertical coherence of the shallow water ambient noise field

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Abstract

A shallow water noise model is used to simulate the vertical coherence of an acoustic noise field due to sea surface noise. The coherence between two vertically separated sensors is calculated from the Fourier transform of the received noise intensity as a function of vertical arrival angle. The vertical noise directionality is derived from a uniform distribution of sources at the ocean surface, an energy flux propagation model and a plane-wave bottom reflection coefficient for a multi-layered elastic seabed. The propagation model allows for an arbitrary sound speed profile in the water column and includes attenuation by sea water. This simple model clearly demonstrates the influence of noise source directivity, seabed parameters, and the sound speed profile on the vertical coherence of the noise field. Data-model comparisons will be made with data collected on Western Bank, a shallow water area south of Nova Scotia where the geo-acoustics of the seabed is well known. Data were collected at frequencies from 15 Hz to 1200 Hz, for a sensor separation of 1 m.

1. Introduction

The motivation of this work is to invert seabed properties from underwater acoustics measurements and to predict the noise gain of a vertical array in shallow water. To achieve these goals, the use of ambient noise can be advantageous since it is an ever-present source in the ocean. It has already been shown that some seabed properties can be extracted from the spatial characteristics of the ambient noise field. For example, Buckingham and Jones [1] have estimated the compressional sound speed of surficial sediment from the structure of the vertical directionality of the noise field. Carbone *et al.* [2] have estimated both the compressional and shear speeds of the upper layers using vertical noise coherence measurements. The advantage of using noise coherence over noise directionality is that the former is an easier measurement: only two sensors are required, while a whole array of sensors is needed for the latter.

Chapman [3] developed a model to estimate the vertical ambient noise coherence in a simple shallow water environment. The approach is based on an energy flux propagation model. In this paper we extend the original model to include a multi-layered elastic seabed, seawater absorption, and an arbitrary sound speed profile in the water column. The method has the advantage of being simple while allowing for a complicated environment, without intensive numerical computations.

Harrison [4] used a similar ray based technique, and it was found to give results similar to that of a full wave development. Even though the structure of the noise coherence is more sensitive to the seabed than to sea state conditions, our study showed that it is important to include the sound speed profile in both the seabed and water column to obtain an adequate description of the vertical noise coherence. This point will be demonstrated by comparing our model results with vertical noise coherence data from Western Bank, a shallow water area south of Nova Scotia, Canada.

2. Model description

The coherence between two vertically separated sensors is calculated from the Fourier transform of the noise intensity at an underwater receiver as a function of vertical arrival angle. For frequencies of 100 Hz to 2000 Hz, the main noise source is wind or sea surface agitation. Cron et al. [5] have shown that surface noise sources are effectively dipoles at these frequencies. Cron and Sherman [6] and Cox [7] have shown how the surface source directivity relates to the noise directionality and spatial correlation at a receiver in the water column. Talham [8] went a step further by adding a seabed and seawater absorption, and he calculated the noise directionality from above for a bottom mounted receiver. Our technique is based on the above references, but includes the contribution of noise from both above and below a receiver in the water column.

In an isovelocity environment, the acoustic intensity (or power density relative to a 1-Hz band) per unit solid angle at a receiver in the water column is (see Chapman [3] for full development):

$$I_+(\theta) = I_0(\theta)/(1 - V(\theta)) \qquad (\theta>0), \tag{1a}$$

$$I_-(\theta) = I_0(|\theta|)\cdot V(\theta)/(1 - V(\theta)) \qquad (\theta<0), \tag{1b}$$

where $I_+(\theta)$ and $I_-(\theta)$ are the noise intensity from above and below the receiver respectively; $I_0(\theta)$ is the direct contribution from the sea surface (without bottom interaction); and $V(\theta)$ is the plane wave intensity reflection coefficient of the elastic seabed which we get from Brekhovskikh [9]. The factor $I_0(\theta)$ is related to the effective source strength and directivity function at the sea surface for a horizontally homogeneous distribution of mutually incoherent point sources.

Along with sea water absorption, a dependence upon receiver depth (*z*) and water depth (*H*) is added. Considering the following relations at the boundaries:

$$I_+(\theta_0,0)=I_0(\theta_0)+V_S(\theta_0)I_-(\theta_0,0) \text{ and } I_-(\theta_H,H)=V_B(\theta_H)I_+(\theta_H,H), \qquad (2)$$

where $V_S(\theta_0)$ and $V_B(\theta_H)$ are the surface and bottom reflection coefficients; θ_0, θ_H are the angles at the sea surface and bottom corresponding to the angle θ at the receiver, we obtain, at receiver depth:

$$I_+(\theta,z)=I_+(\theta_0,0)e^{-\alpha L_+} \text{ and } I_-(\theta,z)=I_-(\theta_H,H)e^{-\alpha L_-}, \qquad (3)$$

where L_+ and L_- are the path lengths for the energy coming from the boundaries from above and below the receiver. The use of path lengths in this manner was justified by Harrison [4].

In the case of an isovelocity profile: $\theta = \theta_0 = \theta_H$, $L_+ = z/\sin\theta$ (path length from the surface to the receiver) and $L_- = (H-z)/\sin\theta$ (path length from the bottom to the receiver). For an arbitrary sound speed profile θ_0, θ_H, L_+ and L_- are estimated with a simple ray model. L_+ and L_- take into account the energy refraction introduced by the sound speed profile. For example, in an upward refracting scenario, L_- at shallow angles is the path of acoustic energy coming from the sea surface and refracted upward below the receiver depth.

The noise intensity profile calculated from eqn. (3) is converted to noise coherence following the method of Cox [7]. The vertical noise coherence $\Gamma_V(k,d)$ [function of kd, where k is the acoustic wavenumber (k =2π*frequency/ sound speed at the sensors) and d is the vertical separation between the two sensors] is the normalized Fourier transform of the intensity:

$$\Gamma_V(k,d)=\int_{-1}^{1}\mathrm{d}(\sin\theta)I(\theta)e^{ikd\sin\theta}\Big/\int_{-1}^{1}\mathrm{d}(\sin\theta)I(\theta). \qquad (4)$$

For a multi-layered bottom, $V(\theta)$ will likely be frequency dependent. In such a case, the function $\Gamma_V(k,d)$ needs to be evaluated independently for each frequency of interest, given a constant sensor separation, or vice-versa.

3. Influence of sound speed profile (water column)

The impact of seabed parameters on the modelled vertical coherence has already been discussed by Desharnais and Chapman

[10]. We will restrict our discussion here to the impact of the sound speed profile on the coherence.

To demonstrate our point, we will use three different sound speed profiles: a linear upward-refracting profile (sound speed of 1500 m/s at the surface to 1520 m/s at the bottom), an isovelocity profile (sound speed constant at 1500 m/s) and a linear downward-refracting profile (sound speed of 1520 m/s at the surface to 1500 m/s at the bottom). A water depth of 100 m, and a receiver depth of 50 m were used in all three cases. The chosen seabed is a sand bottom typical of the Western Bank area south of Nova Scotia: compressional speed = 1650 m/s, shear speed = 260 m/s, compressional attenuation = 0.46 dB/λ, shear attenuation = 1.3 dB/λ, density = 1.8 g/cm^3.

Figure 1 shows the relative intensity (dB) as a function of angle at the receiver (the units are relative to the surface source strength). Positive angles are from above the receiver, negative angles are from below.

The intensity curves are asymmetrical, higher noise contributions coming from above the receiver. The singularity at 0° in the case of the isovelocity profile (solid line) is due to the theoretical nil noise contribution from the horizontal. The humps near ±23° correspond to the critical angle at the bottom (slightly different depending on the water sound speed at the interface). In the case of a downward refracting profile (long-dashed line), we get the famous noise notch at ±6.6°. No energy at angles shallower than $\pm\cos^{-1}(1510/1520)$ will reach the receiver, giving infinite negative intensity levels at these angles. For an upward refracting profile (short-dashed line), lower losses at the seabed will imply higher noise intensity near the horizontal. Energy at angles shallower than $\pm\cos^{-1}(1510/1520)$ will simply not interact with the bottom, giving very large intensity levels (not infinite however, since water absorption will have a small effect).

The normalized Fourier transform of the intensity curves of Fig. 1 (following eqn. (4)) gives the coherence curves (as a function of kd) in Fig. 2. In the upward refracting case (short-dashed line), the high intensity levels resulted in very high coherence of the acoustic energy over large kd (or large vertical sensor separations). On the contrary, the downward refracting profile (long-dashed line), with higher bottom interactions, leads to much lower coherence levels, or reduced vertical spatial correlation of the acoustic noise. The isovelocity water (solid line) case lies between the two other cases.

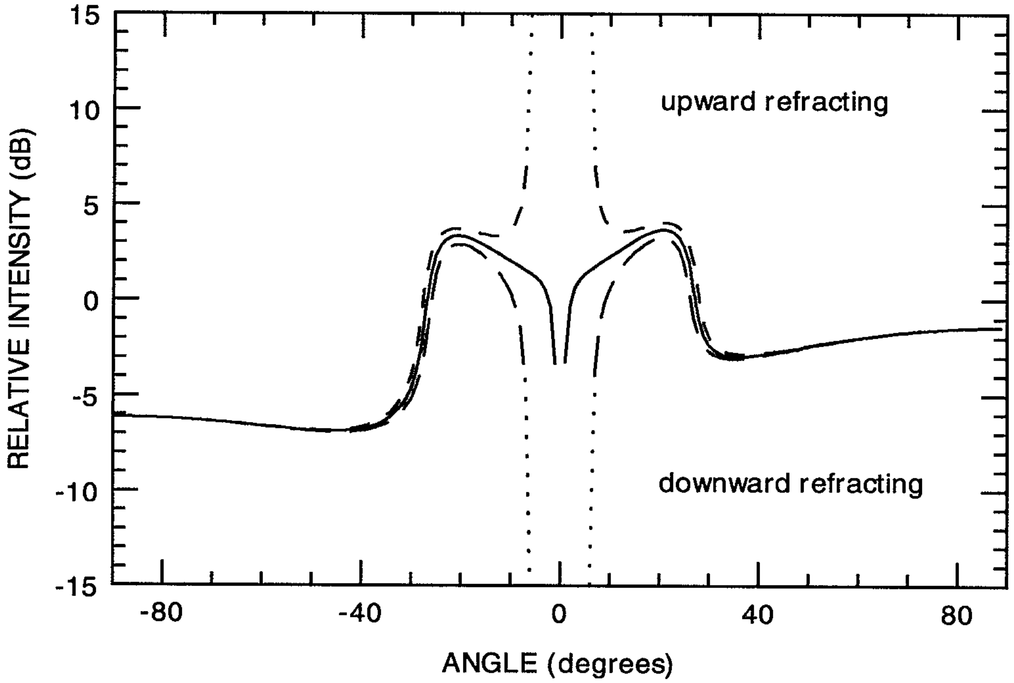

Figure 1. Relative intensity as a function of angle for an upward refracting profile (short-dashed line), isovelocity profile (solid line) and downward refracting profile (long-dashed line).

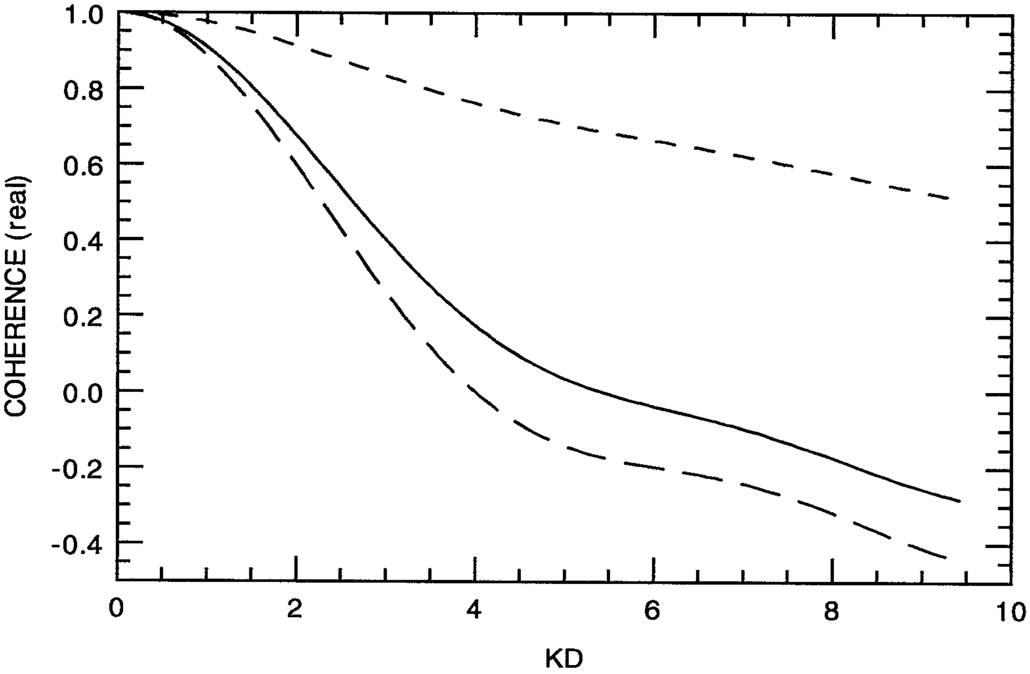

Figure 2. Coherence (real part) as a function of kd (same line symbols as Fig. 1).

It can be seen from Fig. 2 that the sound speed profile in the water column can have a very large effect on the vertical noise coherence. This effect can be as large, and even larger than that of the seabed.

4. Data-model comparisons

To emphasize the point made in the above section, we present vertical noise coherence data from Western Bank. A vertical array was deployed over most of the water column, and two pairs of sensors, 0.91 m apart and at 35 and 65 m depth, were used to build the data set. The measurements were made periodically, covering 65 min over a 3:11 period. The data were split into 1-min sets, and averaged over the entire period. The frequency resolution is 2 Hz, and the data go up to 1024 Hz. The water depth is 76 m at the site. During the collection period (28 May 96), the winds increased from 14 to 19 kn, with a sea state of 2. No shipping was recorded within 35 km from the array, except at the very end of the experiment when a ship came within 6 km. The data are represented as 2 grey areas in Fig. 3. The dark grey zone represents the mean ± standard deviation of the pair of sensors located at 35 m depth; the light grey zone represents the data for the 65 m pair; the medium grey zone is the overlap between the two zones.

Two modelled coherence curves are also shown in Fig. 3. The seabed parameters were taken as 37.5 m of sand (as described in Section 3) overlying a tertiary bedrock: compressional speed = 2000 m/s, shear speed = 800 m/s, compressional attenuation = 0.08 dB/λ, shear attenuation = 2.7 dB/λ, density = 2.2 g/cm^3. The measured sound speed profile at the site, shown in Fig. 4, was downward refracting. The model results are basically the same for both receiver depths (solid line) due to the constant sound speed in the lower part of the profile. The dashed line show the result for an isovelocity profile.

The model does reasonably well at estimating the coherence for both receiver depths, although the fit is better for the data from the deeper pair of sensors. The higher coherence in the data at small kd for the 35 m pair is unexplained. It may be due to shallow water shipping traffic noise near the coast being converted to shallow angle noise at the receiver location. The resulting noise directionality pattern would be enhanced near horizontal angles, and the coherence would likely be higher at small kd.

The model results also show that much higher noise coherence can be expected at high kd with an isovelocity profile than with the real sound speed profile. If the isovelocity profile model results were used to estimate the seabed parameters, a much higher compressional sound speed would be obtained.

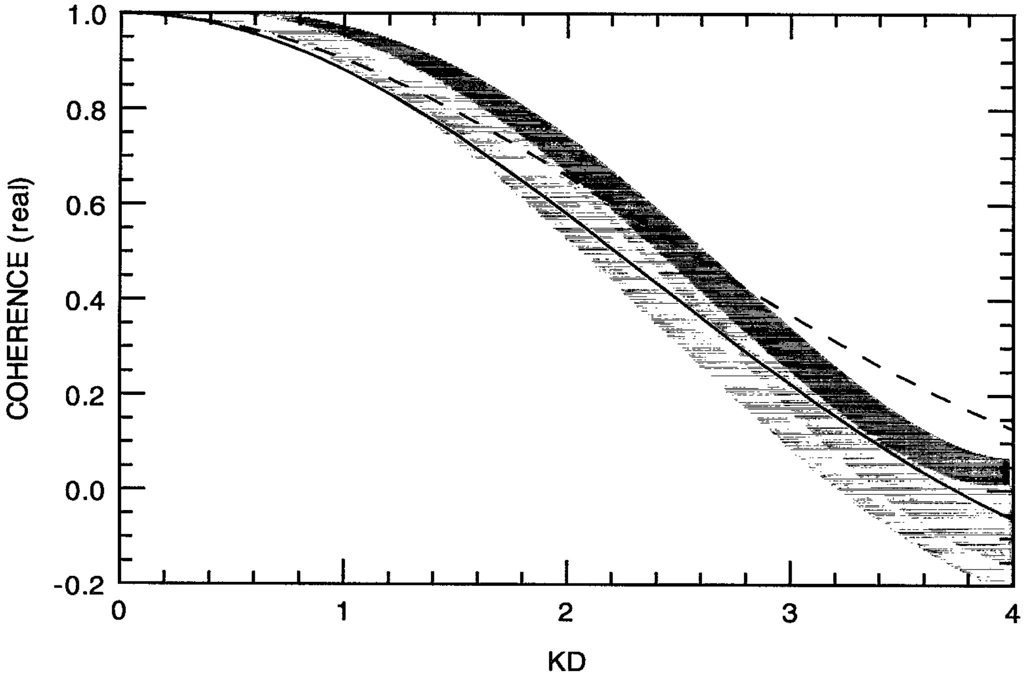

Figure 3. Coherence (real part) as a function of kd. Dark grey zone: data, 35 m; light grey zone: data, 65 m; medium grey zone: overlap between two previous zones; solid line: model, sound speed profile of Fig. 4; dashed line: model, isovelocity profile.

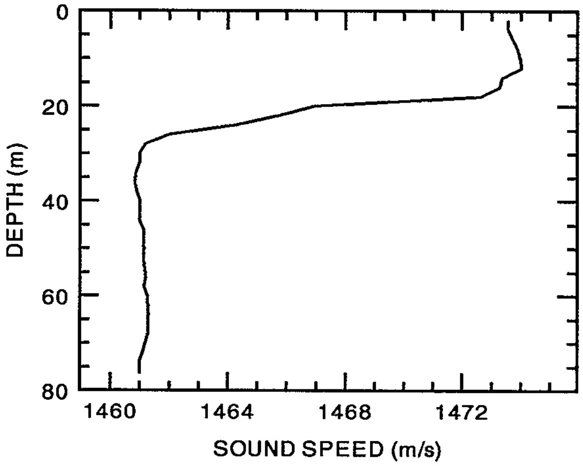

Figure 4. Measured sound speed profile at Western Bank.

5. Concluding remarks

A simple model of vertical noise coherence was presented, based on a uniform distribution of sources at the ocean surface, an energy flux propagation model, and a plane-wave bottom reflection coefficient for a multi-layered elastic seabed. The model was used successfully to model vertical coherence data at Western Bank. The model can be used to infer seabed properties from coherence measurements.

The actual noise levels and their variations due to wind speed do not affect the coherence strongly since it is by definition a normalized measurement. However, the sound speed profile in the water column, as in the seabed, has a directive effect on the noise spatial distribution, and therefore on the noise coherence. Poor knowledge of the oceanographic environment can lead to poor estimates of seabed parameters.

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