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The A.B. Wood Memorial Lecture:

SURFACE-GENERATED NOISE IN SHALLOW WATER: A MODEL

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INTRODUCTION

In many underwater acoustic applications such as sonar, communications, and position fixing, we often combine signals from an array of hydrophones to form a receiving beam that can be steered in various directions. As well as providing information on the source direction, beamforming enhances the signal-to-noise ratio, as only that portion of the noise arriving within the beam is important. To determine overall system performance in such cases, we must consider the noise *directionality* as well as the noise *level*. This paper deals specifically with a model of ambient noise due to sources at the ocean surface in a shallow water environment, with particular emphasis on noise directionality.

Although there are diverse sources of ocean ambient noise [1], there always exists that component due to the action of wind, waves, and precipitation at the ocean surface. Indeed, under the right conditions, this component may predominate. As these sources are distributed more-or-less uniformly, and as the acoustic propagation conditions usually (but not always) are independent of bearing, we find that the azimuthal dependence of the surface-generated noise field is weak. However, the intensity of the noise arriving at a receiver may depend strongly upon the angle of elevation above or below the horizontal plane. We call this functional dependence of received noise intensity upon angle of elevation the *vertical noise directionality*, for short.

In shallow water (i.e. on continental shelves, or in channels and harbours) the presence of an acoustically reflecting seabed allows noise from surface sources to arrive at a submerged receiver along a multitude of paths that reflect from the seabed and the sea surface any number of times. Noise arriving from a particular direction may have originated from several independent surface patches. In summing up all these contributions to determine the directionality of the noise field, the acoustic properties of the seabed become important. Since the reflectivity varies with grazing angle and changes from one seabed type to another, both the noise level and directionality will be sensitive to the seabed type.

The shallow water noise model to be presented in this paper will be based on several simplifying assumptions. We will assume that the sources themselves are uniformly distributed at the surface, that they are independent, and that their radiation pattern is arbitrary. For this simple model, we will assume that the ocean is a non-absorbing, isospeed, layer of constant depth, so that acoustic rays are straight lines and acoustic intensity spreads spherically from point sources. The seabed reflectivity will be based on the plane-wave reflection coefficient at a plane boundary between a homogeneous fluid and a homogeneous, lossy, elastic solid. We will see how these elements combine to provide a noise directionality function whose form is quite sensitive to seabed type.

Furthermore, we will see how vertical noise directionality (which is difficult to measure) transforms into noise coherence between vertically-separated hydrophones (which is easier to measure). We will then apply the model to interpret experimental data collected from two shallow water sites having quite different seabeds.

REVIEW OF PREVIOUS WORK

Cron and Sherman [2] theoretically described the spatial correlation of noise from a surface distribution of independent directive sources in a homogeneous ocean without a bottom. Liggett and Jacobson [3] demonstrated the equivalence of independent directive sources and spatiallycorrelated simple sources. Cron et al. [4] compared correlation models with ocean data and concluded that the surface noise sources were effectively dipoles. Cox [5] related source directivity to received noise directionality and thence to spatial correlation of the noise field.

Talham [6] introduced the effect of a reflecting seabed (combined with acoustic refraction and absorption in the seawater); he considered a bottom-mounted array and calculated noise directionality only from above. Buckingham modelled the array gain of a vertical line array in shallow water [7,8] and proposed a shallow water noise model based on normal mode theory. He applied the model to a study of horizontal noise coherence [10]. Kuperman and Ingenito [11] developed a shallow water noise model, also based on normal modes, but which is capable of handling more complex oceanographic and geo-acoustic environments. Hamson [12,13] used this model in her study of vertical and horizontal line array response in shallow water. Buckingham and Jones [14] used the relation between seabed reflectivity and spatial coherence of ambient noise to devise a technique for determining the sediment sound speed from ambient noise cross-power measurements in shallow water.

A MODEL OF VERTICAL NOISE DIRECTIONALITY IN SHALLOW WATER

We will use the basic ideas introduced by Cron and Sherman [2] and Cox [5] that relate surface source directivity to received noise directionality, and then introduce the effects of seabed reflectivity following Talham [6], but we will look at noise directionality both above and below the horizontal plane through the receiver. This approach avoids the normal mode method of Buckingham [9], and produces comparable results, but cannot treat the complex environments of Kuperman and Ingenito [11].

We start with the noise received at a sensor within an infinitely deep isospeed ocean from a distribution of surface sources. Both the noise radiated by the sources and the received noise will be independent of direction in the horizontal plane, so we need only be concerned with the dependence upon angle above and below this plane. We imagine that there are σ mutually incoherent point sources per unit surface area, each radiating acoustic power P; in the final result only the product σP appears and this may be regarded as an effective surface source strength. As we are dealing with noise, quantities such as power and intensity should be understood as spectral densities, i.e. relative to a 1 Hz band. The acoustic intensity a distance R from an individual point source in a direction θ below the horizontal plane is then $PS(\theta)/2\pi R^2$, in which the source directivity function $S(\theta)$ is normalized so that

$$\int_0^1 d(\sin\theta)S(\theta) = 1. \tag{1}$$

From the vantage point of a submerged receiver, noise arrives from independent sources in all directions above the horizontal plane. Following Cox [5], the acoustic intensity received per unit solid angle is

$$I_0(\theta) = \begin{cases} \dfrac{\sigma P}{2\pi} \dfrac{S(\theta)}{\sin\theta} & (\theta>0), \\ \\ 0 & (\theta<0), \end{cases} \tag{2}$$

in which θ at the receiver is positive above the horizontal plane. [This notation differs from Cox's, who uses the angle α from the surface normal; we have $\sin\theta$ where he has $\cos\alpha$, etc.] Note that, with no absorption, the result is independent of the depth of the receiver below the surface: within an element of solid angle, as receiver depth is increased, the spherical spreading loss of the noise from the surface sources is exactly compensated by the increase in the size of the contributing surface patch. The $\sin\theta$ denominator is due to the inclination of the surface to the propagation direction: a given element of solid angle projects upon a larger surface patch at smaller grazing angles. The relationship between source directivity $S(\theta)$ and received noise directionality $I_0(\theta)$ is illustrated in Figure 1 for the case $S(\theta)=3\sin^2\theta$, the commonly-used dipole source directivity.

Having accepted this, let us now consider the effect of a lossy, reflecting seabed at constant depth H. Not only can noise reflect from the seabed and arrive at the receiver from below the horizontal plane, but noise ariving from any given direction above or below the plane may originate from several (actually, an infinite number of) surface patches, as illustrated in Figure 2. The effect of the multiply-reflected paths is most easily understood using the method of images. The multiple surface patches contributing to the intensity received within an element of solid angle are replaced by patches of the same size on image planes above and below the real ocean, evenly spaced by 2H. Since the intensity arriving directly from the surface is independent of receiver depth (neglecting absorption), then the intensity from the image planes is also independent of their distance. If we didn't need to account for bottom reflection loss, the intensity received from every image plane would be identical to that received directly from the surface. The reflecting seabed has a simple directional effect: only a fraction $V(\theta)$ of the intensity of a ray is reflected, where $V(\theta)$ is the plane wave intensity reflection coefficient of the seabed. Noise from the n^{th} image of the surface (above or below the real surface) transits n images of the seabed, representing n lossy seabed reflections. The intensity from the n^{th} image is then

$$I_n(\theta) = I_0(|\theta|)\, V^n(\theta), \qquad (3)$$

in which we define $V(\theta)$ to be symmetric about $\theta=0$. Expression (3) is equally good above or below the horizontal plane.

The total intensity per unit solid angle due to all due the image sources (i.e. due to all the reflected paths) is the sum n=1,2,3... of all these terms:

$$I_{images}(\theta) = \sum_{n=1}^{\infty} I_n(\theta) = I_0(|\theta|)\frac{V(\theta)}{1-V(\theta)} \qquad (4)$$

Combining this symmetric contribution from the images with the direct contribution in expression (2) gives us the total, asymmetric, noise intensity per unit solid angle:

$$I(\theta) = \begin{cases} I_0(\theta)\,\dfrac{1}{1-V(\theta)} & (\theta>0), \\[2ex] I_0(|\theta|)\,\dfrac{V(\theta)}{1-V(\theta)} & (\theta<0). \end{cases} \qquad (5)$$

Note that the intensity arriving from below the horizontal differs from that arriving from above the horizontal by the factor $V(\theta)$ representing one additional seabed reflection. Expressions (1), (2), and (5) constitute the simple noise model. We need only to specify the surface source strength σP, the source directivity $S(\theta)$, and the seabed reflectivity $V(\theta)$.

Calculations of noise directionality

Much progress has been made in shallow water acoustics by modelling the seabed as a homogeneous, lossy, elastic solid [15]. We assume that the water layer has sound speed c_w=1500

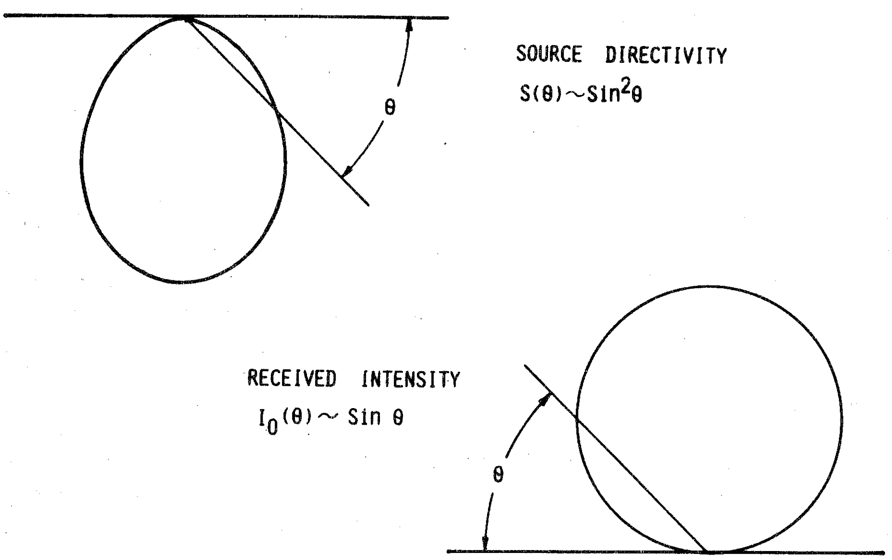

Fig. 1 Noise source directivity $S(\theta)$ and received noise directionality $I_o(\theta)$ for dipole sources.

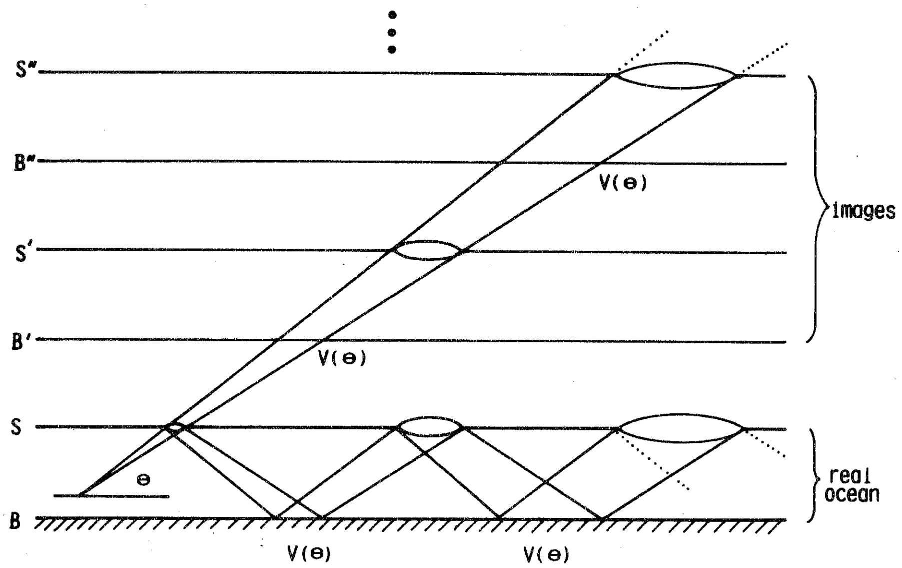

Fig. 2 Using the method of images to account for noise arriving via multiple bounces. $V(\theta)$ is the intensity reflection coefficient. A similar diagram may be drawn for noise arriving from below.

m/s and density ρ_w=1 g/cm^3. The acoustic parameters at our disposal are the density ρ [g/cm^3], the compressional wave speed c_p [m/s], the shear wave speed c_s [m/s], and the associated plane-wave attenuation coefficients k_p and k_s [dB/m-kHz]. An important derived parameter is the critical angle associated with transmitted compressional waves, $\theta_c=\cos^{-1}(c_w/c_p)$. Below this grazing angle, compressional waves do not radiate into the seabed. These parameters are listed in Table I for six hypothetical seabed types, labelled A-F, that correspond very roughly to silt, fine sand, coarse sand, gravel, glacial till, and soft sedimentary rock. The values are based loosely on Hamilton's [16] work. Using these values, the plane wave intensity reflection coefficient $V(\theta)$ was calculated for each seabed using Brekhovskikh's [17] expression for a fluid/solid boundary. The bottom reflection loss, which is $-10\log V(\theta)$ in dB units, is plotted for each seabed in Figure 3. One interesting property of this bottom model is that $V(\theta)$ is independent of frequency, even with absorption effects included.

Table I: Seabed Acoustic Properties

Sediment Label	Density [g/cm^3]	Sound Speeds [m/s]		Attenuations [dB/m-kHz]		Critical Angle [degrees]
	ρ	c_p	c_s	k_p	k_s	θ_c
A	1.6	1550	125	.50	2.0	14.6
B	1.7	1700	200	.35	1.25	28.1
C	1.8	1850	300	.25	.75	35.8
D	1.9	2000	450	.20	.50	41.4
E	2.0	2150	650	.15	.30	45.8
F	2.1	2300	850	.10	.20	49.3

The dipole source directivity $S(\theta)=3\sin^2\theta$ is used throughout this work, as this has been established by Cron et al. [4] as appropriate for surface-generated noise models, and it also corresponds to the normal mode models [8,11] that employ a layer of independent monopoles just below the sea surface. This choice combines with the six $V(\theta)$ curves of Figure 3 to produce the six curves of noise directionality $I(\theta)$ shown in Figure 4, calculated from expression (5). Actually, the quantity $10\log I(\theta)$ is plotted, relative to an arbitrary reference, as the source strength σP remains unspecified.

This model of noise directionality exhibits a strong sensitivity to seabed type, as expected. All of the curves show a degree of asymmetry, with more noise arriving from above than from below. This is most evident for seabed A, which also has the highest overall bottom reflection loss. Seabeds B and C show a strong concentration of noise about the horizontal, within the critical angle determined by the value of c_p. These are comparable with Buckingham's normal mode results [9] for a low-loss seabed. The harder bottoms D,E, and F show peaks in the noise directionality in the vicinity of the critical angle, associated with the local minima of bottom reflection loss. In these cases, the high bottom loss below the critical angle is due to the generation of shear waves in the seabed, and the noise intensity from these directions is correspondingly lower. The seabed types A-F are somewhat ideal compared with the actual seabed, which is layered and also varies laterally, but using them gives us some idea of the relative importance of acoustic parameters such as compressional speed, shear speed, etc.

<u>Noise level</u>

If $I(\theta)$ is the noise intensity received per unit solid angle, then the total intensity is just the integral of $I(\theta)$ over 4π steradians, provided that the waves arriving from different directions are *uncorrelated.* Otherwise, correlated arrivals lead to interference effects and spatial variation (i.e. inhomogeneity) of the received noise level. Since we have argued that noise can arrive at the

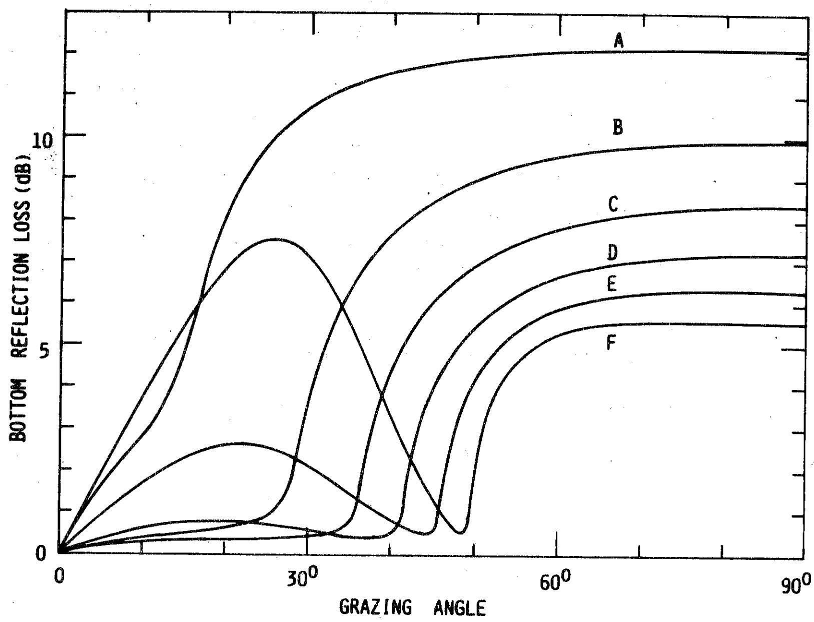

Fig. 3 Bottom reflection loss [-10logV(θ)] versus grazing angle θ for the six seabeds of Table I.

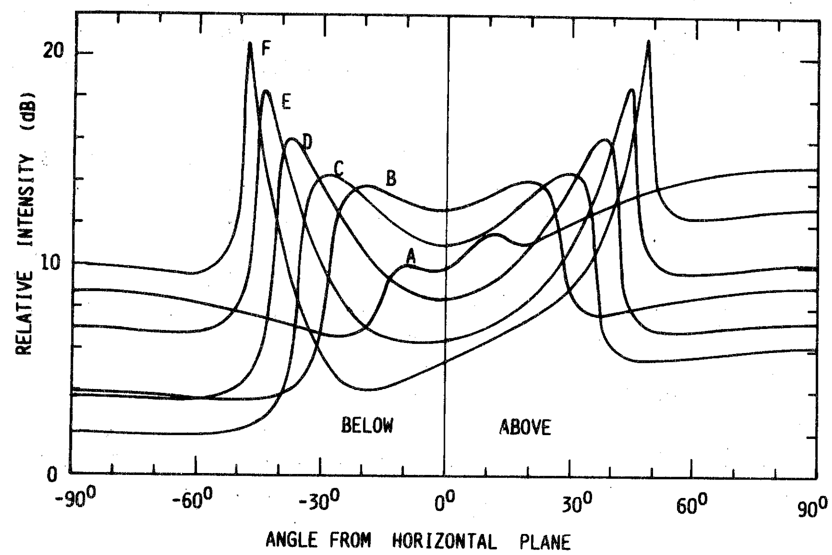

Fig.4 Relative noise intensity [10logI(θ)] versus angle θ above or below the horizontal plane.

receiver from the same surface patch via a multitude of paths, the assumption of an uncorrelated noise field cannot be justified, strictly speaking; however, there is some support [9] for the view that these effects are small and that the shallow water noise field may be treated as quasi-homogeneous away from the boundaries, provided that the frequency is not too low. We may then regard the integral of $I(\theta)$ as the spatial average of the received noise intensity. The noise level, in terms of mean-squared pressure, is then

$$N = 2\pi Z_W \int_{-1}^{1} d(\sin\theta)\, I(\theta) = \sigma P Z_W \int_{0}^{1} d(\sin\theta)\, \frac{S(\theta)}{\sin\theta}\, \frac{1+V(\theta)}{1-V(\theta)} \tag{6}$$

in which Z_W is the specific acoustic impedance of seawater. Assuming that the source factor σP is determined by the wind and wave conditions, we can see that for the same environmental conditions the noise level will depend upon the seabed type through its dependence upon the seabed reflectivity $V(\theta)$. Even if we were confident about the other elements of the model, in order to predict absolute noise levels we would have to calibrate the source factor σP as a function of frequency for different sea states, wind speeds, etc.

VERTICAL COHERENCE OF SHALLOW WATER NOISE

It is difficult to directly measure noise directionality, as this would require an array providing a narrow beam, which means a large aperture. It is much easier to measure a related quantity, the correlation of the noise between two spatially-separated hydrophones, which we will call the noise coherence. Also, signal processing engineers may prefer to think in terms of elements of the noise coherence matrix rather than noise directionality, as these are the quantities that are manipulated in beamforming algorithms. For a diffuse noise field of uncorrelated plane waves, Cox [5] has shown the relationship between the noise directionality and the noise coherence. Noise at a frequency f in a medium of sound speed c has an acoustic wavenumber $k=2\pi f/c$; if the hydrophones are a vertical distance d apart, the vertical coherence function $\Gamma_V(k,d)$ is the normalized Fourier transform

$$\Gamma_V(k,d) = \int_{-1}^{1} d(\sin\theta) I(\theta) e^{ikd\sin\theta} \Big/ \int_{-1}^{1} d(\sin\theta) I(\theta). \tag{7}$$

For the simplest case of isotropic noise, $I(\theta)$=constant and $\Gamma_V(k,d)=\sin(kd)/kd$, which has zeros at $kd=\pi, 2\pi, 3\pi,...$ This means that the inter-element spacing of a uniform line array may be adjusted so that noise at a particular frequency is uncorrelated for any pair of hydrophones, while a combination of phase shifts or time delays may be applied to the hydrophone signals to steer a beam in any desired direction relative to the array axis. Anisotropic noise of the type shown in Figure 4 will have zeros at different locations, so array performance is likely to change.

If the noise directionality $I(\theta)$ is independent of frequency, as in our simple model, then $\Gamma_V(k,d)$ may be regarded as a function of the single dimensionless variable kd. For asymmetric noise fields, the function $\Gamma_V(k,d)$ will have both real and imaginary parts. Using Expression (7), the vertical coherence functions have been calculated for the six seabeds A-F and are plotted in Figure 5 (real parts) and Figure 6 (imaginary parts). Except for seabed A, the imaginary parts are quite small and of little interest; their magnitude is in direct proportion to the degree of asymmetry of the associated noise field. The real parts show a strong sensitivity to seabed type, by the location of their zeros and also by the extent and location of the maxima and minima. The location of the first zero ranges from about $3\pi/4$ to just over 2π for the six cases shown.

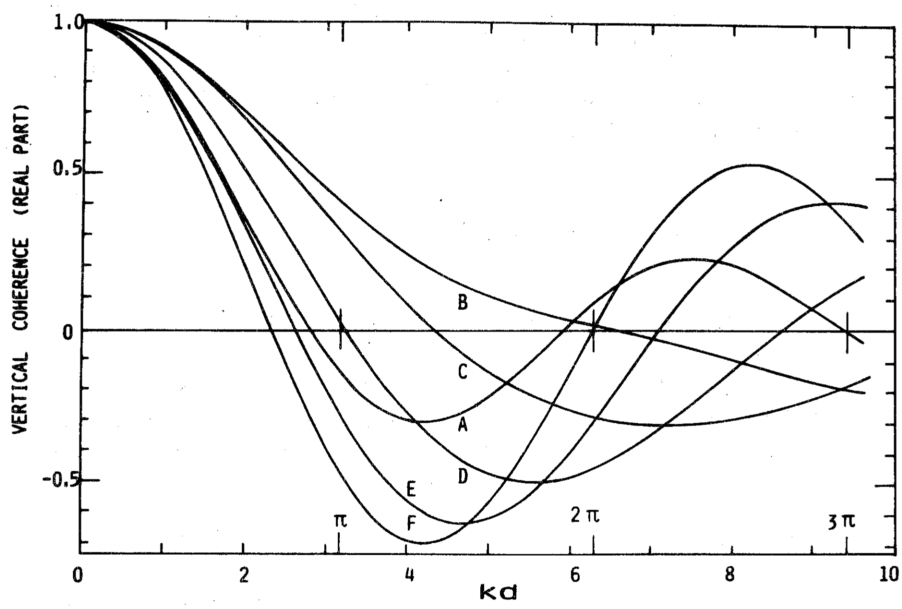

Fig. 5 Real part of the noise coherence versus the normalized vertical spacing kd.

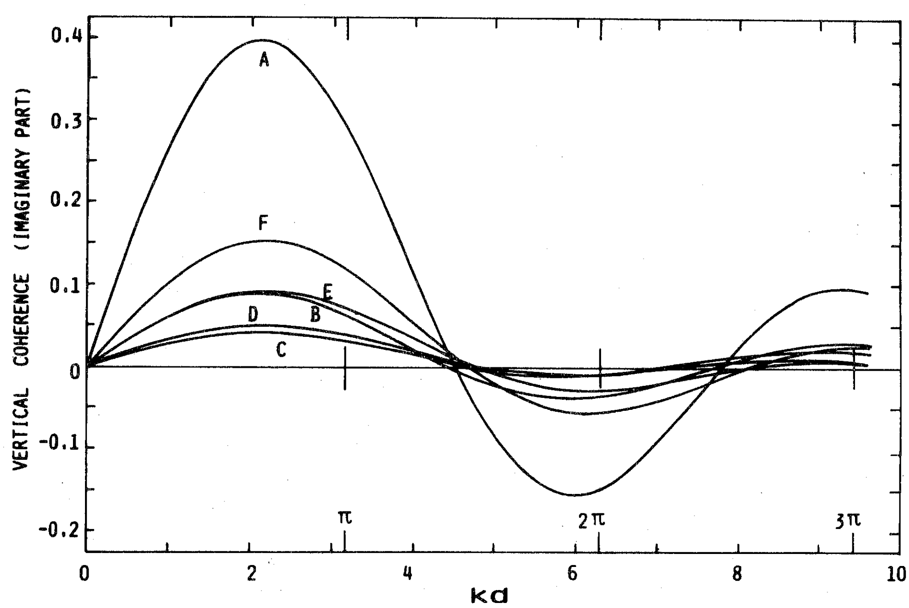

Fig. 6 Imaginary part of the noise coherence versus the normalized vertical spacing kd.

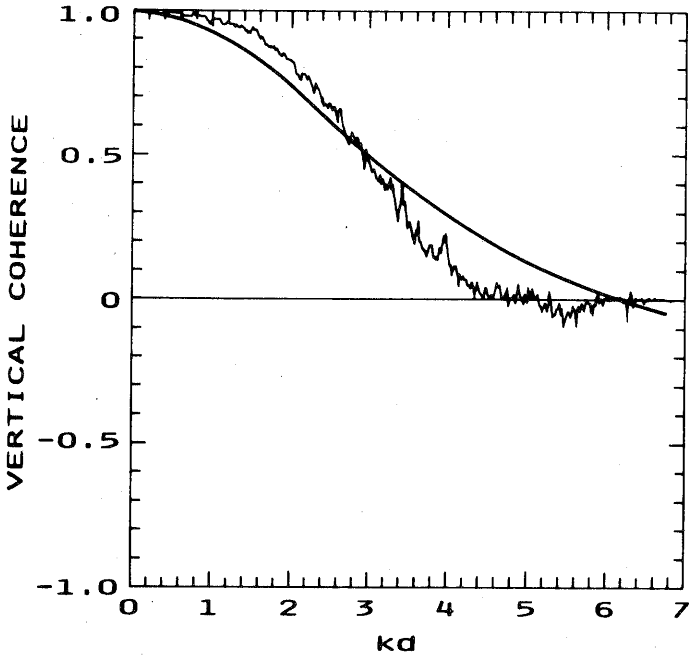

Fig. 7 *Vertical coherence of noise versus kd, both modelled (smooth line) and experimental (uneven line) collected over a sandy bank in shallow water.*

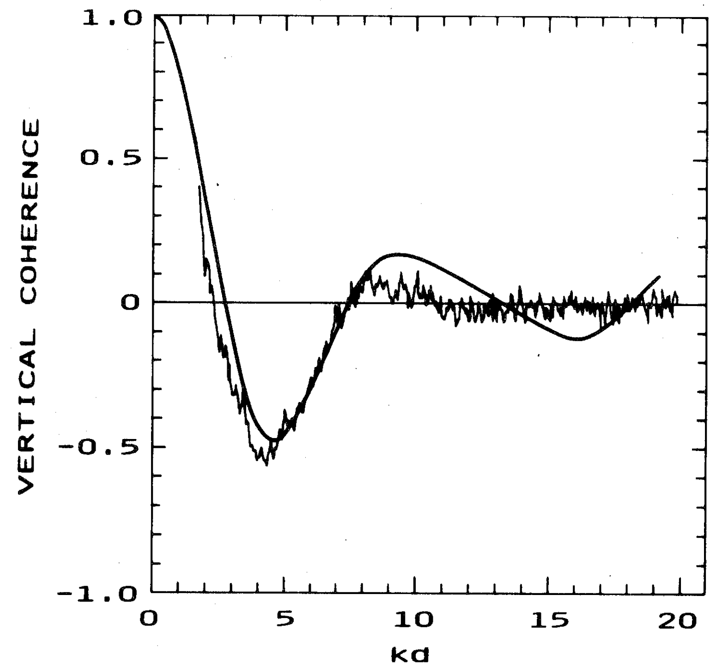

Fig. 8 *Vertical coherence of noise versus kd, both modelled (smooth line) and experimental (uneven line) collected over glacial till in shallow water.*

SURFACE-GENERATED NOISE IN SHALLOW WATER: A MODEL

DREA has collected noise coherence data with a vertical array from several shallow water sites having different seabed types. By analysing data at fixed hydrophone spacing over a range of frequencies, noise coherence was measured over a range of kd values. Two examples of these data are shown in Figures 7 and 8; the first is from an area with a sandy bank and the second is from an area with a harder bottom that we think is gravel or glacial till. As the coherence data from the two sites are quite different in character, it is tempting to interpret them with the aid of our simple model. The "best fit" modelled coherence curves are shown as solid lines in the figures. The model inputs for Figure 7 were very close to seabed B (fine sand), while those for Figure 8 were between seabed D (gravel) and seabed E (glacial till). Although the agreements between experiment and model are not perfect, we should be encouraged that such a simple model is capable of reproducing the principal features of the data.

PROPOSED REFINEMENTS OF THE MODEL

As the theory stands, there is no reason why the seabed reflectivity could not depend explicitly upon frequency, as would be the case for a multi-layered seabed model. In this event, the coherence would be a function of the separate variables k and d, and a comparison of the model and the data shown would not be so straightforward. Another frequency-dependent effect is acoustic absorption in the seawater. As a side effect, this would introduce a dependence upon receiver depth and water depth. Allowing a depth-dependent sound speed profile alters the noise directionality by introducing refraction effects: the emission angle at the surface and the grazing angle at the seabed is different from the ray angle at the receiver. The effects of absorption and refraction in the seawater will be included in a refined version of this noise model.

CONCLUDING REMARKS

A model of surface-generated ambient noise in shallow water has been presented, based on simple elements governing the contributing factors of surface source directivity, acoustic propagation in the ocean, and acoustic reflection at the seabed. The model provides a direct functional relation between noise directionality and a combination of source directivity and seabed reflectivity. Consideration of six typical seabed types shows that the modelled noise directionality is quite sensitive to the acoustic properties of the seabed. The modelled vertical noise coherence is also sensitive to seabed type and experimental coherence data have provided encouraging support for the model. Lack of perfect agreement between model and experiment has suggested that some refinements are necessary.

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ELECTRIC, MAGNETIC AND ACOUSTIC NOISE GENERATED UNDERWATER DURING OFFSHORE PILING OPERATIONS

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INTRODUCTION

There is an offshore requirement to transmit data underwater without cables over short ranges on offshore platforms, during the installation phase when piles are driven into the sea-bed round the legs of the structure. Very large impulsive forces are involved in the underwater piling operation and the associated pressure waves and structural vibrations contain frequency components over a wide range. Strain and acceleration measurements made on the pile being driven actually contain information that relates to the bearing strength of the foundation [1,2], and these measurements are used to monitor the progress of the pile.

In order to transmit signals by some means in such a difficult environment requires a knowledge of generated noise levels that could cause interference. Electric field, magnetic field, acoustic and optical transmission systems are all possible contenders for the wire-less link and are the subject of a continuing study by the author. It is evident that quantitative data on the amplitude and frequency spectrum of noise generated by piling and other offshore activities is a pre-requisite in the design of a suitable transmitter-receiver link. No such data could be found in the literature and consequently a series of experiments was planned to obtain the raw information required. The first measurements were carried out in 1985, during the piling operation on a North Sea platform, the experiment being sponsored by FUGRO B.V. Geotechnical Engineers, of Leidschendam, Holland. The electronic equipment used was built at Heriot-Watt University to the author's specification and measurements were made to his requirements.

NOISE GENERATED DURING OFFSHORE PILING

It was decided to make wide-band measurements of electric field, magnetic field, and acoustic signal levels, synchronised with the hammer blow of the piling equipment. While it is obvious that very substantial acoustic noise levels are generated, the sources of E-M wave signals from a steel structure are not so evident. No major sources of industrial electrical noise are present on the structure during piling but the steel piles and other structural items carry residual magnetisation which, when moved rapidly, is expected to generate substantial time-changing E-M fields. This is in addition to changes in the local magnetic field due to the movement of material of high relative permeability.

This is very much an unknown area experimentally, as regards systematically recorded data, but an estimate of a possible field can be made. If the earth's magnetic field is taken as 80 AT/m (1 oersted), then the remanent flux density in a sample of steel could rise to 80 x μ_0 x μ_r Wb/m^2(T),

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