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DETERMINATION OF SEDIMENT SOUND SPEED FROM THE VERTICAL DIRECTIONALITY OF AMBIENT NOISE IN THE WATER COLUMN

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INTRODUCTION

The conventional in situ methods of determining the speed of sound in bottom sediments use an energetic sound source such as a sparker, boomer or airgun, and a receiver array of hydrophones towed by a ship located some distance away. Sound travelling through the bottom arrives at the receiver, to provide a measurement of the sound speed in the bottom. Alternatively, bottom samples may be taken and their acoustic properties determined in the laboratory. Both techniques are slow and very costly; so a large area survey is a formidable undertaking.

In this paper a relatively inexpensive technique is described for surveying rapidly large areas of the ocean bottom. The method is based on in situ acoustic measurements, but no acoustic sources are involved nor are any surface ships required. Instead, the directional properties of the surface-generated acoustic ambient noise field (which is always present in the ocean) is exploited using vertical line array (VLA) sonobuoy receivers deployed from an aircraft. RF signals containing the ambient noise data in the frequency range 0.1-1 kHz are transmitted back to the same aircraft, where they are recorded and processed.

The new technique is appropriate to continental shelf regions, where the water depth is less than 200m (shallow water). In such channels the ambient noise has a modal character, due to the multiple reflections from the surface and bottom. Because of the bottom interactions, the signals from the VLA sonobuoys, representing a spatial sampling of the ambient noise field, contain enough information to extract the critical grazing angle of the bottom interface and hence the compressional sound speed in the bottom sediment (assuming that the sound speed in the water column is known from XBT data).

In deeper water fewer bottom interactions occur and the method cannot be expected to work. However, it is in exactly those regions where the technique does work that the bottom properties are often required; for example, in connection with the offshore hydrocarbon industry, and of course in many shallow water acoustics applications, where the properties of the bottom significantly affect the nature of the sound field in the overlying ocean channel.

The two main advantages of the new method are speed, conferred by the high mobility of the aircraft, and relatively low cost. A limitation of the technique is that it gives only the sound speed in the sediment just below the bottom interface and not the sound speed profile down through the sediment. Thus, it is perhaps best regarded as a tool which is suitable for making preliminary explorations aimed at identifying potentially interesting regions, which could then be further investigated using traditional seismic refraction or core sampling methods.

Ambient noise in shallow water

A theoretical model of wind-generated ambient noise in a shallow water channel of the Pekeris type[1] was developed recently by Buckingham[2]. The Pekeris channel consists of an isovelocity water column with sound speed c_1, overlying a fast sediment with uniform sound speed $c_2 > c_1$ (Fig 1). Thus, the boundary between the water column and the sediment shows a critical grazing angle $\alpha_c = \cos^{-1}(c_1/c_2)$. In the noise model[2], the noise sources are represented by a layer of impulsive monopoles lying just below the sea surface.

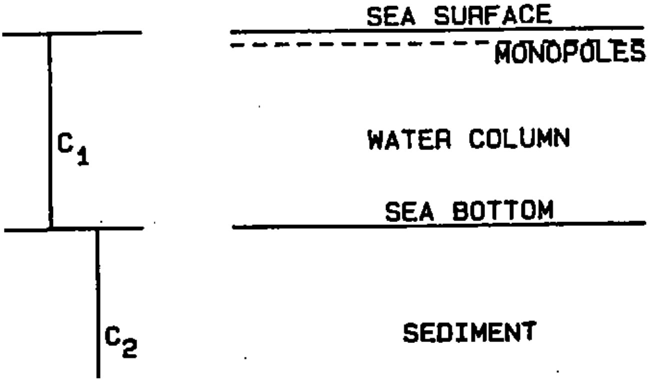


Fig 1 Pekeris channel with monopoles representing noise sources randomly located in a layer just below the sea surface

The spatial coherence of the noise field at any two points in the channel is derived from a statistical argument based on the Pekeris solution for acoustic propagation in the waveguide. By making the appropriate transformation, the spatial coherence can be expressed as a directional density function. Because of the assumed (statistical) symmetry in the distribution of the noise sources, the directional density function shows no azimuthal variation, but depends only on the vertical angle, θ.

$$F(\theta) = \left.\begin{matrix} (a_0 + a_1) & \left(\frac{\pi}{2} - \alpha_c\right) < \theta < \frac{\pi}{2} + \alpha_c \\ a_0 & \text{otherwise} \end{matrix}\right\} , \quad (1)$$

where a_0 and a_1 are constants (independent of θ), and θ is measured down from the upward vertical. Equation (1) states that the noise is a superposition of an isotropic component (a_0) and a predominantly horizontal component (a_1) extending out to an angle α_c either side of the horizontal. The latter component represents noise incident at the receiver from many distant sources and the isotropic component represents the contributions from nearby, overhead sources. The directional density function must satisfy the normalisation condition[2]

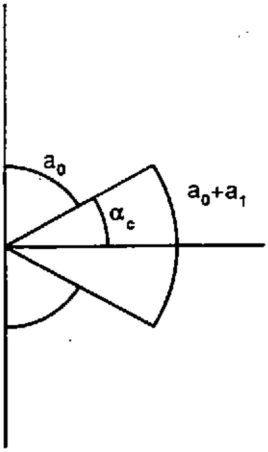


Fig 2 Theoretical directional density function of the ambient noise in shallow water

$$\frac{1}{2}\int_0^{\pi} F(\theta) \sin\theta \, d\theta = 1 , \quad (2)$$

where leads to the constraint that

$$a_0 + a_1 \sin\alpha_c = 1 . \quad (3)$$

If two point sensors are arranged vertically in the noise field, the spatial coherence function between the noise fluctuations at the sensors is

$$\Gamma(\bar{\omega}) = \frac{1}{2}\int_0^{\pi} F(\theta) \exp(j\bar{\omega}\cos\theta) \sin\theta \, d\theta , \quad (4)$$

where

$$\bar{\omega} = \omega\ell/c_1 . \quad (5)$$

In equation (5), ω is the angular frequency and ℓ is the separation of the two sensors. On substituting equation (1) into equation (4), and using the result in equation (3), we find that

$$\Gamma(\bar{\omega}) = a_0 \frac{\sin \bar{\omega}}{\bar{\omega}} + (1 - a_0) \frac{\sin(\bar{\omega} \sin \alpha_c)}{\bar{\omega} \sin \alpha_c} . \qquad (6)$$

This expression involves just two unknown parameters, a_0 and α_c. These can be determined by making measurements of $\Gamma(\bar{\omega})$ between vertically disposed pairs of hydrophones in the water column. Equation (6) thus provides a basis for extracting the critical grazing angle α_c, and hence the sound speed in the sediment, c_2, from the directionality of the ambient noise in the channel. The technique is described below.

Experimental procedure

To measure the vertical coherence of the ambient noise, we have used VLA research sonobuoys, as illustrated in Fig 3. These are receive-only buoys, designed as general tools for investigating shallow-water acoustic fields and are, in fact, far more sophisticated (and expensive) than is actually necessary for the ambient noise measurement. The hydrophone array has an aperture of 34 metres and consists of eleven sensors in total arranged to form four nested arrays each containing five sensors. These sub-arrays each cover an octave band of frequency, and the four octaves span the range 62.5 Hz to 1 kHz. The signals from the sensors are time-division multiplexed in the buoys and transmitted to the aircraft over an RF link. On being de-multiplexed, the eleven sensor signals are recovered and subsequently analyzed. The vertical alignment of the array is maintained within 2° by a drogue and a weight on the lower end of the cable; and a compliant section decouples the array from the motion of the upper flotation unit. This design ensures a stable configuration of sensors, and also minimises flow noise in the system, since the drogue, and hence the array, drifts with the water column. A battery of lithium cells gives the buoys a lifetime in excess of eight hours.

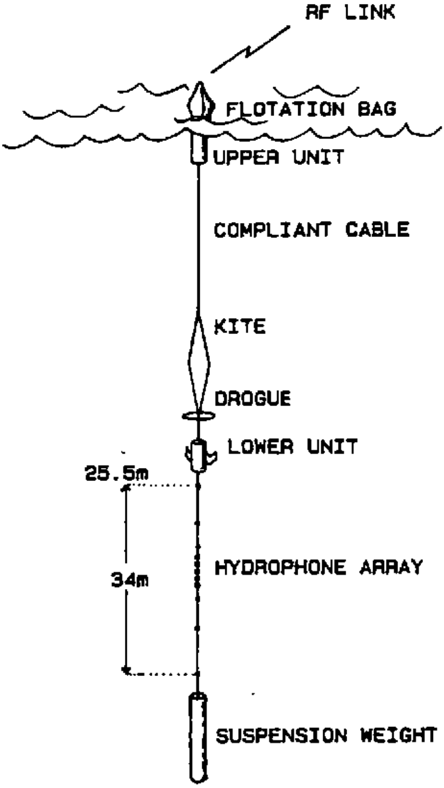


Fig 3 Schematic of VLA sonobuoy

A system dedicated to the ambient noise measurement could be made much simpler, with just a pair of vertically separated hydrophones for sensing the ambient noise field. These could be incorporated into a sonobuoy, or a data-logging buoy[3] drifting freely around the ocean along a recorded track. The remote sensing capability of either system would mean that large areas of the ocean could be covered quickly and efficiently, at relatively low cost.

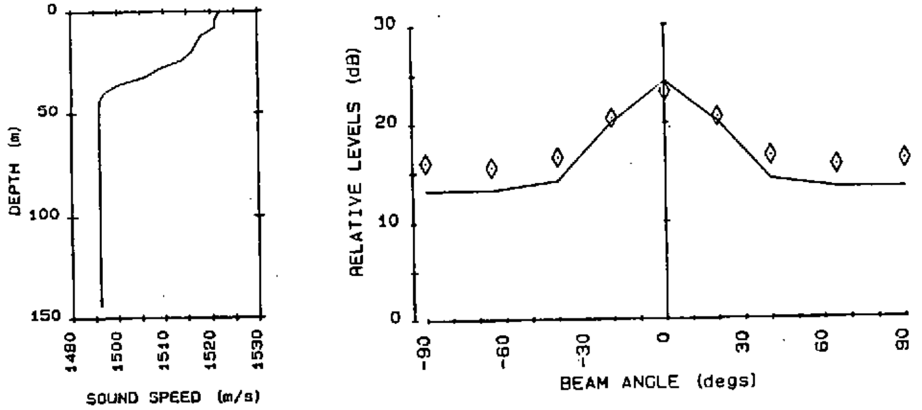
Measurements of the ambient noise using VLA sonobuoys were made at half a dozen sites around the UK coast in areas where the water depth is between 100 m and 200 m. The trials sites have a variety of propagation conditions and all are flat or very slowly shelving. The positions of the sites and other available data are listed in Table 1.

Table 1. Environmental data for the six sites around the UK coast where the VLA ambient noise trials were conducted

							obtained using noise technique	
Site	Position	Water depth (m)	Bottom type	Transmission loss	Sea state	Wind speed m/s	Critical grazing angle α_c	Sound speed c_2, m/s
Celtic Sea South	49°10'N, 08°42'W	148	Very fine sand	Low-loss	1	1.5	26.2°	1670
Celtic Sea North	51°05'N, 08°12'W	104	Chalk	High-loss	1	1.5-5	42.8°	2044
Hebrides South	56°29'N, 08°10'W	140	Silt, broken shells	High-loss	3-4	5	29.4°	1722
Hebrides North	58°32'N. 06°55'W	178	Sand, gravel, pebbles, broken shells	Low-loss	2-3	3.7-5	23.4°	1634
North sea	58°06'N, 00°30'W	124	Sand, silt	Low-loss	1-2	3-5	23.0°	1630
South West approaches	49°20'N, 06°27'W	120	Rock, sand, shells	Low-loss	3	2.5-5	12.0°	1534

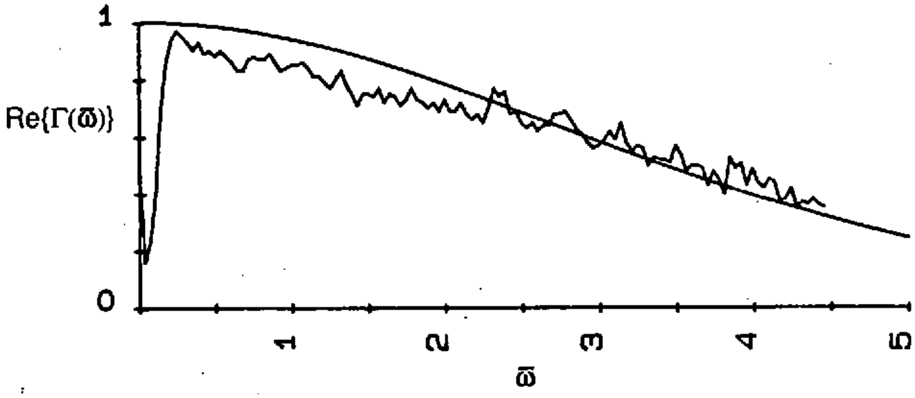
At each site a VLA sonobuoy was deployed and the ambient noise data from all the hydrophones in the array were recorded. These data were then beamformed at 800 Hz to provide a direct measure of the directional density function of the noise field. The normalized cross-spectral density (or coherence function) was also formed for each pair of hydrophones in the array and plotted as a function of normalized frequency $\bar{\omega} = \omega \ell / c_1$, where ℓ is the separation of the two sensors and c_1 is the sound speed in the water column above the bottom interface. The frequency resolution in the coherence function plots is 2 Hz.

An example of the results obtained is shown in Fig 4. These data were gathered at the Celtic Sea South site. Fig 4a shows the sound speed profile in the channel, Fig 4b the directional density function of the noise at 800 Hz and Fig 4c the coherence function of the noise from two sensors at a mean depth of 42 m and separated by a distance $\ell = 1$ m. The directional density function plot in Fig 4b shows noise power per Hz per unit solid angle as a function of beam angle. A peak in the noise around the horizontal appears prominently,



(b) measured noise directional density function
◇Beamformer data,—coherence plot data

(a) sound speed profile



(c) coherence function plotted against $\bar{\omega}$

Fig 4 Celtic Sea South site

superimposed upon an isotropic noise component. This is consistent with Fig 2 and the argument in the preceding section. Extracting the critical grazing angle from Fig 4b, however, is not easy because of the considerable smoothing introduced by the relatively broad beams of the array. The coherence function data in Fig 4c are in a much more suitable form for extracting α_c, by comparison with the theoretical expression in equation (6).

Curve fitting

We wish to 'fit' equation (6) to experimental data of the sort shown in Fig 4c, in order to determine the two unknown parameters a_0 and sin α_0. A least-squares curve fitting procedure is not appropriate because of the form of equation (6), so an alternative must be sought. A satisfactory method is described below.

To begin, values of the measured coherence function Γ (which is real in our case, since the noise field is symmetrical about the horizontal) are taken at N regularly spaced values of $\bar{\omega}$. If the n^{th} value of Γ is $\Gamma(n\bar{\omega}_0)$, taken at $\bar{\omega} = n\bar{\omega}_0$, then from equation (6)

$$\Gamma(n\bar{\omega}_0) = a_0 \frac{\sin n\bar{\omega}_0}{n\bar{\omega}_0} + (1 - a_0) \frac{\sin(n\bar{\omega}_0 \sin \alpha_c)}{n\bar{\omega}_0 \sin \alpha_c} . \qquad (7)$$

Adding all N values of $\Gamma(n\bar{\omega}_0)$ gives

$$S_N \equiv \sum_{n=1}^{N} \Gamma(n\bar{\omega}_0) = \frac{a_0}{\omega_0} \sum_{n=1}^{N} \frac{\sin n\bar{\omega}_0}{n} + \frac{(1 - a_0)}{\bar{\omega}_0 \sin \alpha_c} \sum_{n=1}^{N} \frac{\sin(n\bar{\omega}_0 \sin \alpha_c)}{n} . \qquad (8)$$

Now, the summations here converge very rapidly, and provided N is greater than six or so it can be safely replaced by infinity. But the function $\frac{\sin(2\pi nx)}{n}$ summed from $n = 1$ to $n = \infty$ is known[4] to be the first Bernoulli polynomial, $B_1(x)$:

$$B_1(x) = -\frac{1}{\pi} \sum_{n=1}^{\infty} \frac{\sin(2\pi nx)}{n} = (x - \tfrac{1}{2}) . \qquad (9)$$

Thus, we have from equation (8),

$$S_N \approx -\frac{\pi}{2}\left[\frac{a_0}{\bar{\omega}_0}\left(\frac{\bar{\omega}_0}{\pi} - 1\right) + \frac{(1 - a_0)}{\bar{\omega}_0 \sin \alpha_c}\left(\frac{\bar{\omega}_0 \sin \alpha_c}{\pi} - 1\right)\right] , \qquad (10)$$

which can be rearranged to give

$$\beta = a_0\left\{1 + \frac{(1 - a_0)}{a_0 \sin \alpha_c}\right\} , \qquad (11)$$

where $$\beta = (2S_N + 1)\frac{\bar{\omega}_0}{\pi} . \qquad (12)$$

is known from the experimental data.

As a second condition, we take the measured value of Γ at $\bar{\omega} = \pi$ (corresponding to half-wavelength spacing):

$$\Gamma(\pi) = \frac{(1 - a_0)}{\pi \sin \alpha_c}\sin(\pi \sin \alpha_c) . \qquad (13)$$

The last expression here is obtained by eliminating a_0 using equation (11). If we put

$$\gamma = \frac{\pi\ \Gamma(\pi)}{(\beta - 1)} , \qquad (14)$$

which is also known from the experimental data, then from equation (13)

$$\sin(\pi \sin \alpha_c) - \gamma(1 - \sin \alpha_c) = 0 . \qquad (15)$$

This equation can be solved numerically for $\sin \alpha_c$ using Newton's method, and then a_0 is determined from equation (11):

$$a_0 = \frac{(\beta \sin \alpha_c - 1)}{(\sin \alpha_c - 1)} . \qquad (16)$$

Thus, the two unknowns α_c and a_0 can be evaluated from the data, as required.

Results and conclusions

As well as the experimental coherence function data for the Celtic Sea South site, Fig 4c also shows equation (6) fitted to the data using the procedure outlined above. The values of the two unknown parameters found for this case are $a_0 = 0.22$ and $\alpha_c = 26.2°$ (corresponding to a sediment sound speed $c_2 = 1670$ m/s). An independent measure of α_c obtained from a careful investigation of the bottom properties at this site[5], gives a value of 28° (c_2 = 1699 m/s), representing very close agreement with the ambient noise result.

The values of a_0 and α_c deduced from the coherence function data can be used to estimate the directional density function of the noise as seen by the array. This is achieved by convoluting the beam pattern of the array with the directional density function, $F(\theta)$, given by equations (1) and (3). The result is plotted for comparison with the measured directional density function in Fig 4b. A satisfactory fit is obtained, which is further evidence that the curve fitting technique gives reasonable estimates for a_0 and α_c.

The values of α_c and c_2 determined using the ambient noise method are listed in Table 1 for all six sites visited. Chapman and Ellis[5] give $\alpha_c = 51°$ for the Celtic Sea North site, which is 8° higher than the value obtained by the noise field method. This site is known to have a chalk bottom which strongly supports shear, and this may be responsible for the discrepancy. No independent data are available for the remaining four sites, although the value of $c_2 = 1634$ m/s obtained for the North Sea site is consistent with the value expected of a sand/silt sediment[6].

In conclusion, the remote sensing technique described in this paper provides a quick, inexpensive means for sampling the compressional sound speed c_2 in the sediment underlying shallow ocean channels. It relies on the vertical directionality of the ambient noise in the water column, and this appears to be a stable property of the noise field, unlike the absolute level of the noise which is highly variable. We have found that the method works satisfactorily and consistently in conditions ranging from sea state 1 to sea state 6, the high sea state limit being determined largely by washover of the sonobuoy upper unit causing data drop-out. The robustness of the new ambient noise method implies reliability, which is a desirable feature of any large-scale surveying technique. Moreover, the extraction of the critical grazing angle by curve fitting to the coherence data could be easily automated, which is a further attractive feature of the technique.

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