DERA

Institute of **Acoustics**

Volume 23 Pt 2 2001

Acoustical Oceanography

Southampton Oceanography Centre
9 – 12 April 2001

Proceedings of the Institute of Acoustics Volume 23 Part 2 2001

Acoustical Oceanography

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Proceedings of the Institute of Acoustics Conference on Acoustical Oceanography, 9-12 April 2001, Southampton Oceanography Centre

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ISBN: 1 901 656 34 9

Printed by Bath University Press, Bath, UK.

Historical notes

Cover photo: Porthcurno beach at Poldhu on the Lizzard Peninsular in Cornwall, England.
In 1870 a chain of telegraph cables linking Britain with India was completed. Porthcurno was chosen as the landing point for the British end of this cable link. The company that laid the cable into Porthcurno was the Falmouth Gibraltar and Malta Telegraph Company, founded by John Pender in 1869. On December 15, 1902, Guglielmo Marconi transmitted the first radio (wireless telegraph) message across the Atlantic Ocean, from Table Head in Glace Bay, Nova Scotia, to Poldhu, Cornwall, England. In 1929 the Falmouth Gibraltar and Malta Telegraph company began to operate world radio communications through a merger with Marconi's radio network and it was renamed 'Imperial and International Communications'. The name changed once again in 1934 to 'Cable & Wireless'. At its height, Porthcurno was the world's largest cable station, with 14 telegraph cables in operation. After exactly a century as a working cable station, in 1970 the last telegraph circuit closed at Porthcurno, ending the village's life as a telegraph station. However, Cable & Wireless continued to expand its training facilities with students attending from all over the world, until in 1993 the Cable & Wireless college at Porthcurno closed. (Photograph *© 2000, J. W. L. Clarke, Reproduced with permission*).

HMS Warrior During her heyday *HMS Warrior* was the most formidable warship the world had ever seen. Built in 1860, she was the world's first iron-hulled armoured battleship, and was larger, faster and more heavily armed than any warship afloat. Nick-named "the black snake", at 418 ft she was 25% longer than any previous naval warship. Overnight, she made every other warship obsolete. Constructed of wrought iron, she was powered by both steam and sail, and required a crew of 705 officers and men. Skilled muscle power was needed to fire her 40 guns, spread her 15 sails, steam her ten boilers and turn capstans to raise the 5 ton anchors. The 36 ton propeller was twin blade, 24 ft from blade tip to blade tip. Six hundred men were required to raise the propeller and banjo unit out of the water. This could be done to reduce drag or change a blade (a spare was always carried). It took just over 26 months from the start of building to *Warrior* being commissioned. She was probably responsible for a decade of uneasy peace with France.

Foreword

This volume comprises the papers presented at the Institute of Acoustics Underwater Acoustics Group Conference on "Acoustical Oceanography", held at the Southampton Oceanography Centre on 2-9 April 2001. Whilst there has been a substantial series of conferences organised by the *IOA UWG* (see *page 424*), this is the first on this topic, and at this venue.

The growth of Acoustical Oceanography in recent years has provided a fascinating diversity of opportunity. From ocean scale acoustic tomography exploiting frequencies of tens of Hertz, to the use of the MHz regime to measure zooplankton and suspended sediment, the spatial and temporal scales cover orders of magnitude. For the acoustician this scale is illustrated by the search to understand the origin of sounds, which can range from the ocean scale to the sub-metre scale critical to surf zone mechanisms. For the oceanographer, acoustic techniques have provided tools which can not only obtain datasets more quickly than existing methods, but offer the opportunities of enhanced resolution. This might, for example, be used for non-intrusive classification of zooplankton or sediment types. Most importantly, hitherto unobtainable ocean parameters can be quantified using data gathered using acoustic systems. In such cases, calibration must be based on the acoustics.

Acoustical Oceanography is therefore truly interdisciplinary. Whilst many acoustical oceanographers might be reluctant to restrict themselves to the label of a single discipline, to our knowledge we have amongst the authors of the papers in this volume those who would call themselves, primarily, biologists, geologists, chemists or marine archaeologists. In addition to these, and to the acousticians and the oceanographers, there is a significant representation from the Underwater Acoustics community, where expertise developed for defence purposes is evolving into acoustical oceanographic projects.

This volume contains 53 papers, distributed through 10 topical sections, plus one devoted to the Opening Address. The volume includes papers associated with the Roy Griffiths Memorial Lecture and the A. B. Wood Medal Lecture, 6 invited papers, and 5 student papers. The latter will be competitively assessed, in conjunction with the associated poster and the student's oral presentation, for a prize. This is to be presented at the Conference dinner on *HMS Warrior* (see the preceding 'Historical notes').

We are extremely grateful to the reviewers. Around two thousand suggestions were made for the improvement of the papers contained within this volume. We are grateful to the authors for taking these into account in amending their works. There were originally 80 submissions for inclusion in this volume. All the conference presentations have an associated paper in the Proceedings (those papers selected for poster presentation were asked to provide, in addition, a short oral presentation).

The production of this volume has been sponsored by the Defence Evaluation and Research Agency, and for that we are indebted. The Office of Naval Research provided assistance for the travel costs of some delegates. We would also like to thank Roy Bratby and Linda Canty of the *IOA* for the administration of the budget, registration and publicity. We are grateful to the other members of the *IOA UWG* for helpful suggestions. Associated with the conference is a Manufacturer's Exhibition, and the committee is grateful to Brian Phillips (Marine Acoustics Ltd.) and Martyn Hill (University of Southampton) for assistance in its organisation.

TGL is grateful to the Institute of Sound and Vibration Research for providing him with support from Sue Brindle and Gill Jewell, who maintained the databases and web page. The provision of time in which to work on this project was made possible through the Royal Society Leverhulme Trust Senior Research Fellowship Scheme, the support of which he gratefully acknowledges.

T. G. Leighton (Chairman)

Conference Organising committee: G. J. Heald, H. D. Griffiths, G. Griffiths

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1. Introduction:
Acoustical oceanography in perspective

Acoustical oceanography in perspective: new physics for a simple inversion

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Abstract

Following a brief introduction to the modern techniques of acoustical oceanography, an example is described in which a second-order statistical property of ambient noise in shallow water is inverted to yield the geo-acoustic parameters of the sediment. The inversion scheme exploits the correlations that are known to exist between the sediment parameters of interest. These parameters include the compressional and shear wave speeds, the density, bulk modulus and porosity.

1. Introduction

Acoustical oceanography embraces all the techniques that employ sound as a means of gathering information about the ocean environment. These techniques involve some form of inversion procedure: a sound field is detected with one or more sensors and inverted to yield the required information. For instance, the location of a sound source may be determined by inverting the acoustic arrivals on a vertical line array of hydrophones. More generally, the output of an inversion may be the estimated values of the parameters which characterize a physical or biological process, or it may take the form of a visual image of an object or a process. In this article, the emphasis is on physical phenomena; and these may be found anywhere from the sea surface, down through the water column to the seabed, and even in the sediment beneath the seafloor.

At the sea surface, wave-breaking, a highly energetic, wind-driven process, influences the acoustic properties of the ocean primarily by transferring air across the atmosphere-ocean boundary [1]. The bubble cloud formed by a breaking wave is advected downwards by the turbulence [2] that is a by-product of the breaking event. At the penetration depth, where the turbulent diffusion is balanced by the buoyancy, the bubbles cease their downward motion and begin their return to the surface. In the channel of entrained air between the surface and the penetration depth, the sound speed is significantly less than in non-aerated seawater. The properties of this near-surface bubbly channel, including the void fraction profile [3], the bubble size distribution [4], the penetration depth, and the velocity structure of the embedded turbulence, as well as the statistics of the wave breaking events themselves [5, 6], have all been investigated using acoustic inversion techniques.

In the mid-regions of the water column, internal waves may be present along with smaller-scale turbulence [7] and thermal microstructure. Mesoscale phenomena, for instance the eddies that spin off open-ocean currents such as the Gulf Stream, also influence the dynamics and acoustic properties [8] of the mid-depth regions. The temporal and spatial properties of these phenomena may be established from ocean acoustic tomography [9], and the velocity structure extracted with Doppler sonar. On a global scale, acoustic thermometry, involving trans-oceanic, low-frequency (• 70 Hz) acoustic propagation through the deep sound channel, yields estimates of ocean temperature, which may in turn provide an indication of global warming over an extended observation period [10].

Beneath the water column, the seabed supports the propagation of sound (compressional) waves and shear (transverse) waves [11]. Both are useful tools for imaging the stratification and larger-scale geological structures down to depths of several kilometers below the seawater-sediment interface. The roughness of the seabed itself can also be imaged, using a side-scan sonar located in the water column. Naturally, the spatial resolution in these side-scan images improves at higher frequencies, although range is then sacrificed due to greater attenuation. At an operating frequency of 450 kHz, a side-scan sonar is capable of revealing very detailed features of the seabed, whilst lower frequencies may be more suitable for locating large objects on the seafloor such as shipwrecks and other items of archaeological interest.

Many of the techniques of acoustical oceanography rely on a dedicated sound source to transmit a pulse of sound which ensonifies the ocean. In these active systems, the echo from the target, say a bubble cloud [12] beneath the sea surface or a geological feature of the seabed, contains the information of interest. Passive techniques differ in that they exploit the sound radiated by the target itself, for instance, an individual bubble which rings for a few tens of milliseconds immediately after formation [13]. A third type of technique, which is neither active nor passive, takes advantage of the ambient noise in the ocean as a source of acoustic energy. Some of this naturally produced sound, from breaking waves and a variety of biological sources, is incident on the target, which modulates the scattered energy with its characteristic signature. This "fingerprint" information about the target, which may be almost any object in the ocean with an acoustic impedance differing from that of seawater, can be extracted from the scattered signal. It may be used, for example, to create images [14] of the target space in much the same way that conventional photographic images are formed of objects illuminated by natural ambient light (daylight) in the atmosphere.

The parameter estimation techniques of acoustical oceanography take a variety of forms. One that has achieved considerable success is Matched Field Processing (MFP) [15], which has application in source location and environmental parameter estimation. In essence, MFP employs an acoustic propagation model to predict the acoustic field at a receiver array and compares the predicted arrivals with the observed field at the sensors. This process is repeated for many different sets of the input parameters, representing, for example, the properties of the bottom, and the set giving the best fit to the observations is taken to be representative of the channel. It is usually implicit in MFP codes that the members of the set of parameters being sought are uncorrelated, and few if any constraints are put upon the range of values that a given parameter may reasonably take.

Currently, determining bottom properties is a hot topic amongst acoustical oceanographers, largely because it presents a serious challenge to their acoustic inversion schemes. The wave properties of interest are the speed and the attenuation of the compressional and shear waves. In addition, some attempt is usually made to recover the mechanical properties, notably the porosity, density, and mean grain size, of the sediment. This parameter-estimation problem is especially difficult if, as in most MFP codes, no prior information about the relationships between the parameters is incorporated into the inversion procedure.

Interestingly enough, such prior information, although often not utilized, is available. Many bottom-data sets published over the past thirty years show that the wave and mechanical parameters of the sediment are not independent but are highly correlated. Hamilton [16] and Richardson [17] have represented the correlations empirically by fitting regression curves to the data. More recently, the correlations have been investigated through a theoretical model of wave propagation in granular materials, including marine sediments, developed by Buckingham [18]. The model is based on the physics of inter-granular interactions, and it predicts simple relationships between the bottom parameters which match the observed correlations with some precision.

With a theoretical knowledge of the correlations, it is possible to devise acoustic inversion schemes that are somewhat simpler than the conventional approaches for determining bottom geo-acoustic parameters. The remainder of this article addresses one such inversion technique [19], which exploits naturally occurring sound in the ocean. Introduced in its original form over a decade ago, this ambient noise inversion methodology has recently been significantly enhanced by incorporating the theoretical correlations between bottom parameters into the inversion procedure. The result is an inversion tool which returns a wealth of information about the seabed with a minimum of investment in wet-end hardware and data-inversion software.

2. Shallow-water ambient noise directionality

One of the principal sources of ambient noise in shallow water, along with shipping, local boat traffic, and biological sources such as snapping shrimp [20, 21], is wave-breaking on the sea surface. Away from the immediate vicinity of the coast, biological sources and local surface traffic are often negligible and wave noise from randomly occurring, Poisson distributed breaking events over the sea surface is the predominate source of natural sound in the ocean. The bandwidth of the wave-breaking noise extends from several hundred Hertz up to 20 kHz or above.

At these frequencies, the shallow water channel acts as an acoustic waveguide in which the sea surface approximates a perfectly reflecting, pressure-release boundary. The sea bottom is more complicated, usually behaving as a moderately efficient acoustic reflector with properties which depend on the geo-acoustic parameters of the sediment. It should not be surprising, then, that theoretical models [22, 23] of wave-generated noise in shallow water indicate that the angular distribution, $F(\theta,\phi)$, of the noise intensity is sensitive to the bottom type. Here, the function F, the directional density function of the noise, is a second-order statistical quantity, θ is the polar angle measured from the upward vertical, and ϕ is the azimuthal angle. The normalization of F is such that

$$\int_0^{2\pi}\int_0^{\pi} F(\theta,\phi)\sin\theta \, \mathrm{d}\theta \mathrm{d}\phi = 4\pi \quad . \tag{1}$$

With wave sources uniformly distributed, statistically, across the sea surface, and assuming an ocean and sea bed that are horizontally stratified, F is independent of ϕ and the normalization reduces to the condition

$$\tfrac{1}{2}\int_0^{\pi} F(\theta)\sin\theta \, \mathrm{d}\theta = 1 \quad . \tag{2}$$

In (2), $F(\theta)$ is independent of lateral position in the ocean, that is to say, the noise field is statistically homogeneous in the horizontal.

For the simple case of an isotropic noise field, F would take a constant value of unity, according to (2). Isotropy, however, is not usually a characteristic of ocean noise, especially in shallow water because of the proximity of the bottom. As an example of how the sea bed affects the vertical distribution of the noise, consider the idealized case of a water column of uniform depth and constant sound speed, c_1, overlying a homogeneous, fluid-like sediment with sound speed $c_2 > c_1$. This so-called fast bottom shows a critical grazing angle, α_c, for sound incident from above. An acoustic ray in the water column with a grazing angle less than α_c will be totally reflected from the bottom, whilst a ray steeper than α_c will penetrate the bottom and suffer a severe reflection loss.

Most of the noise arriving at a receiver in the water column will be generated by distant wave-breaking events at horizontal ranges greater than the water depth. The effect of the fast bottom on this propagating noise is to remove the high-angle rays, leaving the remaining energy concentrated within a vertical sector extending out to α_c either side of the horizontal. If the noise intensity within this sector is approximated as uniform, the shallow-water vertical directional density function, F_{sw}, from the normalization in (2), is

$$F_{SW}(\theta) = \begin{cases} (\sin\alpha_c)^{-1} & \text{for } \frac{\pi}{2} - \alpha_c \le \theta \le \frac{\pi}{2} + \alpha_c \\ 0 & \text{otherwise} \end{cases} . \tag{3}$$

This result is greatly over-simplified, since it neglects not only the discrete nature of normal mode propagation in the channel but also the near-vertical, or continuous, contribution to the noise from local surface sources.

Nevertheless, (3) serves well to illustrate that, in shallow water, the vertical directionality of the noise depends strongly on the acoustic properties of the bottom. From a measurement of F_{sw}, an elementary inversion of (3) yields the critical grazing angle of the bottom; and once α_c is known, it is a trivial matter to obtain the sound speed in the sediment from Snell's law:

$$c_2 = \frac{c_1}{\cos\alpha_c} , \tag{4}$$

In this expression, the sound speed, c_1, in the water column will generally be available as part of the environmental support data taken at the time of the noise measurement.

The type of inversion for the bottom sound speed represented by (4) is simple and effective. It exploits the vertical directionality of the noise, which is stable and predictable. By way of contrast, the noise level would be a poor choice for inversion because of its variability, which makes it difficult to predict with any degree of precision. Of course, the simplistic description of the noise directionality in (3) could be improved by using a more realistic formulation, but the principles of the inversion would remain the same. In fact, for practical reasons, it is preferable to abandon the directional density function altogether and exploit an alternative measure of the noise field, the spatial coherence function.

3. Noise coherence

A direct measurement of the vertical directionality of the noise requires a vertical array of hydrophones with an aperture comparable with the depth of the ocean channel. Such an array is a narrow band receiver which is costly to construct and to deploy. An alternative approach [19] employs just two hydrophones, vertically aligned and separated by about 1 m, as illustrated in Figure 1. This simple configuration of sensors will return the spatial coherence of the noise over a broad band of frequencies. The vertical coherence function, Γ_{xy}, between the noise fluctuations at sensors x and y, is a complex quantity defined as

$$\Gamma_{xy} = \frac{\overline{S_{xy}}}{\sqrt{\overline{S_{xx}}\,\overline{S_{yy}}}} , \tag{5}$$

where $\overline{S_{xy}}$ is the cross-spectral density between sensors and $\overline{S_{xx}}$, $\overline{S_{yy}}$ are the power spectra at x and y, respectively. Over most of the channel, away from the boundaries, the noise is quasi-homogeneous in the vertical, in which case these two power spectra are essentially the same.

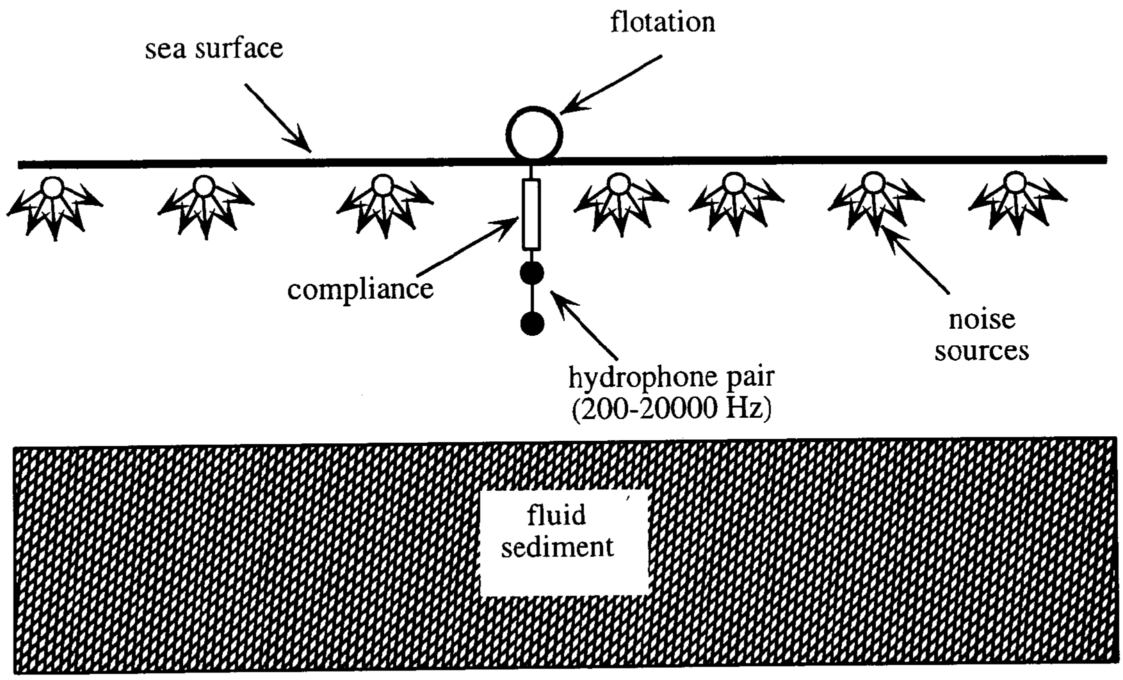


Figure 1. Schematic showing the vertically aligned pair of hydrophones used to record ambient noise.

The coherence function of spatially homogeneous noise is related to the directionality through a finite Fourier transformation [24]:

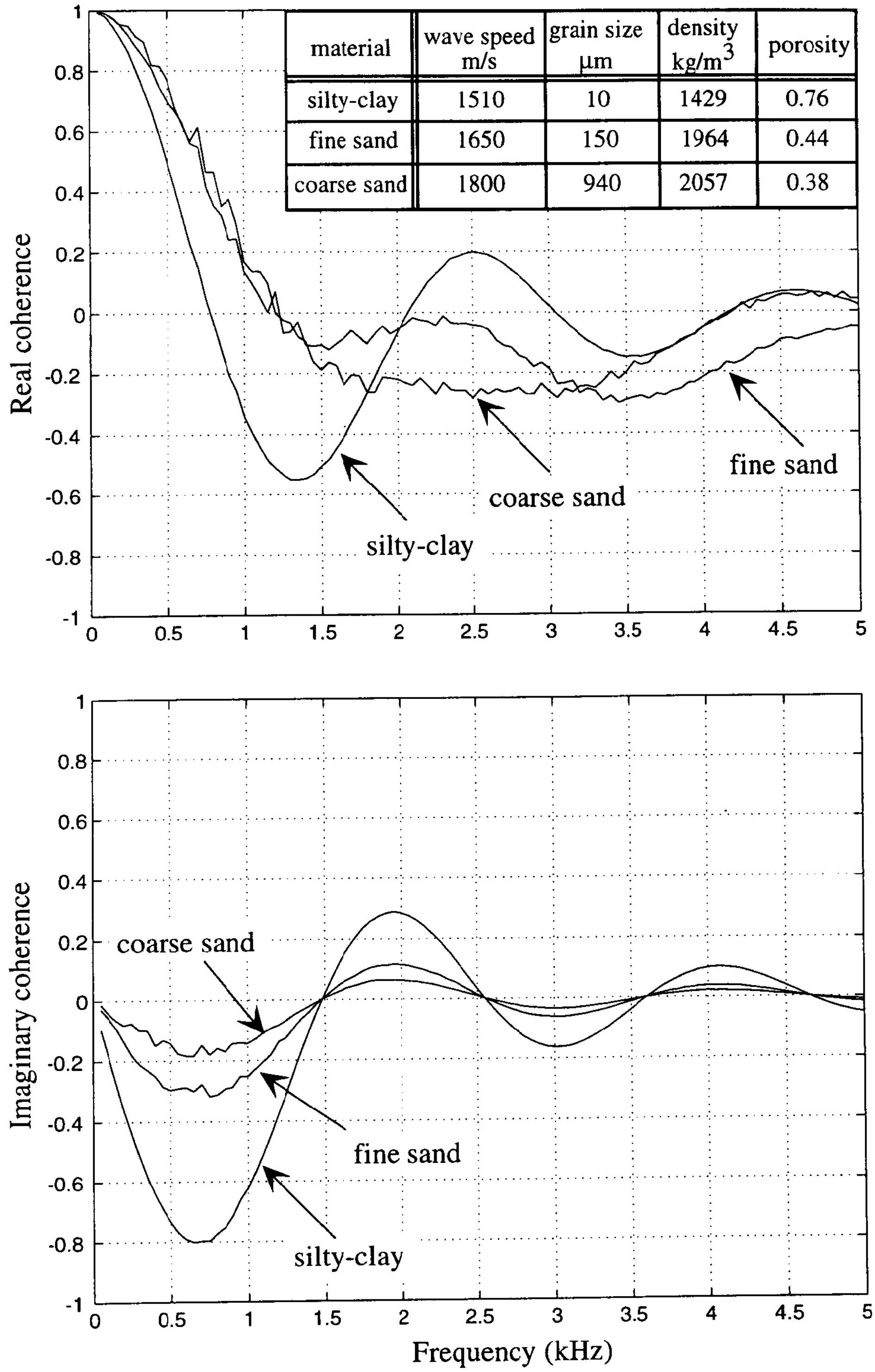
$$\Gamma_{xy} = \frac{1}{2}\int_0^{\pi} F(\theta)\exp(-jkd\cos\theta)\sin\theta \, d\theta \qquad (6)$$

where d is the separation of the sensors, $k = \omega/c_1$ is the acoustic wavenumber in the water column at angular frequency ω, and $j = \sqrt{-1}$. It is not difficult to show that the real and imaginary parts of Γ_{xy} represent, respectively, the symmetrical and asymmetrical components of $F(\theta)$ about the horizontal. Thus the coherence function of (symmetrical) isotropic noise, Γ_{iso}, is real with the well-known form

$$\Gamma_{iso} = \frac{\sin kd}{kd} \quad . \qquad (7)$$

The oscillatory nature of this expression is characteristic of noise coherence functions in general, including those representative of noise in shallow water. Since the directional density function, $F(\theta)$, of shallow-water noise depends on the geo-acoustic parameters of the bottom, the same must also be true of the corresponding spatial coherence function, Γ_{xy}. In general, the directional density function varies with frequency, in which case Γ_{xy} depends on frequency and sensor separation separately, unlike the function on the right of (7) which involves just the product kd.

Figure 2 shows the real and imaginary parts of the coherence function, as they vary with respect to frequency, for three sediment types spanning almost two decades of grain size: a silty-clay, a fine sand and a coarse sand. The curves were computed for an isovelocity Pekeris channel [25] of depth 50 m, with a sound speed in the water column of 1500 m/s. The sensor separation was set at $d = 0.73$ m. Beneath the channel, the homogeneous sediment was characterized by geo-acoustic parameters derived from Buckingham's theory of wave propagation in unconsolidated granular materials [18]. Although the theory includes a full account of transverse waves in the sediment, the effect of shear on the coherence of the noise in the water column is minor and has not been included in the curves in Figure 2.



material	wave speed m/s	grain size µm	density kg/m^3	porosity
silty-clay	1510	10	1429	0.76
fine sand	1650	150	1964	0.44
coarse sand	1800	940	2057	0.38

Figure 2. Theoretical noise coherence in the vertical for three sediment types (the properties of which are tabulated at the top of the figure).

It is obvious that the bottom has a profound effect on both the real and imaginary parts of the coherence function. Although the curves for the two sands in Figure 2 are similar, they are still easily distinguishable; and they bear little resemblance to the curves for silty-clay. Physically, the reason for the differences between the coherence curves for the sand and silty-clay bottoms concerns the sound speed in the two types of sedimentary material.

In silty-clay, the sound speed is almost the same as that in the water column, and hence the bottom is essentially transparent to much of the incident acoustic energy from distant noise sources. After multiple bottom reflections, much of this sound is lost to the water column and never reaches the receiver. Most of the noise at the array arrives directly from overhead sources and propagates near-vertically downward rather than horizontally. This gives rise to a highly asymmetrical noise field, consistent with the large oscillations in the imaginary part of the coherence function for silty-clay shown in Figure 2. The sand bottoms, on the other hand, are relatively fast and much of the energy from distant sources is totally reflected by the bottom. Thus, the water column acts as an effective waveguide and much of the energy arriving at the receiver is distributed approximately symmetrically about the horizontal. This accounts for the weak oscillations in the imaginary part of the coherence for the sand bottoms in Figure 2.

4. Ambient noise inversion

The differences between the curves in Figure 2 are sufficient to suggest that the vertical coherence of the noise may be inverted to obtain the bottom type. The procedure is straightforward, involving a noise model which includes the sound speed profile in the water column and the geo-acoustic properties of the bottom. Prior knowledge of the correlations between the geo-acoustic parameters of the sediment reduces the complexity of the inversion to an elementary level: essentially, only one parameter is varied to achieve a fit of theoretical to measured coherence curves. Central to this process is the porosity, N, which may be regarded as the independent variable. Most of the remaining sediment parameters (the compressional wave speed, c_p, the shear wave speed, c_s, the density, ρ_s, the bulk modulus, κ_s, the mean grain diameter, u_g, and the three grain-to-grain shearing coefficients, μ_s, λ_p and n) are dependent variables which can all be expressed as simple algebraic functions of N.

In January 1996, the vertical coherence of the noise was measured in Jellicoe Channel, a shallow-water site close to Little Barrier Island, New Zealand [26], some 64 km north of Auckland. The channel is 50 m deep, and the two hydrophones, vertically separated by 0.73 m, were located at mid-depth. The seabed in the region consists of a fluid-saturated sand layer about 100 m thick overlying greywracke rock. Occasionally, a vessel transiting along a shipping lane about 10 km way contributed significantly to the noise field, but most of the time the noise was due predominantly to wave breaking. The wind speed ranged between 7.5 and 10 m/s.

Figure 3 shows the real and imaginary parts of the coherence function, as measured at frequencies up to 5 kHz. Also shown is the theoretical coherence, real and imaginary parts, with the "best" fit to the data, achieved simply by adjusting the porosity, N. The theoretical curves were computed for an exponential, downward refracting sound speed profile with an e-folding depth of 4485.3 m, which is a good representation of the measured profile. From the curve fits in Figure 3, the following estimates for the geo-acoustic parameters were obtained: $c_p = 1610$ m/s, $c_s = 70$ m/s, $\rho_s = 1899$ kg/m^3, $N = 0.48$, and $u_g = 88$ micrometers.

An obvious advantage of the correlation technique is that sediment parameters which affect the noise coherence in the water column only weakly, if at all (such as the shear speed and the density), are still returned by the inversion. The dozen or so expressions for the correlations have been discussed in several recent articles [18, 27-30] and are not repeated here.

5. Concluding remarks

Acoustic techniques provide an effective means of gathering information about the ocean and all it contains. This is the realm of acoustical oceanography. The problems that are addressed by the modern acoustical oceanographer are diverse, ranging from bubble sizing to sediment-parameter estimation. Passive and active acoustic systems are employed in many novel ways to obtain subtle measures of complicated processes. Natural sound in the ocean is exploited as a covert means of investigating oceanic phenomena without disturbing fish stocks and marine mammal populations. As a discipline, acoustical oceanography is healthy and progressing rapidly, returning unique data sets that are directly relevant to the development of national and international policies for the protection and preservation of the environment in which we live.

6. Acknowledgment

This work was supported by the Ocean Acoustics Code (Dr. J. Simmen), Office of Naval Research under Grant No. N00014-93-1-0054.

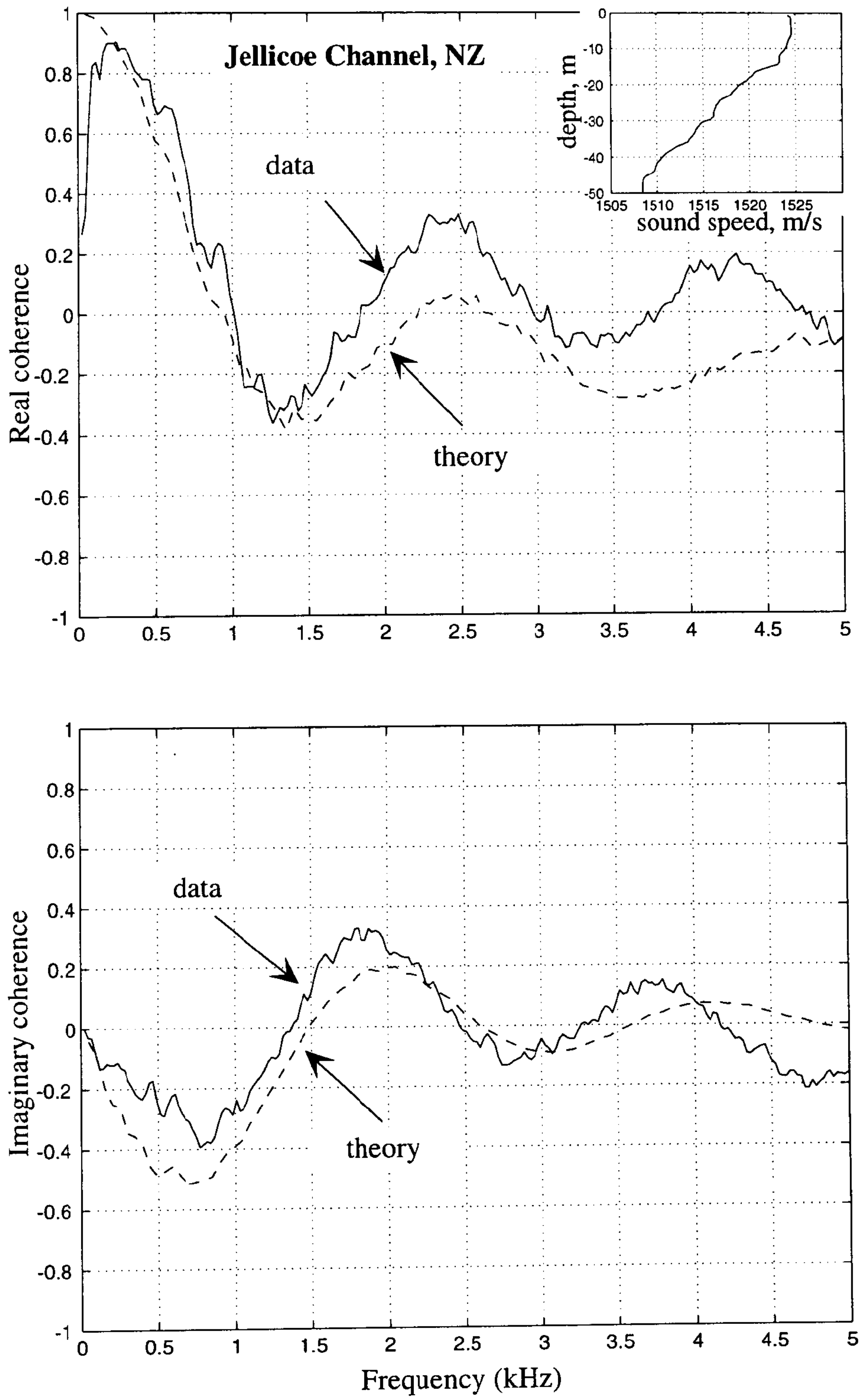


Figure 3. Vertical coherence of ambient noise in Jellicoe Channel with sensor separation $d = 0.73$ m. The sound speed profile in the water column at the time of the measurement is shown in the inset.

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