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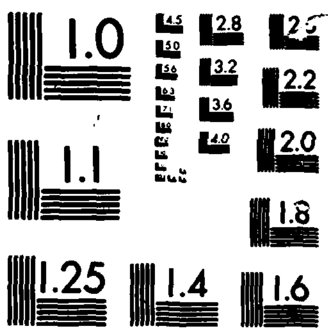


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Pierre Zakarauskas




Defence Research Establishment Atlantic

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# AMBIENT NOISE IN SHALLOW WATER: A SURVEY OF THE UNCLASSIFIED LITERATURE

Pierre Zakarauskas

February 1986

Approved by R.F. Brown Director/Underwater Acoustics Division

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## ABSTRACT

The Technical Memorandum reviews the literature since 1962 on underwater ambient noise. Particular attention is paid to those factors which influence noise levels and directionality in shallow water. Infrasonic noise, seismic noise in the sea bed, ship generated noise, and wind generated noise are considered. Noises of biological origin are acknowledged but not described in detail. The importance of understanding sound propagation phenomena, including bottom interaction, and of modelling is discussed. Suggestions for future research on shallow water noise are offered. This document does not constitute a summary of results, but rather is an account of work done and principles applied.

## RESUME

L'article passe en revue la littérature sur le bruit ambiant sous-marin publiée depuis 1962. On paie une attention particulière aux facteurs qui influencent le niveau et la directionalité du bruit ambiant en eau peu profonde. On considère les régimes infrasonique et séismique, aussi bien que le bruit produit par le traffic océanique et l'intéraction du vent avec la surface de la mer. Le buit d'origine biologique est reconnu, mais n'est pas considéré en détails. On discute de l'importance de comprendre les phénomènes de propagations, comme l'influence du sous-sol sous-marin, ainsi que de développer des modèles environnementaux du bruit. On offre des suggestions pour de futures recherches dans ce champ. Ce document ne constitue pas un résumé de résultats, mais est plutôt un compte rendu de travaux effectués et de principles appliqués.

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# 1. INTRODUCTION

## 1.1 Motivation

As greater use is made of the underwater environment, a detailed knowledge of underwater ambient noise is necessary. In the military context, the development and improvement of anti-submarine warfare (ASW) acoustic detection and localization systems depends on this knowledge. The more that is known of the noise and signal characteristics, the better detection systems can exploit their differences to improve the signal-to-noise ratio. These include such differences as spectral shape, spatial distribution and coherence, cross-correlation spectra, etc., between the signal and the noise.

In the non-military context, ocean ambient noise constitutes a background noise in measurements for fisheries, oceanographic or oil exploration purposes. It is also a limiting factor in the performance of acoustic instruments and in the control by acoustic means of research instrumentation. Moreover, the ambient noise in itself may be of biological or oceanographic interest. An interesting recent example is infrasonic noise, which has been found to be related to microseisms. Both infrasonic noise and microseisms are caused predominantly by non-linear wave-wave interactions, a subject which is attracting growing attention.

Much effort has been expended in measuring and modelling the characteristics of the signal field in shallow water ocean areas, with much success. However, a proportional effort has not been invested into investigating the shallow water noise field, especially with respect to directionality. Moreover, special efforts are needed in shallow water because of the inadequacy of deep water methods when applied in shallow water.

The present review brings together much of the open literature on ambient noise in shallow water, and some representative results in deep water when relevant to the discussion. It reports an emerging consensus on identifying the important factors affecting ambient noise levels and coherence.

The main areas of possible research on underwater ambient noise relate to its dependence on time and location, its directional distribution, both vertical and horizontal, and its sources. A good understanding of the mechanisms contributing to ambient noise production helps us to model and predict the ambient noise characteristics in a given area, so we need not rely solely on empirical models. This is one reason why research is done in mechanisms of noise generation.

## 1.2 Some definitions: ambient noise and shallow water

The definition of ambient noise is in general dependent on the observer. One observer's noise may be another's signal, leading us to a first definition: noise is what is left after the desired signal has been removed. The noise component which is generated by the data collection and recording system is called system noise; noise external to the system is ambient noise. However, for a general discussion such as this one, this observer-dependent definition is not very appropriate, and it is proposed to use the following one: ambient noise is the acoustic part of the signal after the contributions from obvious identifiable sources have been removed. The latter can be considered as interference rather than noise. For example, the sound radiated by a nearby ship does not constitute ambient noise, but the noise generated by a distribution of several distant vessels does, and is called shipping noise. The pseudo-sound caused by turbulent pressure fluctuations on a hydrophone in a current, called flow noise, does not qualify either, because it is not acoustical (radiating) in nature. However, because flow noise is difficult to separate from ambient noise, measurements of the ambient noise have often been contaminated by flow noise. Therefore results from studies on flow noise have been incorporated in this review.

Shallow water areas are generally thought to include all of the continental shelves, but can not be defined uniquely in terms of depth. Frequency is an important parameter too. What most characterizes shallow water acoustics is not only the occurrence of multiple bottom bounce paths, which may occur as well in deep water, but also the interference effects they produce in travelling sound waves. When the acoustic wavelength is of the same order of magnitude as the water depth, one is facing a shallow water environment. This means that at 1 Hz and below all the oceans on earth can be considered shallow water. On the other hand, one can consider a large, 50 meter deep lake to be a deep water environment when using a 10 kHz sonar to map the bottom.

We will be particularly concerned with ambient noise in shallow water, where shallow water is defined by wavelength comparable to depth. In the great majority of the cases considered in this review however, it can be assumed to correspond to the continental shelves. Although most of the important characteristics of the production and propagation of noise in deep water may also be found in shallow water, the multiple interactions of sound with the bottom makes the shallow water environment more difficult to analyze and model.

## 1.3 Normal modes

When the dimensions of the acoustic channel are not very large compared to the acoustic wavelength, one must use wave theory to describe the acoustic field. One representation of the solution to the wave equation with boundary conditions constitutes normal mode theory. Most shallow water models are based on normal mode theory. The simplest and the first such model is the Pekeris model [Pekeris, 1948], consisting of a homogeneous fluid layer overlaying a liquid half-space of higher impedance. The part of the solution corresponding to transported energy is expressed in terms of a sum of functions describing vertical pressure variations, called normal modes. A normal mode propagates in a given channel for each incidence angle of the travelling wave which leads to constructive interference. A wave impinging on the bottom and surface with an angle in between two of these discrete values will be damped out. The number and shape of the modes are determined by the depth of the channel, the bottom composition, and the frequency of the acoustic wave. The upper limit of possible grazing angles between the acoustic rays and the horizontal is called the critical angle and depends on the composition of the bottom. For a grazing angle greater than the critical angle, some energy is lost into the bottom at each bounce and the corresponding ray attenuates with range much faster than the normal modes. At close range to the source, these rays may constitute a significant portion of the acoustic field and may not be ignored. At longer ranges this continuum of rays may be sufficiently attenuated so the normal modes satisfactorily describe the significant portion of the acoustic field. Figure 1 illustrates the geometry of these different cases. For a detailed exposition of the theory of normal modes in shallow water, see (Tolstoy and Clay, 1966).

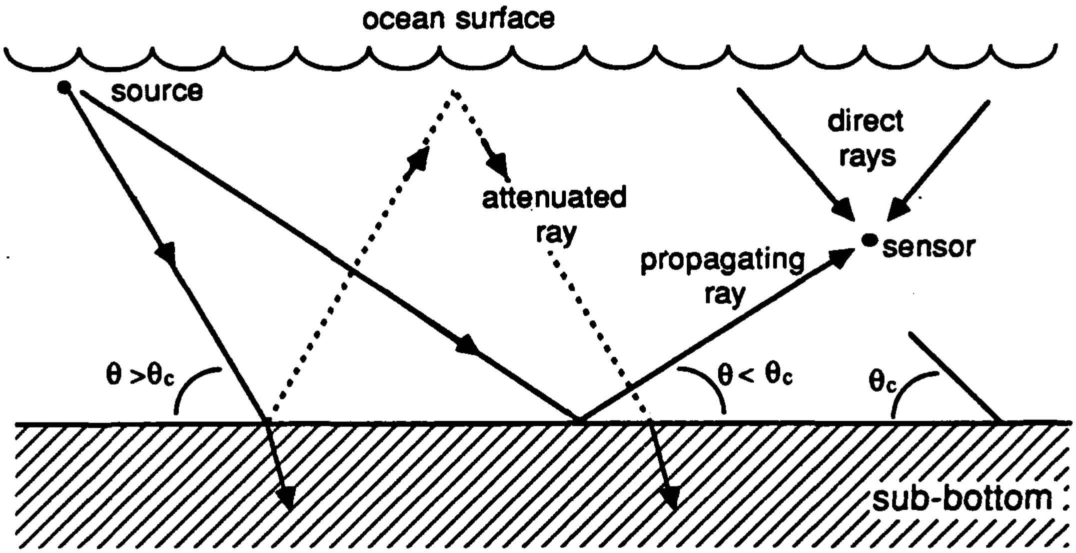


*Figure 1. Geometry of propagating and non-propagating rays in shallow water.*

## 1.4 Shallow water acoustics versus deep water acoustics

It is important to distinguish the differences between shallow and deep water from the acoustical point of view. Several factors cause the shallow water acoustic environment to be more variable (in both space and time) than the deep water one. Firstly, because of the generally strong interactions of the acoustic waves with the seabed, the acoustic properties of the seabed are a prime consideration in describing the propagation characteristics of shallow water. However, the bottom composition and structure are generally poorly known, highly variable from place to place, and reliable data are often difficult to obtain. Secondly, the sound speed profile of the water column itself shows great variability in time and space, not only seasonal and diurnal, but also depending on the weather. This happens when the sun heats up the upper surface layer, or a storm mixes uniformly the whole water column. In the deep ocean, only the topmost layer is affected by these phenomena.

Another difference between shallow and deep water has already been mentioned, and is the normal mode versus ray propagation. This point is all too often overlooked when dealing with shallow water environments. This means that the intensity, phase and coherence of sound waves may display depth dependence rapid enough to be noticeable across an acoustic array. The use of standard beamforming methods in such a case would then result in some degradation of the array response.

## 1.5 The need for arrays

As has already been mentioned, an important difference between signal and noise is often their spatial characteristics. Generally speaking, noise arrives from all directions while the desired signal is usually highly directional. It is necessary to use arrays of hydrophones or other directional sensors to exploit some of these differences. An understanding of the spatial characteristics of the ambient noise field is necessary in order to predict the performance of existing arrays in shallow water. Moreover, such knowledge can be used to design new array systems exploiting these characteristics. For example, in deep water, distant shipping noise is found to come predominantly from the horizontal direction, but some of the signal often arrives at higher angles via bottom bounce paths. We are looking for such a guiding principle in studying ambient noise in shallow water.

## 1.6 Outline of this review

In Section 2, we will examine results of ambient noise measurements, starting with Wenz's 1962 review, concentrating on concepts relevant to shallow water acoustics but neglecting deliberately the literature relating to ice produced noise, which forms a field of study on its own. Section 3 describes the ambient noise models, which bring observations and theories together in trying to predict ambient noise levels and array performance in shallow water. In the Conclusions, we will review what is known, state some of the outstanding questions, and propose a few new topics for research.

# 2. EXPERIMENTAL RESULTS

## 2.1 Previous reviews

One of the most well-known and thorough reviews of underwater ambient noise is the one undertaken by Wenz (1962). It still stands as a cornerstone of the field. Wenz brings together, compiles and compares the results of several investigations, and proceeds to classify the different regions of the noise spectra according to their types and sources: wind-dependent, wind-independent and low-frequency. It is worthwhile to review his major observations, both as a basis of comparison of more recent work, and for its instructiveness. The other three reviews that were found during this literature survey were the ones by Wenz (1972), Von Winkle (1979), and Urick (1984). Let us start with Wenz's first review.

### 2.1.1 Wenz's review

#### 2.1.1.1 Infrasonics

The infrasonic region is usually defined to include frequencies from 1 to 20 Hz. The small amount of data available at the time in this range shows very little wind dependence, from 1 to 10 Hz, with a -8 to -10 dB per octave slope. Ocean surface waves can be an important noise source in this frequency range. Hydrostatic pressure variations proportional to water level can be important in shallow water (for depth < ~100 m). Experimental data show a high correlation between the acoustic energy flowing in the water and the seismic energy flowing in the bottom. The direction of the flow of energy was not known at the time Wenz wrote his review.

Wenz brings attention to a mechanism for low-frequency wind-independent sea noise: turbulence in the water around the hydrophone. Wenz estimates the pressure fluctuation amplitude and plots the resulting spectra for different values of the oceanic current.

#### 2.1.1.2 Wind-dependent ambient noise

This noise is situated in the range 50 Hz to 10 kHz, with a broad maximum between 100 and 1000 Hz. The main source is thought to be the oscillation of air bubbles from surf or breaking waves. Wenz reports the results of several studies and measurements of generation of sound by air bubbles or cavitation. There is evidence to support the existence of microbubbles in the sea even when the wind is low. Another wind-dependent source Wenz pointed out is water droplets hitting the surface from spray or rain.

#### 2.1.1.3 Wind-independent ambient noise

This type of noise is detected in the region 10 to several thousand Hertz and therefore partly overlaps with the wind-dependent noise component. It is produced by both biological sources and oceanic traffic. Wenz distinguishes between *traffic noise*, which comes from a number of ships travelling a large distance from the listening station, and *ship noise*, which comes from one or a few ships at relatively close range.

Noise of biological origin has been observed within the whole range of frequencies covered by then available systems, from 10 Hz to 10 kHz. Most of the biological noise is made of transient sounds; clicks, whistles, etc., which are often repeated and can even sound like a continuous sound as in the case of the crackling of snapping shrimp. The biological noise spectrum varies with time and location, and can show diurnal or seasonal patterns. Most of the time, biological noise can easily be recognized, due to its transient nature, but the source might be hard to identify.

Major topics which are not covered in Wenz's 1962 review, because of lack of data at the time, are the temporal and spatial characteristics of ambient noise.

Wenz's 1972 review is more limited in scope, focusing mainly on the historical development of research in sea ambient noise. Some valuable recommendations for future research are given toward the end of his article. Among the new material included in this 1972 review is some material on noise directionality in deep water and correlation between power spectrum levels and environmental factors. We will come back to these developments in detail later on.

### 2.1.2 Von Winkle's review

#### 2.1.2.1 Overview

Apart from Wenz's cornerstone study of 1962, and his follow-up of 1972, at least one more short review of experimental results was written about ocean ambient noise by W.A. Von Winkle (1979). He reviews and displays final results of several studies, starting with Knudsen, Alford and Emling's summary of World War II research, through Wenz, Little, Vidale and Houston, Piggot, and Perrone, to the directional measurements in deep water of Fox, Von Winkle, and Becken (although the authors' names were mentioned, Von Winkle does not supply complete references in his paper). A large part of the review is devoted to comparing the final curves obtained by the various researchers from data obtained largely in shallow water. Some conclusions coming out of these comparisons are:

- Below 1000 Hz, the older studies showed higher noise levels than recent ones.
- There is good agreement among studies for the level of ambient noise from surface agitation, but the agreement breaks down when comparing shipping noise level predictions. Differences are of the order of 5 to 14 dB.

The importance of the acoustical properties of the sea bottom is not cited in Von Winkle's review.

#### 2.1.2.2 Comments

Much effort has been invested in producing noise-level curves from measurements over hundreds of sites. These curves were intended to predict noise levels at any point as a function of shipping density in the area, and sea state or wind speed. As will be explained later on, this goal is ill-fated. In shallow water, the acoustic properties of the bottom are as important a factor in predicting noise levels as shipping or wind speed, and earlier studies, such as Von Winkle's, did not take this factor explicitly into account.

Von Winkle's proposal of collecting smaller quantities of data over wider geographical areas to average out the variation can only yield averaged curves, corresponding to few real sites, and no real understanding of the factors influencing underwater noise. The trend in the last few years has been to collect the largest quantity of data possible over a few carefully selected areas, and work out the contribution of each factor, such as bottom composition and roughness, bathymetry, etc.

### 2.1.3 Urick's review

The most recent in-depth review of the research on underwater ambient noise noted by the author was by Urick (1984). Urick's review includes the sources and variability of ambient noise, its dependence on receiver depth, the directionality and coherence of noise in deep water, biological noise and noise in the Arctic. What is not covered in his review is the directionality and coherence of noise in shallow water, and environmental modelling. One of his comments about shallow water ambient noise is:

> *In shallow water, in the absence of local shipping and biological noise, wind noise dominates the noise of distant shipping over the entire frequency range. The reason for this is that the deep favorable propagation paths traveled by distant shipping noise in deep water are absent in shallow water; in other words, the poor transmission in shallow water screens out the noise of distant ships and allows locally generated wind noise to dominate the spectrum at all frequencies.*
>
> (Urick, 1984, page 2-33)

However, shallow water areas include some regions of very intense shipping and oil exploration. These regions often have ambient noise levels well in excess of those found in deep water. Therefore, the local shipping condition is another factor which causes site dependency in shallow water.

## 2.2 Noise levels in deep water

The basic features of Wenz's review are still very relevant today. However, considerably more knowledge of the "grey areas" has been obtained since then. This includes the very low frequency spectrum and the statistical properties in the time domain of the noise field. (The spatial properties are considered in the next section). A compilation of ambient noise power spectra from Kibblewhite and Ewans (1985) and Ross (1976) is shown in Figure 2.

### 2.2.1 Infrasonics

Perrone's data (1974) were taken during an 8 day study, at a site 2290 meters deep near the Grand Banks, with a bottom mounted hydrophone, in the 1 to 250 Hz region. His data in the 1 to 4 Hz range show a strong wind-speed dependence that decreases with increasing frequency. Above 4 Hz, little such dependence is evident. This is a novel feature relative to what was known previously. Perrone also points out that it is easy to subtract the contribution from shipping noise, as it increases and decreases within a few hours, whereas wind-generated noise varies on the time scale of one day or so. Perrone reports a slope of -20 dB/octave in the 2-5 Hz range, compared with -10 dB/octave quoted by Wenz.

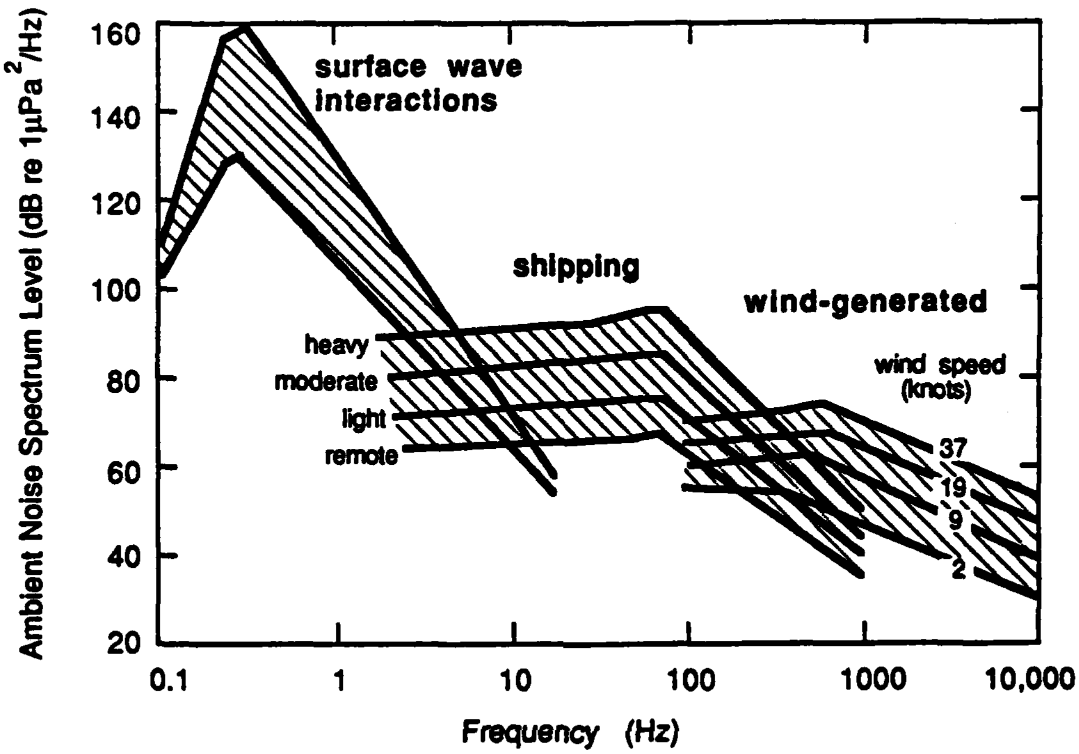


*Figure 2. Underwater ambient noise power spectra.*

Perrone's classification scheme for ambient noise sources based on correlation time is extended in his 1975 paper. He states that the variability of ambient noise in time and in location comes from its ship-generated portion, while the wind-generated noise is fairly constant in shape.

Precisely, what Perrone does is to classify the different noise sources according to the zero-axis crossing time of the autocorrelation function of the noise levels. For wind-generated noise data, the zero-axis crossing occurs at a time shift of between 26 and 40 hours, comparable to the zero-axis crossing of the wind autocorrelation itself. On the other hand, the shipping noise autocorrelation zero-axis crossing time occurs between 4 to 8 hours. For a signal composed of a mixture of shipping and wind-generated noise, the autocorrelation zero-axis crossing depends on the ratio of the two contributions, i.e. between 8 and 26 hours. This technique requires long term (longer than 2 weeks) ambient noise collection.

Bendig (1982) uses a different approach to ambient noise classification. By examining grey-scale intensity time-frequency plots of ambient noise recordings, he exploits the interference patterns of the broadband ship noise (Lloyd mirror effect) to detect and count the number of ships in the area, and their distance from the sensor.

Fraser, Merklinger and Stockhausen (1978) review results from a series of ambient noise measurements made in 1977 in the Atlantic ocean with suspended arrays. They report a local minimum near 5 Hz. The range of variation of the main noise level between different stations covered 20 dB above 5 Hz, and less than 10 dB below 5 Hz. In agreement with Perrone, they report no wind dependence of the noise at 7.5 Hz. They concluded that the noise they recorded below 5 Hz was non-acoustic in nature and related to the coupling of their arrays with surface motion. Later work (Cotaras, Merklinger and Fraser, 1983) with 5 m diameter horizontal planar arrays suspended to a depth of 300 m yielded data which agree well with that from bottom-mounted hydrophones of Nichols (1981). One more indication that Cotaras, Merklinger and Fraser's ambient noise measurements were not contaminated by self-noise was the measurement of inter-sensor coherence, both within the same array and between two independently drifting arrays. Inter-sensor coherence for frequencies whose wavelengths are much larger than the inter-sensor separation should be nearly unity if the noise is entirely of acoustic nature. This is indeed what they measured, for frequencies down to 1.2 Hz, below which point some mechanical resonances of the array induced uncorrelated noise in the system. They also applied Perrone's classification scheme based on auto-correlation time, and found wind noise to dominate under 4 Hz at three sites, but only up to 2 Hz in the Labrador Sea, where a near surface sound channel produced better long range propagation.

Nichols (1981) measured the ambient noise in the frequency domain 0.02 to 20 Hz, at depths of 13, 300 and 1200 m with bottom mounted hydrophones. Rain showers had no detectable effects on the infrasonic noise. He reports a slope of -14 dB/octave, more in line with Wenz's results than Perrone's.

Talpey and Worley (1984) measured the ambient noise at a 3500 m deep site with a bottom mounted hydrophone, for the frequency band 0.1 to 12.5 Hz. The spectrum level is nearly flat in the region 4 to 12.5 Hz, and rises steeply below 4 Hz. The correlation between the spectrum level and the wind speed is high (0.65 to 0.85) from 1 to 3 Hz, peaking around 2 Hz.

### 2.2.2 Time stationarity

Adams and Jobst (1976) made a statistical study of time stationarity. Frequency-frequency correlation varies greatly in time, passing from perfectly correlated to almost totally uncorrelated within a few minutes, for the frequency range they display in their paper (75 to175 Hz). This study is aimed at establishing bounds within which the wide sense stationarity hypothesis can be applied. Their conclusion is that a few minutes is the longest time period within which it is safe to assume wide sense stationarity. A more detailed treatment of the statistical analysis of ambient noise is presented in Jobst and Adams (1977).

### 2.2.3 Frequency-frequency correlation

Nichols and Sayers (1977) measured frequency-frequency correlation over a 4 1/2 day period, with a bottom mounted hydrophone, for the frequency range 5 Hz to 150 Hz. The main observation is that there is a high correlation between levels at low frequencies and those at the high end of their frequency range, but not with those in the middle of the range. One hypothesis which would explain this observation is that the source of noise near the low and high bounds are the same (and weather dependent), while the middle frequency noise source is of a different nature (i.e. shipping noise).

## 2.3 Noise levels in shallow water

### 2.3.1 Acoustic data:

Again we will begin this section by reporting Wenz's conclusions from his 1962 study. He observes that the shallow water noise levels are in general about 5 dB higher than in deep water, for corresponding wind speed. He attributes this difference to turbulence and current, industrial activities, and at very shallow depth (50 m or less), to hydrostatic pressure changes due to surface waves.

Piggot (1964) conducted an ambient noise measurement with 2 bottom-mounted hydrophones connected to shore by a cable, in 36 m and 51 m of water. He finds that the noise level varied linearly with the logarithm of the wind speed, and that it was season dependent. His proposed explanation is the change in temperature profile in the water column. An important point is that his spectral curves agree in shape (i.e. slope) with Wenz's, but Piggot's results are 2-7 dB higher than what Wenz predicts, depending on the wind. Finally, the deeper hydrophones had noise levels 2-3 dB lower than the one at 36 m, indicating a dependency on water depth.

Urick (1971) made a comparison study at two contrasting shallow water sites, whose principal characteristics were: one off the coast of Florida, with a high ship traffic and a poor sound propagation due to a downward refracting profile; the second in the Gulf of Maine with good propagation conditions due to a sound channel, and little or no traffic. Comparison of the mean spectra shows that the Florida site is noisier by 5 to 10 dB than the Maine site at low frequencies (50-500 Hz), but only slightly noisier at higher frequencies. The high ship traffic at the Florida site is claimed to be responsible for the higher noise level there, but only the sources situated within approximately 5 miles of the hydrophones contributed to the ambient noise, in clear contrast with what happens in deep water. However, the wind-dependent noise at high frequency is found to be the same at both the Florida and Maine sites. Urick's conclusion is that the high-frequency wind-generated noise "*doubtless originates at the sea surface in the immediate vicinity of the measuring hydrophone*."

An experiment designed to test Wenz's hypothesis that current turbulences produce the low-frequency noise (below 10 to 30 Hz) was conducted by Bardyshev, Velikanov and Gershman (1971). They measured ambient noise at depths of 100 to 130 meters, where tidal currents reached a maximum of 0.78 m/s. They find that the use of current shields reduces the pseudonoise level by 10 to 24 dB in the frequency range 2 to 20 Hz for a flow velocity of 0.6 m/s, without attenuating the sound signal. The slope of the spectrum is considerably lower than the one reported by Wenz, at -3.5 to -5 dB/octave.

Nichols (1981) had one of his hydrophones in 13 m of water, the others at 300 and 1200 m. The shallower one showed higher noise levels at low frequencies ($f < 5$ Hz), and a higher standard deviation (5 dB against 2 to 5 dB for the 300 m hydrophone). Nichols used current shielding cases for housing his hydrophones. He did not record wind speeds or bottom ocean currents, but nonetheless infers from comparison with diverse theories of noise generation that, for the frequency range 0.1 to 10 Hz, the likely noise source was non-linear wave-wave interactions.

Worley and Walker (1982) made measurements in the Gulf of Maine with bottom mounted hydrophones in the frequency region 50 to 800 Hz during an 18 month period. They report unusually low levels of ambient noise, highly correlated with wind strength over the whole spectrum. Transmission loss measurements show a very high acoustic attenuation, of the order of 100 dB at 2 miles. Refraction profiles indicate an unconsolidated sediment layer a few tens of feet deep over rock. Shear waves in the rock are suggested as the reason for the high loss. Measurements at another site where transmission loss was lower show much higher noise levels, which are wind-independent below 500 Hz. The conclusion from their study: noise level and significant source are dependent on transmission properties of the bottom.

Another study which came to the same conclusion was conducted by Wolf and Ingenito (1982). They compile the results of ambient noise measurements during equivalent sea-states taken at widely different sites. They find that the noise levels can vary by as much as 15 dB between sites.

In complete contrast to this last study are the conclusions of Wille and Geyer's experiment (1984). They conducted shipborne ambient noise measurements in the Baltic Sea and the North Sea. The sites had different depths (90 m vs 46 m), different thermoclines and different bottom types (mud versus sand and gravel). They recorded the ambient noise in the region 25 Hz to 12.5 kHz. They conclude that "*...even extremely different propagation conditions in shallow water cause no more than marginal changes of the wind-dependent noise level.*" Their conclusion is in such opposition to other measurements and studies that one cannot help but look for an explanation, either in their experimental set up or their analysis method. One important difference in their recording equipment is that they used hydrophones suspended 40 m above the sea bottom by buoy. This can have two effects: to induce a greater amount of flow noise than a bottom mounted hydrophone would experience, and to diminish the effect of the bottom as a noise attenuator. Another point is that their two sites might have been too different, preventing a control of the effect of each variable. In other words, the different effects might have canceled one another. It would be instructive to check this possibility by simulating the environments of the sites they used on an ambient noise model.

Kuperman and Ferla (1985) measured the depth dependency of wind-produced ambient noise at a shallow water site. They find that the noise level was constant with depth to within a couple of decibels. They then fed the noise levels into an ambient noise model of shallow water, together with propagation measurements in the area, to calculate the source strength of wind-generated noise. The resulting source strength can be used by their model to predict the ambient noise at any other shallow water location, given the propagation parameters.

### 2.3.2 Seismic data

An ambient noise study with both ocean bottom seismometers (OBS) and hydrophones was conducted by Brocher and Iwatake (1982) with the purpose of identifying the various sources of noise. The technique they used did not give absolute noise levels, only their variation in time. They find that above 6 Hz, their records show no correlation with the wind data. However, between 1 and 2 Hz, the ambient noise levels (in decibels) are linearly correlated to the logarithm of the wind speed with a proportionality coefficient of 2.4 ± 0.4. They attribute this noise to turbulent pressure fluctuations (Wilson, 1979). Comparison of the hydrophones and geophones shows that on the continental shelf, "*...the ambient pressure fluctuations were larger and more numerous than those recorded by the geophones; on the continental slope (deep water), the opposite was observed. The origin of this discrepancy is unknown.*" They report some events which are consistent with being generated by bottom currents, lasting usually on the order of a few minutes. Nearby airgun profiling plagued 2 of their $5^1/2$ day study. Ship traffic was another important source of noise, and its level was up to 11 dB above the ambient noise, dominating it for less than one percent of the time. A high level of biological activity is identified in the form of short (less than 5 s) impulses recorded by the geophones, but not by the hydrophone. This indicates that the noise was not acoustic in nature, but rather was generated by organisms touching the OBS. Because these events dominated up to 17% of the time, their existence must be taken into account when interpreting data from OBS ambient noise measurements. Seismic events amounted to only 0.7% of the time during the 2 day study.

One ground-breaking experiment concerning the origin of low-frequency ambient noise and microseisms was conducted by Kibblewhite and Ewans (1985). They wanted to further investigate the close relationship between sound pressure on the sea floor and low amplitude seismic activities, known as microseisms. It is known that non-linear wave-wave interactions (Goncharov 1970, Hughes 1979) are not attenuated with depth and are significant at all sites (Harper and Simpkins, 1974). Kibblewhite and Ewans recorded ambient noise with seismometers based both on the ocean floor and inland. The area they chose to perform the experiment (off the west coast of New-Zealand) is particularly well suited for such a study, because of the regular pattern of winds which often swing rapidly through 180°, creating opposing seas. The depth at the experiment site was 110 meters. They recorded wind speed and direction hourly, air and sea temperature, and the wave height and direction.

The important theoretical characteristics of the non-linear wave-wave interactions Kibblewhite and Ewans were trying to establish are that the frequency of the generated sound field is twice the frequency of the generating surface wave, and proportional to the square of the wave amplitude (Brekhovskikh, 1966; Lloyd, 1981).

Kibblewhite and Ewans' results are striking: "*...comparison of any sea spectrum and its seismic equivalent will identify peaks in the wave spectrum with corresponding peaks in the microseism spectrum at or very close to twice the frequency.*" The microseisms appear in the range 0.05 to 1.0 Hz.

Very intense microseism activity was recorded by Kibblewhite and Ewans, both on land and by the OBS during each of the several times when the wind shifted direction 180°, then dropped, as the new sea entered a steady state, even though the wave levels were still as high. The authors explain the high noise to wind correlation by the lag between wind-change and sea change. Under variable conditions, the microseism and low-frequency ambient noise correlate better with wind speed and direction changes than with the sea itself. By plotting the logarithm of microseism amplitude against the logarithm of ocean wave amplitude, Kibblewhite and Ewans find a slope of 2.06 with a correlation coefficient of 0.81, thereby confirming the square law relation.

Kibblewhite and Ewans' final conclusion is that wave-wave interactions are the dominant mechanism of noise generation from 0.1 to 5 Hz.

## 2.4 Directional ambient noise measurements

### 2.4.1 Deep water

Numerous ambient noise studies have been made in deep water with arrays of hydrophones to measure the directionality of the noise field. Only a few representative ones will be reported here.

Fox (1964) conducted a measurement of the vertical directionality of ambient noise in 14500 feet deep water with a vertical array of 40 hydrophones, beamforming from horizontal to vertical upward, at four frequencies: 200, 400, 750 and 1500 Hz. The ambient noise shows a peak toward the horizontal at low sea state for all frequencies, but "*...as the sea state increases, the vertical and near vertical contributions increase more rapidly than do the horizontal contributions.*"

The source of the horizontal noise has since been identified with distant shipping, and the vertical contribution with wind-generated noise. Arase and Arase (1974) report a similar measurement, trying to extract the directionality of the source field. Assuming a uniform distribution of surface sources, monopole sources give the best fit to the experimental curve. At high sea state, dipole sources would show better agreement.

Stockhausen (1975a, 1975b) develops an empirical and a numerical model to describe the effects of bottom absorption and surface scattering on ambient noise. He shows that propagation conditions influence noise directivity at the sensor in an amount comparable to the difference between $\cos\theta$ and $\cos^2\theta$ source directivity, thereby masking its effect.

Fraser, Merklinger and Stockhausen (1978) review ambient noise measurements made by DREA with suspended arrays. They report that noise arrives at the hydrophones closer to the horizontal at stations north of the 50th parallel. Horizontal directionality measurements with drifting arrays show that the dominant noise source in a narrow beam may be a distant ship beyond 200 km. Also, Cotaras, Merklinger and Fraser (1983) report some evidence from later work that the wind-generated noise is close to 3-D isotropic.

Merklinger and Lanham (1978) have conducted a trial in which they visited eleven locations in the North Atlantic, and recorded ambient noise with a suspended vertical array of twelve hydrophones. Within the 2.9 - 180 Hz limits imposed by inter-element spacings and total length of the array, they found the noise to come predominantly from the horizontal, except at one location over the Mid-Atlantic ridge. Comparison with Wenz's curves shows that most of the samples had higher noise spectrum levels than those associated with "heavy shipping" conditions.

Burgess and Kewley (1983) used a suspended vertical array to isolate the wind-dependent component of ambient noise which is produced locally above the array. The surface source level as a function of wind speed, and the bottom reflection loss, are deduced from the difference between the vertical upward and downward noise intensities, with the help of a simple propagation model. The surface source level spectrum is found to be surprisingly flat (white) for high wind speed, in contrast to typical ambient noise spectra. The difference is explained by the frequency-dependent effect of the absorption of the sea bottom.

### 2.4.2 Shallow water

Very little experimental work has been published about noise directionality in shallow water, even though a number of models of vertical directionality in a waveguide have been flourishing in the past few years. The major development has been the realization that the bottom parameters are crucial in determining the ambient noise characteristics. During earlier attempts to describe ambient noise in shallow water, the depth or location dependency was often overlooked, in an attempt to extend the homogeneity condition of deep water acoustics. One example of this is the Ross and Bluy (1976) measurement of ambient noise correlation as a function of hydrophone separation. They measured the cross-correlation between hydrophones, and then proceed to plot the correlation of the sound field as a function of separation between sensors. In doing so they implicitly make the assumption that the noise field was homogeneous throughout the water column. However, if the channel cannot support enough modes (> 10 modes) or if the seabed has too high an absorption coefficient, the field is probably not homogeneous. The case Ross and Bluy studied does not necessarily meet these conditions, especially at low frequencies. It retrospect, it appears necessary to take into account the depth of each hydrophone pair, and show explicitly the depth dependence of inter-sensor correlation. It is worth noting theirs is the only paper I have found presenting experimental results on ambient noise vertical directionality in shallow water.

### 2.4.3 Horizontal directivity

Horizontal arrays can be used in ambient noise measurements in order to isolate different noise sources, such as ships, whales, on-shore activities, etc. One such measurement was performed off the California shore by Wilson, Wolf and Ingenito (1985) to determine the proportion of noise contributed by breaking surf on the beach. During heavy surf, at 9 km from shore, there was a difference of 10 dB at 300 Hz between beams directed toward shore and seaward. This suggests that a significant portion of the ambient noise on the continental shelf might originate from the beach, and therefore create anisotropy of the noise field in the horizontal.

### 2.4.4 Seismometer measurements

A few measurements of ambient noise by OBS have been reported. Because they record on 3 axes, 1 vertical and 2 horizontal, one sensor is enough to provide directionality information. Moreover, they can detect transverse waves in the bottom. One such experiment (Brocher et al, 1981) measured the signal-to-noise ratio for a hydrophone and each of the 3 geophone axes, at depths of 67m, 140m and 1301m on the continental margin off Nova Scotia. Within the bandwidth of the recording instruments (1 to 30 Hz), the vertical geophone had a better signal-to-noise ratio than either horizontal geophone axis or the hydrophone, at all ranges. The differences were up to 10 dB. This is because the very low-frequency signal most efficiently propagates along the bottom in the form of an interface wave, whereas part of the noise consists of a horizontal displacement (Love wave).

Schmalfeldt and Rauch (1980) used an OBS to measure the horizontal directivity of ambient noise, as well as its spectrum. The ambient noise is slightly directional, and has a spectrum very similar to the one recorded by the accompanying hydrophone. The ship noise could easily be picked up at a distance of 1 km by the geophone, and its bearing calculated by the polarization of the interface wave propagating at the bottom-water boundary.

## 2.5 Flow noise

The fact that current turbulence is an important source of noise at low frequencies was suspected by Wenz (1962), and verified by Bardyshev, Velikanov and Gershman (1971), as described in Section 2.3.1. This means that the infrasonic part of the acoustic data presented in Wenz's paper might have been contaminated by flow noise.

To quantify the contamination of ambient noise data by flow noise, McGrath, Griffin and Finger (1976) measured the pseudo-noise caused by the relative motion of water past a hydrophone in a tank. The relative current varied from 0.25 to 0.45 knots. It gave rise to sound pressure levels of 105 dB//µPa for a current of 0.4 knots at 1 Hz, and 91 dB for the same current at 2 Hz. This represents a slope of 14 dB/octave. These levels are at the lower limit of recorded oceanic ambient noise as cited by McGrath (1975).

With the intent to verify whether or not their ambient noise measurement was contaminated by non-acoustic noise, Buck and Greene (1980) measured the cross-correlation of two hydrophones independently suspended from the ice-covered surface at 60 meters from each other. Since the inter-sensor separation was 0.04 wavelengths at 3.2 Hz, a near perfect correlation would be expected at this frequency when the recorded signal is purely acoustic in nature. The average correlation coefficient was 0.8 with a standard deviation of 0.23. The minimum correlation was 0.19, indicating a very high contamination by non-acoustic noise. Unfortunately, they did not have a current meter available, and therefore could not measure any possible cause to effect relation between the two. They verified however, that the cross-correlation was not related to the wind speed or direction during the time of their experiment.

Cotaras, Merklinger and Fraser (1983) also applied the inter-sensor coherence technique as a verification that their ambient noise measurements were not contaminated by flow noise (see Section 2.4.1).

In view of the above results on flow noise, it is recommended that future measurements of ambient noise in the infrasonic range should include also an assessment of inter-sensor correlation whenever possible. Such precautions should become the standard in infrasonic noise measurements.

## 3. ENVIRONMENTAL MODELLING

In their quest for understanding the factors which contribute to and influence underwater ambient noise levels and directionality, researchers in the field increasingly have made use of environmental models in the past few years. These models have three parts. First, a spatial distribution of noise sources (i.e. wind, ships, etc.) is specified, as well as the location and depth of the receiver. Second, the source levels, depths and directivity patterns are specified. And third, a propagation model is applied between the source distribution and the receiver. If the propagation model includes calculation of the phase of the sound waves, then the response of several hydrophones can be combined to model the response of an array. Such models can be used for several purposes.

One of the applications of environmental models is that they can predict high noise areas or directions where search for signals of interest would be very difficult. Another application is to model the response of different acoustic listening devices, with the aim of improving system performances. Finally, the conjunction of ambient noise source models and propagation models can lead to an improvement of both through comparison with measurements. Let us first look at environmental models for the deep water environment, which is usually simpler to model than the shallow water one.

### 3.1 Deep water

Among the class of models whose goals are to predict noise levels, a very good example is the wind-generated noise model of Wilson (1983). The author uses his own results of analytical studies of wind-generated noise (Wilson, 1979, 1980) to obtain source level densities of his model. Source level is derived from noise level by comparison through a few selected experiments where the propagation conditions are simple and easy to model (for example measurements of ambient noise by a deep hydrophone in a region of poor bottom reflection).

Wilson reports that among wind-generated noise sources, the wave-wave interactions dominate at frequencies up to 10 Hz, turbulent pressure fluctuations from the wind hitting the rough ocean surface is the dominant mechanism from 10 Hz to 80 Hz, and noise from spray and whitecaps takes over from 80 Hz up. The exact frequency at which the levels of the various sources cross are highly wind-dependent however.

Wilson then applies a deep water transmission loss model to the noise source levels distributed over large areas, at distances greater than 15 nautical miles. The contribution from sources at short range is added explicitly from ambient noise level curves derived analytically (Wilson, 1979; 1980). Model predictions and measurements agree within a few dB, both for the 10 day averaged spectrum, and on a day-by-day comparison.

Talham (1964) was the first to introduce a noise model allowing for multi-path propagation (bottom and surface bounces). The result is an expression for the directional noise field as a function of vertical arrival angle. He considers several forms of surface source directionality. His model predicts that most of the ambient noise should arrive at angles close to the horizontal, in agreement with deep sea ambient noise measurements at low-sea state, which are dominated by shipping noise. Best agreement with measurement is reached when the source directionality function is equal to one.

The homogeneity which is often assumed to characterize the deep water environment, coupled with the introduction of some simple boundary conditions, allows some simplifying assumptions to be made about the noise field. Henry Cox (1973) derives explicit expressions for the cross-sensor correlation and the frequency spectrum of a pair of sensors placed in arbitrary positions in a noise field described by an arbitrary directional distribution of uncorrelated plane waves. He does this by expanding the field directional distribution in spatial harmonics, then deriving a general analytical expression for the cross-correlation of the field between two arbitrary positions in space. He applies his result to the case of a uniform distribution of sources with directivity $cos^{2m}(\theta)$, $m$ being a free parameter of the model. The important advantage of this model is the ease of obtaining results for arbitrary positions of the sensors, allowing one to predict the response of any arrangement of sensors. We will now examine the corresponding models for the shallow water case.

## 3.2 Shallow water

The ambient noise level models developed for deep water are not adequate for shallow water environments without one important modification: the substitution of a shallow water propagation loss model. Such a propagation loss model takes into account the effect of the presence of the bottom on sound propagation, in terms of the bottom density and velocity profiles, and can incorporate additional factors such as shear waves, roughness, etc.. The two other elements of an environmental model, i.e. source levels and source distribution, remain unchanged. But because of the difficulty of gathering complete data about the acoustic properties of the bottom and due to the variability of the bottom, shallow water models will usually be less reliable than their deep water equivalents.

An environmental acoustical modelling program has been under way at the SACLANT ASW research center since about 1977. All of the three models discussed below use the Kuperman and Ingenito (1980) noise model as their propagation loss component. The random noise sources are represented by an infinite sheet of monopoles located at an arbitrary depth below the surface. The reflection of the emitted sound waves upon the surface couples with the source to produce dipole sources, which is the source behavior needed to account for experimental results.

Jensen and Kuperman (1979) describe the propagation models in use at SACLANTCEN and the first results from noise modelling. Their noise model includes the near-field solution of the wave equation, such as direct path or one bottom bounce, as well as the far field (normal modes). They obtain the signal-to-noise ratio and the correlation function between two sensors at arbitrary positions as a function of depth.

A more complete description of a model called RANDI II and its results are presented by Hamson and Wagstaff (1983). It is an extension of the one by Jensen and Kuperman described above, and it can perform either coherent or incoherent mode summation. Several sample outputs are presented, as well as comparison with measurements at two different sites. Ambient noise measurements were performed at these two sites using a towed array, and their environment was simulated by RANDI II and then compared. The first site was in a deep water basin. The second site was 130 m deep, situated near the edge of the continental shelf. The bottom was composed of sand and rook in the shallow water region. Previous propagation loss measurements concluded that shear waves must be included in the rock to account for the results. The ship distribution was recorded by an aerial survey taken during a previous trial, and was assumed to be representative of the ship distribution at the time of the trial. This latter point diminishes the value of the comparison between measured and modelled ship noise directivity.

Hamson and Wagstaff give some examples of the theoretical response of vertical and horizontal arrays. For the vertical array, the shipping and total ambient noise are displayed separately. The interesting point is that for the particular case they study, most of the shipping noise comes from angles close to the horizontal, and most of the wind-induced noise comes from angles close to the vertical. The results are encouraging. Their model is able to reproduce most of the features of the measured noise distribution, leading the authors to the conclusion that "*...the response of other sonar systems operating at this site could therefore be predicted with some confidence*".

The latest addition to the SACLANTCEN shallow water ambient noise simulation study was by Hamson (1985). She studies the theoretical response of a vertical array to wind-generated noise as a function of the source directionality, the bottom composition and the sound-speed profile of the water column. She uses the parametrization of Liggett and Jacobson (1965) to characterize the noise pressure directionality, which is of the form $\cos^m\alpha$, where the source directionality parameter $m \geq 1$, and the angle $\alpha$ is taken from the vertical. Results are presented for values of $m$=1, 2 and 3. A value of $m$=1 corresponds to uncorrelated sources in the Kuperman and Ingenito noise model, and to dipole sources in general. She assumes a unit source level, to allow the effect of various parameters to be studied. Absolute noise levels can be found for different wind speeds by using a frequency-dependent scaling factor.

After comparing shallow and deep water results, Hamson concludes that the noise levels in shallow water surpass those in deep water by approximately the contribution of the normal modes. In some cases, like hard bottom and winter conditions, high noise intensity is found within 30° of the horizontal. This is in striking contrast with deep water acoustics, where wind-generated ambient noise is 3-D isotropic or has a bias toward the overhead vertical.

Hamson finds that the determining parameters of array response are the directionality parameter $m$ and the bottom type. The effect of increasing $m$ is to reduce the discrete mode component relative to the continuous field. This comes about because of the greater amount of energy sent toward the bottom (low $\alpha$) for higher $m$. This effect is more pronounced for soft bottoms, where absorption is higher.

Buckingham (1979, 1985) has been doing acoustic environmental modelling of shallow water using a few simplifying assumptions allowing him to derive interesting results without the need for numerical propagation modelling on computer. His aim is to derive general features of the ambient noise in shallow water. Hence he makes the assumption that the sound speed is the same throughout the water column (isospeed). This assumption is not considered critical to the generalization of his conclusions. Guided by the conclusion of Kuperman and Ingenito (1980) that the ambient noise is dominated by distant sources when the bottom is a low-loss boundary, Buckingham assumes that "*Continuous radiation from nearfield sources may be neglected and that the only significant contribution to the noise field is in the form of modal energy from more distant sources.*" This condition must be respected when considering the range of application of the model's conclusions.

Buckingham (1980) concludes from his model that, away from the boundaries, the noise field can be considered quasi-homogeneous if the channel supports a number of modes greater than about ten. This implies a considerable simplification in the description of the noise field spatial characteristics. The noise is found to arrive at a number of discrete angles on each side of the vertical, up to a maximum angle of ($\pi/2 - \theta_c$) where $\theta_c$ is the critical angle of the bottom, defined in Section 1.3. Each angle of arrival to the sensor corresponds to a pair of plane waves arriving on each side of the horizontal. The pairs of waves coming at the lowest angle corresponds to the first mode, the second pair to the second mode, etc.. This is one case where a direct correspondence can be established between normal modes and plane waves. Figure 3, extracted from (Buckingham, 1979) illustrates the quasi-homogeneity zone, and Figure 4 sketches the discrete directional arrival of ambient noise.

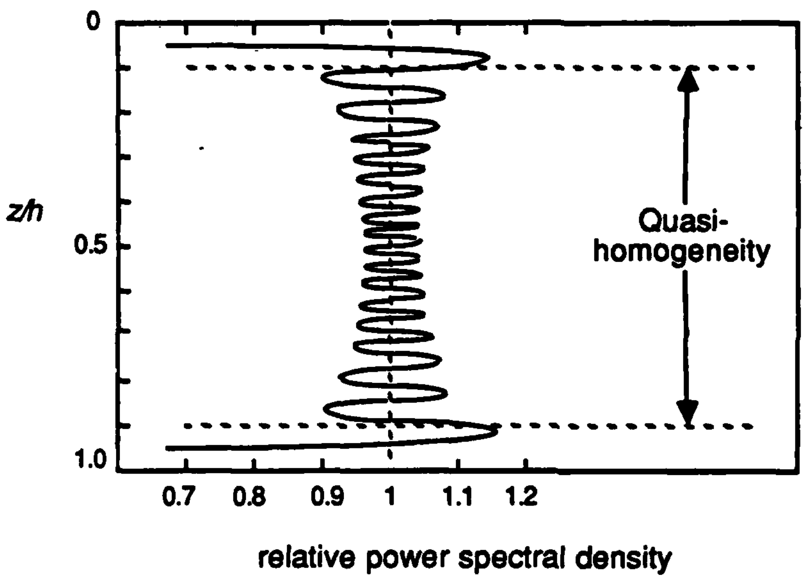


*Figure 3. Quasi-homogeneous zone for ambient noise as a function of depth in Buckingham model.*

Buckingham extends his shallow water ambient noise model to a wedge-shaped ocean in his 1985 paper. Again, he finds that, away from the boundaries and if a sufficient number of modes can propagate, a zone of quasi-homogeneity exists.

In an attempt to measure the source level of wind-induced ambient noise, which is an input of any environmental model, Kuperman and Ferla (1985) conducted an experiment in a shallow region of the Mediterranean Sea. They collected ambient noise during five consecutive days, as well as recording wind speed, wave height, and propagation loss data. By comparing the experimental data with predictions from an ambient noise model, the effects of the spectrum source level and propagation conditions are separated. It is found that wind speed influences noise levels more than the wave height does. Moreover, the contribution from the nearfield dominated the noise field at this site.

They plot the source spectrum level of wind-generated noise for various wind speeds between 10 and 40 knots, in the frequency range 50 to 3200 Hz. This is one example of cooperation between modelling and measurement in the process of improving both.

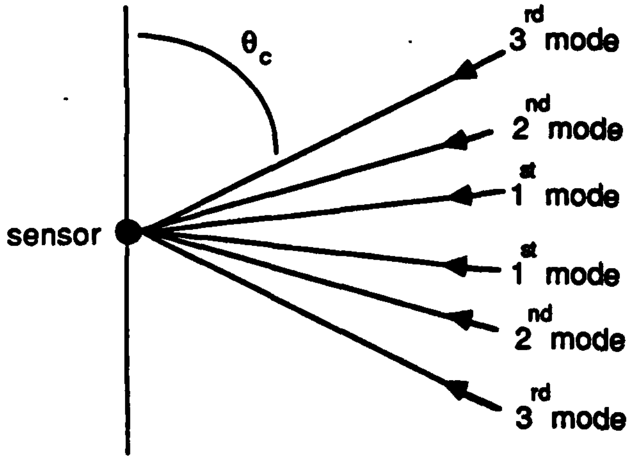


*Figure 4. Sketch of the discrete arrival angle of ambient noise in shallow water in Buckingham model.*

# 4. CONCLUSIONS

## 4.1 Experiment

The experimental data available from shallow water provide information about the ambient noise level dependence on bottom type, total depth, sea-state and wind speed. Results of a few experiments on horizontal directionality have been published, both from acoustic arrays and ocean bottom mounted geophones. Most data confirm that ambient noise in shallow water is considerably more site-dependent than its counterpart in deep water, and that a knowledge of the propagation characteristics of the bottom is of prime importance in the prediction of noise levels at a particular site. In other words, characteristics of the ambient noise at one site cannot be generalized to other sites unless it is known their acoustic properties are the same.

The areas of research which most need experimental data are the ones using multisensor information, in conjunction with complete knowledge of propagation conditions at the sites. The lack of data is most noticeable with respect to the vertical directivity of shallow water ambient noise. Such ambient noise data are needed to validate and improve the numerous ambient noise models and to set the free parameters of the theories, such as the source-directivity parameter $m$ for wind-generated noise (see Section 3.2). A study taking into account the influence of sensor depth and bottom types is very much needed.

As was demonstrated by Wilson, Wolf and Ingenito (1985) by their measurement of surf noise directivity, horizontal acoustic arrays can be used to isolate noise sources (see *Section* 2.4.3). Many more applications of this technique can be found. One can expect shipping and traffic noise to be highly directional in shallow water, as well as some forms of biological noise (e.g. whales). More use should be made of horizontal arrays to identify and study specific noise sources.

There still has not been any experiment on the influence of bottom currents on ambient noise in the ocean, mostly because of the experimental difficulties involved. Turbulence from oceanic currents was a factor which was strongly suspected as an important source of noise in several ambient measurements by ocean bottom-mounted hydrophones and geophones (Wenz, 1962; Bardyshev et al, 1971; Nichols 1981; Brocher and Iwatake, 1982; McGrath et al, 1976; Buck and Greene, 1980). A study of the correlation between current measurements and ambient noise data is needed to establish definitively whether there is a link.

The two hydrophone method advocated by Buck and Greene (1980) merits attention. For physically uncoupled hydrophones, as was their case, this method permits one to measure the true ambient noise power spectrum. If the use of the two hydrophone method was generalized for underwater ambient measurements, it would greatly help to resolve the controversy over the acoustic or non-acoustic nature of some of the infrasonic ambient noise.

## 4.2 Modelling

Acoustic environmental and propagation modelling, including summation of complex pressure at each hydrophone of an array, provides a very important insight into the effect of the existence of a waveguide on the array. General characteristics of the ambient noise at a particular site can now be predicted based on propagation data and wind speed. The simulation programs are at a stage where it is possible to test the response of different array configurations and signal processing to different environmental conditions. One can modify at will the geometry and weighting of the array, the position of the source, or the parameters of the environment. This allows one to test the response of the array under completely controlled conditions. It is also possible to separate the contributions from continuous and discrete modes, or from shipping and wind-generated noise, which is not possible with data from sea trials. This allows an inexpensive assessment of existing or new array design. The promising systems can then be put to the test in a real situation.

The main use of analytical models such as those developed by Buckingham (1979,1985) will be to place in perspective the important features of ambient noise in shallow water. This will be of help to interpret the numerical results from more general models run on computers.

Most of the environmental models discussed in Section 3.2 employ the shallow water attenuation model with rough boundaries developed by Kuperman and Ingenito (1977). However, this is a questionable choice when it is used to model wind-generated ambient noise. Their propagation model calculates only the coherent component of sound, corresponding only to the rays which underwent specular reflection. The coherent component represents the minimal magnitude of the signal, but the total acoustic energy arriving at the detector could conceivably be substantially larger than the calculation of the coherent part indicates. It therefore does not seem appropriate to use this propagation model in the case of ambient noise, when the quantity of interest is the total power arriving at the hydrophone. On the other hand, the unaccounted part of the acoustic energy is likely to become significant only when either or both of the boundaries present important roughness. Also, one must consider the subsequent propagation of the scattered energy: if it is scattered into higher-order, more highly attenuated modes, it may not contribute substantially to the resulting noise field.

Nonetheless, the use of simulation programs should become common place as a very useful tool in understanding and predicting ambient noise in shallow water, and subsequently in designing acoustic arrays and signal processing methods adapted to specific shallow water environments.

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The ~~Technical Memorandum~~ reviews the literature since 1962 on underwater ambient noise. Particular attention is paid to those factors which influence noise levels and directionality in shallow water. Infrasonic noise, seismic noise in the sea bed, ship generated noise, and wind generated noise are considered. Noises of biological origin are acknowledged but not described in detail. The importance of understanding sound propagation phenomena, including bottom interaction, and of modelling is discussed. Suggestions for future research on shallow water noise are offered. This document does not constitute a summary of results, but rather is an account of work done and principles applied.

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