# Surface generated underwater noise in open and enclosed waters

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## ABSTRACT

Measurements of surface noise in open and enclosed waters show differences in spectral characteristics, particularly at frequencies below a few hundred hertz. This paper compares measurements in Woronora Dam, a freshwater reservoir south of Sydney, with those from the partly enclosed waters of Spencer Gulf and with measurements in the open ocean. It also discusses possible reasons for the differences and the insights these give to mechanisms of sound generation by breaking waves. The lowest measured noise levels in Woronora Dam were well below those usually measured at sea. Very low frequency noise cause by a non-linear effect of surface wave interaction peaked at higher frequencies than at sea, consistent with the higher frequency peak in the surface wave spectrum. Noise from breaking waves at frequencies above 100 Hz showed a similar dependence on wind speed as observed at sea for locally measured wind speeds, but levels were much lower for the same wind speeds and did not show the low frequency (below a few hundred hertz) component evident at sea.

## 1 INTRODUCTION

The extensive studies of ambient noise in the ocean during the Second World War established that noise from breaking waves over the sea surface is a major component of the noise (Knudsen et al., 1948) and a dependence of the noise level on the sea state was evident. From a large number of measurements, Wenz refined the description of sea surface noise in terms of a dependence on wind speed rather than sea state (Wenz, 1962). While wind speed and sea state are correlated in the equilibrium conditions of a fully developed sea, this is not generally the case. His well known wind-dependent curves are spectra with broad peaks at around 500 Hz and with levels increasing with wind speed. These spectra decreased with increasing frequency above 500 Hz at a rate asymptotic to about 18 dB/octave. While they decreased below 500 Hz, they were truncated at 100 to 200 Hz (depending on wind speed) below which wind-dependent noise was obscured by the noise of shipping. Measurements by Perrone showed that the noise from breaking waves was far better correlated with wind speed than with wave height, with the wave height lagging he wind speed (Perrone, 1969). This is contrary to the expectation that noise from breaking waves should depend on wave height and supported the classification in terms of wind speed by Wenz. Hence the noise from breaking waves has become known as “wind-dependent noise.”

Wind-dependent noise may be considered to be the prevailing ambient or background noise of the ocean, since it is always present and usually the dominant component over some part of the frequency band. The other main components are traffic noise (the noise of distant shipping) and biological choruses (produced when large numbers of animals are calling) (see Cato, 2012 for a detailed discussion including comparison with noise in the Australian Indo-Pacific region). Traffic noise varies substantially with geographical region and the presence of biological choruses varies with time of day and season. Wind-dependent noise varies by about 20 dB as wind speeds vary between 5 and 30 knots (2.5 and 15 m/s), as commonly occurs in the ocean. Although sound propagation in the ocean is very variable, a 20 dB change typically occurs over a factor of ten in distance. Hence this typical variation in wind speeds causes a wide variation in the range of detection of sonar and in the distance marine animals can hear sources of interest – typically by a factor of ten. Understanding and quantifying wind-dependent noise is thus important for understanding sonar performance or the use of sound by marine animals.

## 2 THE NATURE OF SEA SURFACE NOISE AND THE LIMITATIONS IN KNOWLEDGE

There appear to be two main components to wind-dependent noise: the broad peak in the spectra at around 500 Hz (the mid frequency component) and a low frequency component dominant at frequencies below 100 to 200 Hz. The characteristics of the two components are shown in Figure 1 from ambient noise prediction curves for the Australian Indo-Pacific region (Cato, 1997) and are broadly similar to the spectra observed in other ocean areas, though there are some interesting differences in partly enclosed waters which are discussed below. The change in shape of the spectra at 100 to 200 Hz differentiates the mid frequency component from the low frequency component. The mid frequency component extends to tens of kilohertz and the characteristics are well established from a large number of measurements, although there may be some variation with geographical region, wind fetch and wave age. This component is generated by the oscillation of myriads of air bubbles immediately on their formation from air is entrainment as surface waves break (Banner and Cato, 1988; Medwin and Beakey, 1989).

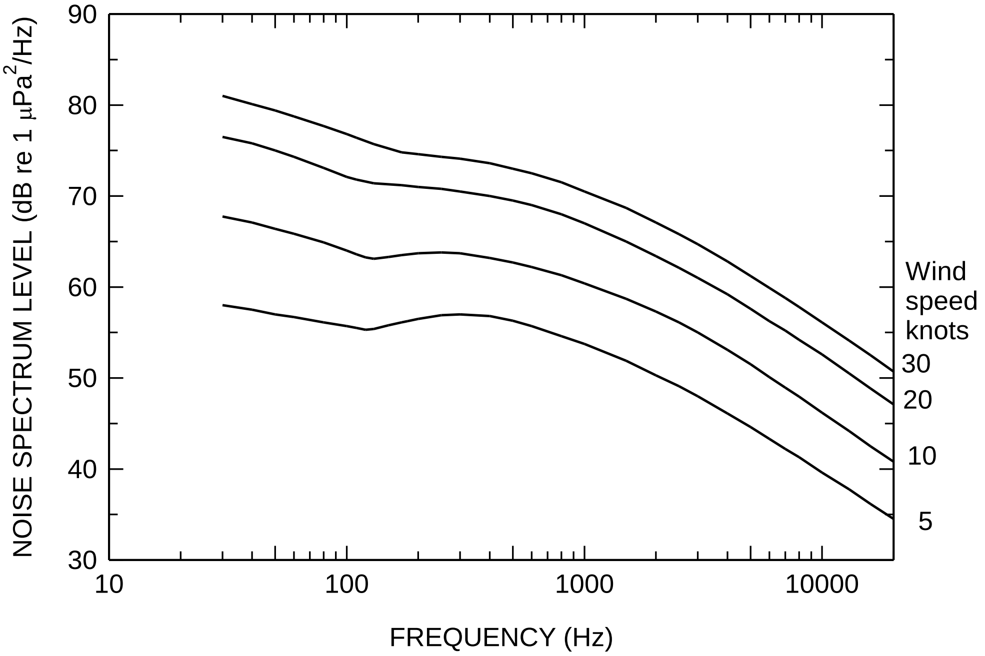


Figure 1. Wind-dependent noise predictions for the Australian Indo-Pacific region (Cato, 1997) showing the two components.

The low frequency component of wind-dependent noise is less well understood because it is more difficult to measure. In the northern hemisphere, where most measurements of ambient noise have been made, traffic noise often obscures this low frequency component. Although the results presented by Wenz showed evidence this component (Fig. 1.e, Wenz, 1962), he did not include a low frequency component in his ambient noise prediction curves, and many later prediction methods have followed Wenz (e.g. Urick, 1983). Many studies, however, have shown evidence for the low frequency component and quantified it as a function of frequency and wind speed. These have included studies in the northern hemisphere (e.g. Piggott, 1964) but particularly around Australia and New Zealand (e.g. Cato, 1976; Burgess and Kewly, 1983; Cato and Tavener, 1997a) and waters shielded from traffic noise (e.g. Reeder et al. 2011). Even so, there is significantly more variation in the reported spectra of the low frequency component compared with the mid frequency component. The reasons for this variation and the factors upon which it depends are not clear.

## 3 MEASUREMENTS

Measurements were made from the Defence Science and Technology Group's hydrophone calibration facility on a pontoon in Woronora Dam, a fresh water supply dam south of Sydney. Ambient noise, wind speed and surface wave height measurements were made simultaneously using the setup shown in Figure 2. The acoustic recordings were made using a Z3B hydrophone (General Instrument Corporation) and preamplifier in a canister moored on the bottom in 35 m water depth about 100 m from the pontoon. The system was connected to the pontoon by cable and the data recorded on an FM tape recorder (Nagra IV-SJ). The frequency response recorded was from 0.33 Hz to 24 kHz (–3 dB points). The recording chain was calibrated *in situ* by projecting known signals from the pontoon, as well as calibrating the individual components. Initial measurements showed particularly low noise levels, so low that they were close to the electronic noise of the preamplifier which had been designed for use at sea. Consequently, this was replaced for the measurements by a Princeton Applied Research model 185, normally used in their phase lock amplifier. It was modified to include a power supply, a calibration test signal and a remote switching control. This preamplifier had a very high input impedance and exceptionally low electronic noise, particularly at low frequencies.

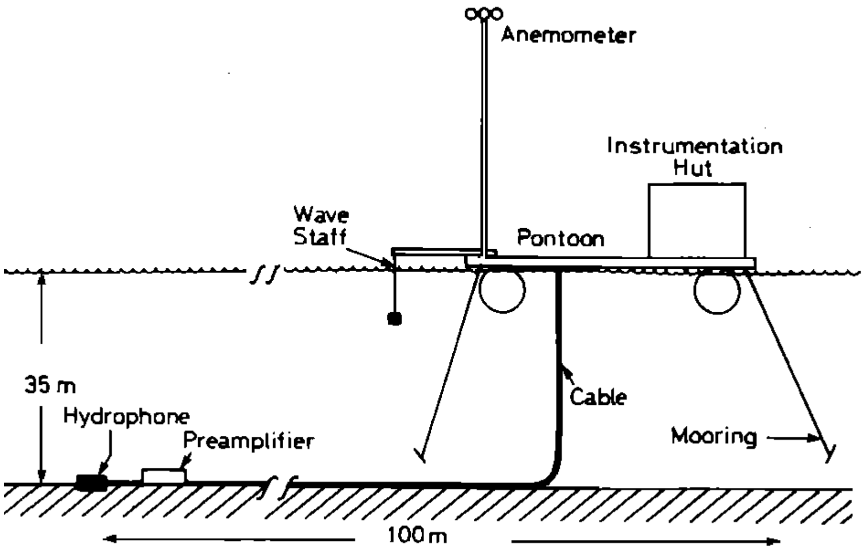


Figure 2. The measurement setup in Woronora Dam.

The surface wave height was measured by means of the variation in the capacitance between a vertical insulated wire and the surrounding water as the water level varied. The resulting electrical signal amplitude modulated a 5 kHz tone that was then recorded on a Nagra III tape recorder. The wind speed was measured with a Casella anemometer on a mast fixed to the pontoon at a height of 7.5 m and corrected to the equivalent at the standard height of 10 m, and recorded by a data logger.

Comparison is made with measurements at a number of sites in the partly enclosed waters of Spence Gulf (SA) and at two sites off Perth (WA). The water depths were 40 m except for one site off Perth where it was 400 m. Ambient noise was sample recorded from an ITC 1032 hydrophone by an autonomous system moored on the sea floor. At all 40 m depth sites, wind speed was measured by a Young anemometer at 3 m height on a mast on a buoy and mooring designed to maintain the mast as close to vertical as possible. The result were corrected to the standard 10 m height. See Cato et al. (Cato et al.,1995) and Cato and Tavener (Cato and Tavener, 1997a) for more details.

## 4 RESULTS

An example of the ambient noise spectrum in Woronora Dam for a wind speed of 8 m/s (about 16 knots) is shown in Figure 3 together with the system electronic noise. The broad peak at 500 to 1,000 Hz is the mid frequency wind-dependent noise component and is about 15 dB lower than this component at the same wind speed in the Wenz curves (Wenz, 1962) or the Australian ocean measurements (e.g. Cato, 1997). The level of this peak varies with wind speed and the frequency of the peak moves lower with increasing wind speed (range 2 to 16 m/s). The low frequency component, however, is missing. Below 100 Hz, the data show no dependence on wind speed. At 100 Hz, the measurements are below the lowest levels measured at sea in the many measurements in the Australian Indo-Pacific region (Cato, 1997). Hence ambient noise in Woronora Dam is characterised by being much lower than measured at sea with no evidence of the low frequency component of wind-dependent noise.

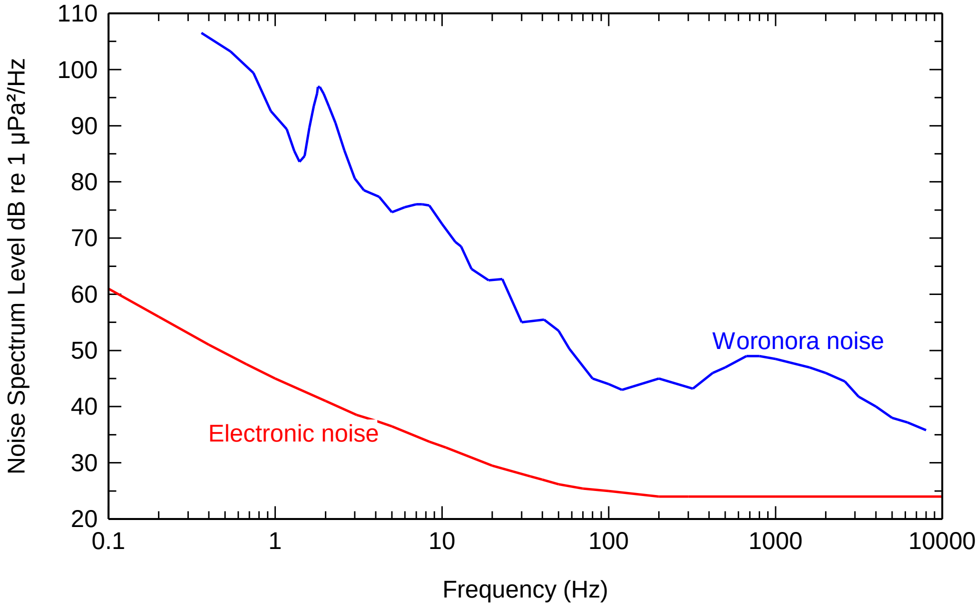


Figure 3. An example of the ambient noise spectra in Woronora Dam for a wind speed of 8 m/s (about 16 knots) together with the measuring system electronic noise.

The peak in the spectrum at 2 Hz is the non-linear effect of interaction between surface waves of similar frequency but opposite or almost opposite wave number. This peak is well predicted by theory using the surface wave height measurements as a function of frequency from the pontoon and using the horizontal spread in surface wave height wave number spectral from measurements at sea (Cato, 1991b). This peak is at a much higher frequency than observed at sea where it is typically in the frequency range 0.2 to 0.3 Hz for a well developed sea. This difference is directly attributable to the differences in the frequencies of the peaks in the surface wave spectra, since the peak in the noise spectra occurs at twice that in the surface wave spectra. In Woronora Dam, the surface waves are much smaller than at sea and the sprectra peak at about 1 Hz compared with around 0.1 Hz or so in the ocean.

Measurements of wind-dependent noise in partially enclosed sea waters show some departures from the general characteristics measured in open waters and illustrated by the spectra of Figure 1. The trends are for the low frequency component levels to be lower than in the open ocean while those of the mid frequency component are similar. Also and the peak in the mid frequency component tends to move to lower frequencies as wind speeds (and thus noise levels) increase, so that it dominates the low frequency component. See Cato and Tavener for a comparison of measurements in the partly enclosed waters of Spencer Gulf with those off Perth (Cato and Tavener, 1997a), Poikonen and Madekivi for measurements in partly enclosed brackish waters in the Gulf of Finland (Poikonen and Madekivi, 2010), and Reeder et al. for measurements in the enclosed waters of the Tongue of the Ocean (Reeder et al. (2010). The Woronora results show similarity in the dominance of the mid frequency component and the tendency of the spectral peak to move to lower frequencies with increasing wind speed.

## 5 DISCUSSION

Consideration of the possible mechanisms of sound generation of wind-dependent noise components may help to explain the differences in measurements between, Woronora Dam, partly enclosed sea waters and open ocean waters.

While the oscillation of bubbles formed by wave breaking appears to be the source of the mid frequency component of wind-dependent noise, it seems unlikely that this is the mechanism for the low frequency component, based on the bubble size distributions typically measured in the ocean. The resonant frequency of an oscillating bubble is inversely proportional to the bubble radius (Strasburg, 1953) and the estimated frequencies from the measured bubble sizes are consistent with the mid frequency but not the low frequency component. It has, however, been suggested by Properetti and independently by Carey and Browning that collective oscillation of clouds or plumes of bubbles formed when the orbital motion of a breaking wave takes the bubbles downwards may be the source of the low frequency component (Properetti, 1988; Carey and Browning, 1988). Each produced models of the sound generated and considerable support for this mechanism has been shown by laboratory measurements by Loewen and Melville (Loewen and Melville, 1994). Such bubble clouds may extend several metres below the surface (Thorpe 1982).

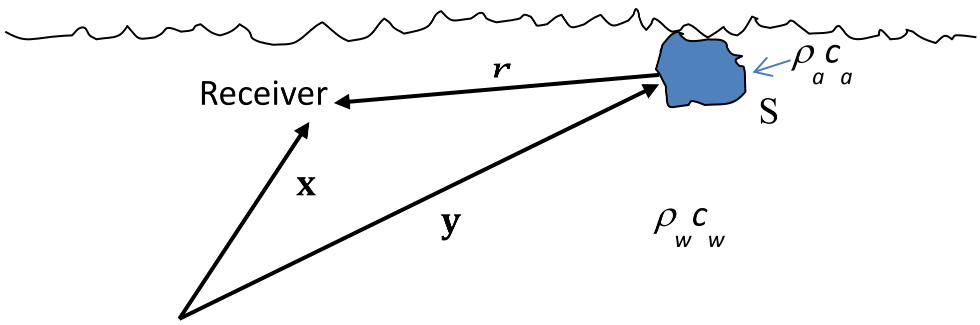


Figure 4. Diagrammatical representation of sound generation by bubble clouds.

Some insight into the mechanism of sound generation by bubble clouds can be provided by the theory of sound generation by oscillation fluid interfaces, i.e. surfaces separating fluids of different density and/or sound speed (Cato, 1991a). The bubble cloud will oscillate as a monopole acoustic source if the sound pressure at position **x** and time *t* is given by

$$p_m(\mathbf{x}, t) = \frac{1}{4\pi c_0^2} \int_S l_i \frac{\partial}{\partial t} [(\rho_w c_w^2 - \rho_a c_a^2) u_i ] \frac{dy}{r} \tag{1}$$

where $l_i$ is the direction cosine normal to the surface in the outward direction, $\rho$ and $c$ are density and sound speed respectively and subscripts $w$ and $a$ refer to values either side of the interface ($c_0$ is chosen as the speed of sound at the receiver). For an air bubble in water, $w$ would refer to the water and $a$ would refer to the air inside the bubble. For a bubble cloud, $w$ would refer to the surrounding water and $a$ to the fluid mixture of water and bubbles inside the cloud. Also, $u_i$ is the velocity in the $x_i$ direction and **y** is the position of an element of source and $r = |\mathbf{x} - \mathbf{y}|$. The integrand is to be evaluated in retarded time $\tau = t - r/c_0$.

The points to note here are that the source strength depends on the change in volume of the cloud and the difference in $\rho c^2$ either side of the interface. If Equation 1 is applied to an air bubble in water, the very large difference in $\rho c^2$ between air and water shows why a bubble is such a significant source. The density inside a bubble cloud is similar to that in the surrounding water, but the difference in the speed of sound inside the cloud compared to that of the surrounding water may be substantial. Prosperetti points out that even for a 1% gas volume fraction, the speed of sound inside the cloud would be about 100 m/s, even though the density would be little different to that of water (Prosperetti, 1988). This would provide a large difference in $\rho c^2$.

A significant difference between Woronora Dam and the open ocean is that the surface waves in the Dam are very small and there is no swell. In the partly enclosed waters mentioned above, the swell is much smaller than in the open ocean because the dimensions do not allow the very long fetch required to develop large swell. Bubble clouds require the orbital motion of swell to drive the bubbles down to significant depth to produce the clouds. The scale of orbital motion increases with surface wave length and swell has large wave lengths. Hence, if bubble clouds are the source of the low frequency wind-dependent component, you would expect this component to be absent in Woronora Dam and much lower in partly enclosed waters. This may help explain the observed differences in the level of the low frequency component.

Another difference between Woronora Dam and the ocean is the fresh water versus sea water. Bubble production in fresh water is substantially less than in sea water (Slauenwhite and Johnson, 1999) possibly by as much as a factor of ten. The much smaller number of bubbles generated may partly explain why the noise levels in the Dam were substantially less than in those in the open ocean.

The surface area in Woronora Dam is a lot less than in the ocean and this may explain some of the difference in noise levels. However, the downward directionality of the sound would tend to mitigate this difference. Bubbles and bubble cloud sources are close to the surface so the interference with their surface image would result in the energy being radiated preferentially downwards. For example, a simple model shows that about 90% of the energy arriving by direct path at a hydrophone on the bottom comes from an area at the surface with radius three times the water depth and for one bottom reflection about 9 times the water depth (Cato and Tavener, 1997b). These areas are within the area of the water surface in the Dam. The effect of bottom reflected paths is to extend the area of sources but this is compensated for by the greater spreading loss in propagation to the receiver. The reflection loss would further reduce the contribution of bottom reflected paths. Further modelling is required to understand the significance of the surface area as an explanation of the differences in levels between Woronora Dam and the ocean.

## 6 CONCLUSIONS

There are some interesting and important differences between the wind-dependent noise in Woronora Dam, partly enclosed seas and the open ocean. Further studies of these differences and their causes may improve our understanding of wind-dependent noise in terms of the sound generation and propagation to a receiver, and thus improve our ability to reliably predict wind-dependent noise.

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