BUBBLES AND THE SOUND OF BREAKING SURF

GB Deane

Marine Physical Laboratory, 0238
Scripps Institute of Oceanography
La Jolla, CA 92093-0238

ABSTRACT

Wave breaking, whether induced by wind-wave interaction in the open ocean or shoaling in the surf zone, is accompanied by the entrainment of air. The volume ratio of air to water during breaking is large and can exceed 50% near the breaking crest[1]. The entrained air forms bubbles, which range in diameter from 10's of microns to centimetres and are packed into plumes immediately beneath the breaking wave crest. The subject of this paper is the effect that these bubbles have on the underwater noise that accompanies wave breaking. There are two acoustic effects of interest, which are the pulse of sound a bubble radiates at the instant of creation and the strong acoustic absorption of quiescent bubble clouds.

The burst of sound that bubbles radiate at the instant of creation is well known[2], and it is now generally accepted that the sound of ringing bubbles is responsible for the wind-induced component of oceanic ambient noise above a few hundred hertz. Similarly, ringing bubbles are the dominant source of underwater surf noise between 500Hz and 50kHz[3]. Typically, newly formed bubbles generate sound for a few 10's of milliseconds but remain in the water column for 10's to 100's of seconds.

In their quiescent state, clouds of bubbles significantly alter the acoustical properties of bubble-free water. The presence of the bubbles reduces the sound speed and increases the absorption relative to the bubble-free values. In the low frequency limit, where absorption is negligible, the classical result for the change in sound speed is given by Wood's equation[4]. In the high void fraction bubble plumes formed beneath breaking surf, the sound speed can fall to 1/3 of its bubble-free value and absorption values as high as 100dB per meter have been observed[5]. The strongly absorbing, quiescent bubbles left in the bubbly residue behind shoaling waves (see Fig. 1) cause the noise from breaking surf to exhibit a distinctive radiation pattern. The clouds of bubbles absorb most of the sound radiated from the breaking crest, with the exception of the break points at the crest ends. The net effect is that, from behind the wave, the breaking noise appears to radiate from compact acoustic sources which follow the ends of the breaking wave crest.

1. ACOUSTICALLY ACTIVE BUBBLES AND SURF NOISE GENERATION

Fig. 1 shows two breaking waves observed from the cliffs of La Jolla Shores overlooking Scripps Pier. The pier pilings in the background, spaced 30 feet apart, provide a reference scale.

BUBBLES AND THE SOUND OF BREAKING SURF

The colour of the water varies according to the amount of air entrained and the white areas indicate regions with high void fractions of air. The breaking wave crest is the foamy region at the leading edge of the wave. The wave break points are at the ends of the breaking crest and delineate the region of breaking and unbroken crest. The bubbly residue is the region of bubble-filled water that trails the breaking crest.

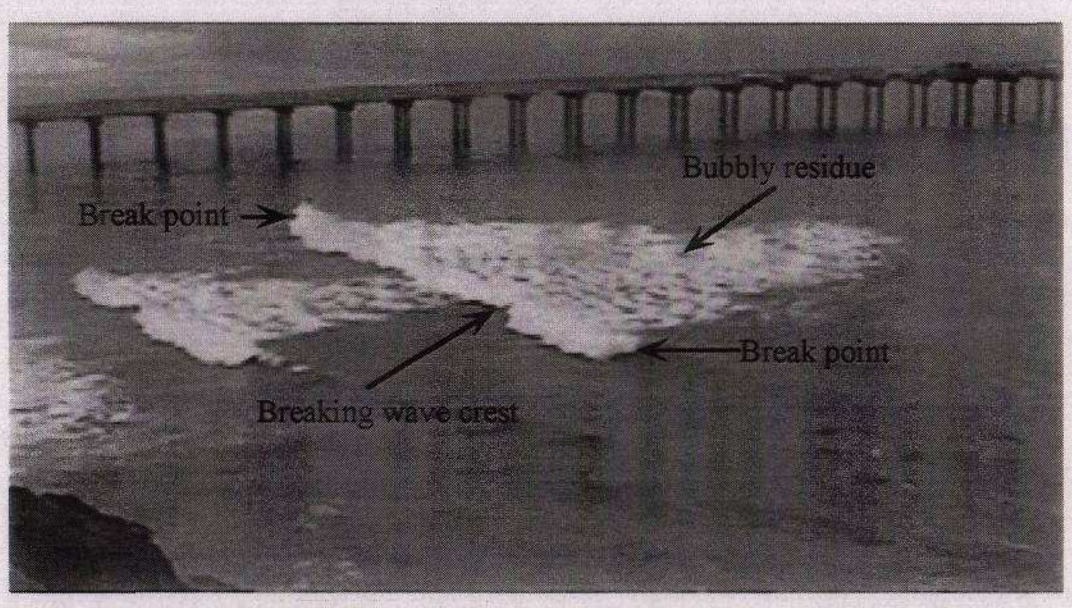

Figure 1: The foam patterns made by two wave breaking north of Scripps Pier.

As a wave shoals and breaks, a series of bubble plume injection events occur. Fig. 2 shows an underwater photograph of the bubble plumes formed beneath breaking surf at La Jolla Shores beach. The formation of such plumes is accompanied by the creation of a large number of bubbles, each of which radiates a pulse of sound at the moment of formation. The overall effect is a broad-band burst of noise.

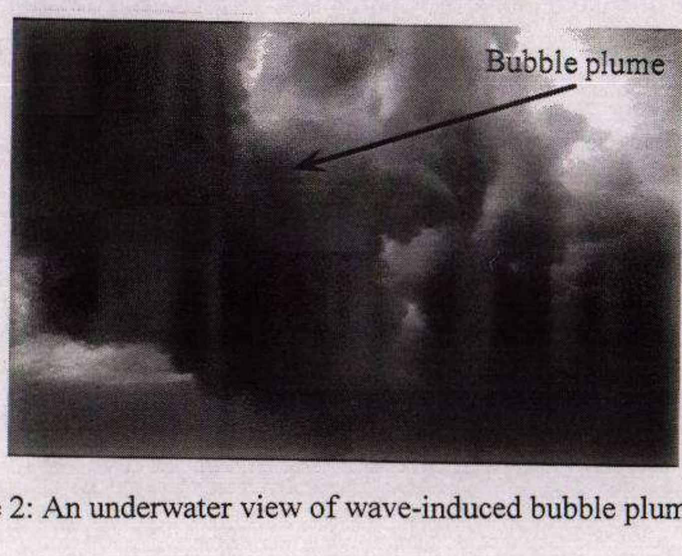

Figure 2: An underwater view of wave-induced bubble plumes.

BUBBLES AND THE SOUND OF BREAKING SURF

Fig. 3 shows spectrograms of noise measured directly beneath two waves, which broke along only a few meters of wave crest and consequently formed only a few bubble plumes. The spectrograms

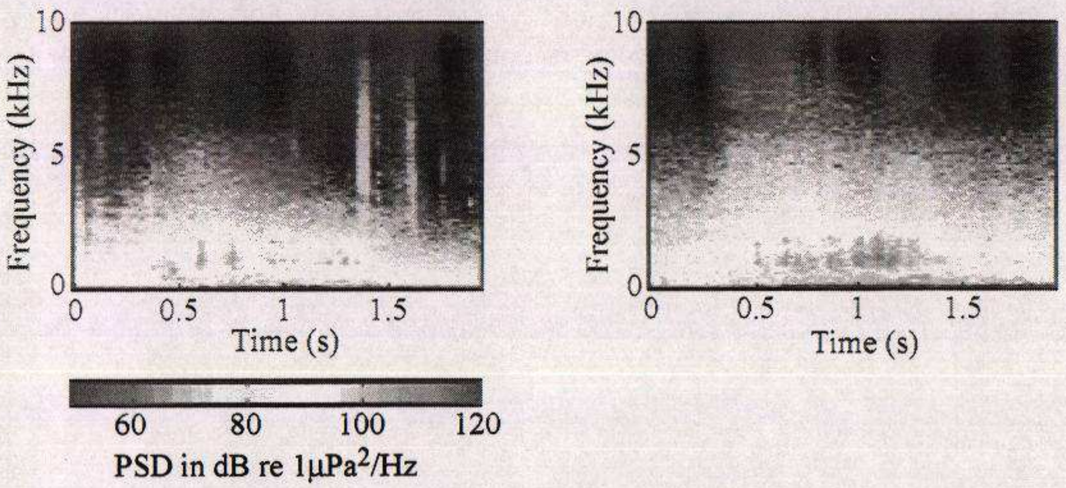

Figure 3: Spectrograms of breaking wave noise.

show a number of vertical bands, corresponding to broad-band noise bursts that persist for roughly 50ms. The strong implication is that bubble formation is intermittent in nature, and most likely associated with the formation of discrete bubble plumes. Breaking waves with plume injection rates greater than about 20 events per second create bursts of sound which overlap and the wave noise spectrograms for more energetic breaking waves appear relatively uniform. The time-averaged power spectral density of the noise from many plume injections is shown in Fig. 4. This figure shows the power spectral density of surf noise measured approximately 20m behind energetically breaking surf. Sound levels significantly higher than the background noise spectrum can be seen over a frequency band from 400Hz to 22.5kHz, which was the upper limit of the recording system.

2. ACOUSTICALLY QUIESCENT BUBBLES AND SURF NOISE DIRECTINALITY

Bubbles entrained in water both decrease the sound speed and increase acoustic absorption beyond bubble-free values. The increased absorption in particular has two significant effects on wave noise propagation. The first is related to the generation of sound by forming bubble plumes. Because of the high void fractions of air in these plumes, the acoustic absorption is very high and the sound from ringing bubbles in the interior of the plume is rapidly absorbed. The net result is that only a thin shell of ringing bubbles on the exterior of the plume are audible outside the plume. The second effect is caused by the bubbly residue trailing the wave (see Fig. 1). As the wave moves shoreward, the breaking wave crest injects acoustically active plumes adjacent to the strongly absorbing bubbly residue. The residue absorbs the seaward propagating noise radiated from the entire length of breaking crest with the exception of the crest break-

BUBBLES AND THE SOUND OF BREAKING SURF

seaward side, the breaking wave noise appears to radiate from compact regions which follow the break-point trajectories.

An accurate description of these effects relies on an understanding of acoustic absorption in bubble plumes, which in turn requires knowledge about the number and distribution of bubble sizes within plumes. The very high void fraction of air in these plumes makes the distribution difficult to

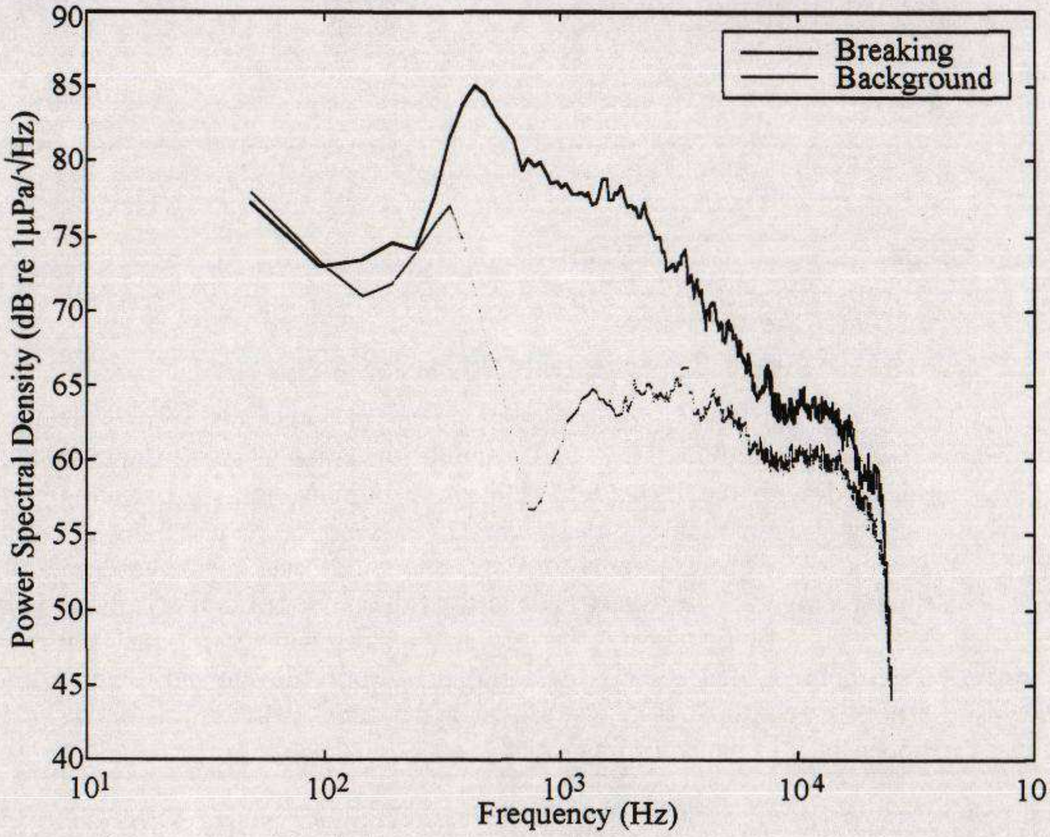

Figure 4: The time-averaged noise power spectral density for a single breaking wave.

measure using traditional acoustical and optical bubble sizing methods. However, the recent development of an underwater imaging camera designed to operate in high void fractions has provided some initial size distribution data from within and immediately beneath breaking wave crests. The camera operates by creating a thin sheet of light directly in front of a camera installed in an underwater housing. Any air-water boundaries within the illuminated water volume scatter light into the camera, providing images such as those illustrated in Fig. 5.

The pictures in Fig. 5 were taken within bubble plumes beneath small (order 15cm) breaking waves in the surf zone. Bubbles in the water column appear as bright rings in the images, which

BUBBLES AND THE SOUND OF BREAKING SURF

can be sized and counted using automated computer image analysis. The result of such an analysis is shown as a bubble size distribution plot in Fig. 6. The plot shows the measured bubble density, in bubbles per cubic meter of water, per micron of bubble radius increment, as a function of bubble radius.

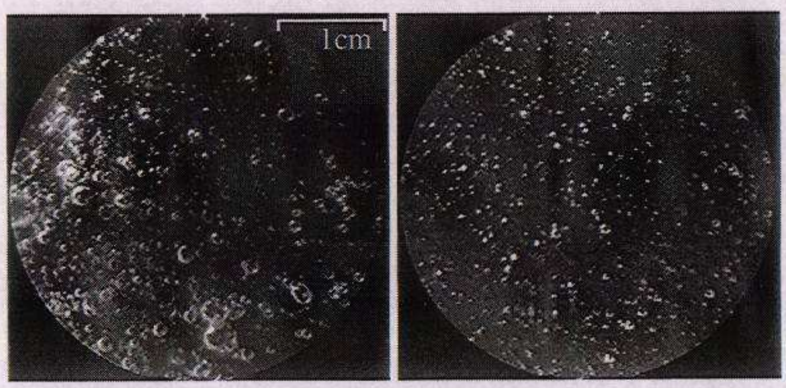

Figure 5: Images of bubbles taken in wave-induced bubble plumes.

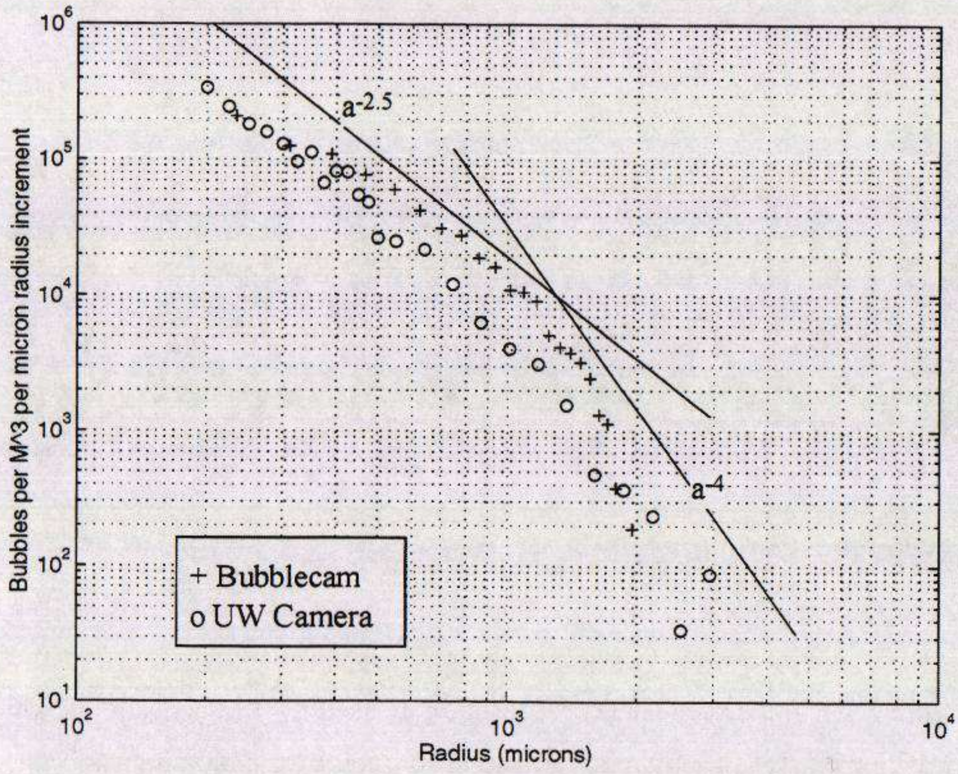

Figure 6: Bubble size distributions beneath breaking surf.

BUBBLES AND THE SOUND OF BREAKING SURF

Measurements of the size distribution made beneath waves of different height and on different days are shown for comparison. The void fraction for these distributions is roughly of order 5%. From the distributions in Fig. 6, it is possible to calculate the acoustic absorption of the bubbly mixture, which leads to the prediction that the sound speed in surf-induced bubbles plumes can be less than 100m/s and absorption can be higher than 80dB per meter at 1kHz.

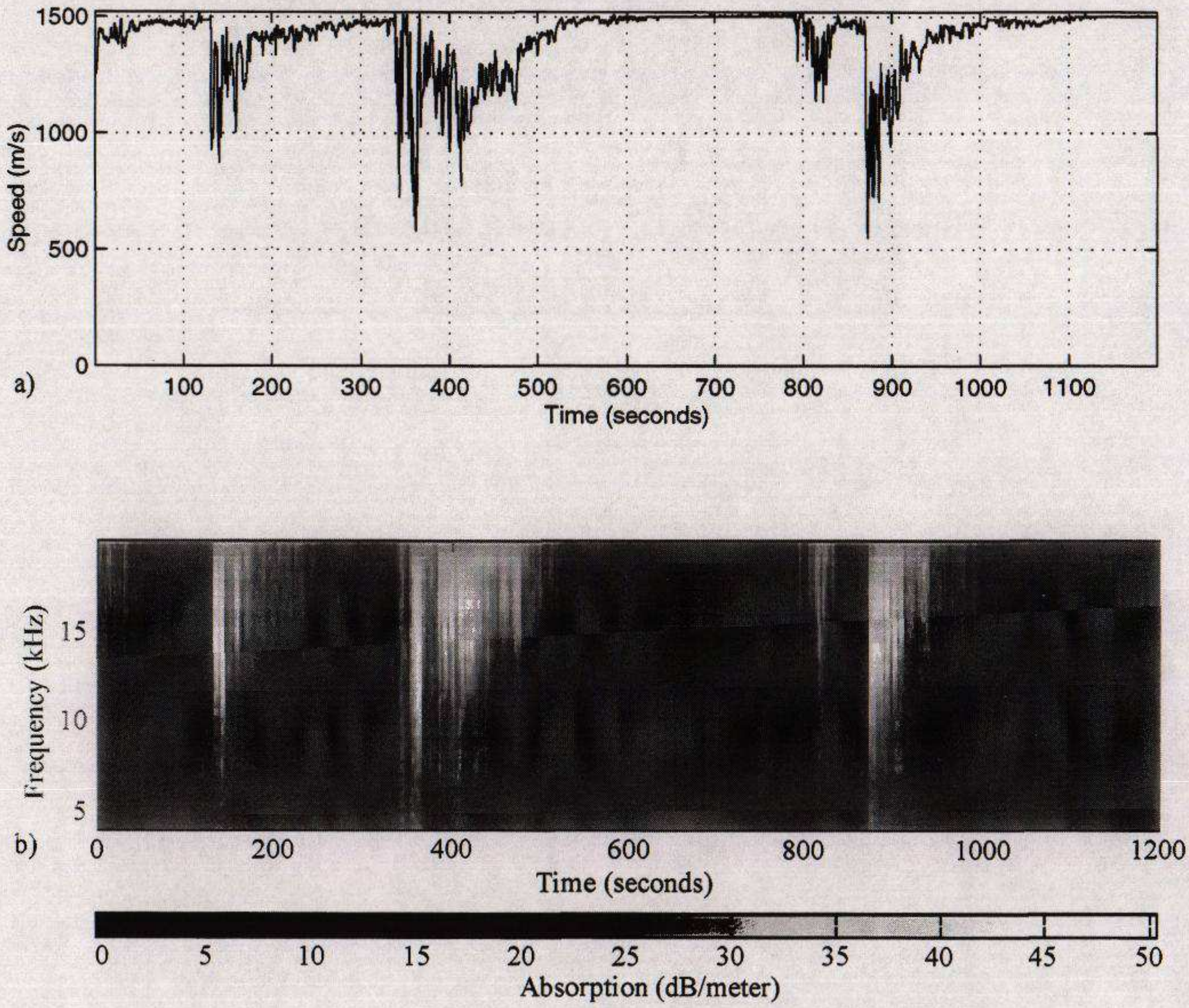

Figure 7: a) Sound speed and b) absorption measured 70cm beneath breaking surf.

Actual measurements of the sound speed and absorption by bubble plumes in the surf zone are in substantial agreement with these conclusions, although the effects are not quite so severe as those predicted using Foldy's equation. Fig. 7a shows a 20 minute plot of the sound speed as a

BUBBLES AND THE SOUND OF BREAKING SURF

function of time inferred from time-of-flight measurements made 70cm beneath breaking surf over a 30cm path. Three breaking events can be seen in the plot at 120s, 330s and 800s, and sound speeds as low as 600m/s are can be seen (the lowest sound speed observed was 300m/s). The duration of the events is around 300s. Over this time-scale, the sound speed increases as bubbles are lost the water column through dissolution and buoyancy. Fig 7b shows measurements of the acoustic absorption as a function of frequency and time over the same time and propagation path as the time-of-flight measurements. Periods of low sound speed can be seen to coincide with periods of high absorption, with values of 50dB per meter being approached above 10kHz.

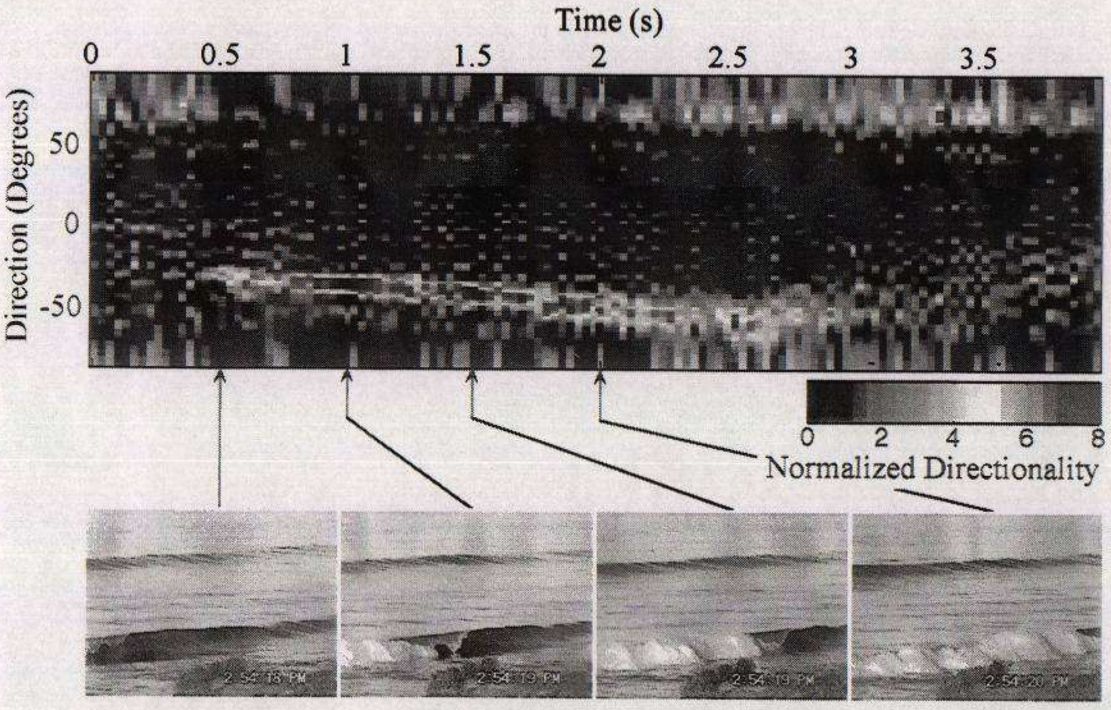

Figure 8: The horizontal directivity of a single breaking wave measured behind the wave.

The final figure, Fig. 8, shows the effect of the absorbing bubbly residue on the directionality of the surf noise observed on the seaward side of the breaking wave. The top panel shows the measured wave noise directionality of a single shoaling wave inferred from broad-band wave noise coherence measurements made approximately 25m behind the breaking wave. The normalised directionality is plotted as a function of azimuthal angle and time with positive angles indicating shoreward propagating energy and negative angles indicating seaward propagating energy. The bright red stripe running diagonally along the bottom of the plot follows the track of the shoaling wave break point, as shown by the sequence of photographs beneath the directionality plot.

BUBBLES AND THE SOUND OF BREAKING SURF

3. REFERENCES

[1] E. Lamarre and W. K. Melville, 'Void fraction measurements and sound-speeds in bubble plumes generated by breaking waves', J. Acoust. Soc. Am., 95 p317-1328 (1994)
[2] M. S. Longuet-Higgins, 'Bubble noise mechanisms-A review', in *Natural Physical Sources of Underwater Sound* (Kluwer Academic, Dordrecht, 1993) p419-452
[3] G. B. Deane, 'Sound generation and air entrainment by breaking waves in the surf zone', J. Acoust. Soc. Am., 102 p2671-2689 (1997)
[4] A. B. Wood, *A Textbook of Sound* (Macmillan, New York, 1955)
[5] G. B. Deane, 'Acoustic hot spots and breaking wave noise in the surf zone', J. Acoust. Soc. Am. (in press)