

MARINE MAMMAL SIGNALS IN BUBBLY WATER

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1. INTRODUCTION

Marine mammal calls often propagate through bubbly water, be it generated under breaking waves, wakes, or even by the mammals themselves. Two hypothetical circumstances are of particular interest: the possible use of acoustic signals to trap prey in bubble nets; and the possible ability of dolphin sonar to operate in bubbly water (such as the surf zone) that would confound the best man-made sonar, despite the fact that the dolphins possess 'hardware' which is comparatively mediocre [1].

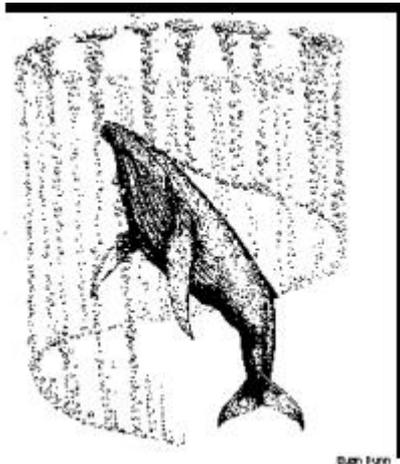
2. THE BUBBLE NETS OF HUMPBACK WHALES

For many years there has been speculation as to the mechanism by which humpback whales (*megaptera novaeangliae*) exploit bubble nets to catch fish [2]. It has been known for decades that single whales, or groups, might dive deep and then release bubbles to form the walls of a cylinder, the interior of which is relatively bubble-free (Figure 1a,b) [3]. The prey are trapped within this cylinder, for reasons previously unknown, before the whales lunge feed on them from below (Figure 1c). When the whales form such nets, they emit very loud, 'trumpeting feeding calls', the available recordings containing energy up to at least 4 kHz. Leighton *et al.* [2] proposed that these calls may trap the fish in the following manner. A suitable void fraction profile would cause the wall to act as a waveguide. Assume the scales permit the use of ray representation. Figure 2 shows how, with a hypothetical tangential insonification, the mammals could generate a 'wall of sound' around the net, and a quiet region within it. The natural schooling response of fish to startling by the intense sound as they approach the walls would, in the bubble net, be transformed from a survival response into one that aids the predator in feeding [2]. The frequencies in the feeding call are indeed in the correct range to excite resonances in fish swim bladders and, given their sensitivities [4], presumably such excitation could discomfort the fish sufficiently for it to return to the interior of the net.

Figure 2b plots the raypaths (calculated using standard techniques [5]) from four whales whose beam patterns are represented by a 10° fan of 281 rays, for a bubble net in which the void fraction increases linearly from zero at the inner and outer walls, to 0.01% at the mid-line of the wall. The proposed 'wall of sound' and quiet interior are clearly visible. Even if the whales do not create sufficiently directional beams and insonify tangentially, the bubble net might still function through its acoustical effects. The 'wall of sound' effect in Figure 2b is generated from those rays which impact the wall at low grazing angles. Those rays which never impact the wall do not contribute to the 'wall of sound'. If rays of higher grazing angle impact the net, they may cross into the net interior, though their amplitudes would be reduced by the bubble scattering, and attenuation alone would generate a quieter region in the centre of the net.

The actual acoustics of the cloud will of course be complicated by 3D effects and the possibility of collective oscillations; and even, speculatively, bubble-enhanced parametric sonar effects [6]

which might be utilized by whales, for example to reduce beamwidth or generate harmonics, sum- and difference-frequencies etc.



(a)



(b)

Figure 1: (a) Schematic of a humpback whale creating a bubble net. A whale dives beneath a shoal of prey and slowly begins to spiral upwards, blowing bubbles as it does so, creating a hollow-cored cylindrical bubble net. The prey tend to congregate in the centre of the cylinder, which is relatively free of bubbles. Then the whale dives beneath the shoal, and swims up through the bubble-net with its mouth open to consume the prey ('lunge feeding'). Groups of whales may do this co-operatively (Image courtesy of Cetacea.org). (b) Aerial view of a humpback bubble net (photo-



(c)

graph by A. Brayton, reproduced from [7]). (c) Humpback whales lunge feeding (Image courtesy of L. Walker, <http://www.groovedwhale.com>).

At frequencies sufficiently high to drive the bubble cloud in an inertia-controlled fashion, the bubbles produce an increase in sound speed. The wall is outwardly-refracting, and rays are no longer trapped within the cloud. The refractive effect of these bubbles on sound speed becomes negligible at even higher frequencies, although of course acoustic attenuation and scatter may be great. A variety of ray behaviours is possible, from reflecting straight off the net to traversing it and the interior with barely any refraction (Figure 2c) [2]. Such frequencies would not be effective in trapping prey, even if the prey could perceive them. However if scattering losses permit (and it is

by no means certain they would), is it possible that, given these refracted paths, such frequencies could be used for echolocation of the contents of the net?

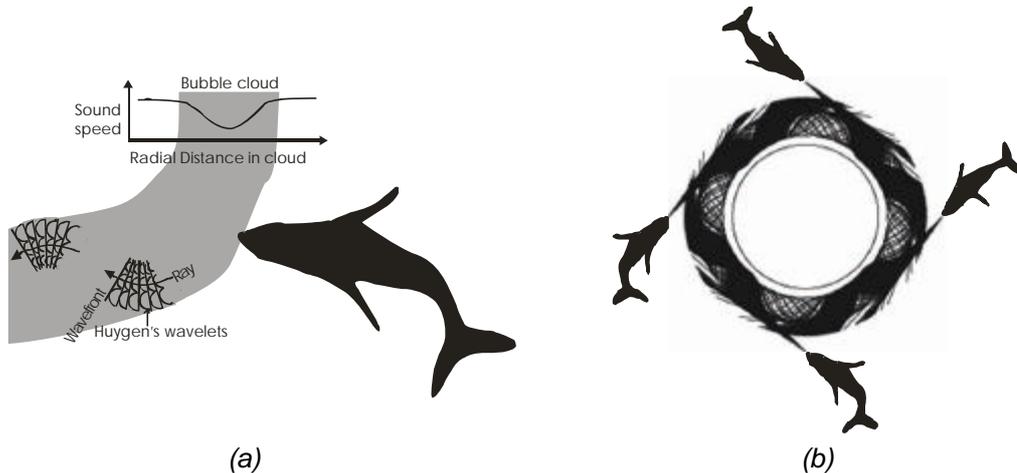
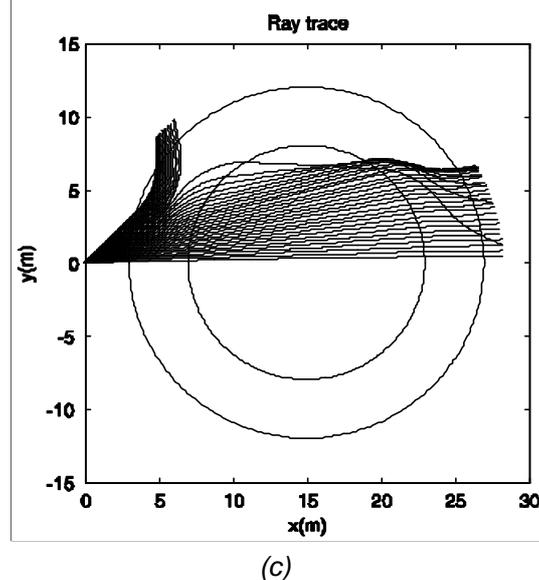


Figure 2: (a) Schematic of a whale insonifying a bubble-net (plan view), illustrating the sound speed profile in the cloud and, by Huygen's construction, sample ray paths. The sound speed profile assumes void fractions are greatest in the mid-line of the net wall, and assumes that the bubbles pulsate in stiffness mode. Hence the closer a Huygens wavelet is to the mid-line, the smaller the radius of the semicircle it forward-plots in a given time. Rays tend to refract towards the mid-line. (b) Four whales insonify an annular bubble net described in the text. The inner circle represents the inner boundary of the net wall. The outer boundary is obscured by the rays. Computed ray paths, 281 rays with an angular extent of 10° are used to model the call of each whale, refract as in (a). The rays gradually leak out, although some rays can propagate around the entire circumference.



Plotting of a raypath is terminated when it is in isovelocity water and on a straight-line course which will not intersect the cloud. This refers to rays whose launch angles are such that they never intersect the net; and to rays which, having entered the net and undertaken two or more traverses of the mid-line, leave it. (c) Example ray paths computed for the case where the sound speed increases towards the centre line of the annular bubble net. For this simulation, however, the source has a 45° beamwidth in order to illustrate the variety of ray bending that is possible (a 10° beam, as used in (b), tends to cause all rays follow a similar path, either traversing the net or refracting out of it, depending on the angle with which it intercepts the outer wall of the net). (Figure by T. G. Leighton, S. D. Richards and P. R. White [2]).

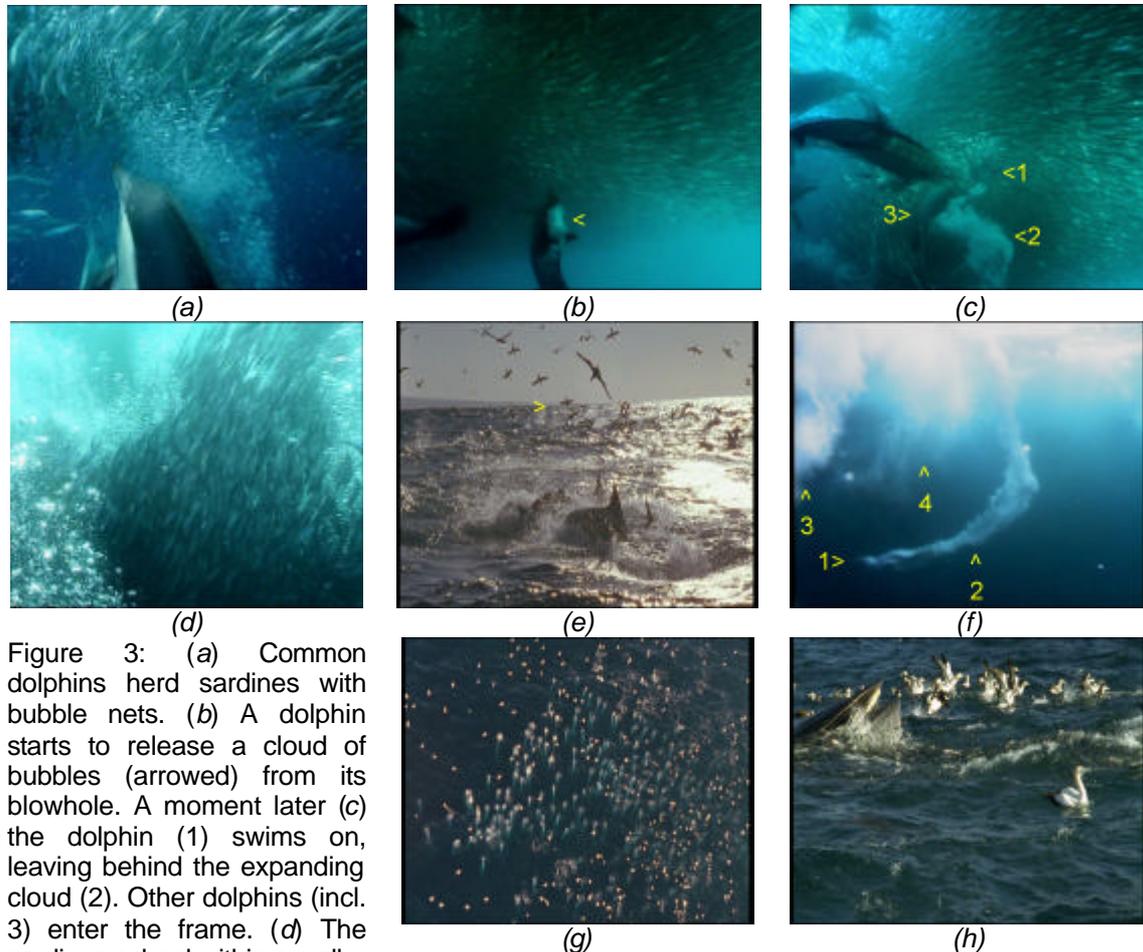


Figure 3: (a) Common dolphins herd sardines with bubble nets. (b) A dolphin starts to release a cloud of bubbles (arrowed) from its blowhole. A moment later (c) the dolphin (1) swims on, leaving behind the expanding cloud (2). Other dolphins (incl. 3) enter the frame. (d) The sardines school within a wall of bubbles that they are reluctant to cross, whilst (e) gannets dive into the sardine shoal to feed, folding their wings just before entry (arrowed). (f) On diving, a gannet (1) entrains a bubble plume (2). Plumes a few seconds old (3, with an older 4) have spread. (g) An aerial view shows hundreds of tight bubble plumes beneath airborne gannets. (h) A Bryde's Whale joins the feed. It surfaces with open mouth, which it then closes, sardines spilling from it. Images courtesy *The Blue Planet* (BBC). See also Byatt *et al.* [15].

With humpback whales the probability appears to be low. Echolocation is normally associated with *odontoceti*, and although there are suggestions that humpbacks may exploit it [8,9], there is to date no evidence that they have used it to locate schools of prey. Although there is evidence of directionality in the songs of humpback whales [10,11], Figure 2b should not be interpreted as implying they can generate a 10° beam – we do not know one way or the other. Similarly, the highest reported frequencies generated by humpbacks correspond to harmonics in recordings in excess of 15 kHz [12] and 24 kHz [11], close to the bandwidth of the recording equipment. Exploitation of the inertia-controlled regime, as described above, would probably require higher frequencies.

Leighton [13,14] however pointed out that some very interesting bubble acoustics may be involved with other marine creatures. This is the topic of the next section.

3. DOLPHIN ECHOLOCAION IN BUBBLY WATER

Dolphins have also been observed to feed using bubbles [15] (Figure 3a-d), and the echolocation clicks of bottle nosed dolphins (*tursiops truncatus*) for example have been found to contain frequencies up to 170 kHz [16]. It would perhaps be asking a lot for dolphins to identify fish amongst the strong bubble scatterers, although the environments which they naturally might encounter are similarly complex [17]. The prospect of trapping low frequency sound in a bubble cloud to herd prey, whilst simultaneously echolocating with higher frequencies, is attractive but perhaps unlikely.

For the bubble population assumed in the plotting of Figure 2b, the attenuation at 4 kHz (the higher end of the frequency range used in the feeding calls) has been calculated to be 6 dB/m. However at the higher frequencies used by dolphins in echolocation, the attenuation increases. At 170 kHz it is in excess of 200 dB/m.

However, as Leighton points out [14], such calculations assume that the bubbles undergo linear pulsations in the steady state, whereas dolphins use short pulses of sufficiently high amplitude to drive bubbles into nonlinear oscillation. A theory for modelling such acoustic propagation has recently been developed [18], together with an exploration of how these nonlinear effects might occur and indeed be exploited.

It is very likely that, for dolphin sonar to operate effectively in bubbly water, the dolphins would have to undertake signal processing which takes into account the nonlinearities they are generating [14]. This is because, whilst the best sonar hardware is superior to that available to dolphins, the dolphins can still echolocate in environments (suspended sediments etc.) which confound the best man-made systems [1]. The processing must therefore be making the difference. Given the severe scattering, attenuation and reverberation the dolphin would have to counteract were its sonar to operate in bubbly waters, a nonlinear process would seem to be a strong possibility. Leighton [14, 18] suggests, for example, the use of closely-spaced pulses of opposite polarity [13, 14, 19]: subtraction of the scattering from these enhances the scattering from linear targets, such as solids, compared to that from nonlinear ones (such as those bubbles which are pulsating nonlinearly).

4. CONCLUSIONS

This paper has outlined some of the interactions between the acoustic emissions of marine mammals, and the bubbly environment through which they may propagate. It may however be that exploitation of the schooling of fish in response to startling using bubble acoustics is more widespread, if perhaps less elegant, than the scheme of Figure 2b. The filming associated with Byatt *et al.* [15] shows bubble plumes generated by gannets (Figure 3e-g) diving into a shoal of sardines which dolphins have herded to the sea surface. These plumes will no doubt complicate an underwater sound field already populated by the calls and bubble emissions of dolphins, and the entrainment noise of the gannet bubble plumes, and could further stimulate the sardines to school [13, 14, 19]. Gannets, dolphins, sharks and whales etc. (Figure 3h) all benefit from this, although to what extent this is intentional is unknown.

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