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Hypotheses regarding exploitation of bubble acoustics by cetaceans

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Bubbles are the most acoustically active naturally occurring entities in the ocean, and cetaceans are the most intelligent. Having evolved over tens of millions of years to cope with the underwater acoustic environment, cetaceans may have developed extraordinary techniques from which we could learn. This paper outlines some of the possible interactions, ranging from the exploitation of acoustics by humpback whales (*Megaptera novaeangliae*) in bubble nets to trap prey, to techniques by which coastal dolphins (e.g. of the genus *Cephalorhynchus*) could successfully echolocate in bubbly water (a hypothesis which has led to the development of a man-made sonar which can penetrate bubble clouds, and a range of possibilities for homeland security.)

1 Introduction

The authors are aware of no direct evidence to test the hypotheses outlined in this paper. Indeed the legal and funding frameworks in the UK strongly inhibit the acquisition of such evidence either to prove or disprove these hypotheses. In the absence of such evidence, the authors do not advocate for the adoption of either hypothesis: the scientific method would have to be applied rigorously to test the hypotheses against evidence without bias as to the outcome, but this option is not open to the authors. Therefore this paper is restricted to stating the hypotheses and to explain some of the interesting discussion points which arise from them.

Section 2 describes the hypothesis that acoustics may be involved in the use of bubble nets for feeding by humpback whales (*Megaptera novaeangliae*). Section 3 describes a hypothetical method, which has been successfully implemented in test tanks with man-made sonar, by which odontocetes might effectively echolocate in bubbly water.

2 The bubble nets of humpback whales

Several species of cetacean use bubble nets to assist in the catching of prey. The hypothesis that these nets may be used to generate a ‘wall of sound’ to trap prey was first applied to the case of humpback whales (*Megaptera novaeangliae*) [1]. In 2004, Leighton *et al.* [1] proposed that humpback whales use bubble nets as acoustics waveguides to create a sonic trap for prey. It had been known for decades that humpback whales, either singly or in groups, sometimes dive deep and then release bubbles to form the walls of a cylinder, the interior of which is relatively bubble-free. The prey are trapped within this cylinder, for reasons previously unknown, before the whales ‘lunge feed’ on them from below. When the whales form such nets, they emit very loud, ‘trumpeting feeding calls’. Leighton *et al.* showed a how a suitable void fraction profile would cause the wall of the cylinder to act as a waveguide, creating a ‘wall of sound’ with a relatively quiet interior at the centre of the cylinder. They hypothesized that any prey which attempted to leave the trap prey would enter a region where the sound is subjectively loud and furthermore could excite swim bladder resonances [2-5]. In response, the prey would school, and be trapped ready for consumption (the bubble net turning the ‘schooling’ survival response into an anti-survival response).

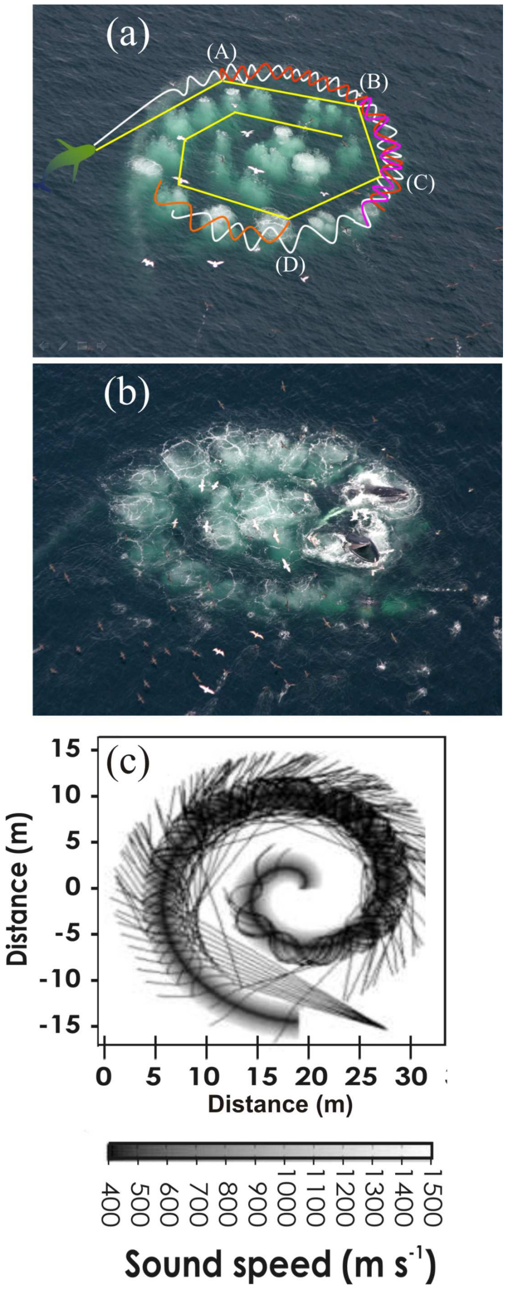


Fig. 1. (a) and (b) show two photographs (by Tim Voorheis www.gulfofmaineproductions.com, taken in compliance with United States Federal regulations for aerial marine mammal observation) of the formation of a spiral bubble net. In (a), schematic ray paths in white show the refractive path n the bubbly arm of the spiral, whilst the yellow rays show the reflective path in the bubble-free arm of the spiral, which reinforces the attenuated sound field in the bubbly water by partial transmission (producing the red ray at A, the pink ray at B, and the orange ray at D). In (c) this net has been transposed into a ray tracing model (see [15, 16]): the region free of sound rays in (c) is coincident with the location in (b) where the whales rise to catch the herded prey.

The circular geometries modelled by Leighton *et al.* [1] were based on the frequent description in the literature of humpback bubble nets as ‘circular’, or as bubble ‘rings’ [6-15]. The authors then proceeded to hypothesize about the acoustical properties of spiral bubble nets [15, 16], whereby refraction in the bubbly layer, and reflection from it during propagation in the bubble-free arm of the spiral, generate a wall of sound (Fig. 1).

Of course there are a range of possible explanations for why the prey become trapped by the net, and it is possible that different mechanisms work for different species (e.g. an acoustical swim bladder resonance may operate for some fish, whilst for other creatures (such as krill) a tactile or mechanical effect may dominate.

Humpback whales are not the only marine mammals to make bubble nets. However, for smaller echolocating mammals, the bubbles present a potential nuisance to feeding not present for a larger mammal which lunge feeds, a topic which is explored in the next section.

3 Echolocation in bubbly water

Having seen video images of dolphins using bubble nets in conjunction with the herding of fish, Leighton [2, 3] proposed that echolocation in bubbly water might be accomplished by using Twin Inverted Pulse Sonar (TWIPS), since (given that the best man-made sonar would not function in such an environment), either the dolphins had such a functionality (through TWIPS of some other process), or they were ‘blinding’ their own sonar during this hunt. Of course, it may be that within such bubble nets the odontocetes accept that clutter from bubble echoes will compromise their own sonar, and use the bubbles to startle or confuse the prey through multiple reflections of their own emissions. Given the practical and legal constraints on studying odontocetes, the chosen approach was to test whether a manmade sonar could be made to detect targets despite such bubble clutter: The TWIPS hypothesis was tested through simulation [17, 18] and experimentation in a test tank, where TWIPS has indeed been shown to work [19-22] (Fig. 2).

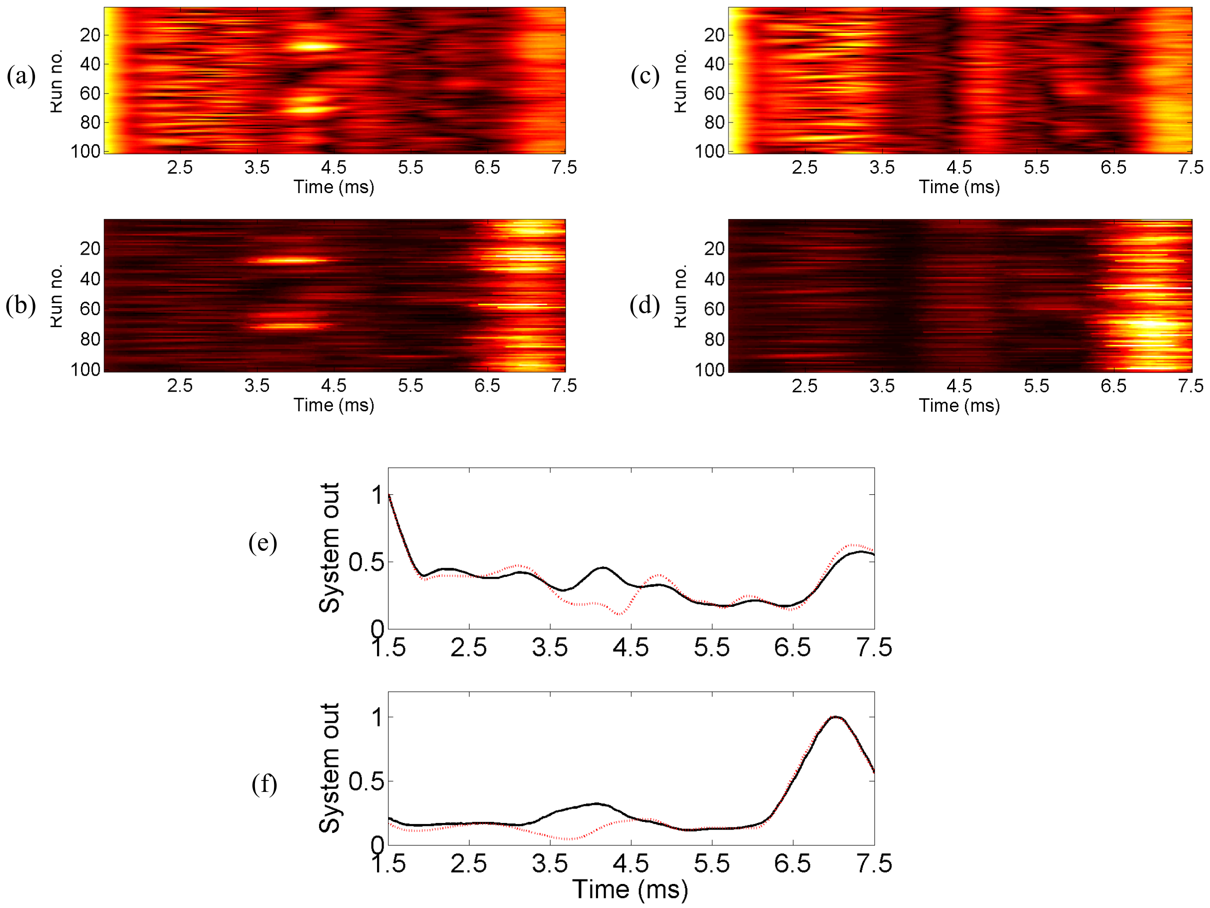
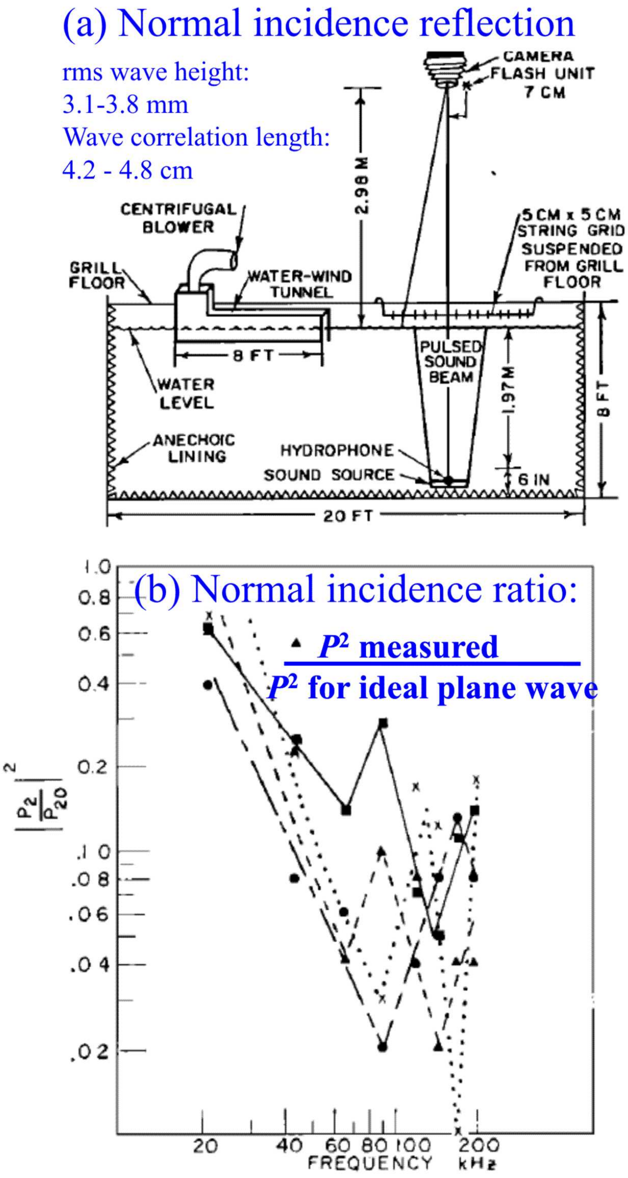


Fig. 2. The output of the TWIPS2 function P_-^2 / P_+ when for an interpulse time of 100 ms, produced by stacking 100 consecutive echo time histories (see ref. [22] for details). In each of these figures, the target is located between 2.75 and 3.75 ms, and the bubble cloud between 1.5 and 2.5 ms. The echo from the back wall of the tank occurs at around 6.75 ms. Panels (a) and (b) show the case with the target present, and panels (c) and (d) show the case with the target absent. Panels (a) and (c) are produced using standard sonar processing. In panel (b) the same data as for ‘a’ has been reprocessed using TWIPS. In panel (d) the same data as for ‘c’ has been reprocessed using TWIPS. Panel (e) shows the means of the acoustic returns processed using the standard returns; Panel (f) shows the means of the acoustic returns processed using TWIPS. In (e) and (f), the black solid line shows the results when the target is present, and the red dotted line shows the results when the target was not present. In (f) TWIPS2 reliably detects both of the linear scatterers: the back wall (at ~6.75 ms) that is always present, and the metal disc (at ~3.75 ms) when it is present (black line), at much greater levels than any other scatterers (bubbles) present. The same cannot be said of standard sonar (in (e)).

Given that TWIPS can be made to enhance target detection in bubbly water in a test tank, primarily through clutter reduction, the question remains as to whether odontocetes employ something like this.



(a) Normal incidence reflection

(b) Normal incidence ratio:

Fig. 3. By observing the echoes generated by normal-incidence insonification of an air/water interface by an upwardly-looking sonar (the apparatus shown in (a)), Medwin [23] demonstrated that small ripples on the surface can reduce the amplitude of the echo significantly, even for normal-incidence conditions.

As stated earlier, there is no direct evidence for this. The following discussion of the hypothesis can therefore be treated as nothing more than speculation designed to promote discussion. Features of interest include the following:

(i) Some species of odontocete have been observed transmitting at very high source levels [24]. Source levels of 228 dB re 1 uPa peak-to peak (~126 kPa 0-pk) have been recorded from *Tursiops gilli* (Pacific bottlenose dolphin), *Tursiops truncatus* (Atlantic bottlenose dolphin), *Pseudorca crassidens* (False Killer whale), although these are not members of the shallow-water species which have been identified with the recording of multiple pulses [22] (and the source of such multiples has not definitively been shown to be the animal's emission at source, as opposed to surface reflections). Furthermore, the peak frequency of the emission of these three high-amplitude species is, at ≥100 kHz [24], higher than would be optimal for generating nonlinearities in an oceanic bubble population [25]. Measurements to date suggest that the peak frequencies are too high, and the source levels too low, to give strong evidence of the likelihood of TWIPS being used by those species for which there have been greater or lesser suggestions of multiplies pulses [22]: *Cephalorunchus commersonii* (Commerson's dolphin, 120-134 kHz, 50 Pa 0-pk) *Cephalorunchus hectori* (Hector's dolphin, 112-130 kHz, 18 Pa 0-pk), *Neophocaena phocaenoides* (Finless porpoise, 128 kHz, no data on SL), *Phocoena phocoena* (Harbour porpoise, 120-140 kHz, 63 kPa), and *Phocoenoides dalli* (Dall's porpoise, 120-160 kHz, 158 Pa 0-pk). The main drawback in this assessment is the difficulty in making measurements from creatures using narrow beams, let alone in bubbly water in the wild. As such there is no evidence of twin inverted pulses being generated at sufficiently high amplitudes, let alone at the low kHz frequencies which are optimal for generating nonlinearities in a wide distribution of bubble sizes.

(ii) What facility is offered to odontocetes if the animal is sensitive to frequencies greater than twice the upper frequency content of its own echolocation emissions? Whilst a mismatch of this sort can in some animals indicate the requirement to hear environmental dangers (such as the echolocation emission of a predator), for those animals which themselves generate the highest frequencies they are likely to encounter, is the purpose of hearing more than an octave above their maximum emission frequency indicative of the requirement to detect nonlinearities? Whilst careful study of individual animals has produced valuable audiograms [26] (and for example show a harbour porpoise which would have trouble hearing the second harmonic of its peak frequency), the dataset is from those species which emit multiplies pulses is sparse. It would be interesting to process the artificial TWIPS returns through a filter based on such an audiogram, although of course the primary evidence would be the detection in the wild of high amplitude multiple pulses in a bubbly environment.

(iii) Dolphin test tanks can present acoustic environments very different from those found in the wild: the authors are not aware of any published data on whether odontocetes alter or adapt their emissions when their environment contains bubble clutter.

(iv) Whilst the majority of acoustic examinations of odontocetes have focused on free-ranging species such as *Tursiops truncatus*, those species which are restricted to shallow waters [22] may be more appropriate adapted to the acoustics of shallow water environments. Such adaptation may have developed through both evolutionary and cultural means [22].

(v) Twin pulses have been detected from some odontocetes, and the phase of the second pulse has been shown to be an inverse of the first pulse. This second pulse has been explained away in terms of the second pulse originating from a surface reflection [27]. Whilst possible in specific circumstances, such suggestions should be critically and quantitatively examined against the feasibility of producing the observed fidelity of the second pulse, e.g. in duplicating the amplitude of the first pulse (Fig. 3). Indeed the amplitude degradation that has been observed in surface reflections and cunningly exploited to estimate the range to animals [28]. It should be noted that, if twin inverted pulses of identical high amplitudes could be generated at range from a source using surface reflections, they could be used as an effective TWIPS source in exactly the same way as when the source produces the multiples directly (as was done in Fig. 1 for a man-made source, and which is not an unfeasible process given that phase inversion might be expected as a result of reflections off internal air sacs [29]).

4 Conclusions

TWIPS has been shown to work in a test tank, enhancing the detection of a metal target in bubbly water through clutter reduction. TWIPS can be seen as the first stage of clutter reduction, after which other techniques (e.g. target characterization through resonant scattering; SAS or SAR) can be employed, provided that the frequency ranges for these is appropriate for that required to make TWIPS operable in the bubble population under examination [25]. Furthermore, not only will the TWIPS principle work for a wide range of incident acoustic pulses (chirps, pseudorandom sequences etc.), it will also work for EM signals (Radar, Lidar, THz radiation, Magnetic Resonance Imaging) in order to discriminate between linear and nonlinear scatterers. These would of course have to operate under the limitation that high field amplitude is required at the targets (so that for example a bistatic source might need to be dropped close to the ground if aerial radar were to be used to detect tanks or mobile phone circuitry which is otherwise hidden by foliage – Fig.4).

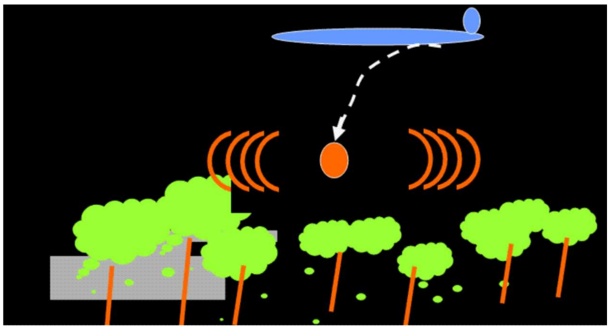


Fig. 4. Schematic of an aerial EM source being dropped closer to a forest in which a tank is suspected of being hidden.

Alternatively acoustic waves could be used in combination with EM signals (e.g. whereby a hand-held or AUV sonar distinguishes the solids from the bubbles, whilst the EM classifies the solids in terms of rocks, metals, or circuitry – Fig. 5). Differentiation of the echoes (with the associated conversion between odd and even harmonics) may be used to create further distinguishing methods. TWIPS-like methods offer a range of possibilities, from cryptography and communications (where exploitation of the nonlinearity inherent (or even hidden) in the harmonics of signals could be exploited) or ultrasonic surgery (where the linear scattering from large bubbles can be used to distinguish them from the nonlinear scattering of smaller bubbles, a process which may be important in the ultrasonic treatment of tumours).

The question of whether TWIPS or some other nonlinear techniques is used by odontocetes to suppress bubble clutter is unanswered. The authors have proposed two tests, but these have been unfunded: (i) determine if high amplitude twin inverted pulses are generated in nature; (ii) construct a source capable of delivering such signals in the test tank and TWIPS process them after filtering through a audiogram. A third test (examining whether wild animals which habitually encounter bubbly water through bubble netting or shallow-water environments adapt their echolocation signals suppress bubble clutter) would not be legal under UK law.

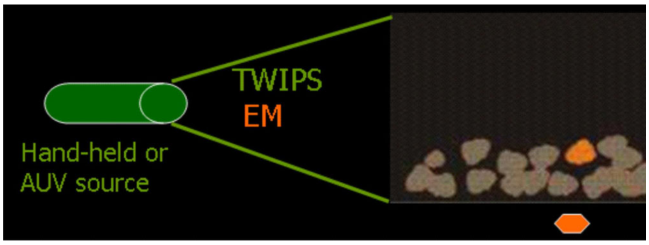


Fig. 5. A hand-held or AUV device (in green) deploys sonar to distinguish linear scatterers from bubble clutter (not shown), and then uses EM to distinguish which linear scatterers are mineral (grey-brown) and which contain circuitry (orange; including a buried device).

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