

HYPOTHESES ON THE ACOUSTICS OF WHALES, DOLPHINS AND PORPOISES IN BUBBLY WATER

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Abstract: *The use made of acoustics for communication and echolocation by cetaceans is well-known. We are also familiar with the ability of gas bubbles in the ocean to complicate and confound human attempts to achieve these tasks for ourselves. Some cetaceans must deal with bubbles as a result of their location (for example as occurs with those species restricted to coastal regions): others actively generate bubbles to aid their feeding. Data is scarce as to what extent, if any, cetaceans have exploited the acoustical effects of bubbles, or undertake tactics to compensate for their deleterious effects. The absence of data provides a fruitful opportunity for hypothesis. 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. These hypotheses are then used to develop practical sonar technology for use in bubbly waters.*

Keywords: *Bubble, odontocete, cetacean, humpback whale, dolphin, sonar*

1. INTRODUCTION

Observations of cetaceans in bubbly water have stimulated thought on the extent to which these animals either exploit the potent acoustical properties of bubbles, or compensate for the deleterious effects bubbles might have, when attempting communication or echolocation in bubbly waters. Certainly humans are aware of the deleterious effects bubbles can have on sonar, to the extent where there exists no satisfactory man-made sonar for use in bubbly coastal waters or ship wakes. Some cetaceans must deal with bubbles as a result of their location (for example as occurs with those species restricted to coastal regions): others actively generate bubbles to aid their feeding. 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 sonar system is developed, not by mimicking the echolocation signals of odontocetes, but by asking what system could be designed to overcome the deleterious effects of bubbles on sonar if it must operate in bubbly water. Whether any species of odontocetes use such a system is uncertain.

2. THE BUBBLE NETS OF HUMPBACK WHALES

Several species of cetacean use bubble nets to assist in the catching of prey, including the short-beaked common dolphins (*Delphinus delphis*) and the Bryde's whale [1]. The most famous bubble nets are those used by humpback whales (*Megaptera novaeangliae*), although the mechanism by which they trap prey has never been conclusively proven. The hypothesis that these nets may be used to generate a 'wall of sound' to trap prey was first proposed in 2004 [2, 3]. 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 unknown reasons, 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.* [2, 3] showed 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 (Figure 1(a)). They hypothesized that any prey which attempted to leave the trap would enter a region where the sound is subjectively loud and furthermore could excite swim bladder resonances [2, 4-6]. 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). Whilst forming an attractive hypothesis, however, it is clear that the attenuation of the sound by the bubbly water will require considerably more acoustic power to be projected into the net (e.g. using multiple sources) than would be the case were such attenuation not to occur.

The circular geometries modelled by Leighton *et al.* [2, 3] were based on historical photographs (e.g. Figure 1(b)) and the frequent description in the literature of humpback bubble nets as 'circular', or as bubble 'rings' [7-16]. The authors were then alerted (by Dr Simon Richards) to high-quality photographs showing the development of spiral bubble nets. The authors hypothesized [16, 17] that such nets would allow the formation of a 'wall of sound' with greatly reduced problems of bubble attenuation, 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 (Figure 2).

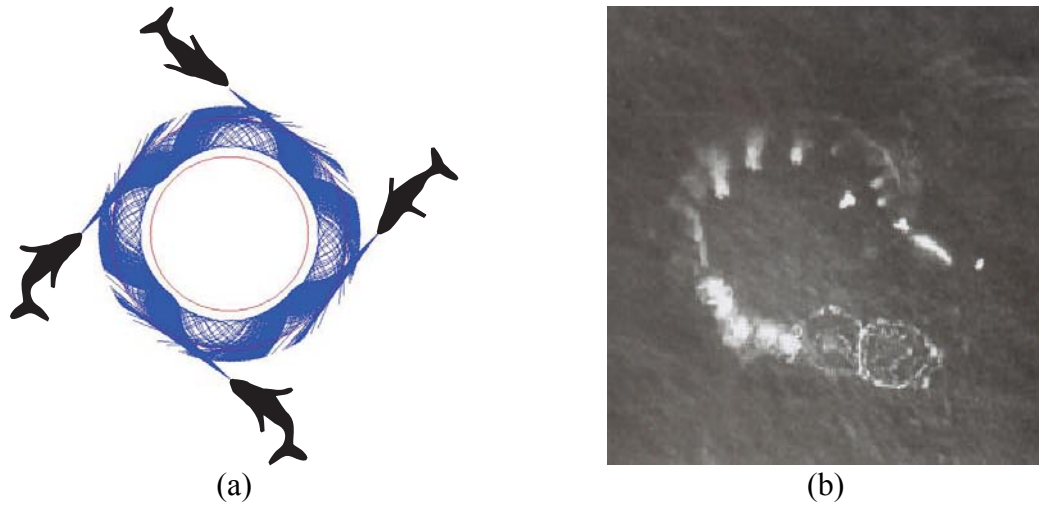


Fig. 1: (a) Plan view (from [2,3]) of four whales insonifying an annular bubble net (having 20 m mean diameter and a wall width of 4 m). Here the bubbles are driven in stiffness-controlled mode such that the sound speed decreases linearly from 1500 m/s at the walls (i.e. the sound speed in bubble-free water), to 750 m/s at the cloud midline (corresponding to a void fraction there of $\sim 0.01\%$). The rays are coloured blue, and the locations of the inner and outer walls of the net are shown in red. Computed ray paths, where each whale launches 281 rays with an angular extent of 10° , and then refract. (b) Aerial view of a humpback bubble net (photograph by A. Brayton, reproduced from reference [18]; the author has obtained permission from the publisher to use this image but has been unable to contact the photographer).

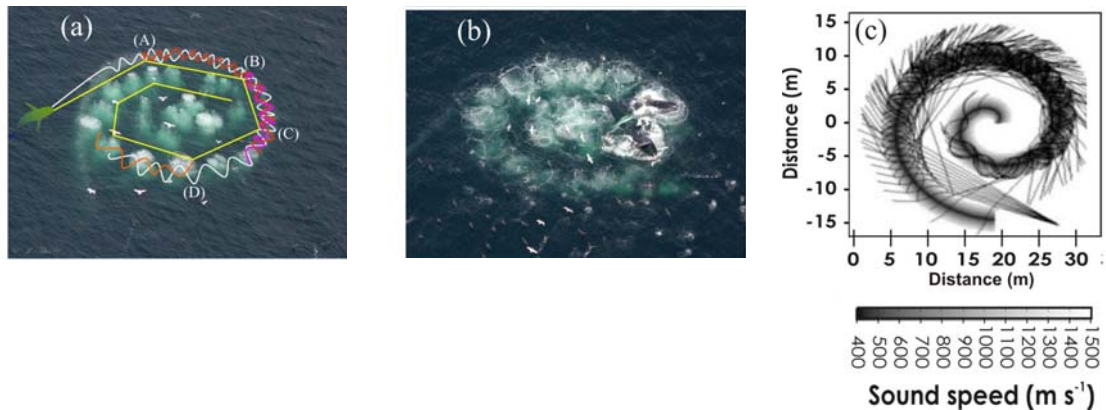
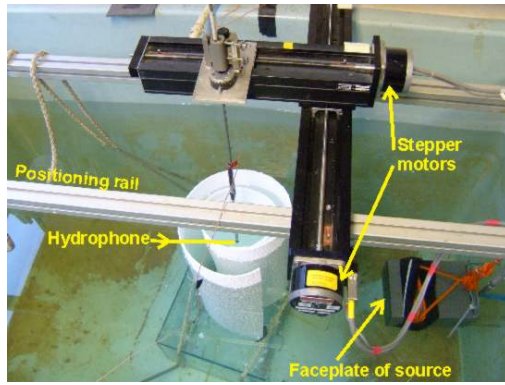
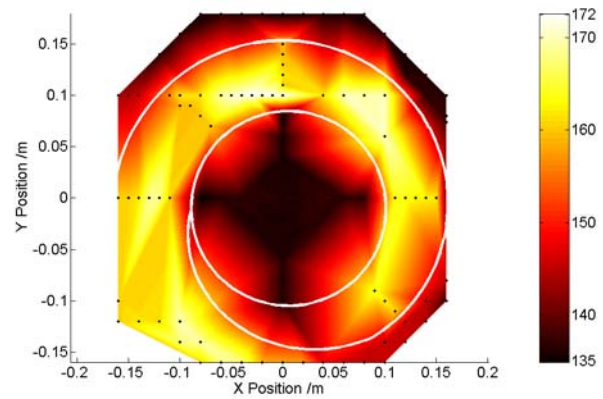


Fig. 2: Panels (a) and (b) show photographs (by Tim Voorheis www.gulfofmaineproductions.com, taken in compliance with United States Federal regulations for aerial marine mammal observation) of the formation of a spiral bubble net. Superimposed upon the photograph in (a), schematic ray paths in white show the refractive path in 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) the spatial features of the net in (b) have been transposed into a ray tracing model (see [16, 17]), with a putative sound speed profile based on Wood's equation: the region free of sound rays in (c) is coincident with the location in (b) where the whales rise to catch the herded prey.



(a)



(b)

Fig. 3: (a) A simple scale model spiral net of 0.3 m outer diameter, with a closed centre, made from expanded polystyrene in water. The base of the spiral is fixed to an upturned aquarium, such that all of the expanded polystyrene except the top 10 cm is submerged. The spiral is 0.6 m tall and a 1.57 m length of expanded polystyrene (of 7 mm thickness) was required to complete the two full revolutions of the spiral. (b) Measured acoustic field in horizontal plane in demonstration spiral bubble net of expanded polystyrene (1:100 scale, so that the Blacknor Technology sound source projected a 375 kHz tone-burst into the open end of the spiral). The white line shows plan view position of spiral. Data only exists for the discrete measurement points shown as black dots: between these the colour indicates an interpolation and so, whilst visually appealing, cannot include the zero-pressure at the spiral wall. Colour scale: rms sound pressure level (dB re 1 μ Pa) at each measurement location, time-averaged over the entire 2 ms window from the start of one tone-burst signal to the start of the next (these tone-burst signals are characterized by an ~ 8 μ s free-field duration of a 375 kHz basic frequency sinusoid), so that all the reflections within the spiral were included in the calculation. See references [16, 17] for details.

Of course there is 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).

Testing the proposal would require field trials beyond the current (and likely future) means of the authors. In the meantime the evidence to support this proposal is indirect. The location where the whales surface in Figure 2(b) is the location where the sound field amplitude in Figure 2(c) is modelled to be low (and where we might expect prey to congregate), but this may be coincidence. More photographic data, preferably correlated with undersea measurements of the distributions of bubbles and prey, would be welcome (noting that the visual impression of bubble concentration may be dominated by the presence of large bubbles, and underestimate the presence of smaller bubbles which can often have a more potent effect on the sound speed [19]). Record of what proportion of nets are, and are not, made with feeding calls, and whether this correlates with the species of prey trapped in the net, would provide a useful guide to the prey-specific effectiveness of the various mechanisms by which the net might operate. Tank tests can provide provocative measurements of sound fields (Figure 3), but need to be interpreted with care. Indiscriminate bubble generation may place bubbles at the correct location, but use bubbles of the incorrect size (scaled for the insonification frequency, which is in turn scaled for the net size), and so

provide a bubble net with refractive acoustic properties which differ from those found in the field [16, 19, 20]. This is particularly a problem when scaled-down nets are created, and it was to avoid misleading results from this effect that expanded polystyrene was used in the test of Figure 3. This is because it removes the refraction element from the propagation and concentrates on the reflection components. That this then produces a spiral with a quiet centre is not unsurprising, given the geometry of polystyrene [16]. However despite the inability to provide conclusive evidence, this hypothesis has proved popular: The authors were last year informed (by S. Robinson, of NPL) that the narration for a National Geographic documentary [21] refers to bubble netting in the following terms: “Humpbacks demonstrate a high level of coordination, such as the strategy the use to maximize fish catches. It is called bubble netting. Up to 20 of them work together to harvest a swirling ball of fish. One whale encircles them in a ring of bubbles. Simultaneous high pitched calls from others below may form a wall of concentrated sound within the bubbles, packing the bait ball tighter. At the surface the bubbles and noise enclose the writhing fish. The whales lunge up together, scooping in hundreds of kilos of food in their accordion-like mouths”. Whilst a BBC documentary in 1993 on humpback bubble netting did not mention the acoustics [22], a more recent one focused on the calls of the humpbacks during bubble netting [23].

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

The attenuation caused by bubbles to the calls of humpback whales was mentioned in the preceding section. However when human sonar is used in bubbly water at the higher frequencies exploited for echolocation by odontocetes, the ability of bubbles to generate clutter can become overwhelming. Video images of dolphins using bubble nets in conjunction with the herding of fish stimulated the deduction that, since the best man-made sonar would not function in such an environment, either the dolphins had such a functionality in their sonar, or they were ‘blinding’ their own sonar during this hunt [2, 4]. Given the restrictions which did not allow the authors to make field measurements or undertake experiments with odontocetes, it was proposed that one way of investigating this conundrum was to determine whether it would be possible for a human to devise a sonar which could operate with enhanced efficiency in bubbly water [2, 4]. One such solution was proposed, Twin Inverted Pulse Sonar (TWIPS), whereby the signal contains two pulses, one the inverse of the other [2, 4]. The pulses could be tonal, chirps, pseudorandom sequences etc., limited only by the requirements to excite nonlinearities in the bubbles, and to have sufficient fidelity that one is the inverted mimic of the other when they reach the bubbles (which places further requirements that the interpulse time not be so short that the pulses overlap, or too long that changes in the environment degrade the mimicry) [24]. The success of such a sonar would not of course prove that odontocetes use it, but would open up the possibility that such solutions exist.

TWIPS works in the following manner (see reference [25] for details). The echoes of the two pulses are added to form P_+ (which enhances even powered nonlinearities in the scatter and suppresses the odd-powered nonlinearities, including the linear scatter). This P_+ therefore can be used to enhance the scatter from bubbles [26]. The echoes of the two pulses are also subtracted one from the other to form P_- (which enhances odd powered nonlinearities (including the linear components) in the scatter and suppresses the even-

powered nonlinearities). This P_- can be used to suppress some of the bubble scatter, but not all of it. Further enhancement and suppression can be found through ratios of these so-called “TWIPS1 parameters”. Such so-called “TWIPS2” functions therefore feature ratios such as P_+ / P_- and P_- / P_+ . Although such ratios are susceptible to noise, they provide a number of attractive features:

- Advantages in detection through enhancement of nonlinear scatterers and suppression of linear ones, and vice versa;
- Advantages in classification, since a feature which is strong in P_+ / P_- but disappears in P_- / P_+ is likely to be a nonlinear scatterer (e.g. a bubble in sonar applications); and a feature which is strong in P_- / P_+ but disappears in P_+ / P_- is likely to be a linear scatterer (e.g. a solid target in sonar);
- TWIPS2 automatically removes the need for range correction, appropriate application of which depends on knowledge of the environment, specifically whether the scenario is reverberation-limited or noise-limited – TWIPS2 does away with the need to make that decision.

The TWIPS hypothesis was tested through simulation [27, 28] and experimentation in a test tank, where TWIPS has indeed been shown to work [29-32] (Figures 4 and 5).

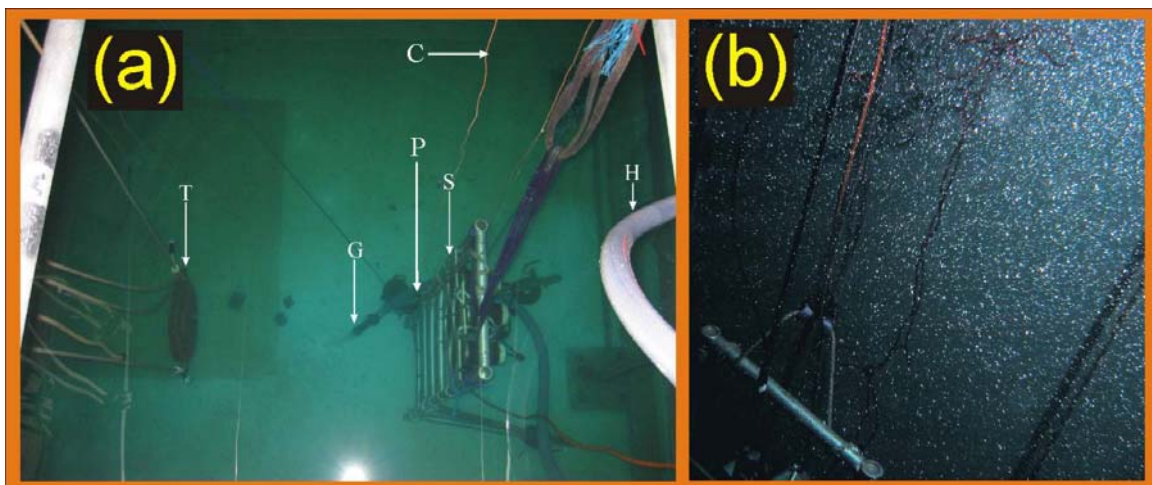


Fig. 4: (a) Photograph looking down into the water of an underground water tank, 8 m × 8 m × 5 m deep, in which a rigid frame holds 4 transducers in a Maltese Cross. A target (T) is aligned on the horizontal acoustic axis, 2.00 m from source. Also on the acoustic axis, a hydrophone (P) is placed in front of the source faceplate (the cable to the hydrophone is marked C). The photograph is taken just as hose (H) begins to feed bubbles through a nozzle (G) into otherwise bubble-free water. (b) Photograph from the top of the water column, showing the scaffolding bar at the top of the frame which holds the source. That bar is at a depth in the water of 2.03 m, and its length is 0.8 m.

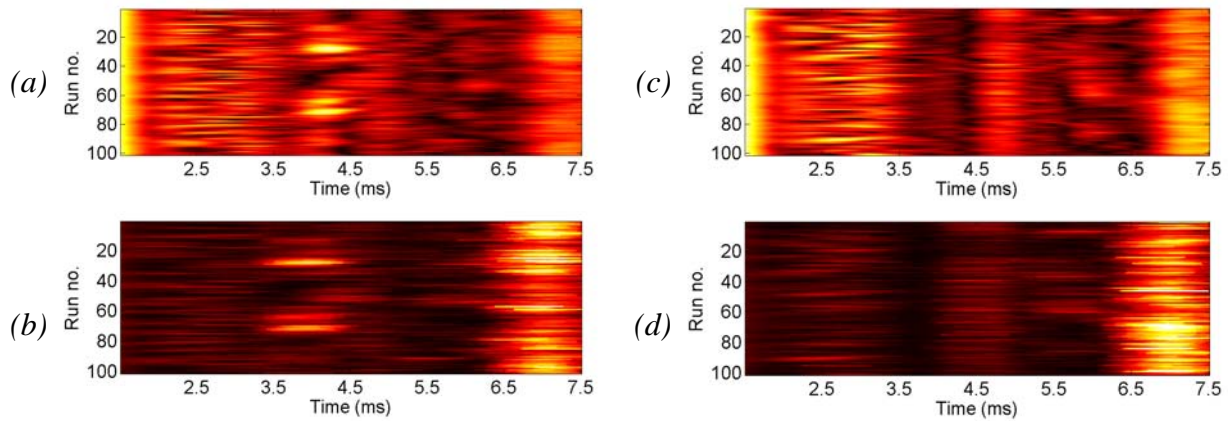


Fig. 5: The output of the TWIPS2 function P_-^2 / P_+ for an interpulse time of 100 ms, produced by stacking 100 consecutive echo time histories (see ref. [32] for details). In each of these figures, the target is located between 2.75 and 3.75 ms, and the bubble cloud between 1.5 and 2.5 ms. The echo from the back wall of the tank occurs at around 6.75 ms and of course can also be treated as a secondary target for TWIPS to enhance. 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.

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.

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 [33]. Source levels of 228 dB re 1 μ Pa @ 1 m peak-to-peak (\sim 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 [32]. Furthermore the source of such multiples has not definitively been shown to be the animal's emission at source, as opposed to surface reflections (although of course TWIPS could function using surface reflections if these resembled an inversion of the direct pulse with sufficient fidelity). Furthermore, the peak frequency of the emission of these three high-amplitude species is, at \geq 100 kHz [33], higher than would be optimal for generating nonlinearities in an oceanic bubble population [19, 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 [32]: *Cephalorhynchus commersonii* (Commerson's dolphin, 120-134 kHz, 50 Pa 0-pk), *Cephalorhynchus 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. However such measurements have not been conducted on wild animals in bubbly water, and it is possible that the animals could adapt for those conditions when faced with them.

- (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 [34] (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 multiple 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 [32] may be more appropriately adapted to the acoustics of shallow water environments. Such adaptation may have developed through both evolutionary and cultural means [32].
- (v) Tests on the ability of cetaceans to detect phase and second harmonic components would be very interesting. There is evidence that some bats have this capability [35].

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 [36]. 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. Indeed the amplitude degradation that has been observed in surface reflections and cunningly exploited to estimate the range to animals [37]. 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. 5 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 [38]).

4. CONCLUSIONS

The hypothesis that humpback whales enhance the capability of bubble nets by forming a ‘wall of sound’ has not been proven, but has proven to be sufficiently persuasive to be included in television wildlife documentaries. 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. TWIPS can not only enhance detection under appropriate circumstances, but also allows classification, since an item which disappears when the echoes from the two pulses are added, can be identified as a linear scatter. Conventional sonar cannot do this. 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 and, furthermore, between those nonlinear targets which scatter the second harmonic and those which scatter the third harmonic. A range of applications can be found by pairing off a given radiation with target field which contains scatters for the various linear and odd and even harmonics. Lidar for example will scatter nonlinearly off combustion products, whilst second harmonic radar imaging has already been investigated. Some technologies (e.g. MRI) already employ multiple pulses, and might be enhanced if attention was paid to the phase of those pulses. Since practical application needs high amplitude signals close to the source and the clutter, bi-static modalities may be preferred in some circumstances (e.g. with satellite or aerial detection systems).

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). 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) [24].

The question of whether TWIPS or some other nonlinear technique 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 an 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. If a conclusion must be drawn from the sparse data currently available, it is that the low signal amplitudes detected to date from creatures associated with multiple pulses in the wild are too low to excite significant bubble nonlinearities in a population covering a wide span of radii, and this would preclude TWIPS from being used by odontocetes.

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