TWO HYPOTHESES ABOUT CETACEAN ACOUSTICS IN BUBBLY WATER

TG Leighton Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton SO17 1BJ, UK (Corresponding author: tgl@soton.ac.uk)
DC Finfer Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton SO17 1BJ, UK
PR White Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton SO17 1BJ, UK

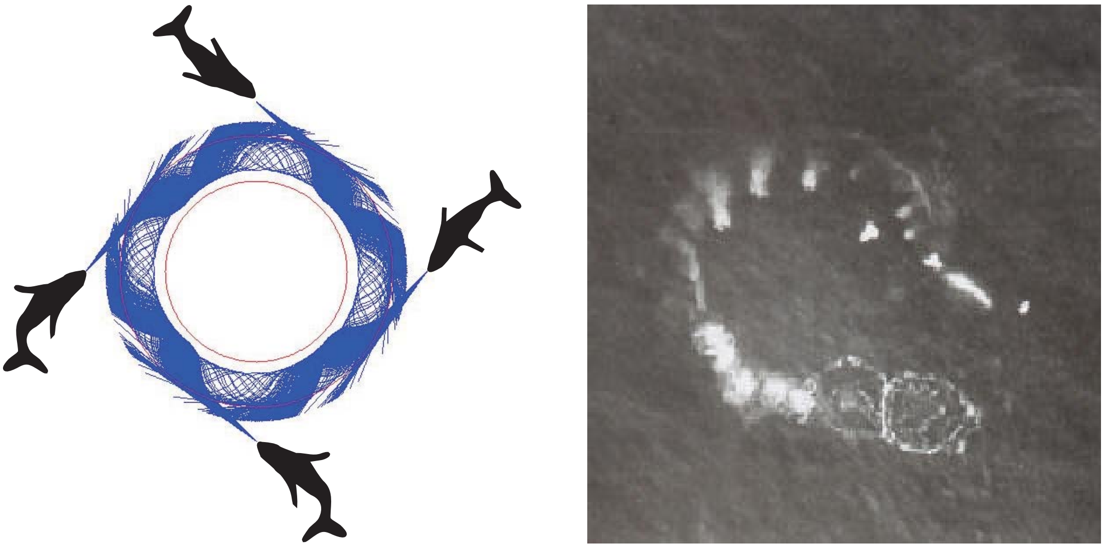
1 INTRODUCTION

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.

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 prey 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).



(a) (b)

Figure 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 ~ 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 but has been unable to contact the photographer).

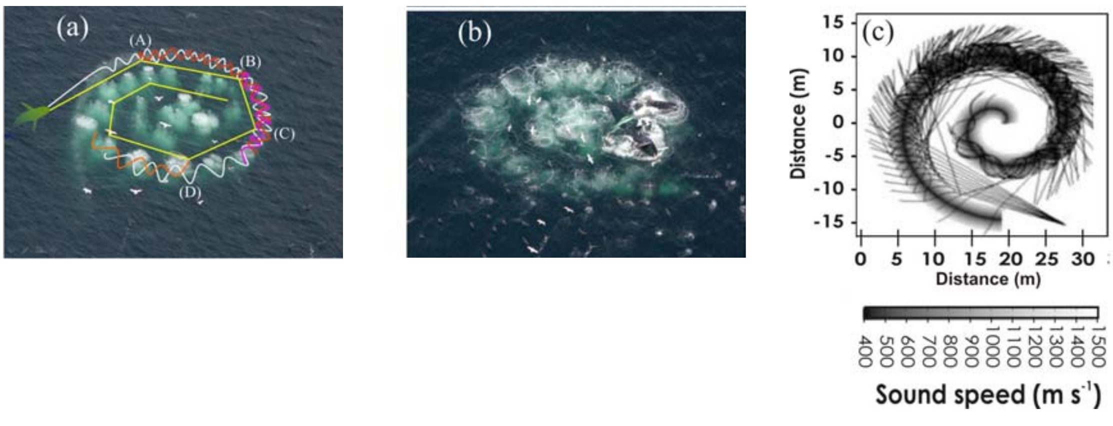
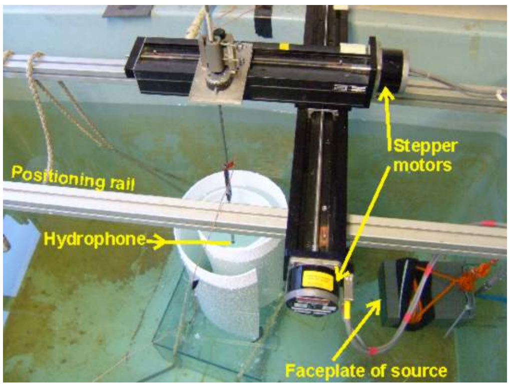
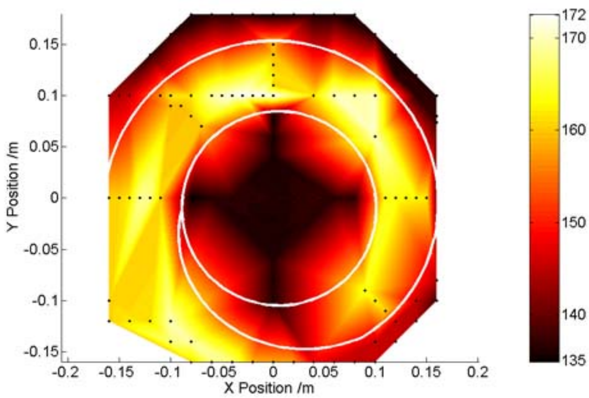


Figure 2: Panels (a) and (b) show photographs (by Tim Voorheis www.gulfofmaineproductions.com, taken in compliance with United States Federal regulations for aerial marine mammal observation) of the formation of a spiral bubble net. Superimposed upon the photograph in (a), schematic ray paths in white 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.

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, 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 and the authors were surprised to be informed (by S. Robinson, of NPL) that he had seen it mentioned in a National Geographic documentary [21].





(a) (b)

Figure 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 μPa) 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 μs 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.

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 odontocetes use higher frequencies for echolocation, 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 (given that 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 on the authors of field measurements or experimentation 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) [22]. 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.

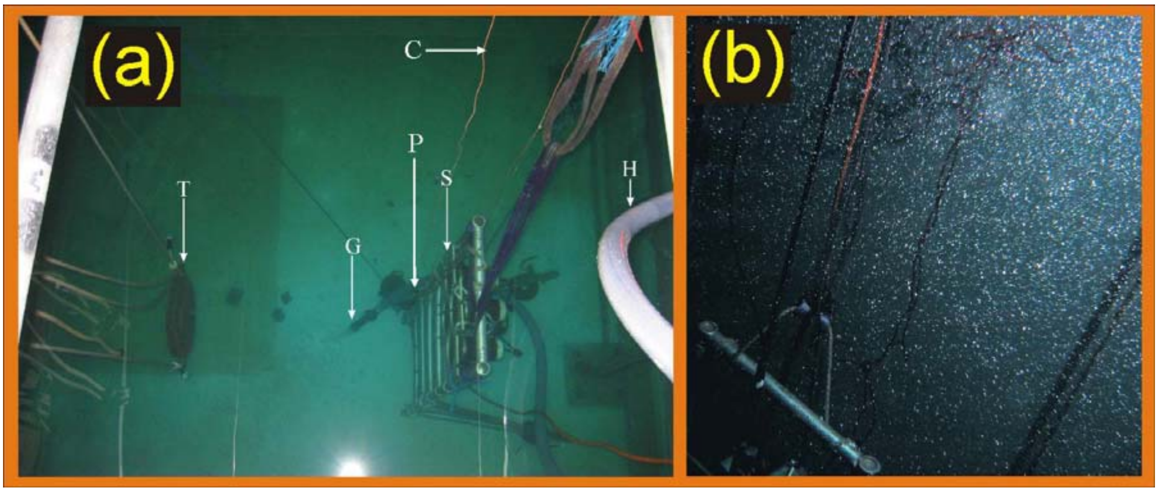


Figure 4: (a) Photograph looking down into the water of an underground water tank, 8 m × 8 m × 5 m deep, in which a rigid frame holds 4 transducers in a Maltese Cross. A target (T) is aligned on the horizontal acoustic axis, 2.00 m from source. Also on the acoustic axis, a hydrophone (P) is placed in 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.

TWIPS works in the following manner (see reference [23] 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 [24]. 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 [25, 26] and experimentation in a test tank, where TWIPS has indeed been shown to work [27 -30] (Figures 4 and 5).

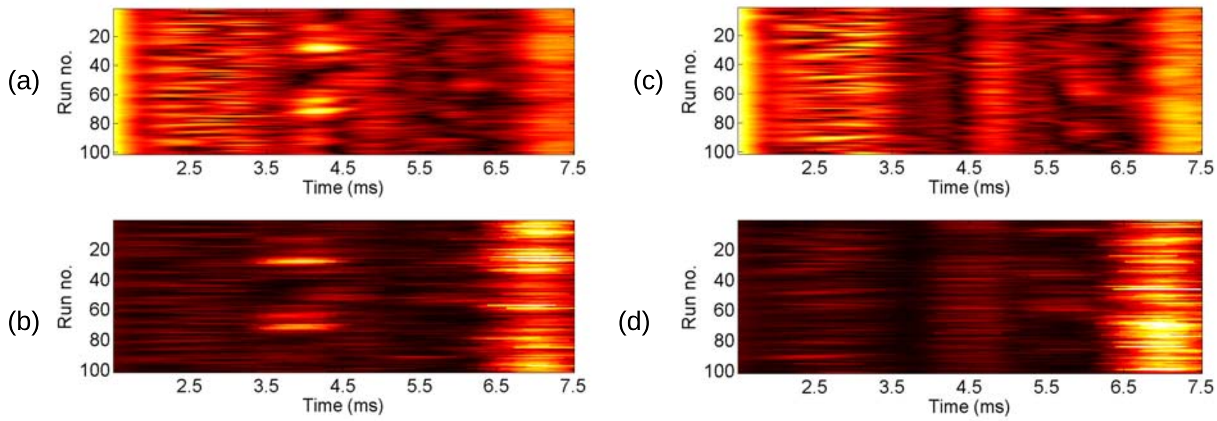


Figure 5: The output of the TWIPS2 function P_-^2 / P_+ for an interpulse time of 100 ms, produced by stacking 100 consecutive echo time histories (see ref. [30] for details). In each of these figures, the target is located between 2.75 and 3.75 ms, and the bubble cloud between 1.5 and 2.5 ms. The echo 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 [31]. Source levels of 228 dB re 1 μPa @ 1 m 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 [30]. 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 ≥100 kHz [31], higher than would be optimal for generating nonlinearities in an oceanic bubble population [19, 23]. 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 [30]: *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 [32] (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 [30] may be more appropriate adapted to the acoustics of shallow water environments. Such adaptation may have developed through both evolutionary and cultural means [30].

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 [33]. 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 [34]. 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 [35]).

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 [**Error! Bookmark not defined.**]. 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. 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.

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) [22].

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.

ACKNOWLEDGEMENTS

No funding has been secured to support this work. The authors are grateful to Jules Jaffe for suggesting that krill might be herded in the humpback's bubble net through tactile stimulation from the bubbles. The authors are grateful to Justin Dix for loan of a sonar source.

REFERENCES

1. D. R. Neumann, and M. B. Orams. Feeding behaviours of short-beaked common dolphins, *Delphinus delphis*, in New Zealand. Aquatic Mammals, 29(1): pp. 137-149, 2003.

2. T. G. Leighton. From seas to surgeries, from babbling brooks to baby scans: The acoustics of gas bubbles in liquids. Int. J. Mod. Physics B, 18: pp. 3267-3314, 2004.

3. T. G. Leighton, S. D. Richards, and P. R. White. Trapped within a ‘wall of sound’: A possible mechanism for the bubble nets of humpback whales. Acoustics Bulletin 29: pp. 24-29, 2004.

4. T. G. Leighton. Nonlinear bubble dynamics and the effects on propagation through near-surface bubble layers. In High-Frequency Ocean Acoustics, Eds. M.B. Porter, M. Siderius, and W. Kuperman, (American Institute of Physics Melville, New York) AIP Conference Proceedings 728, pp. 180-193, 2004.

5. T. G. Leighton, S. D. Richards, and P. R. White. Marine mammal signals in bubble water. In Bio-sonar and Bioacoustics Systems, Proc. Inst. Acoustics, 26(6): 6 pages, 2004.

6. T. G. Leighton, P. R. White, D. C. Finfer, and S. D. Richards. Cetacean acoustics in bubbly water. In Proc. Int. Conf. Underwater Acoustic Measurements, Technologies and Results, J.S. Papadakis and L. Bjorno, eds. (Crete) pp. 891-898, 2005.

7. F. A. Sharpe. Social foraging of the southeast Alaskan Humpback whale, *Megaptera novaeangliae*. PhD Thesis, University of Washington, 1984.

8. F. E. Fish. Performance constraints on the maneuverability of flexible and rigid biological systems. In Proc. 11th Int. Symp. on unmanned untethered Submersible Tech., pp. 394-406, 1999.

9. F. A. Sharpe, and L. M. Dill. The behaviour of Pacific herring schools in response to artificial humpback whale bubbles. Canadian Journal of Zoology-Revue Canadienne de Zoologie, 75: pp. 725-730, 1997.

10. R. A. Blaylock. The marine mammals of Virginia with notes on identification and natural history. VIMS Education Series No. 35: VSG-85-05, 1985.

11. F. E. Fish, and J. J. Rohr. Review of dolphin hydrodynamics and swimming performance. SPAWARS System Center Tech. Rep. 1801, San Diego, 1999.

12. C. M. Jurasz, and V. P. Jurasz. Feeding modes of the humpback whale, *Megaptera novaeangliae*, in Southeast Alaska. Sci. Rep. Whales Res. Inst., 31: pp. J 69-83, 1979.

13. J. H. W. Hain, G. R. Carter, S. D. Kraus, C. A. Mayo, and H. E. Winn. Feeding behavior of the humpback whale, *Megaptera novaeangliae*, in the Western North Atlantic. Fish. Bull. 80: pp. 259-268, 1982.

14. L. A. Finley, S. Nicol, and D. L. MacMillan. The effectiveness of a bubble curtain for preventing physical damage to antarctic krill in captivity. Marine and Freshwater Behaviour and Physiology, 36(4): pp. 285-293, 2003.

15. T. R. Kieckhefer. Humpback facts: a beginner’s guide to a unique creature. Upwellings (publ. Pacific Cetacean Group), pp. 4-5, 1996.

16. T. G. Leighton, D. Finfer, E. Grover, and P. R. White. An acoustical hypothesis for the spiral bubble nets of humpback whales and the implications for whale feeding. Acoustics Bulletin, 22(1): pp. 17-21, 2007.

17. T. G. Leighton, D. Finfer, E. Grover, and P. R. White. Spiral bubble nets of humpback whales: An acoustic mechanism. In Proc. 2nd Int. Conf. on Underwater Acoustic Measurements, Technologies and Results, (J.S. Papadakis and L. Bjorno, eds.) Heraklion, Crete, pp. 583-588, 2007.

18. H. Williams, Whale Nation, Jonathan Cape, London, 1988.

19 T. G. Leighton. What is ultrasound? Progress in Biophysics and Molecular Biology. 93(1-3): pp. 3-83, 2007.

20 T. G. Leighton. The Acoustic Bubble, Academic Press, London, 1994.

21 National Geographic, Humpbacks: Cracking the Code, Television documentary 2008.

22 T. G. Leighton, P. R. White, and D. C. Finfer. Hypotheses regarding exploitation of bubble acoustics by cetaceans. In Proceedings of the 9th European Conference on Underwater Acoustics, (ECUA2008), Paris, France, 29 June - 4 July, pp. 77-82, 2008.

23. T. G. Leighton, P. R. White, and D. C. Finfer. "Contrast enhancement between linear and nonlinear scatterers" European Patent Application 06755621.7 and US Patent Application 11/917,990; from International patent application number PCT/GB2006/002335 (filed 26 June 2006); claiming priority from UK patent application GB 0513031.5, University of Southampton, 2005.

24. D. H. Simpson, T. C. Chien, and P. N. Burns. Pulse inversion Doppler: a new method for detecting nonlinear echoes from microbubble contrast agents**.** IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control. 46(2), pp. 372-382, 1999.

25. T. G. Leighton, D. C. Finfer, and P. R. White. Bubble acoustics: What can we learn from cetaceans about contrast enhancement? Proc. 2005 IEEE Int. Ultrasonics Symp. (Rotterdam) pp. 964-973, 2005.

26. T. G. Leighton, P. R. White, and D. C. Finfer. Bubble acoustics in shallow water: possible applications in Nature. In Proc. Int. Conf. on Boundary influences in high frequency, shallow water acoustics (Bath, UK) pp. 433-440, 2005.

27. T. G. Leighton, D. C. Finfer, and P. R. White. Sonar which penetrates bubble clouds. Proc. 2nd Int. Conf. on Underwater Acoustic Measurements, Technologies and Results, (J.S. Papadakis and L. Bjorno, eds.) Heraklion, Crete, pp. 555-562, 2007.

28. T. G. Leighton, D. C. Finfer, and P. R. White. Cavitation and cetacean. In Proceedings of the 19th International Congress of Acoustics (Madrid, Spain) Paper PL003, pp. 1-31, 2007.

29. T. G. Leighton, D. C. Finfer, and P. R. White. Cavitation and cetacean. Revista de Acústica, 38(3-4): pp. 37-81, 2007.

30. T. G. Leighton, D. C. Finfer, and P. R. White. Experimental evidence for enhanced target detection by sonar in bubbly water. In Proceedings of the 7th European Acoustics Association Int. Symp. on Hydroacoustics, 11, pp. 181-202, 2008.

31. W. W. L. Au. The sonar of dolphins, Springer-Verlag, New York, pp. 133-137, 1993.

32. R. A. Kastelein, P. Bunskoek, M. Hagedoorn, W. W. L. Au, and D. de Haan. Audiogram of a harbor porpoise (Phocoena phocoena) measured with narrow-band frequency-modulated signals. J. Acoust. Soc. Am., 112(1): pp. 334-344, 2002.

33. S. Li, K. Wang, D. Wang, and T. Akamatsu. Origin of the double- and multi-pulse structure of echolocation signals in Yangtze finless porpoise (Neophocaena phocaenoides asiaeorientialis). J. Acoust. Soc. Am., 118(6): pp. 3934–3940, 2005.

34. R. Aubauer, M. O. Lammers, and W. W. L. Au. One-hydrophone method of estimating distance and depth of phonating dolphins in shallow water. J. Acoust. Soc. Am., 107(5) Pt. 1: pp. 2744-2749, 2000.

35. W. W. L. Au, R. A. Kastelein, K. J. Benoit-Bird, T. W. Cranford, and M. F. McKenna. Acoustic radiation from the head of echolocating harbor porpoises (Phocoena phocoena). J. Experimental Biology, 209: pp. 2726-2733, 2006.