SONAR WHICH PENETRATES BUBBLE CLOUDS

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Abstract: *Man-made active sonar does not operate well in bubbly water. However dolphins and porpoises not only function effectively in shallow coastal waters, but also at times generate large bubble fields to assist with catching prey. Possible physics solutions to target detection in bubbly water are proposed, and the validities of such proposed acoustical solutions are explored through theory, simulation and experimentation. Whether the solutions are exploited by cetaceans is uncertain. However the efficacy of the new methodology in test tanks, and the implications for man-made sonar, are demonstrated.*

Keywords: *Bubbles, dolphin, porpoise, sonar, target, cetacean acoustics*

1. INTRODUCTION

In 2004, Leighton [1, 2] noted that some species of *odontocete* not only can operate effectively in bubbly shallow water, but at times even generate bubble clouds when hunting, and proposed that they may be using Twin Inverted Pulse Sonar (TWIPS – see Fig. 1) and other nonlinear techniques to enable their sonar to operate effectively in these environments. This paper shows experimental evidence for the effectiveness of TWIPS.

There is need for a method which allows active sonar to operate in shallow coastal waters (the littoral zone), a problem which, despite significant investment, has not previously been solved. Quoting Rear Admiral W.E. Landay (Chief of Naval Research, Marine Corps for Science and Technology). O. Kreisher wrote *'The explosive ordnance disposal divers and the marine mammals run counter to the drive to get people out of the minefields, Landay said, but they provide "so much flexible capability" that they are likely to remain. The divers and the mammals work mainly in very shallow water and the surf zone, which "continues to be the most challenging environment" for mine warfare, he said'* [3].

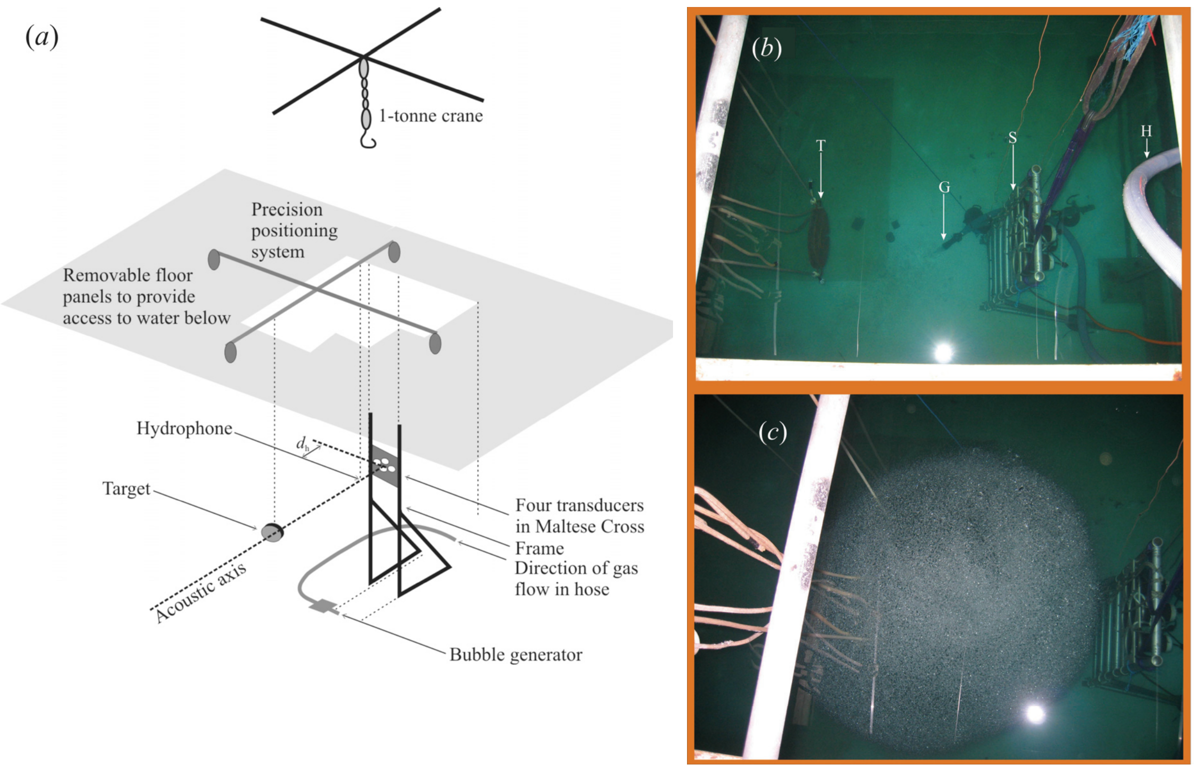
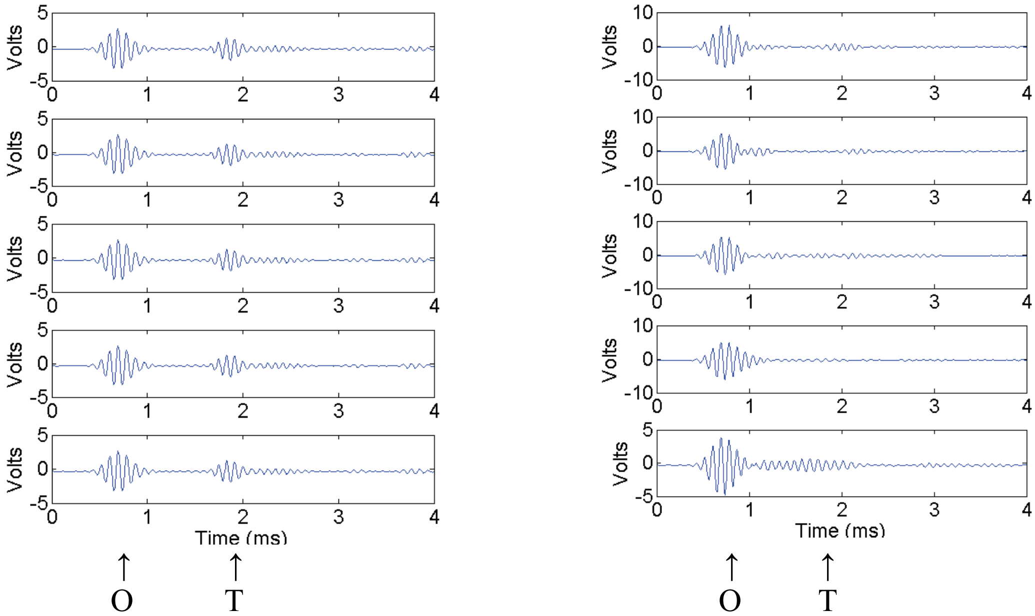


Fig. 1: (a) Schematic of proof-of-principle TWIPS experiment. Below the floor (shown shaded) is an underground water tank, 8 m × 8 m × 5 m deep. A rigid frame holds 4 transducers in a Maltese Cross, A hydrophone and a target are aligned on the horizontal acoustic axis, the hydrophone behind d_h=0.40 m in front of the source faceplate . (b) Photograph looking down into the water. Target (T) is 2.00 m from source (S). Hose (H) feeds bubble generator (G) (c) The same perspective as (b), but now with bubble cloud.

The limitations of active sonar in shallow water have become of paramount importance in the last decade. Military operations (e.g. mine detection, landings, and the protection of harbours and shipping lanes for military, commercial and aid craft) cannot rely on the decades of sonar experience built up for deep water applications during the Cold War. Such advances in sonar are also required because of the increasing use of sonar in shallow waters (e.g. for fisheries, surveying, and to cope with bottom sensing in increasingly-crowded and wake-filled waters by commercial and leisure craft). By far the most potent degradation of sonar performance comes from the presence of bubbles, which occur in the many millions per cubic metre in coastal waters. TWIPS provides a technique for detecting targets which would otherwise be obscured by bubbles. The principle by which the technique works is detailed elsewhere [4].

2. EXPERIMENT

Following simulations which indicated that the TWIPS procedure would be viable [5-7], the authors undertook experiments [4] to verify these predictions. In the proof-of-principle experiments (Fig. 1), the bubble clouds had dimensions of O(1 m), and contained bubbles ranging in radii resembling that found in the ocean [8]. It should be pointed out that (i) the efficacy of TWIPS decreases as the bubble size distribution increases, so that proof that it works with such a wide ocean-like distribution is important; and (ii) the characteristics of the bubble cloud were only measured after the successful deployment of TWIPS reported here: this was not a case of using *a priori* information on the bubble cloud in order to optimise the insonification signal or the processing.



(*a*) (*b*)

Fig. 2: A sequence of consecutive signals from the hydrophone of Fig. 1(a), arbitrarily selected for display. In (a) no bubbles are present. The first of the outgoing twin pulses (O, propagating out from source to target) is shown, followed around 1 ms later by the returning echo from the target (T, which propagates back from target to source). The second in the pair of TWIPS pulses is sent out 20 ms afterwards, and produces corresponding echoes. In (b) bubbles are present. Although the outgoing pulse is relatively stable, there is significant clutter from the bubbles and the signal from the target is attenuated.

The outgoing waveform characteristics are described elsewhere [4]. It consists of two pulses sent out 20 ms apart, the second having reversed polarity with respect to the first. The waveform prior to 1 ms in Fig 2(a) shows the first of this pair of pulses in the absence of bubbles, under which conditions it has a temporal peak pressure amplitude (0-peak) of around 25 kPa at 1 m from the source, and 15 kPa at the target. The target is a steel disc of diameter 415 mm and thickness 50 mm, and at range 2 m from the source. Its calculated target strength is -10 dB.

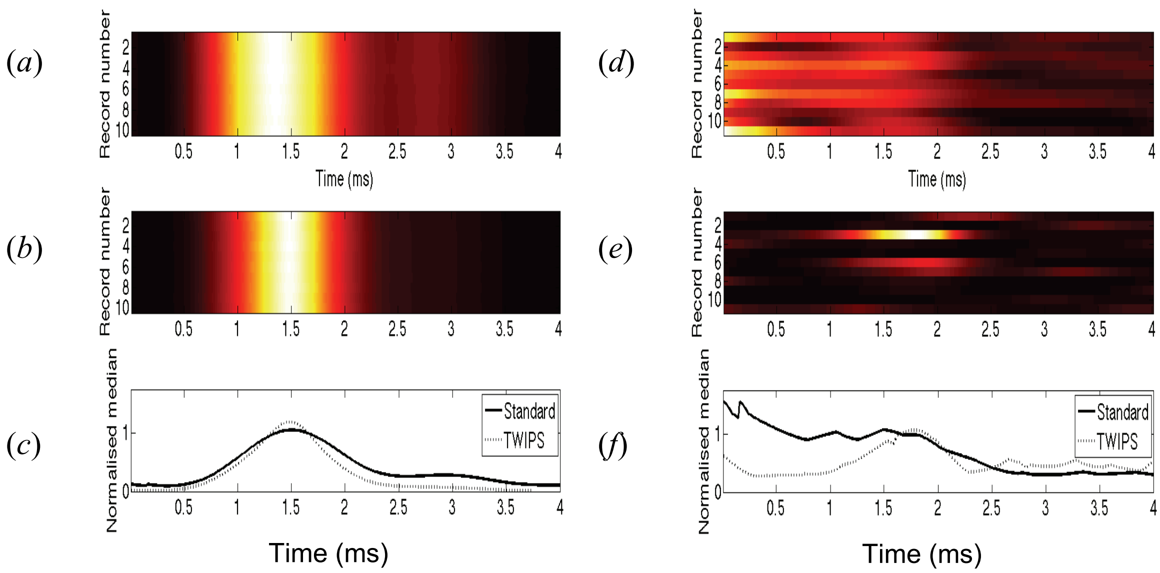


Fig. 3: For both standard sonar (Panel (a) & (d) and TWIPS2a (Panel (b) & (e)) (as defined in reference [4]), hydrophone signals of the type shown in Fig. 2 are stacked consecutively one above the other, with start time t=0 chosen to be after the outgoing pulse (labelled O in Fig. 2) has passed over the hydrophone. Panels (a)-(c) refer to measurements taken in the absence of bubbles. The target is clearly visible at t~1.4 ms to both standard sonar (Panel (a)) and TWIPS2a (Panel (b)). When the normalised median of these 10 signals is calculated in (c), both standard sonar and TWIPS2a clearly show the target. Panels (d)-(f) shows the equivalent plot as for (a)-(c), but now with the introduction of a bubble population [8]. In (d) standard sonar can no longer see the target: the image is dominated by scatter from the bubble cloud. In (e) the scatter from the bubble cloud has been suppressed, and that from the target has been enhanced, such that the target is clearly visible. In (f) TWIPS2a clearly shows the presence of the target (note the suppression of the echoes from the bubbles), whilst standard sonar does not.

Fig. 2 shows a sequence of hydrophone records, arbitrarily chosen, which demonstrate the effect which the presence of bubbles have on the detectability of the target. When 10 such returns (arbitrarily chosen) are stacked (Fig. 3), the ability of TWIPS to detect the target when it is hidden by bubbles is clearly demonstrated. The agreement between the experiment, and the simulations made in 2005 before any experiment was planned [5-7], is spectacular. An example of this is found in the intermittent manner in which TWIPS2a detects the target. This feature was predicted in the simulations [6-7], and is one that could be offset in human or dolphin sonar by the use of a train of clicks: note that no fitting or adjustment parameters have been used with this data.

3. DOES TWIPS EXIST IN NATURE?

Section 2 provided experimental evidence that TWIPS can detect targets in bubbly water where conventional sonar techniques fail. From the earliest days, however, the impetus in finding a sonar solution for shallow bubbly water had been come from the dilemma relating to species of *odontocete*, described in section 1 [1]. That dilemma is, specifically, that species which rely so heavily on echolocation not only inhabit shallow coastal waters, but at times also make bubble nets, begging the question of whether any *odontocete* use TWIPS [1]. Following the proposal of TWIPS, conversations between the authors and members of the cetacean research community revealed that multiple pulses are indeed sometimes observed from *odontocete*. Whilst under very still conditions a reflection from the water/air interface could produce a phase-inverted signal, a search of the records by the authors revealed that six species of dolphins and porpoises (all belonging to the genera *Cephalarynchus* and *Phocoena*) in fact have been reported to create multiple pulses deliberately [9-11]. These species are listed in Table 1. The primary habitats for all members of these genera are shallow waters - the same waters for which TWIPS was invented as a sonar solution.

(*a*) (*b*)

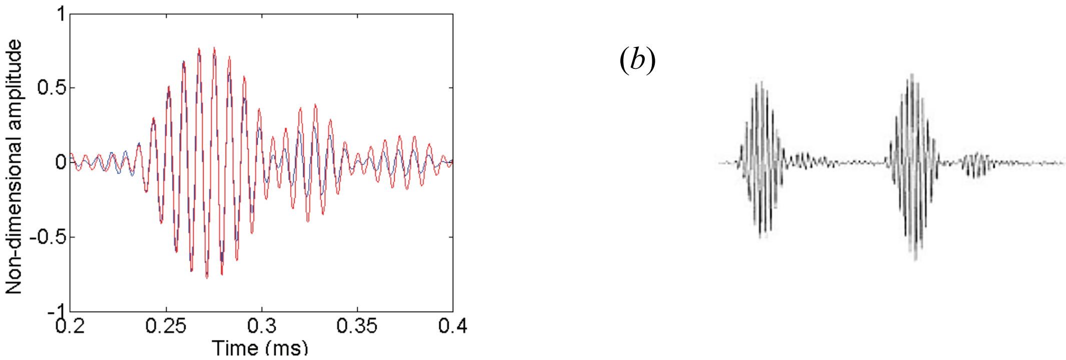


Fig. 4: (a) Two closely-spaced pulses from Hector's dolphin have been overlaid, having first inverted the 2nd pulse (shown in red). This then closely overlays the 1st pulse (shown in blue) indicating that the 2nd pulse was originally phase-inverted with respect to the 1st. However this is not conclusive evidence, because the data had to be oversampled by a factor of 10 because most of the energy within the signal falls just below the folding frequency. (Raw data courtesy Steve Dawson, University of Otago, processed by the authors). (b) Emission by Yangtze finless porpoise [12]. Axes not available. The 2nd wavepacket occurs ~300 μs after onset of 1st. Data-limited analysis suggests 2nd packet is inverted with respect to 1st.

Pre-existing acoustic data for these mammals is scarce and, as a result of the wide bandwidth and high frequencies of the sounds they produce, it is often not sampled at a sufficiently high frequency to allow accurate phase analysis. Nevertheless phase analysis by the authors of recordings of Hector's dolphin (supplied to them by Dr Steve Dawson of the University of Otago, Dunedin, New Zealand) strongly suggests that this species is capable of deliberately generating phase inverted pulses (Fig. 4(*a*)).

Furthermore, the twin pulses detected from the Finless Porpoise were also shown to be phase inverted by Li *et al.* [12] (Fig. 4(*b*)). However those investigators assumed that the Finless Porpoises themselves did not generate twin inverted pulses, but rather that they generated a single pulse and that second pulse was the result of a reflection of the initial pulse from the air/water interface. Dawson and Thorpe [11] point out that while surface reflections may sometimes dominate the acoustic response, there have been many cases recorded where the multi-pulse structure (the inter-pulse timing and relative amplitude) does not vary considerably. In such cases, he argues, this would indicate that the multi-pulse is in fact emanating directly from the moving animal, as the structure of a signal inclusive of significant surface reflections would alter as the animal moved closer or further away from the hydrophone.

Convincing historical evidence which would suggest that the interpretation of multiple pulses as surface reflections is incorrect, is found in a 1966 paper by Medwin [13], who addressed the surface reflections from a wind driven surface. This paper showed reasonable agreement between Kirchhoff scattering theory and experiment. Medwin fixed an up-looking send/receive transducer on the bottom of the tank, and played 8 tones 20 times. The tones used were linearly spaced from 21.5 kHz to 194 kHz. The tank surface was maintained at a near-constant roughness throughout the course of the experiment, so that, in dimensional terms, the higher frequency measurements effectively modelled rougher seas. For anything more than superficial roughness (e.g. as the wavelength approaches the median size of surface disturbance), it becomes very difficult to obtain reflections of amplitude greater than about half that obtained when the surface was smooth and flat.

Species	**Primary Habitat**	**Ref.**
Dall's porpoise, *Phocoena dalli*	Near-shore, warm temperate to sub-arctic waters of the Northern Pacific Ocean.	[14,15*]
Harbour porpoise, *Phocoena phocoena*	Coastal waters of subarctic & cool temperate North Atlantic & North Pacific. Often inshore.	[10]
Finless Porpoise, *Neophcaena phocaena*	In-shore waters of Asia	[12]
Commerson's dolphin, *Cephalorhynchus commersonii*	Near-shore waters <100 m depth, incl. east coast of Argentina, southern Chile, & Indian Ocean	[9]
Hector's dolphin, *Cephalorhynchus hectori*	New Zealand coastal waters. Often in estuaries	[16]
Chilean/Black dolphin, *Cephalorhynchus eutropia*	Coastal Chile	[17]

Table 1: Species for which there is tentative evidence for the deliberate use of multiple pulses for sonar in shallow water, with sources for that evidence referenced. Note: Awbrey et al. [15] made the first high frequency recordings of Dall's porpoise, but our group were unable to obtain this report.

One coastal dolphin which is not listed in Table 1, but which belongs to the genera *Cephalarynchus*, is Heaviside's dolphin (*Cephalorhynchus heavisidii*). This is because the authors are unaware of any acoustic data in the public domain on this species, which is confined to coastal Africa. However, given the close evolutionary ties between Heaviside's dolphin and the other dolphins of its genus [18] and the relative similarities of their limited habitats, we propose that acoustic measurements of Heaviside's dolphin could reveal the presence of multiple phase-reversed pulses.

Undoubtedly the major hindrance in answering whether these mammals do in fact exploit TWIPS is the lack of acoustic records which were taken in a manner specifically designed to determine the relevant features of the pulses. As stated above, the sampling frequency must be sufficiently great to allow robust analysis of the phase. Multi-element acquisition systems should be used to show undoubtedly that multi-pulses emanate from the species in question, and are not the result of environmental reflections as some investigators have proposed [12]. The environmental conditions must be sufficiently challenging to stimulate the cetacean to use twin-pulse techniques, if it is capable of that. The measurement must be at the spatial peak of the projected beam which *Cephalorynchus* and *Phocoena* produce, and not off-axis as is easily done given the narrow beamwidths observed [8, 11, 16, 19]. This is because TWIPS is dependent on nonlinear bubble dynamics, which in turn require high amplitude acoustic waves. Whilst careful measurements of the most closely studied dolphin (*Tursiops truncatus*, the Bottlenose dolphin, which is not a member of *Cephalorynchus* or *Phocoena* and does not produce twin pulses) has shown [10] that they can produce 126 kPa peak-to-peak at a range of 1 m, specific measurements of the type described above need to be undertaken to determine the maximum amplitudes which can be generated by *Cephalorynchus* and *Phocoena*. Whether or not cetaceans do indeed exploit TWIPS, the possibilities for man-made sonar applications have been demonstrated.

4. CONCLUSIONS

TWIPS sonar has been used to detect targets in bubble clouds which are invisible to conventional sonar. The possibility that *odontocete* might use TWIPS is intriguing, but by no means settled: the question of whether the pulse amplitudes are sufficient, and whether the frequency range is appropriate, need to be settled. Furthermore there are those who adhere to the hypothesis that the second pulse is the result of a surface bounce, and not deliberately generated by the animal. It would be intriguing to investigate whether any of the species identified in Table 1 adapt their sonar for bubbly conditions, or show an enhanced ability in shallow water (their primary habitat) compared to free-ranging species, such as *Tursiops*, that have dominated testing and training by humans. There have been extensive recordings of the emissions of the Harbour Porpoise (*Phocoena phocoena*), a shallow-water animal. Harbour porpoise emissions have been analysed by our group for the presence of equi-amplitude phase-reversed pulse pairs, but no such acoustic emissions have yet been identified

Regardless of these intriguing questions, man-made sonar has now been demonstrated as reaching the stage where TWIPS sonar can be experimentally demonstrated, which offers the possibilities not only for applications of sonar in shallow water, but also for a range of EM applications, including radar, lidar and THz radiation [4].

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