BUBBLE ACOUSTICS IN SHALLOW WATER: POSSIBLE APPLICATIONS IN NATURE

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Gas bubbles are the most potent naturally-occurring entities that influence the acoustic environment in liquids. Upon entrainment under breaking waves, waterfalls, or rainfall over water, each bubble undergoes small amplitude decaying pulsations with a natural frequency that varies approximately inversely with the bubble radius, giving rise to the 'plink' of a dripping tap or the roar of a cataract. When they occur in their millions per cubic metre in the top few metres of the ocean, bubbles can dominate the underwater sound field. Similarly, when driven by an incident sound field, bubbles exhibit a strong pulsation resonance. This paper discusses three examples of how bubble acoustics may find applications in Nature. The first of these is the determination of bubble size distributions through inversion of the sound fields that bubbles generate on entrainment. This can be used not only in testing models of bubble cloud evolution under breaking waves, but also in extraterrestrial environmental assessment. The second application lies in the possible enhancement by humpback whales of the efficiency of the bubble nets they use in fishing. The third speculates on the apparent conundrum, that unless dolphins employ better signal processing than humans currently do, then when they use bubble nets to hunt they are, in this visually confusing environment, nullifying their own most spectacular sensory apparatus. It demonstrates how exploitation of nonlinearities provides routes massively to enhance the contrast between targets and bubble clouds which would otherwise hide them from sonar. Whether dolphins use such techniques is unknown, but the potential to improve human sonar in bubbly waters is clear.

1 Extraterrestrial exploration of bubble acoustics in Nature

After a 7-year journey on NASA's *Cassini* spacecraft, the European Space Agency's *Huygens* probe landed on Saturn's largest moon, Titan, on January 14. It takes a moment to understand the step-change in knowledge that took place on that day. The surface of the planet is obscured with smog, and while we could envisage the possibility of seas, waves and waterfalls, and the equivalent of Earth's water cycle based on liquid methane and ethane, when the investigation of this paper began, we had no sure knowledge that these existed [1-3]. *Huygens* was ingeniously designed to cope with a range of terrains, from liquid to solid, and this investigation addressed two possibilities: if the descent had ended with a splashdown in liquid; or (perhaps less likely) if the landing site had been close to a methane-fall. The characteristics of acoustic sensors tally well the constraints of space travel: acoustic instrumentation is low-cost, rugged and durable, has low power consumption, and generates signals of low bandwidth compared to the imaging systems

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more usually exploited off-world. Indeed, whilst eventually *Huygens* managed to transmit for several hours on the surface, many expected only 3 minutes of battery life would remain after landing. *Huygens* was designed with an acoustic capability [4].

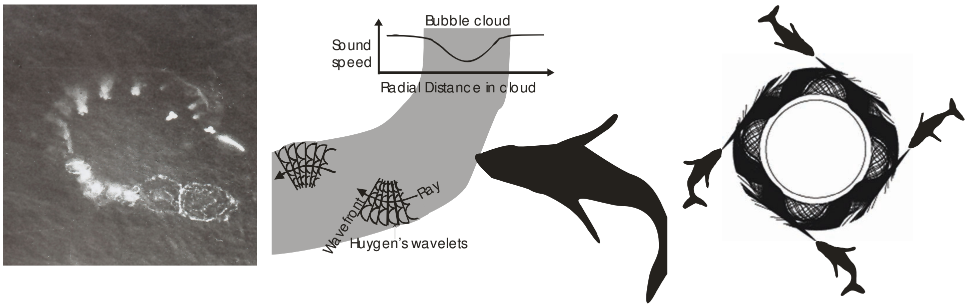
(a) *(b)* *(c)*

Figure 1 (*a*) Mosaic of three frames from *Huygens* indicates convergent flow from a high ridge area to a major river channel. (*b*) Impression by artist (David Seal) of Titan's surface as *Huygens* parachutes down. A "methane-fall" flows from the cliff at left, and methane clouds are visible. Smooth ice features rise out of the methane/ethane lake. (Credits: ESA/NASA/JPL/University of Arizona). (*c*) Power spectral densities for bubble entrainment noise, expressed in dB, simulated for Earth and Titan (based on Southampton University stream) (after [7]). Waterfall and splash-down sounds can be accessed via www.isvr.soton.ac.uk/fdag/uaua.htm.

Whilst it is recognised that acoustic technology could never replace imaging, the possibility was explored as to what could be gained were only the acoustic systems to be operational after landing: “If there is a splash and not a crunch when the probe lands, that would make Titan the first known body other than Earth to have an ocean open to an atmosphere. This would mean there could be babbling brooks and streams; and a beach at minus 180 degrees C” [5]. In the first stage [2], an appropriate model for the emission of bubbles was chosen and used to invert the sound of a terrestrial waterfall (the Salmon Leap, at Sadler’s Mill, Romsey, Hampshire, UK). The Salmon Leap bubble population was then used to estimate the sound that a methane-fall would make, if there were one on Titan which had the same entrainment statistics (not an unreasonable suggestion given the fluid parameters [2]). The reconstructed power spectrum for the terrestrial waterfall agreed with the measured Salmon Leap data, allowing some credibility to be given to the predicted spectrum for Titan. Recordings of these sounds, and similar predictions of possible splashdown sounds, can be accessed via the web page (Fig. 1). Nevertheless, the inversion was conducted without reference to the higher order moments [6], and the associated discrepancies were evident in listening-test comparisons of the measured and reconstructed Salmon Leap data. In addition, whilst the general shape of the predicted spectrum for Titan agreed with back-of-the-envelope calculations [2] and appeared to be physically sensible, the absolute spectral levels seemed to be too high. Therefore a second study completed the same prediction, but using a more stringent inversion routine and on a different waterfall [7]. This clarified the issue of the anomalous excitation amplitude.

2 Possible acoustic exploitation of bubble nets by cetaceans

Marine mammal calls often propagate through bubbly water, be they generated under breaking waves or wakes, though biological decomposition, or even by the mammals themselves. Two circumstances are of particular interest: the possible use of acoustic signals to trap prey in bubble nets; and the ability of dolphin sonar to operate in bubbly water (such as the surf zone) that would confound the best man-made sonar, despite the fact that the dolphins possess ‘hardware’ which is comparatively mediocre [8].



(a) *(b)* *(c)*

Figure 2 (*a*) Aerial view of a humpback bubble net (photo graph by A. Brayton, reproduced from [9]). (*b*) Schematic of a whale insonifying a bubble-net (plan view; sound speed is least at the mid-line of the net wall). (*c*) Four whales insonify bubble net (inner circle inner boundary of the net wall (outer one is obscured by rays) – image by T.G. Leighton and S.D. Richards). See Leighton et al. [2] for details.

2.1 The bubble nets of humpback whales

For many years there has been speculation as to the mechanism by which humpback whales (*Megaptera novaeangliae*) exploit bubble nets to catch fish [10]. It has been known for decades that single whales, or groups, dive deep and then release bubbles to form the walls of a cylinder, the interior of which is relatively bubble-free (Fig. 2(*a*)). The prey are trapped within this cylinder, for reasons previously unknown, before the whales lunge feed on them from below. It is usually assumed that prey are contained by the bubbles alone. However it is certainly known that when humpback whales form such nets, a proportion (as yet unquantified) of them emit very loud, ‘trumpeting feeding calls’, the available recordings containing energy up to at least 4 kHz. Leighton *et al.* [10] proposed that these whales may be using such calls to enhance the ability of their bubble nets to trap the fish, in the following manner. A suitable void fraction profile would cause the wall to act as a waveguide. Assume the scales permit the use of ray representation. Fig. 2(*b*) shows how, with a hypothetical tangential insonification, the mammals could generate a ‘wall of sound’ around the net, and a quiet region within it (Fig. 2(*c*)). The natural schooling response of fish to startling by the intense sound as they approach the walls would, in the bubble net, be transformed from a survival response into one that aids the predator in feeding [3]. The frequencies in the feeding call are indeed in the correct range to excite resonances in fish swim bladders and, given their sensitivities, presumably such excitation could discomfort the fish sufficiently for it to return to the interior of the net.

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

The actual acoustics of the cloud will of course be complicated by 3D effects and the possibility of collective oscillations; and even, speculatively, bubble-enhanced parametric sonar effects [10] which might be utilized by whales, for example to reduce beamwidth or generate harmonics, sum- and difference-frequencies etc. These effects are discussed elsewhere [10].

2.2 Dolphin use of bubble nets

Dolphins, especially *Odontocetti*, have been observed to be adept at hunting in bubbly water, possibly using acoustics. This is in despite of the fact that *Odontocetti* possess relatively mediocre acoustic transduction hardware [8]. In contrast, modern precision naval active sonar systems are confounded by the overwhelming reverberation signals recorded in bubbly water. Leighton [3] argued that *Odontocetti* might overcome their hardware disadvantage by means of novel signal processing. Leighton *et al.* [11] propose the use of various forms of "Twin Inverted Pulse Sonar" (TWIPS), which exploits nonlinear bubble oscillations to reveal linearly scattering objects present in the acoustic field. This paper presents the results of a simulation wherein TWIPS is applied, in the presence of a cloud containing 35 million oceanic bubbles, successfully to reveal the presence of a linearly scattering object approximately equivalent to one small fish.

3 Modelling sonar enhancement in bubbly water using TWIPS

To verify the potential for TWIPS to reveal a linearly scattering object within a bubble cloud, a simulation was developed, incorporating three primary inputs: a bubble cloud, a target, and an input signal. Details are given in [11]. When present, the target is located at the centre of the cloud and assumed to scatter linearly. This paper uses target strengths of -20 and -25 dB (the latter would be equivalent to an Atlantic cod (*Gadus morhua*) [12] of length 330 mm broadside on to a 100 kHz acoustic beam). The bubble cloud is assumed to be a sphere of radius 1 m, containing around 35 million bubbles following the population size distribution as measured by Meers *et al.* [13], such that the void fractions (the ratio of the volume of gas within a cloud to the total volume occupied by the cloud) on the order of 10^{-7} (i.e. 10^{-5} %). The cloud is dynamic, evolving as a consequence of turbulence, buoyancy etc. [3], although the number of bubbles is constant. The insonifying wavetrain is shown in Fig. 3. It consists of two pulses, identical except that the second (the ‘negative’ pulse) has opposite polarity to the first (the ‘positive’ pulse). The amplitudes and frequencies can be found in [11]. By splitting the backscattered time series in half and then subtracting the two half-time-series one from another, scatter from the target can be enhanced with respect to scatter from the bubbles.

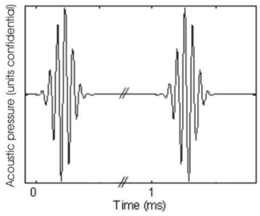


Figure 3 The incident wave (see [11] for details).

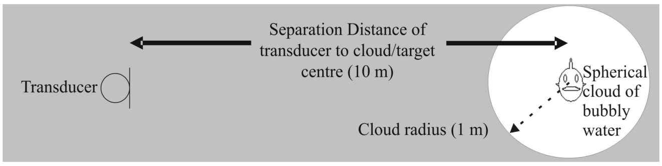


Figure 4 Diagram of simulation geometry for transducer, target and spherical bubble cloud.

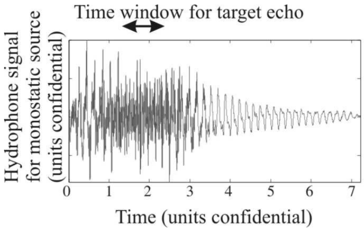


Figure 5 Simulated monostatic backscatter from the seawater containing a 1 m radius spherical bubble cloud containing, at its centre and 10 m from the transducer, a target (target strength TS = -25 dB). The signals each show a typical return (‘positive’ pulse only). The signal from the target is buried is bubble noise: the time window in which its echo is received is labelled. See [11] for details.

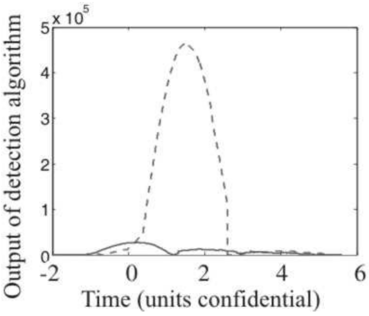
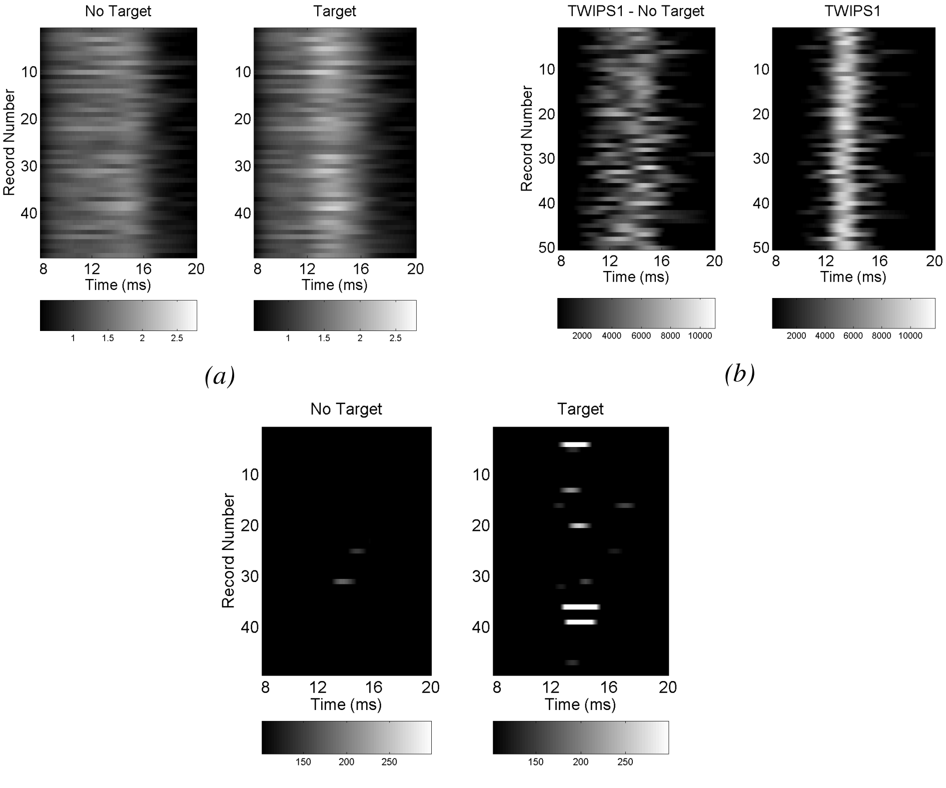


Figure 6 TWIPS2a has been applied to two cases: the bubble cloud on its own (solid line); the bubble cloud with a target of strength TS =-25 at its centre (dashed line) (the data from Fig. 5). The target, which was not discernable in Fig. 5, now gives a signal more than an order of magnitude greater than the scatter from the bubbles. See [11] for details.

The scattered pressure for monostatic operation was calculated from a region of seawater containing spherical cloud of bubbles of radius 1 m, centred on the target (which was at range 10 m from the transducer) (Fig. 4), in order to determine which sonar system could detect whether a target was present in the cloud. The data presented here are for a single return only, with no averaging. A typical echo is shown in Fig. 5: although the time window where the contribution from the target is labelled, it is not possible to see that target. An example time series from one form of TWIPS (TWIPS2a [11]) is shown in Fig. 6: the scatter from the single target fish is more than an order of magnitude greater than from the entire cloud of 35 million bubbles.



(a) (b)

(c)

Figure 7 Fifty pulse pairs (shown in Fig. 3) were projected at the cloud, spaced at intervals of 10 ms, and the echoes processed using (*a*) conventional sonar deconvolution techniques, (*b*) TWIPS1 and (*c*) TWIPS2b. The left plot in each panel shows the case when there is no target present, and the right plot shows the case when a target is inserted at the cloud centre (TS = -20 dB). The cloud, of 1 m radius, contains 35 million bubbles, and evolves appropriately between each ping, as described earlier. (*a*) A single average was formed from the two pulses that make up each pulse pair, such that 50 averages are available for plotting. Each average was plotted as a time history on a one-dimensional line, with a greyscale such that the amplitude of the signal at the corresponding moment in the time history was displayed. These processed echo time histories were then stacked, one above each other, to form an image. (*b*) TWIPS1 processing of the 50 pulse pairs (no averaging) are displayed similarly, by stacking the consecutive grey-scale time series one above the other. were projected at the cloud, spaced at intervals of 10 ms. The TWIPS1 processed echoes were plotted, each as a time history on a one-dimensional line, as in (*a*). (*c*) TWIPS2b processing is used (no averaging) and the image displayed as in (*b*).

In current sonar signal processing, averaging and correlation are used to amplify signals which are consistently found in the same temporal location. Experience has shown that this technique does not yield useful results in the complex, dynamic acoustic environment encountered in a bubble cloud. For the same set of incident pulses, conventional sonar processing was compared with two forms of TWIPS: TWIPS1 and TWIPS2b. TWIPS covers a range of processing techniques, with different capabilities. All are designed to enhance contrast of targets in bubble clouds, both by increasing the scatter from the target and, very importantly, at the same time suppressing the signals from the bubbles. TWIPS1 is designed always to enhance target contrast, producing a reliable enhancement with every ping. TWIPS2b gives much greater contrast enhancements, but not with every ping: the particular form demonstrated here 'glints' on about 10% of pings. However the contrast enhancement is much greater than occurs with TWIPS1. It is particularly useful for sources that have the luxury of insonifying a region with multiple pings.

The implications for sonar imaging can be illustrated by plotting such time histories on a one-dimensional line, with a greyscale such that the amplitude of the signal at the corresponding moment in the time history is displayed: white corresponds to high detected amplitudes, and black corresponds to low detected amplitudes. For conventional sonar (Fig. 7(*a*)), TWIPS1 (Fig. 7(*b*)) and TWIPS2b (Fig. 7(*c*)), 50 pulse pairs were projected at the cloud, spaced at intervals of 10 ms. The processed echoes were then stacked, one above each other, to form an image. As a stationary feature in the display, detection of the target in every ping would correspond to the observation of a vertical white line which is visible when the target is present, but absent from the corresponding sonar plot when the target is absent. The left hand plots in the individual panels of Fig. 7 correspond to the cloud when there is no target present, and the right hand plots of each panel in Fig. 7 correspond to the bubble cloud when the target (TS = -20 dB) is present. In comparing the results, resist the temptation to compare against each other the 'target present' plots in (a)-(c). Rather, mimic the consideration of a sonar operator: Recalling that the same echo can be processed by conventional and TWIPS techniques simultaneously, consider the difference between the left and right plots in each panel, and ask whether a sonar operator or dolphin could tell, from the left panel, that a target was absent; and from the right, whether there is a possible target to investigate.

Standard sonar processing fails to detect the target: There is insufficient difference between the two plots in Fig. 7(*a*) because scatter from the bubbles masks the presence of the target. TWIPS1 detects the target on almost every occasion, such that there is a vertical line on the right of Fig. 7(*b*) compared to the plot on the left (where, importantly, it has suppressed the bubble signal). As stated earlier, TWIPS2 is designed to work spectacularly for about 10% of pings. This feature is shown in Fig. 7(*c*), in that for some pings it fails to detect the target is present at all. However when it does detect one, the amplitude is very high (see plot on the right); when the target is not present (left hand plot), it rarely delivers a high amplitude return, very effectively suppressing the returned signal. The plots all have a linear greyscale and no thresholding has been applied.

4 Discussion and Conclusions

The results suggest that the physics will allow nonlinear acoustics to be exploited to enhance the detection of linearly-scattering targets within bubble clouds. Whether or not dolphins have developed this faculty, is unknown. It is intriguing that they can generate pulses at amplitudes >50 kPa at ranges of 1 m (even to the point where there are some suggestions that they may be self-inducing long term hearing damage). Furthermore some species (e.g. *Platanista minor* and *Platanista gangetica*) which can echolocate in highly turbid environments, have lost the ability to use their eyes. As a platform, dolphins can approach a target and insonify it with many pulses, the short ranges not only promoting the possible exploitation of nonlinearities, but also allowing relatively small changes in the location of the source to insonify a target from significantly different angles, e.g. through head motion. Resolution of this mystery will require careful (preferably open-water) measurements of dolphin sonar pulses in turbid and bubbly environments, taking particular care with measurements of phase. As a result of limitations in state-of-the-art manufactured sonar systems, the spectacular ability for dolphins to detect objects in acoustically complex environments is employed currently by the US Navy for mine-hunting. The development of technology that matches this extraordinary skill set will offer other options.

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