An acoustical hypothesis for the spiral bubble nets of humpback whales, and the implications for whale feeding

Tim Leighton, Dan Finfer, Ed Grover and Paul White

Introduction

In 2004, Leighton *et al [1]* proposed that humpback whales used bubble nets as acoustic waveguides to create a sonic trap for prey, as shown in Figure I. 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 (Figure I). The prey are trapped within this cylinder, for reasons previously unknown, before the whales 'lunge feed' on them from below. When the whales form such nets, they emit very loud 'trumpeting feeding calls', the available recordings containing energy up to at least 4kHz. Leighton *et al* 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. They hypothesized that any prey which attempted to leave the trap would enter a region where the sound is subjectively loud, be startled, and in response school (the bubble net turning the 'schooling' survival response into an anti-survival response). Furthermore, the trumpeting calls encountered in the 'wall of sound' are appropriate for exciting swim bladder resonances in the prey [2-5]. Either or both effects could encourage the prey to remain within the bubble net, and so trap them ready for consumption.

The circular geometries modelled by Leighton *et al* were based on the frequent description in the literature of humpback bubble nets as 'circular' [6-9] - Google returns nearly 12,000 items for the combined keywords *humpback circular bubble net.* Since then however the authors had brought to their attention (by Dr Simon Richards of QinetiQ) the existence of photographs showing the development of a spiral form of bubble nets by humpback whales (Figures 2 and 3). This paper outlines the possible acoustical implications of spiral nets.

The spiral net hypothesis

The authors hypothesize that spiral bubble nets may hold distinct advantages over circular ones [10]. In the circular bubble net of Figure I, the propagating rays which form the 'wall of sound' are confined within bubbly water. As will be shown below, refraction can trap rays within a spiral bubble layer in a similar way [10]. However in both cases the rays trapped by refraction propagate through bubbly water, where the attenuation is greater than it would be for bubble-free water. It is therefore advantageous in forming a 'wall of sound' that the spiral bubble nets contain a second, complementary path, where the containment of the rays works through reflection, and crucially, the propagation occurs through bubble-free water where the attenuation is less. Furthermore the open end of the spiral forms a more robust entry point for the sound, and does not require shallow angles of the sort shown in Figure I in order to create a wall of sound with a quiet interior. The trap is therefore much more tolerant to the positioning of the whale.

There are yet further advantages to the spiral bubble net, compared with the circular one.

The circular net requires closure of the circle in order to create a quiet bubble-free region. Of course the inner end of the spiral could close up upon itself, creating in effect a circular bubble net within a spiral one, with a quiet bubble-free region in the centre in which prey are trapped. However spiral nets do not need such accuracy in their construction: they will still work even if there is no complete closure of the bubble layer surrounding a bubble-free centre; and they will still work even if the centre is not bubble-free. This is because the spiral

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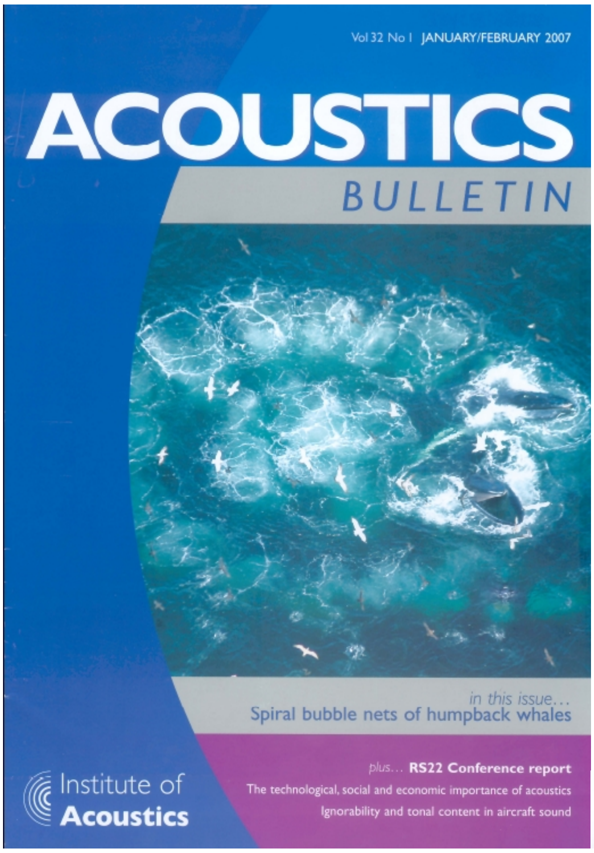

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geometry generates a new region, free of bubbles and sound, within the inside edge of the bubble-free arms of the spiral. The ever-closing spiral wall means that, as they progress into the spiral, the reflected rays meet the outer edge of the bubble-free arm of the spiral with ever-decreasing grazing angles, such that the inner edge of the bubble-free arms remains quieter.

Whilst both the bubble-free and bubbly paths in the spiral individually contribute to the wall of sound, the interactions between them create a synergistic effect: there will be ray paths which propagate at times in the bubble layer, and then leave it to enter the bubble-free layer, of the spiral; and reflections at interfaces between bubbly- and bubble-free water will be only partial.

Figure 4 shows the effect of just one ray as it enters the bubble-free arm of the spiral (all modelling in this paper is restricted by the limitations of ray representation, as discussed earlier [I]). When it first meets the outer edge of the bubble-free arm (at the point labelled A, here with a grazing angle of 34°), the subsequent propagation is represented by two rays: a refracted ray in the bubbly arm, and a ray which is reflected into the bubble-free arm. The refracted ray propagates in the bubbly waveguide. As it approaches the edge of the bubbly water in principle it may of course be internally refracted back into the bubbly water. Alternatively a given ray may intersect the edge of the bubbly waveguide, which in the model results in two rays propagating onwards: one is reflected back into the waveguide, whilst another is refracted into the bubble-free water (either within the spiral, or outside it). Propagation within the bubbly waveguide is attenuated much more than propagation in the bubble-free arm. Because of the absence of attenuation in Figure 4, and because of the ability of rays to multiply at interfaces, there is no information in the figure with respect to acoustic intensity.

The ray which at A reflected into the bubble-free arm of the spiral, propagates through it until it next meets the bubbly water at B, with a reduced grazing angle (here, 29°). Again two rays are shown propagating away from B, a refracted ray (which recharges the attenuated sound field in the bubbly water), and a reflected ray which continues through the bubble-free water towards C. Further reflections at C, D etc occur with reduced grazing angle, each one recharging the field in the bubbly water. The number of reflections is artificially truncated in the calculation at F.

The ever-reducing grazing angle will keep the inner edge of the bubbly net quiet, and the attenuation in the bubble cloud, and loss of energy from the ray in the bubble-free water each time it reflects, serve to reduce the sound field towards the centre of the spiral. In this way, quiet regions are generated. These are not just at the centre of the net, as with the circular net, but also along the inner edge of the bubble-free arm. Fish here will be in bubble-free, quiet water, but trapped within the spiral 'maze': in 2D, few positions will have an exit visible along the line of sight, and in real 3D nets the locations of the predators must be taken into account. Whilst Figure 4 showed the results (without attenuation) of the launching of a single ray into the spiral, Figure 5 shows a ray plot for the launching of a beam. As before, the plot lacks attenuation and requires the generation of both a refracted ray and a reflected one at interfaces, such that intensity information is incomplete. Note that the only rays with large grazing angles in the bubble-free arm have first propagated through the bubbly layer and suffered losses when refracting through the interface at least twice, and hence will be heavily attenuated.

There are clearly simplifications in Figures 4 and 5, some of which were discussed in [I]. As stated earlier, available recordings of the humpback call emitted during bubble net feeding contain significant energy in the 4kHz range. The ray tracing approach used in the model presented here is appropriate for this frequency range, given the overall dimensions of the net. However, to understand the role of low frequency energy emitted during bubble net feeding, modal analysis would be required.

Figures 4 and 5 are, of course, two-dimensional representations, but the key elements would also pertain to a 3D spiral net. Therefore, should the whale emit its feeding call into the net from below, the propagation path in 3D can readily be visualised from this 2D representation. The walls of the net in Figures 4 and 5 are smooth and generate specular reflection, whilst the degree to which the walls of Figure 3 are rough is difficult to estimate, particularly as the visible shape of the net is dominated by the large bubbles: in contrast, the small bubbles can be less easy to see, but are very potent acoustically. The roughness as perceived by the scattered acoustic field depends on the wavelength (λ) and the grazing angle (θ), such that the Rayleigh roughness criterion states a surface is rough if $kh\sin\theta = (2\pi/\lambda)h\sin\theta >> 1$, where h is the mean height of the surface undulations, and k is the wave number. In the absence of data on the geometry of the net which includes all bubbles, it is difficult to make calculations regarding smoothness. Because of the way the spiral continually

Figure 1

Ray model results for the trapping of sound within a circular bubble net (whose boundaries are shown by red circles). From Leighton et al. [1].

Figure 3a

Figure 3b

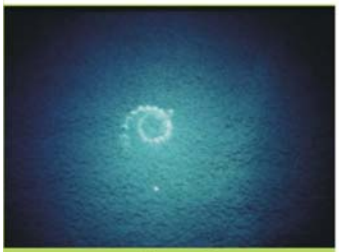

Figure 2

An underwater bubble net generated by a humpback whale. Images from the NMML Galleries are unrestricted. Photograph by J. Olson, NMFS, reproduced courtesy of the National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Alaska Fisheries Science Center, National Marine Mammal Laboratory.

Figure 3c

Three photographs of spiral bubble nets showing the formation of a bubble net, with lunge-feeding occurring in the final frame. Note the presence of opportunistic birds. (Photographs by Tim Voorheis / www.gulfofmaineproductions.com. Photographs were taken in compliance with United States Federal regulations for aerial marine mammal observation.)

reduces the grazing angle of rays as they penetrate further within it, then all else being equal, the inner regions of the spiral may therefore appear smoother, so creating robust regions within the spiral that are bubble-free and quiet. However this trend will be tempered by any change in h along the length of the spiral (reflecting the size of bubbles blown and the age of that portion of the net). The surface will appear most rough for the highest frequencies, which we take as 4kHz [I]. For acoustic fields in bubble-free water, this gives a wavelength of 0.375m, so that for test values of h of 0. I m and I m, the wall will appear smooth for grazing angles less than about 37° and 4° respectively, with commensurately larger angles for lower frequencies. The angles compare well with the sequence of angles recorded in the caption to Figure 4.

Why some nets should be spiral is not clear. It may be a pragmatic or incidental response to practical limitations. Conceivably however the whales could be exploiting the different acoustical properties of circular and spiral nets. These could confer possible advantages to the spiral configuration through the following features.

- A wall of sound can be generated using acoustic paths which propagate in bubble-free water (Figure 4) and hence suffer less attenuation than seen for acoustic paths in bubbly water (to which circular nets are restricted).
- Propagation in the bubble-free arm 'recharges' the heavily attenuated field in the bubbly waveguide as both progress into the spiral, which serves not only to reinforce the wall, but also to attenuate the sound in the bubble-free arm to facilitate the generation of quiet regions in the centre of the net.
- The spiral net contains more scattering interfaces between bubble-free and bubbly water, so that whilst a ray which leaves the circular net is lost from the net, a ray which refracts out of a region of bubbly water in the spiral

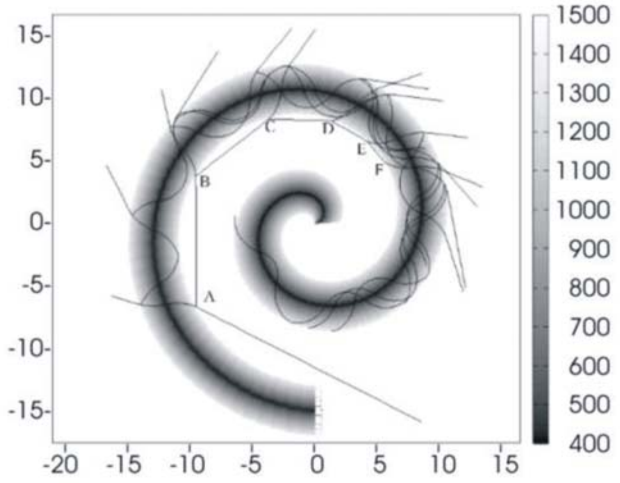

Figure 4

A horizontal plane shows a 2D plan view representation of a spiral bubble net (without a closed centre) is shown, the sound speed (ms-1) being indicated by the greyscale. The Cartesian axes indicate distance in the horizontal plane in metres. Into this net a single ray is launched. This undergoes a series of reflections off the outer wall of the bubble-free arm of the spiral, successively labelled A, B, C etc. At each reflection the grazing angle decreases (34° at A; 29 ° at B; 23 ° at C; 19° at D; 16° at E; 13° at F). Also, at each reflection, not only does a reflected ray propagate further into the bubble-free arm, but a refracted ray propagates into the bubbly-arm of the spiral. Attenuation, which is particularly severe for the rays in bubbly water, is not of course included.

net can remain trapped within the spiral system. Specifically, when a ray leaves the circular bubble net of Figure I it is lost to the 'wall of sound'; but except for rays crossing the outermost interface of the spiral bubble net, rays crossing boundaries in the spiral net remain contained within it.

- A spiral form which contains a closed inner ring of bubbles surrounding a bubble-free centre gives additional acoustic protection to the quiet zone at the centre of the net. High-angle rays need only cross two walls to penetrate the centre of the circular bubble net and degrade its quietness; in contrast, they must cross many such interfaces in the spiral net, reflecting at each boundary and attenuating across the width of several bubbly arms.
- Spiral nets need not be generated to such exacting standards as to contain a closed inner ring of bubbles surrounding a bubble-free centre. They generate quiet, bubble-free zones at locations against the inner edge of the bubble-free arm.
- The geometry of Figure 5 shows how the whale could speculatively obtain feedback on the performance of the spiral net, since the efficiency of the wall of sound could be diagnosed through monitoring the outbound sound as it leaves the spiral.

Discussion

It is no simple matter to test the hypothesis that the acoustic properties of spiral bubble nets may hold some advantages over those of circular bubble nets. If scale experiments are to be conducted, the realism of the model should be critically assessed. For example, it is relatively simple to construct a 1:100 scale model bubble net by submersing expanded polystyrene in water (Figure 6) and obtain measured sound fields which at first sight look convincing (Figure 7). Note that this is a spiral with a closed centre, not an open one of the type modelled in Figures 4 and 5. Because there is only reflection to consider, propagation in such a net is simple to model numerically (Figure 8). The reason for this is that, in this case, the 'bubble net' was made of expanded polystyrene, a solid matrix containing such a high fraction of gas bubbles frozen in place that it acts as a pressure-release interface underwater. No sound propagated in this scaled-down bubble layer, so that the experiment incorporated only the propagation path through the bubble-free arms of the spiral, and did not capture either refraction or propagation within the bubbly arm of the spiral. As a result, the polystyrene model could hardly fail to produce a wall of sound with a quiet interior.

Why use expanded polystyrene at all for this simple demonstration, rather

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See caption for Fig. 11

Spiral Bubble Nets - continued from page 19

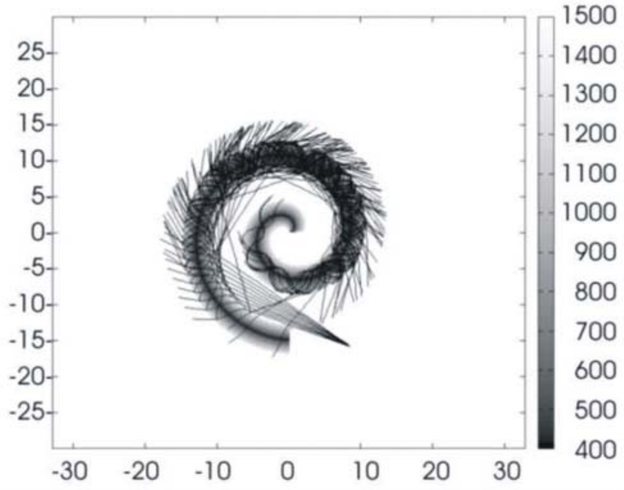


Figure 5

As for Figure 4, a spiral bubble net (without a closed centre) is shown, the sound speed (ms^{-1}) being indicated by the greyscale. The Cartesian axes indicate distance in the horizontal plane in metres. A beam of rays is launched into the spiral. The spiral generates clear regions which are both bubble-free and quiet. Note that whilst the emission of rays from the bubbly arms into the bubble-free arms at the inner regions of the spiral gives the visual impression that these rays will degrade the quietness of these inner regions, the energy contained within them will not be great, as a result of attenuation in the bubbly layer, and also because of reflection losses at the interface between bubbly and bubble-water.

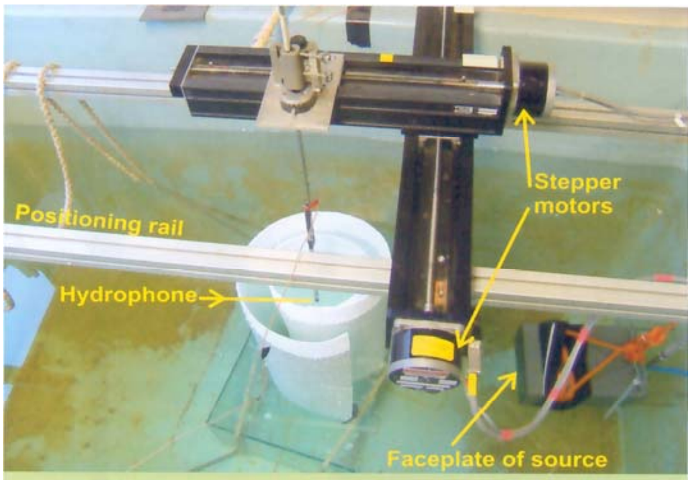


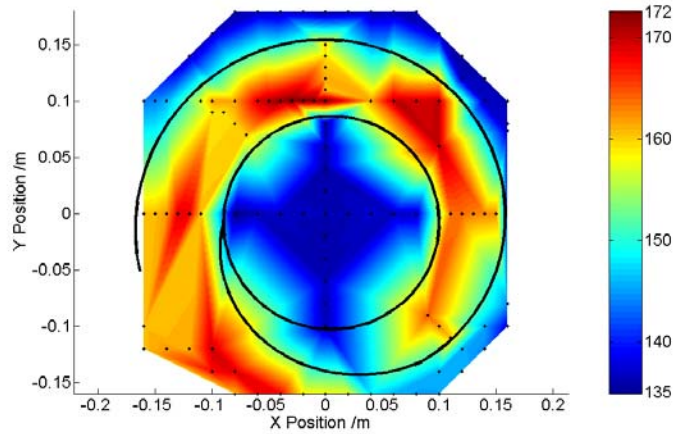
Figure 6

A simple scale model spiral net of 0.3m outer diameter, with a closed centre. The base of the spiral is fixed to an upturned aquarium, such that all except the top 10cm are submerged. The spiral is 0.6m tall and a 1.57m length of expanded polystyrene (of 7mm thickness) was required to complete the full two revolutions of the spiral.

than proceeding directly to a miniature net of real bubbles? The reason is that the polystyrene only models the impedance mismatch between high-void-fraction bubbly water, and bubble-free water: it is better knowingly to eliminate a key feature (the bubble resonance) from the scale model than it would be to include it with inappropriate scaling.

The problem is that, whilst a scale model of a net can readily be made to scale the gross dimensions of the net, it is no simple matter to scale the fine structure of the bubble size distribution. The scaling factor used in this experiment is around I : I00. For this, scaling of the gross features is simple: the model net diameter is 0.3m compared with 30m in the wild, and the acoustic wavelength is 4mm compared with the 400mm chosen to represent the longest wavelength of interest in the net [I]. However such a scaling factor causes problems in generating a suitable bubble population. This is because, whilst the bubble size distribution in the net is not known, it is likely to contain bubbles having radii ranging from centimetres to microns, and this cannot readily be scaled. More importantly, a simple 1:100 scaling is insufficient: as Leighton et al [1] showed, for sound to be trapped within the bubble net by refraction, the presence of bubbles must reduce the sound speed, which happens when the bubbles controlling the sound speed are driven at frequencies less than their resonance frequency (ie they are driven in stiffness-controlled regime) [2,1 I].The resonance frequency of an air bubble in water varies roughly inversely with its radius (for bubble greater than, say, ten microns in radius). For insonification at 375kHz in the scale model, the bubbles which are resonant have radii of less than about 10 microns. Bubbles larger than this would be driven in the inertia-controlled regime [I 1]. The generation of a bubble net of diameter 300mm which contained no bubbles larger than about 10 microns radius would be difficult and expensive, involving biomedical contrast agents, electrolysis, chemical reaction (Figure 9), or other alternative (Figure I0). Whilst production of a circle (or even a spiral) of bubbles in a water tank is not too difficult, ensuring that the resonance effects (and therefore sound speed profile) of the bubbly water are scaled appropriately is difficult. For this reason, only the reflective element was tested in this preliminary scale model (which was devised for an undergraduate project).

To what extent the humpback whales make use of these acoustical properties is not known, as it is difficult to obtain objective measurements of the sound field, and an assessment of whether whales exploit these features would require a survey which correlated behaviour with acoustics. The geometries of nets used have not been surveyed, let alone the relative occurrence of spiral and circular nets. Indeed lunge feeding is seen with other geometries of net (Figure 10), but without simultaneous acoustic information, reliable bubble data and behavioural observations, and in sufficient quantity, it is impossible to be certain as to the extent, if any, to which humpback whales are exploiting these.



The low-resolution map shows the acoustic field measured within a horizontal plane which passed through the midpoint of the spiral shown in Figure 6. The plan view position of the spiral is superimposed. The sound source was custom-made by Blacknor Technology Ltd., and projected a sinusoidal pulse of 375 kHz basic frequency and - 8 µs free-field duration, with horizontal acoustic axis at the mid-depth of the spiral. One pulse was projected every 2 ms. A calibrated Reson TC 4013 hydrophone (shown mounted on a scanning rig in Figure 6) was used to map the sound field generated in the spiral. The colour represents the rms sound pressure level at each measurement location, time-averaged over the entire 2 ms window from the start of one pulse to the start of the next, so that all the reflections within the spiral were included in the calculation (averages taken over the duration of the main pulse will be higher, but the long window more properly reflects the conditions we wish to mimic). The resulting level ranged from 135 to 172 dB re 1 µPa as shown on the colour bar. The discrete measurement points are shown as black dots in the figure. Between these, the sound pressure level value is then interpolated, and it is this surface upon which the vertices are plotted. This results in interpolations crossing the boundary of the polystyrene. Since all other data are interpolated between these measurement points, they should be treated as offering no more than visual effect, the actual data being only that shown at the measurement point. For example, interpolation occurs between points on either side of the polystyrene wall, and so the map will not be influenced by the zero pressure which occurs in the wall. Furthermore the spacing of points around the inner wall of the spiral is insufficient to show any zones of low pressure there, were it to exist the interpolation gives little evidence one way or another of this.

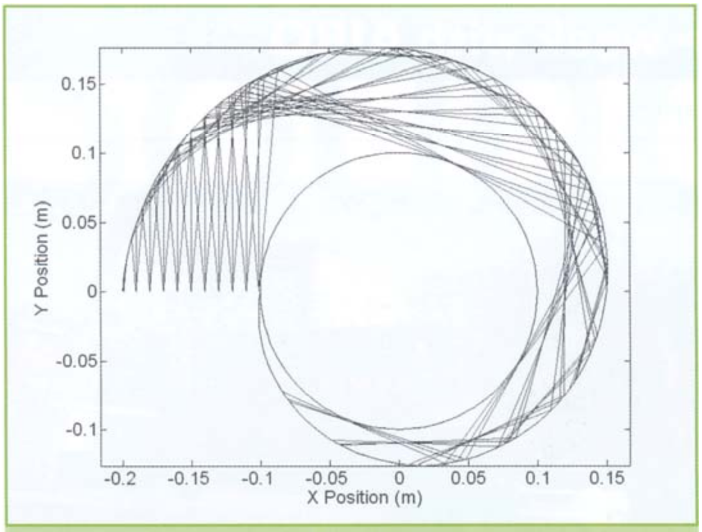


Figure 8

Model of ray propagation within the polystyrene spiral of Figures 6 and 7

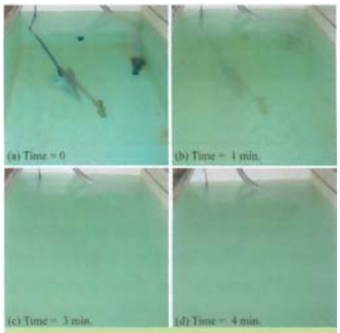


Figure 10

A large-scale generator of small bubbles implemented by the authors, the images corresponding to times of (a) 0, (b) 1 min, (c) 3 min and (d) 4 min after activation of the generator. They show the system filling a tank of normal fresh water (measuring 1.5m by 2.5m by 1.5m) with a dense cloud of minute bubbles, without the production of large bubbles. As a result, the initially clear water turns milky white, obscuring from view the Delta 22 anchor which lies under 1.5m of water and measures 695mm end-to end and a maximum of 310mm between the fluke tips. No chemicals were used.

Figure 11

A whale lunge feeds from what appears to be plane wall of bubbles. However it is not simple from photographs alone to be sure whether the eye can detect the location of all the acoustically active bubbles, and impossible to know what acoustics are being generated. .(Photographs by Tim Voorheis / www.gulfofmaineproductions.com. Photographs were taken in compliance with United States Federal regulations for aerial marine mammal observation). The unclipped version of this image is on page 19.

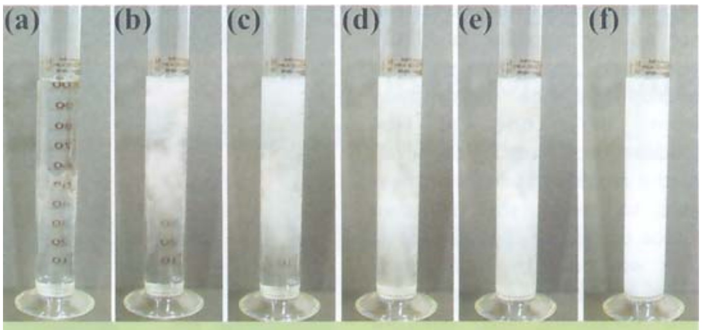


Figure 9

The generation of high concentrations of minute oxygen bubbles in liquid (without the production of any large bubbles) by means of "Sedna's Raven" in a 100 ml measuring cylinder. The whole sequence of photographs (a) to (f) was taken in under a minute. The system was devised with TGL and DCF by Dr Peter Birkin of the School of Chemistry, University of Southampton using hydrogen peroxide over Manganese dioxide (MnO_2) for the purpose of scaling oceanic bubble populations. The results still possess the dynamics of bubbly water, whereas froth would not.

There may be volumes of microscopic bubbles which, although they have a pronounced acoustic effect, are not visible in the photographs, but which can persist for many minutes in the water column. It may be that the formation of spiral nets is simply the by-product of some behaviour designed to achieve another purpose, such as efficient motion during the formation of the net, just as the shape of natural spirals whose response to pressure perturbations is key to their function (eg the cochlea, the nautilus shell) has been attributed to expedient (if the perhaps mundane) explanations such as efficient packing.

However, the ever-decreasing grazing angle which will, if the spiral is sufficiently long, eventually generate wall-hugging surface waves; the robustness to the particulars of the entry; and the possibility of feedback from back-propagating fields all show the remarkable effect of the spiral on fields propagating along it. These are suggestive of possibilities that should be explored.

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Ed Grover currently in year 4 of the undergraduate MEng programme at the Institute of Sound and Vibration Research, and took the data of Figure 7 as part of his year 3 project. He is a student member of the 10A.

Paul White is Professor of Statistical Signal Processing at the Institute of Sound and Vibration Research.

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(Cover photograph credit as for Figure 3c)