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Wall of sound: the bubble nets of humpback whales

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Trapped within a 'wall of sound'

A possible mechanism for the bubble nets of humpback whales

Timothy G. Leighton FIOA, Simon D. Richards FIOA & Paul R. White

ABSTRACT

It has been known for decades that, to trap prey, humpback whales sometimes employ 'bubble nets' in the form of hollow cylinders. The cylinder wall contains a dense population of bubbles, but the interior is comparatively bubble-free. A group of whales may cooperate, diving and then rising in a helix, releasing bubbles to form nets of 3 to 30 metres diameter. The prey congregate in the bubble-free centre and are then consumed by the whales, which rise from below. The imprecision of the explanations of why prey refuse to escape through the walls is probably the reason why, although the phenomenon is described frequently on the internet, it seldom appears in formal scientific literature. This article suggests that the acoustic properties of the nets warrant investigation, and speculates on possible mechanisms by which the nets might act. For example, the trumpeting calls emitted by the whales, when they produce these nets, may become trapped within the bubble wall, generating high intensities there. These calls (which human reporters have subjectively described as disconcerting and even alarming) are so loud that they resound throughout the hull of any nearby ship. This article shows that, under certain insonification conditions, sound can be concentrated within the wall of the net, leaving the inside of the cylinder (where the fish congregate) almost silent. The natural schooling response of fish to the 'wall of sound' which they encounter if they try to leave the trap makes them a compact meal when the whales rise up from beneath, with their mouths open. The possibilities of this, and related acoustical effects, are discussed.

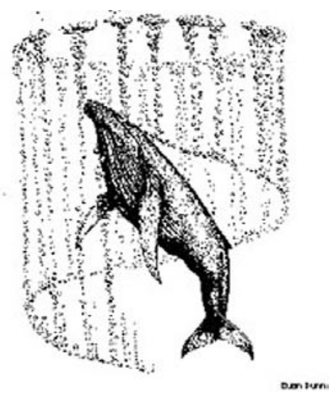

Figure 1 Schematic of a humpback whale creating a bubble net. The whale dives beneath a shoal of prey and slowly begins to spiral upwards, blowing bubbles as it does so, creating a hollow-cored cylindrical bubble net. The prey tend to congregate in the centre of the cylinder. Then the whale dives beneath the shoal, and swims up through the bubble-net with its mouth open to consume the prey ('lunge feeding'). (Image courtesy of cetacea.org)

Humpback whales (*Megaptera novaeangliae*) exhibit a unique feeding behaviour, whereby they encircle schools of prey fish with a hollow cylindrical cloud of bubbles **(1)** up to 30m in diameter, which they create by emitting air through their blowhole, as shown in *Figure 1*. This behaviour is sometimes conducted by a solitary animal and sometimes in groups of 15 or more **(2)**. The humpbacks then lunge feed on the fish (*Figure 2*).

Figure 2 Humpback whales lunge feeding (photograph courtesy of Lisa Walker)

The fish appear to be trapped within the cylindrical bubble cloud: they seem unwilling to pass through the bubble net. This behaviour on the part of the prey is somewhat surprising given the prevalence of bubbles in the upper ocean, and the ability of fish in general to survive breaking waves, waterfalls *etc*. **(3)**. Humpback whales are known to emit very loud calls during feeding activities: 'As the bubbles rise, a whale trumpets a feeding call for a minute or two before sweeping the frequency upwards to cue a synchronous surface lunge. A hydrophone is not needed to hear these sounds. They travel up through the hull and into your ears' **(4)**. Recordings of 'trumpetings' (which can, for example, be heard at **(5)**) may contain energy in the range 100 - 4000 Hz. This paper suggests that the bubble net's trapping ability owes much to the interaction of the whale sounds with the bubbles.

Because the density and sound speed (ρ_c, c_c) of bubbly water differ from those of bubble-free water (ρ_w, c_w), their potential to act as 'bubble screens' for underwater sound (*eg* piling **(6)** and underwater explosions **(7)**) has often been discussed, and even realised. For example, bubble screens have been used to reduce the noise from pile-driving activities in the construction of the new Bay Bridge and Benicia-Martinez Bridge in the San Francisco Bay Area, in order to protect migrating salmon and other fish. Often unsophisticated appeals are made to the way the normal incidence acoustic pressure reflection coefficient $R_{refl} = (\rho_c c_c - \rho_w c_w)/(\rho_c c_c + \rho_w c_w)$ will tend to -1 if the void fraction can be made sufficiently great, through its effect on reducing ρ_c. However the actual effect of underwater bubble clouds is more sophisticated, with refraction in addition to reflection.

Figure 3 illustrates schematically the speculative mechanism for how the bubble nets may cause sound to be trapped within the bubbly region. This plan view shows a section of the bubble net, with the whale emitting sound from outside. As shown by the sound speed graph, the speed of sound varies across the bubbly region, with a minimum on the axis. This will be the case for sound waves of frequencies which are less than the resonant frequencies of the individual bubbles, and where the bubble density is a maximum on the axis. The behaviour of the sound within the bubbly region can be described by Huygens' principle. The new position of a propagating wavefront may be found from the envelope of the small Huygens wavelets spreading out from the previous position of the wavefront. Since the speed of sound near the centre line of the bubbly region is less than that nearer the edge, the wavelets near the axis will have smaller radii than those near the edge (since, in any finite small time, they travel less far). The wavefronts therefore change direction and refract towards the centreline of the region. Even if the interior is not bubble-free, similar refraction occurs provided the void fraction decreases as one moves into the cylinder interior.

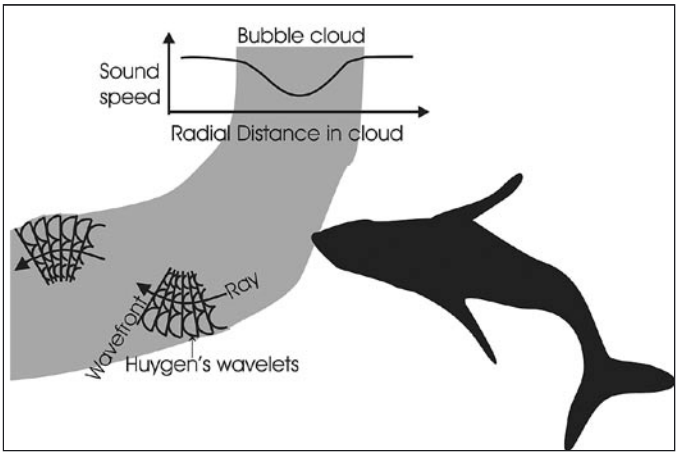

Figure 3 Schematic of a whale insonifying a bubble-net (plan view). According to Huygens' principle, the position of a wavefront (which is locally normal to the rays) can be found from the envelope of small Huygens wavelets which can be thought of as propagating out from the original position of the wavefront. Since the sound speed in the figure is smaller the closer one is to the centre-line of the bubble cloud, the Huygens wavelets form smaller circles there than they do further from this axis. Hence subsequent wavefronts tend to change direction so that the rays refract back into the cloud. Similar effects can of course occur under breaking waves, in vessel wakes, etc.

Method

(a) Sound speed in bubbly water. A fuller account of the bubble dynamics associated with bubble nets is given by Leighton **(8)**. With the subscript w referring to bubble-free water, and c to water within the bubble cloud, the sound speed can be found through the differential of the liquid pressure P with respect to its density ρ, which in turn is related to the bulk modulus B:

$$c_{w,c} = \sqrt{\partial P_{w,c} / \partial \rho_{w,c}} = \sqrt{B_{w,c} / \rho_{w,c}}, \quad (1)$$

where

$$B_{w,c} = - \frac{dP}{\left(dV_{w,c} / V_{w,c} \right)} . \quad (2)$$

ie the ratio of the imposed pressure in the liquid to the proportional change in volume, the minus sign ensuring that the expected quasi-static behaviour (a compressive pressure leading to a decrease in volume) gives a positive bulk modulus **(9)**.

Whilst the addition of bubbles to previously bubble-free water does reduce the density $(\rho_c < \rho_w)$, in quasi-static conditions the reduction in the bulk modulus outweighs this effect in *Eq.1* and the sound speed is reduced $(c_c < c_w)$. This is because, whilst bubble-free water is relatively incompressible, the free gas in bubbly water is readily compressed by a positive dP, such that $\left| dV_c / V_c \right| > \left| dV_w / V_w \right|$ *(Eq.2)*.

A bubble pulsating in response to an incident sound field is however an oscillator (the gas providing the stiffness, and the surrounding liquid the inertia) **(9)**. Whilst the above quasi-static scenario corresponds to the stiffness-controlled regimes, where the bubble is driven at frequencies much less than its resonance, in the inertia-controlled regime (when the frequency of the incident sound field exceeds the resonance) the bubbles are expanding during the compressive half-cycle of the oscillating acoustic field. Hence in this regime the addition of bubbles will increase the sound speed, the effect disappearing at the highest frequencies.

Were humpback whales able to exploit the frequencies at which this would occur, and use these for echolocation of the prey within the bubble net by a whale outside it (a controversial hypothesis **(10)**, but raised in the speculative spirit of this article), it is possible that certain signals would not be significantly refracted by the net. Reflections allowing, they might be effective in echolocation despite the fact that lower frequencies may be trapped in the 'wall of sound'. These effects will now be modelled using ray theory.

(b) Ray theory. The propagation of sound into and around the bubble net has been calculated here using standard ray theory **(11)**. The ray equations may be written

$$\frac{dx}{ds} = c\xi(s), \quad \frac{d\xi}{ds} = -\frac{1}{c^2}\frac{dc}{dx}, \qquad (3)$$
$$\frac{dy}{ds} = c\zeta(s), \quad \frac{d\zeta}{ds} = -\frac{1}{c^2}\frac{dc}{dy},$$

where $[x(s), y(s)]$ is the ray trajectory in the horizontal plane, c is the local sound speed, and $\xi(s)$ and $\zeta(s)$ are auxiliary variables introduced in order to write the equations in first-order form.

The ray equations have been solved by direct numerical integration, using the initial conditions

$$x = x_s, \quad \xi = \frac{\cos\theta}{c(0)}, \qquad (4)$$
$$y = y_s, \quad \zeta = \frac{\sin\theta}{c(0)},$$

where (x_s, y_s) is the source position, θ is the initial launch angle of the ray, and $c(0)$ is the sound speed at the source. This is then repeated for a set of rays representing the beam pattern of the whale's projected sound.

Since field data are lacking, certain parameters needed to be estimated. Whilst there are no data on the size distribution of bubbles in the bubble net, oceanic bubble size distributions produced by breaking waves have sufficient numbers of small bubbles that a frequency of a few kHz or less (such as the humpbacks use) will propagate with reduced sound speed **(12,13,14)**. This is because the buoyant rise speed of bubbles is greater for large bubbles; and, if a bubble descends to greater depth as a result of turbulence or circulation, hydrostatic pressure causes it to shrink. Calculation of the sound

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speeds within the net would require knowledge of the void fraction (the proportion of bubbly water volume which is free gas). Again, there is no field data on what void fractions whales can generate. If the insonification frequency is sufficiently low compared to the majority of bubble resonances, the sound speed in the cloud c_c is relatively independent of the bubble size distribution and depends on the void fraction V (the proportion of free gas in the bubbly water) through **(9)**:

$$c_c = c_w \left(1 - \frac{V}{2} \frac{\rho_w c_w^2}{\kappa p_0} \right) \quad (5)$$

where p_0 is the total static pressure (atmospheric and hydrostatic) at the location of the bubble, and κ is the polytropic index of the gas (which, if air bubbles pulsate adiabatically, takes a value of 1.4). Under such conditions a sound speed of 750ms^{-1} requires a void fraction at 5m depth of less than 0.01% (compare with the measured sound speeds in the caption to *Figure 6*). For the simulation the sound speed is taken to be 1500ms^{-1} in the bubble-free water to be found outside of the net and inside its bubble-free interior. Within the walls of the net, the sound speed for low frequencies of a few kHz is taken to vary linearly, reaching a minimum of 750ms^{-1} along the circumferential centreline of the cloud (*Figure 4a*).

The beam width of the source to be used in the model is also not available in the literature. An angle of 10° was chosen for *Figures 4 and 5*. If humpback whales are able to form narrow beams, this value is not unreasonable, given that a source of radius a ~ 1m does have a ka of ~ 17 for c = 1500ms^{-1}, and ka~34 for c = 750ms^{-1}, at 4kHz (a frequency the whales can certainly produce **(10,15)**), and therefore has the potential to be highly directional. For ray theory to be valid at the frequencies of interest, the wavelength of the sound should be small compared with the scale lengths over which the sound speed varies (at 4kHz the wavelength is ~ 190mm for c_w= 750ms^{-1}).

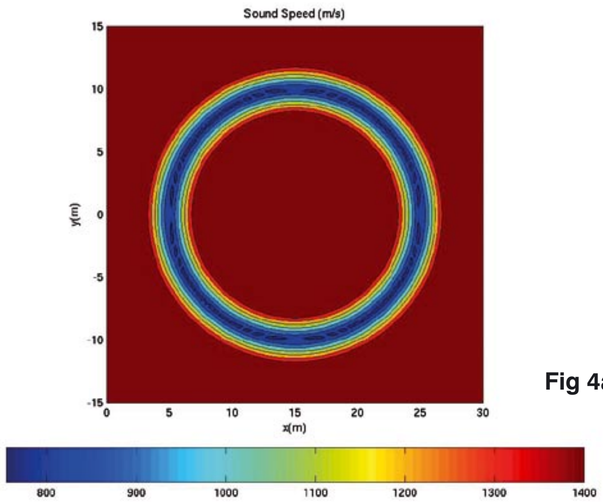

Fig 4a

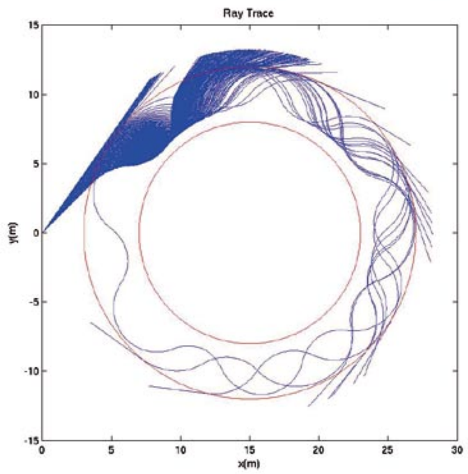

Fig 4b

Figure 4 Simulation of sound trapping in bubble nets, for frequencies appropriate to ray tracing but sufficiently low to generate (a) the sound speed variation in an annular region representing a horizontal slice through the bubble net. (b) The computed paths of 281 rays launched from point (0,0) with an angular extent of 10°. The rays turn about the minimum in the sound speed owing to refraction, resulting in the ducting of sound within the wall of bubbles. The rays gradually leak out, although one ray in this case propagates around the entire circumference.

Results

The bubble net is modelled as an annular region containing the bubble population, whilst the regions in the centre of and outside the annulus are free of bubbles. *Figure 4b* shows a two-dimensional ray diagram representing, in plan view, the interaction of sound with a bubble net, for the sound speed profile shown in *Figure 4a*. This assumes that the insonifying frequency is sufficiently low compared to the resonances of most of the bubbles, such that the sound speed in the net will be lower than that in bubble-free water.

A set of 281 rays covering a beamwidth of 10° is launched from the origin (0,0) and the raypaths are computed by successive numerical integrations of the ray equations. The resulting raypaths are shown in *Fig. 4b*. It will be noted that the rays with launch angles farthest from the y=0 axis travel in straight lines and do not interact with the bubble net. However, those rays which do interact with the bubble net are refracted by the radial sound speed profile. The sound speed is decreasing towards the mid-line of the bubble annulus, and the rays are therefore refracted toward this. Rays which cross the mid-line then propagate through regions of increasing sound speed as they travel towards the inner or outer face of the bubble net, and are thus refracted back inwards. This radial sound speed profile thus forms a waveguide in which sound can be trapped.

The distance which individual rays travel within this waveguide clearly depends upon their initial angle. Many of the rays escape from the bubble net after having been turned only once by the radial sound speed profile. Once they have left the bubble net they will continue to travel in a straight line in the isovelocity ambient water. These rays therefore escape and can never interact with the bubble net again, so the ray tracing algorithm is then terminated. Other rays perform two or three turns about the sound speed minimum before being lost, whilst yet others perform sufficient turns about the minimum to propagate all the way around the circumference of the bubble net. This simulation therefore demonstrates the partial trapping of sound from a single source within the bubble net. The process becomes increasingly effective

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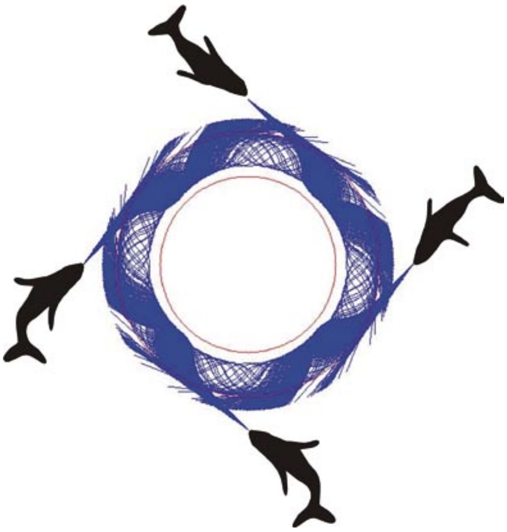

Figure 5 Four whales insonify an annular bubble net having the sound speed profile of Figure 4a, and the launch conditions of Figure 4b.

as more sound sources (whales), distributed around the circumference, become involved (Figure 5).

It is therefore proposed that the whales can create regions of high sound intensity within the walls of the bubble net, whilst the region in the centre, where the prey are concentrated, is relatively free of sound. It is further proposed that this 'wall of sound' is at least partially responsible for containing the prey within the central, quiet region where they are then consumed by the hunting whales.

The ability of the walls of the bubble net to trap sound, with a quiet interior, clearly has potential for herding prey. It would also act as a reverberant cylindrical cavity if insonified from below, examples of which have been demonstrated in the laboratory (*Figure 6*). The whale could generate high amplitude fields in such a reverberant cavity, speculatively to startle the herded prey just prior to feeding. The schooling response of fish to startling (either within the cylinder, or as they approach the walls) will, in the bubble net, be transformed from a survival response into one that aids the predator in feeding.

The actual acoustics of the cloud will of course be complicated by 3D effects and the possibility of collective oscillations **(16,17)**; and even, speculatively, parametric sonar effects **(9)** which might be utilised by whales, for example to reduce beam width or generate harmonics, sum-and difference frequencies *etc*.

The refraction is frequency dependent. If, as discussed earlier, the whales were to utilise frequencies that were sufficiently high, the presence of bubbles in the wall would produce an increase in sound speed, decreasing to the bubble-free value at even higher frequencies (for which there would be no refraction, only scattering and some absorption). For the intermediate situation profiled in *Figure 7a*, where the bubbles in the cloud raise the sound speed to a maximum value of 2250ms^{-1}, a variety of ray behaviour is possible, from reflecting straight off the cloud to traversing it and the interior with barely any refraction. An example is shown in *Figure 7b*.

Such frequencies would not be effective in trapping prey, even if the prey could perceive them. However were sufficiently high frequencies being used to echolocate prey contained within the net (a possibility which is by no means certain **(10)**), by a whale outside it, it is possible that certain signals would not be significantly refracted by the net and so, reflections allowing, might be effective in echolocation. This is despite the fact that lower frequencies may be trapped in the 'wall of sound'.

Conclusions

This article speculates on the previously unconsidered acoustic effects of bubble nets produced by humpback whales. The phenomena described may go beyond the bubble nets themselves, and be used by humpback whales for other purposes (such as by males to guard females during breeding). Man-made bubble clouds might generate similar effects (for example in vessel wakes), and could be exploited in enhancing the acoustic screening of noise by bubble curtains. The generation of 'walls of sound', quiet regions, and reverberant volumes might, speculatively, be

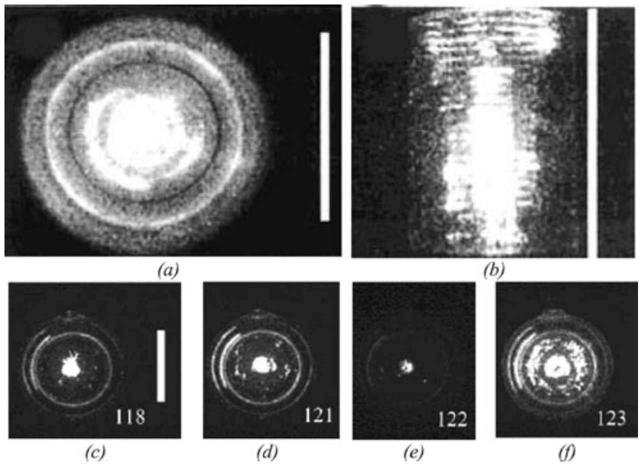

Figure 6 The acoustic pressure antinodes within reverberant water-filled cylinders (insonified from below) are made visible through the chemiluminescence which occurs there. (a) Plan and (b) side views of luminescence (which occurs at pressure antinodes) in a water-filled cell which had a polymethylmethacrylate wall (9.4cm internal diameter, 10cm external diameter; height of aqueous solution 14cm) for insonification at 132.44kHz where the spatial peak acoustic pressure in the liquid was 0.75 bar. The scale bar in frame (a) represents 9.4cm, while the scale bar in frame (b) represents 14cm. Frames (c)-(f) (to which the scale bar of length 5.8cm in frame (c) refers) were taken in a double-walled, water-jacketed cell (5.8cm internal diameter, 8.5cm external diameter, and liquid height 8cm) which was maintained at a constant liquid temperature of 25°C. As the insonifying frequency changed, so too did the spatial peak acoustic pressure, providing the following combinations: (c) 118kHz; 1.36 bar; (d) 121kHz; 1.39 bar; (e) 122kHz; 1.50 bar; (f) 123kHz; 1.80 bar. The effect of tuning into particular acoustic modes is evident. By noting the modal resonance frequencies in these and similar cylinders, the sound speed in this bubbly water was found to be in the range 868 - 1063 ms^{-1}, implying void fractions of 2.9 - 4.2 x 10^{-3} % (it is recognised that the source of bubbles and their dynamics here will differ from those generated in bubble nets). Frames selected from several figures in 'Birkin PR, Leighton TG, Power JF, Simpson MD, Vincotte AML & Joseph PF. *J. Phys. Chem.* A,107, 2003, 306-320'.

used in the protection of fish farms and shellfish beds from predators, and protection of bathing beaches from sharks.

The preliminary tests so far support the speculations. Nevertheless it is recognised that the approach adopted here has limitations, associated for example with the use of ray theory, and the fact that the simple model proposed does not take into account the scattering of sound by the bubbles (such scattering would result in reverberation within the bubble cloud, which would tend to enhance its ability to trap sound). Further testing would require much greater detail on field conditions (*eg* the bubble size distributions and void fractions, and the sound source characteristics) than is currently available. This would apply not just to simulation, but also to any tank testing: if either the experimenter, or whales themselves, provided inappropriate bubble populations or launch conditions, the conditions for the mechanisms discussed above might not be met.

References

1 Sharpe, F. A. & Dill, L. M. The behaviour of Pacific herring schools in response to artificial humpback whale bubbles. *Canadian Journal of Zoology-Revue Canadienne de Zoologie,* **75**, 725-730 (1997)

2 Valsecchi, E., Hale, P., Corkeron, P. & Amos, W. Social structure in migrating humpback whales (*Megaptera novaeangliae*). *Molecular Ecology.* **11**, 507-518 (2002)

3 It should be noted that SDR's response, when TGL suggested the possibility of acoustic effects (*eg* the refraction of *figure 3*) in the net, was to point out that, if the void fraction in the cloud were sufficiently high, fish within it might lose buoyancy and 'sink like stones', in a manner similar to one proposal for the mechanism by which vessels are lost in the Bermuda Triangle.

4 Walker, L. (http://www.groovedwhale.com)

5 Examples available at
http://www.groovedwhale.com
http://www.sfu.ca/biology/berg/whale/abcwhale.html
http://students.ceid.upatras.gr/~pirli/whales/whales.html

6 Würsig, B., Greene, C.R., Jr. & Jefferson, T.A. Development of an air bubble curtain to reduce underwater noise of percussive piling. *Marine Environmental Research*, **49**, 79-93 (2000)

7 Keevin, T. M., Hempen, G. L. & D. J. Schaeffer. Use of a bubble curtain to reduce fish mortality during explosive demolition of Locks and Dam 26, Mississippi River. Pp. 197- 206. In: Proceedings of the Twenty-third Annual Conference on Explosives and Blasting Technique, Las Vegas, Nevada. International Society of Explosive Engineers, Cleveland, OH (1997)

8 Leighton, T. G, From seas to surgeries: The pressure fields produced by non-interacting spherical bubbles at low and medium amplitudes of pulsation. International Journal of Modern Physics B (in preparation) (2004)

9 Leighton, T. G, *The Acoustic Bubble*, Academic Press, London (1994)

10 Mercado, E. and Frazer L. N. Humpback whale song or humpback whale sonar? A reply to Au et al. *IEEE J Oceanic Engineering,* **26**(3), 406-415 (2001)

11 Jensen, F. B., Kuperman, W. A., Porter, M. B. & Schmidt, H. *Computational Ocean Acoustics.* Springer-Verlag, New York, (2000)

12 Medwin, H., Fitzgerald J. & Rautman, G. Acoustic miniprobing for ocean microstructure and bubbles. *J. Geophys. Res.* **80**, 405-13 (1975)

13 Vagle, S. & Farmer D. M. A comparison of four methods for bubble size and void fraction measurements. *IEEE J. Oceanic Engineering,* **23**, 211-222 (1998)

14 Leighton, T. G, Simpson, M. D., Clarke, J. W. L. & Meers, S. D. A Report on the development of an algorithm that incorporates depth dependence in the dispersion relation for bubbly media. *ISVR Technical Report,* **290**, University of Southampton, (2000)

15 Mercado, E. and Frazer L. N. Environmental constraints on sound transmission by humpback whales. *J. Acoust. Soc. Am.*, **106**(5) 3004-3016 (1999)

16 Prosperetti A. Bubble-related ambient noise in the ocean. *J. Acoust. Soc. Am.*, Suppl 1, **78**, S2 (1985)

17 Carey WM. Low-frequency ocean surface noise sources. *J. Acoust. Soc. Am.*, Suppl 1, **78**, S1-S2 (1985)

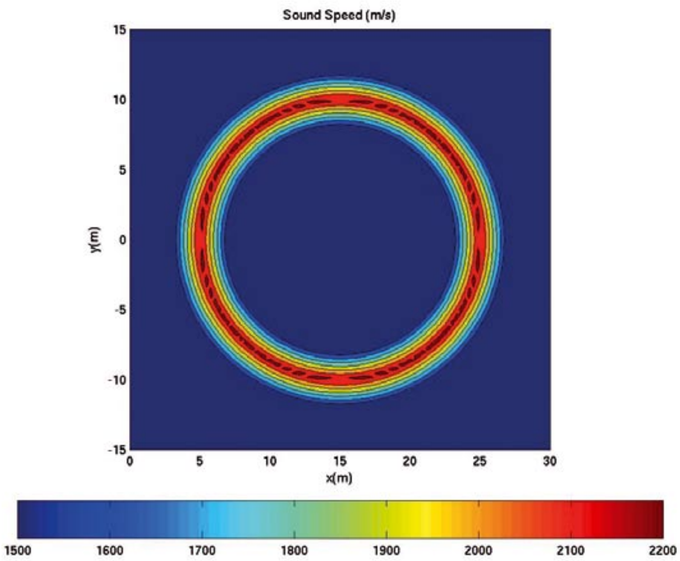

Fig 7a

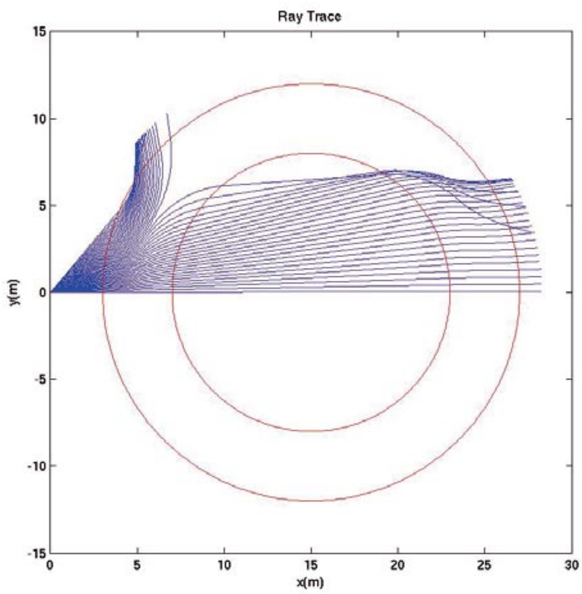

Fig 7b

Figure 7 (a) Sound speed profile possible for acoustic waves of sufficiently high frequency. (b) Example ray paths computed for this sound speed. For this simulation, however, the source has a 45° beamwidth in order to illustrate the variety of ray bending that is possible (a 10° beam, as used in Figures 4 and 5, tends to cause all rays to follow a similar path, either traversing the net or refracting out of it, depending on the angle with which it intercepts the outer wall of the net)

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