Proceedings of the Institute of Acoustics

A NARROW BAND BIO-SONAR: INVESTIGATING ECHOLOCATION IN THE HARBOUR PORPOISE, *Phocoena phocoena.*

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1. INTRODUCTION

The harbour porpoise, the smallest marine cetacean in the Northern hemisphere, is a frequent victim of the continental shelf bottom-set gillnet fisheries with many thousands killed annually. The reasons for this mortality are not clear as these animals possess a sophisticated active sonar system with which they detect, track and intercept small fish targets. The performance and limitations of this animal's sonar are therefore being investigated in order to devise techniques that will minimise cetacean/gillnet interactions.

Source Levels and Spectra were carefully determined in an enclosed environment from signals emitted by two juvenile animals. This paper re-examines these signals and, in the context of the detailed structure of the vestibular air sacs, presents a new hypothesis suggesting that a passive signal processing mechanism exists in these animals which may explain the formation of their unusually narrow band echolocation signals.

The harbour porpoise, *Phocoena phocoena*, is found in cold-temperate and sub-Arctic coastal and continental shelf waters in the Northern hemisphere, Klinowska **[1]**. Its adult length is typically 1.4 - 1.7 m making this one of the smallest cetaceans. The harbour porpoise is not normally maintained in captivity and is a particularly shy and elusive animal to study in the wild. However the successful rescue and subsequent rehabilitation in the Netherlands of several stranded young animals during 1993/4 provided an opportunity to measure echolocation Source Levels (SL) in controlled conditions and to analyse the signal power spectrum **[2]**. These young harbour porpoises produced a relatively narrow band transient sonar pulse repeated in 'click' trains or bursts when encouraged to examine a target whilst supported at a known range. Analysis of pulses, selected when the hydrophone was on the transmission axis, reveal a spectrum peaking near 145 kHz. This frequency agrees with earlier data for juvenile harbour porpoises, Kamminga **[3]**, Møhl & Andersen **[4]** and is a little higher than that reported for adults, Kamminga & Weisma, **[5]** and it would appear that the peak frequency may fall somewhat with increased body size,**[5]**.

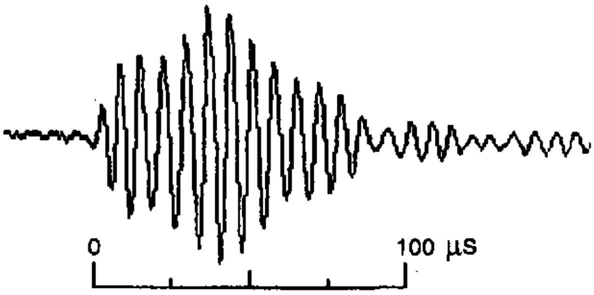

Figure 1 - Echolocation pulse of a 20 month old juvenile harbour porpoise.

The harbour porpoise sonar signal differs from the bottlenose dolphin (*Tursiops truncatus*), often taken to typify the oceanic dolphin, which emits a much shorter and much higher SL signal with a broad spectrum energy peak varying between 80 and 120 kHz, Au **[6]**.

The small, 8.6 m x 6.3 m x 1.3 m deep, concrete holding pool used to measure the porpoise signals was significantly reverberant and these conditions appear to have modified the animal's pulse repetition rates. In these particular tests the harbour porpoises employed inter-click delays which were much longer than the two-way travel time defined by the target range, possibly as an adaptation to improve their signal/reverberation ratio.

In order to assess the capabilities of this biological sonar it is necessary to observe and measure the signal characteristics and try to place these in an operational context with typical prey target sizes. Studies of a wild dolphin's sonar behaviour while foraging Goodson *et al.* **[7]** and Bloom *et al.* **[8]** provided observations suggesting a behavioural model that can be investigated with porpoise data. These wild animal studies show a behavioural adaptation of the sonar pulse repetition rate, in relation to expected or actual target ranges, and the *inter-click* periods provide useful indicators of target detection ranges and of the foraging strategies employed by the animal. The Source Level (SL), power spectrum, Directivity Index (DI), bandwidth and beamwidth are basic parameters that need to be determined when attempting to predict a sonar's performance. Given the maximum Target Strength (TS) of typical large prey (size and species may be established from the stomach contents of bycaught animals) and some measure of the harbour porpoise's acoustic sensitivity, Andersen **[9]**, SL data may be used to indicate probable maximum detection ranges for single fish targets. However, unlike dolphins, the harbour porpoise appears unable to signal to con-specifics with frequency modulated whistles and its trains of clicks may therefore include a communication function unrelated to echolocation. This latter possibility needs consideration when interpreting signals whenever more than one animal may be present.

2. SOURCE LEVELS AND SPECTRUM

Goodson *et al.* **[2]** reports that the SLs of two juvenile harbour porpoises (8 months and 20 months old), when carefully determined in a series of tank tests, gave on-axis maxima around 150 dB re 1μPa at 1 m. The typical echolocation pulse had a duration of around 85 μ s and the waveform consisted of approximately 14 sinusoidal cycles (Figure 1). Typically these oscillations increase in amplitude for the first 5 cycles and then appear to decay exponentially. The signals analysed exhibited a consistent power spectrum (Figure 2) with most energy concentrated between 140 kHz and 160 kHz and a -3 dB bandwidth of approximately 13 kHz. Some energy is also radiated at frequencies in the audible range but these low frequency components are very low in amplitude, typically some 40 dB below the spectral power peak, and can be assumed to be irrelevant when considering echolocation of small fish targets. The single loudest pulse observed in this series of tests was 164 dB re 1μPa at 1m which is similar to the SL reported for adult harbour porpoises in enclosed conditions and less than 10 dB below the average SL values reported for these same animals when observed in lower reverberation conditions, Akamatsu **[10]**

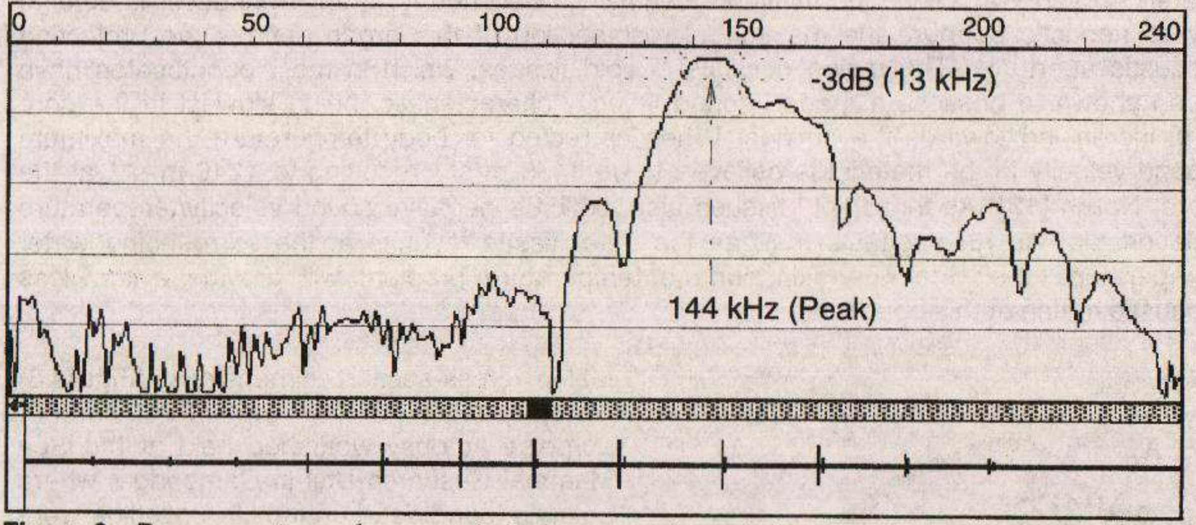

Figure 2 - Power spectrum of an on-axis harbour porpoise echolocation pulse. Upper scale in kHz, 50 dB dynamic range. Lower trace shows the amplitude of the click sequence as the animal tracked a target moving behind the hydrophone.

3. SIGNAL/REVERBERATION RATIOS

The target used to attract the porpoise's attention during these recordings was a visually obvious but acoustically weak small white plastic net attached to a pole that was manipulated to pass between the hydrophone and the pool wall. The porpoise was restrained at set ranges (2, 4 and 6 m) and orientated towards the hydrophone and perpendicular to the wall 1 m behind. The specular echo return from the wall was therefore very strong and the porpoise was attempting to discriminate the weak target from the wall echo target/wall separations of less than 0.5 m. Comparing the amplitude of each transmission signal with the decaying reverberation noise floor immediately preceding it indicated that these animals preferred to delay each transmission until a signal/reverberation ratio greater than 50 dB was obtained. The porpoise made no attempt to *range lock* its inter-pulse period to the two-way travel time, which is a normal behaviour observed during fish interception in open water conditions.

4. BEAMWIDTH ESTIMATION : AN INDIRECT APPROACH.

The practical determination of the porpoise's sonar beamwidth is difficult, and a satisfactory direct measurement requires a multi-channel recording system together with an array of hydrophones to sample the spatial pattern from individual transmitted pulses. In the absence of such direct measurements an estimate of the minimum beamwidth has been made using measurements of the *melon* cross-section, Goodson **[11]**.

This fatty organ, situated in the forepart of the porpoise head, appears to function as an acoustic lens providing the final beam forming and acoustic impedance matching to the water, Aroyan **[12]**. Since the minimum beamwidth obtained from any transducer is defined by its acoustic aperture the maximum cross-section of this organ defines the projecting acoustic aperture. The melon consists of lipid tissues, which in most odontocetes have been shown to possess a graded sound velocity characteristic, being slowest in the core and increasing towards the outside. When corrected for body temperature the maximum sound velocity in the material is believed to be 1435 m s^{-1} reducing to 1246 m s^{-1} at the core, Norris **[13]**. As these lipid tissues also exhibit a negative sound velocity/temperature relationship, Au **[6]** suggests that, as the outer tissue layer is at the surrounding water temperature, then the near-skin surface temperature gradient will provide a low loss acoustic match at this boundary.

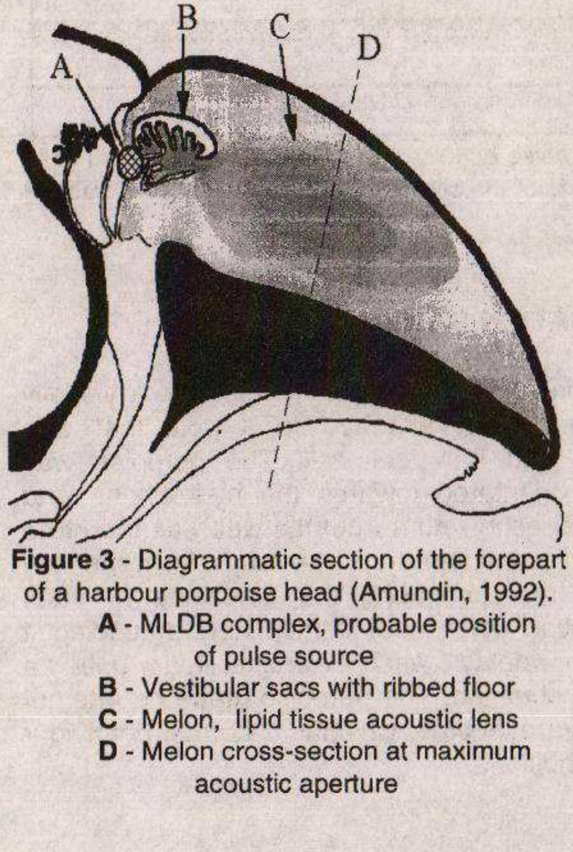

Figure 3 - Diagrammatic section of the forepart of a harbour porpoise head (Amundin, 1992).

A - MLDB complex, probable position of pulse source
B - Vestibular sacs with ribbed floor
C - Melon, lipid tissue acoustic lens
D - Melon cross-section at maximum acoustic aperture

Melon cross-section dimensions (Figure.3) were obtained during the 1994 harbour porpoise autopsy workshop held at the Sea Mammal Research Unit in Cambridge, where animals found dead on the UK coastline were examined. A sub-adult specimen, of equivalent size to the live animals studied in the Netherlands, provided the following melon dimensions: 62 mm (horizontal) and 37 mm (vertical). If λ at 145 kHz is taken as varying between 8.6 and 9.9 mm then these dimensions suggest minimum beam angles of $\approx 9^{\circ}$ in azimuth and $\approx 15^{\circ}$ in elevation. The mobility of the melon tissue and the associated musculature suggest that the animal may have some small capability to increase this cross-section, but this control is limited and the result is unlikely to narrow the beamwidth to less an 8°. This variability may be of use as a 'focus' control to minimise the effect of the near-field when operating at close range.

5. DISCUSSION - SIGNAL GENERATION MECHANISMS

The mechanism which generates the porpoise's oscillatory pulse waveform is not fully understood, but the position of the source(s) have been localised in the dolphin and clearly implicate the MLDB complex (monkey-lips-dorsal-bursae) described by Cranford **[14, 16, 17]**). Although the echolocation signal transmitted into the water by a porpoise is oscillatory in character and unlike that of a dolphin, it now seems possible that this signal may originate as a simple (dolphin-like) wideband impulse from a position associated with the dorsal bursae MLDB complex. Such an impulse could be excited by a cavitation mechanism at the wetted tissue interface between the anterior and posteria bursæ. The SL of this implosive effect is assisted by the raised pneumatic pressure which can exist within the bony nares. If this signal is initiated by a single pressure pulse event, and the functional features of the MLDB structures appear very similar to those in the dolphin, then some other mechanism must be involved which can convert this impulse into the multi-cycle wave form that is projected into the water.

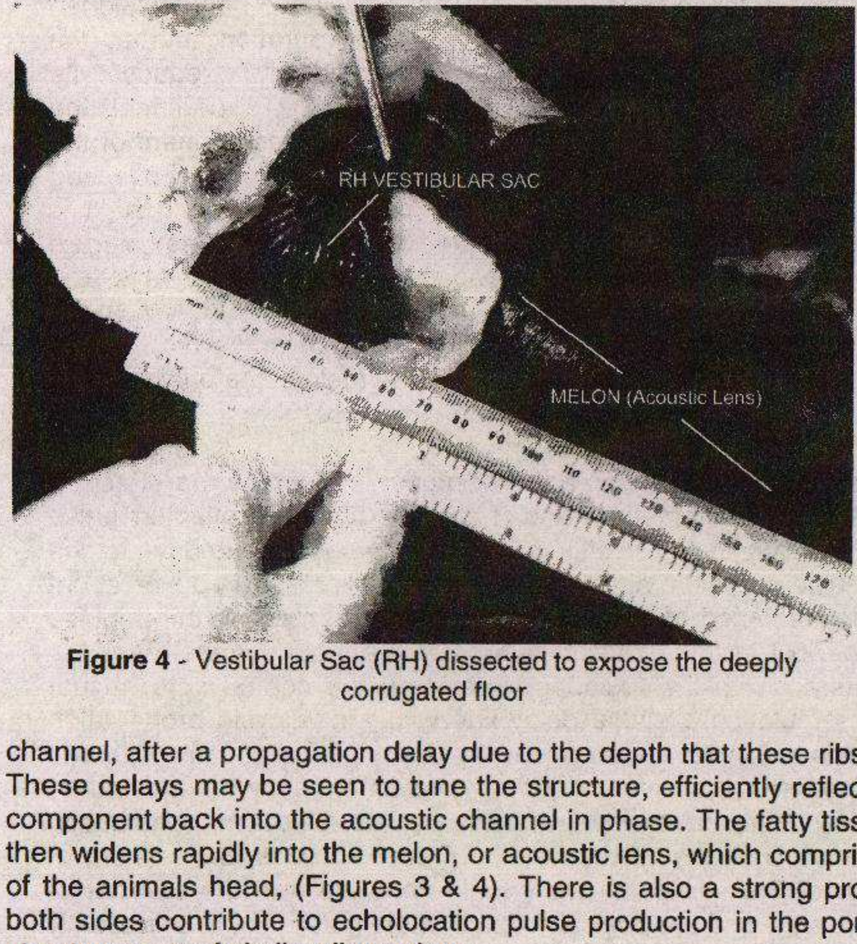

Figure 4 - Vestibular Sac (RH) dissected to expose the deeply corrugated floor

Close examination of the tissues and air sacs associated with the sound path reveals that the saddle-like vestibular sacs are formed quite differently from the dolphin. (Figure 4) It seems possible that the wideband impulse becomes extended in duration as it propagates along a narrow path adjacent to several deeply ribbed transversal corrugations, which form the soft tissue floor of the vestibular air sacs. Such a ribbed structure will capture and reflect the radiating pressure pulse back into the central fatty channel, after a propagation delay due to the depth that these ribs penetrate into the air sac. These delays may be seen to tune the structure, efficiently reflecting a dominant frequency component back into the acoustic channel in phase. The fatty tissue central 'sound channel' then widens rapidly into the melon, or acoustic lens, which comprises the bulk of the forepart of the animals head, (Figures 3 & 4). There is also a strong probability that the MLDB on both sides contribute to echolocation pulse production in the porpoise, especially as these structures are of similar dimensions.

This simple hypothesis is supported by examining the detailed anatomical work carried out by Amundin **[15]** and by Cranford **[14, 16]**. In particular Amundin's tests with a live harbour porpoise breathing a helium/oxygen mixture (*heliox*) demonstrated a frequency shift in the low frequency, low amplitude, signal components but no similar shift was observed at the high frequencies. Since a frequency increase indicates that the sound has travelled at an increased velocity, i.e. within the airway/gas cavities, most of the low frequency component probably originates from the small percentage of pulse energy lost into the vestibular air filled sacs which is then re-radiated from their outer surface at a frequency determined by the resonant air cavity volume. In the harbour porpoise these air sacs are effectively wrapped saddle-like around acoustically conductive fatty tissues, which form a sound conducting core connecting to the melon. Dolphins have similar vestibular sacs which are smooth floored and these function as acoustic baffles to restrict the propagation of the generated acoustic impulse to the forward direction prior to the final beam formation by the melon.

In the harbour porpoise we suggest that this essential function has been supplemented by the effect of the deeply folded floor of these sacs which may act as a *tuned baffle* designed to extend the pulse duration and at the same time significantly reduce its bandwidth. In the heliox experiment the dominant high frequency component of the signal was unaffected by the increased sound velocity properties of the gas. It is therefore safe to assume that these signals do not propagate within the airways and must be generated either in, or at, a (wetted) tissue interface and pass through the fatty channel/melon material to the external water interface.

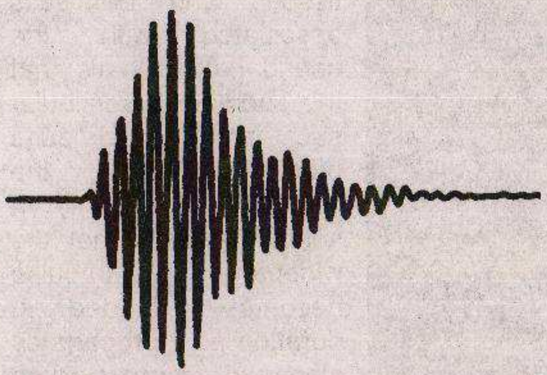

Figure 5 - Adult harbour porpoise waveform

This mechanism was initially explored using a spreadsheet model to examine the effect on the wave form of multiple delay line summation, and it is clear that the reflected pulse returned from each deep corrugation in the vestibular sac floor should contribute to the amplitude of the extended pulse for several cycles. If a single pressure pulse event propagating into a 'rib' is totally reflected at the internal air interface, most of the impulse energy that would otherwise be lost in this direction returns to the main channel after the propagation delay and will interact with the residual pressure in the central core at that instant. A single pulse event stimulating a single delay line with a one cycle propagation delay will convert the impulse to one with an exponentially decaying 'tail'. If this effect is repeated with consecutive delay lines, a waveform, with a centre frequency determined by these delays, will form by adding additional cycles to the initial pulse. Since the contribution added by each 'rib' is superimposed on that excited by the preceding ones, the number of these rib-like folds in the floor of the vestibular sac should correlate with the number of cycles in the signal between the start and the peak amplitude of the pulse. There are usually 5 such folds in the vestibular sac of the adult harbour porpoise.

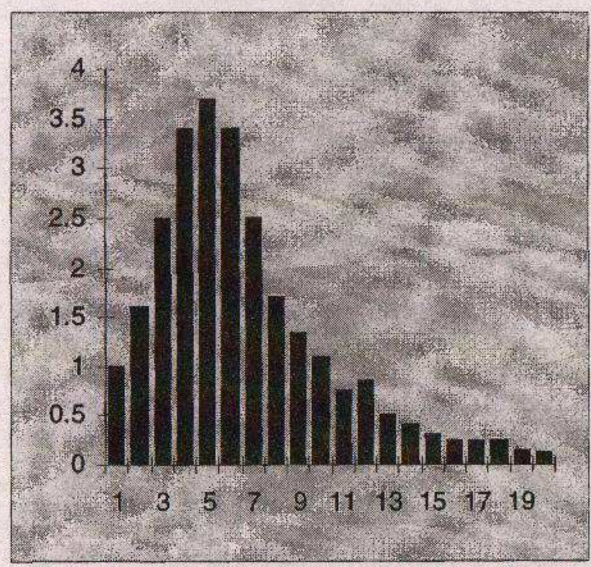

Figure 6 - Extracted Peak to Peak amplitudes taken from the adult porpoise waveform

Some pulse energy is lost into the air sac, since reflection at the tissue/air interface cannot be 100% efficient. The model was further adjusted to examine the effect of varying this percentage lost. Given the typical adult porpoise waveform in figure 5 to replicate, the rate of rise and decay of its amplitude, figure 6, was found to be closely emulated when the boundary loss at each reflection approximated 16% of the incident energy. Since the impulse energy 'lost' into the air filled sac must stimulate the sac's volume resonance, a low frequency, weak artefact will be radiated with little directivity from its outer surfaces. This low directivity component appears in the audible range and is detectable, at very short range, at angles well outside the highly directional high frequency echolocation beam.

Alternatively, and again assuming that the 'delay lines' contribute equally and each generate a one cycle delay at the centre frequency, the formulae:

$$A_m N \begin{cases} U_o(1-a^N)/(1-a) & 1 \leq N \leq m \\ U_o a^{N-m}(1-a^m)/(1-a) & N \geq m \end{cases}$$

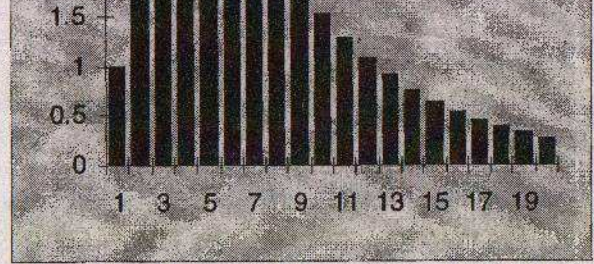

Figure 7 - Modelled data assuming 16% loss at each reflection within the air sac.

may be applied to describe the amplitude 'A_m' (of the output waveform) resulting from the sum of the reverberant contributions from '**m**' delay lines (sac-floor corrugations) at each of '**N**' cycles.

(Letting U_o=1, **m**=5, **a**=0.9|0.8|0.7|....|0.5)
Where **a** = the reflected energy fraction tested).

This simple model illustrated that the resulting waveform envelope was very sensitive to the percentage loss of energy into the air sac with the best fit illustrated in this example occurring at 16%, figure 7.

6. RESULTS

The peak, on axis, Source Levels measured from the two juvenile porpoises in captivity ranged from 140 to 166 dB re 1 µPa at 1 m. These two animals were tested at three fixed distances from the hydrophone (2 m, 4 m and 6 m) and when the maximum values of each test were averaged the animals' SLs appeared closely matched at 149.5 dB re 1 µPa at 1 m. The energy distribution in the spectrum of all of these pulses was remarkably consistent and typified by Figure 2. The Source Level tests were carried out in a small concrete holding pool in relatively shallow water and hence in highly reverberant conditions. The signal/reverberation level at the time of each transmission was also examined and both porpoises showed adaptation to the reverberant environment since the inter-click periods were extended until the reverberation SPL had decayed to some 50 dB below the initial Source Level.

7. CONCLUSIONS

The careful measurement of the echolocation signals emitted from juvenile harbour porpoises has provided accurate waveforms and power spectra confirming that this species uses a narrow band echolocation signal. The limited available literature describes the presence of a low frequency component starting synchronously with each high frequency pulse, but this very weak low frequency part of the spectrum is difficult to observe, except at close range, and appears to be an artifact of the beam forming mechanism. It seems clear that the internal signal propagation path will lose a fraction of its energy into the surrounding air sacs, whose primary function must be to act as baffles ensuring the forward propagation of the echolocation pulse. The re-radiation of this lost energy, from the outer surfaces of the air sacs, will occur at a low frequency defined by the volume resonance of the sac and will therefore have little directivity, but the actual frequency may permit discrimination between adult and juvenile animals. Since the high frequency pulse is beam formed into a narrow cone of sound directed ahead of the animal, the amplitude and frequency spectrum observed will depend critically on the position of the hydrophone relative to this centre axis.

Our hypothesis implicates the folded floor of the vestibular sacs as a passive mechanism which efficiently increases the emitted Source Level whilst extending the signal duration and creating a narrow band emission. However, this theory requires further testing and a mechanical model appears feasible to construct which should provide real data. More precise dimensional data on the geometric construction of these air sacs and the associated *in vitro* tissues in both juvenile and adult specimens will be required if computer modelling is to be successful. The contribution of a single or a double pulse of energy to excite this mechanism, derived from one or both MLDB source positions, requires detailed consideration. The growth of the vestibular sac dimensions (the depth and number of folds forming the sac floor) as the porpoise matures might explain the reported fall in the centre frequency observed in adults (from 140 to 120 kHz). There are some serious difficulties to be overcome when attempting to extract accurate measurements of such structures *post mortem* as the soft tissues distort, and the deflated air sacs lose the tensions which characterise them when inflated. Magnetic Resonance Imaging of live animals has been suggested as a method of obtaining measurements, that would allow more sophisticated three dimensional modelling of this acoustic signal processing mechanism, but this will be a difficult task.

The knowledge gained to date in this and the associated studies, which include field observations of foraging behaviour **[11]**, suggests that the harbour porpoise operates a relatively low power, short range, sonar capable of detecting (ingestible size) single fish targets at ranges out to a maximum distance of about 30 m. The strongest acoustic emissions of this animal are expected to be around 120-140 kHz with SLs, in open water conditions around 160-170 dB re 1 μPa at 1 m. These signals will be confined to a very directional beam (approaching 8^o in azimuth and 14^o in elevation) which is projected directly ahead of the animal. This narrow spectrum beam pattern makes the harbour porpoise particularly difficult to detect in the wild using hydrophones unless the animal is headed directly towards the sensing position. The measured narrow band nature of the pulse (13 kHz $_{-3dB}$) suggests that this bio-sonar is less able to exploit target echo spectrum characteristics for classification than a bottlenose dolphin which can generate a 50 kHz bandwidth pulse at SLs which may be some 50 dB louder. The harbour porpoise clearly possesses a much shorter range lower power sonar than its larger delphinid cousins. This animal is known, from bycatch statistics, to forage on the bottom in water depths which may exceed 150 m. and it is also able to efficiently detect and feed on sand eels and small cephalapods that normally remain buried in or just under the surface of the seabed. Such targets pose an interesting detection task for a sonar system although it may be surmised that the 'hole' in the sand displaced by the body of the prey is actually more detectable than the tissue of the prey itself.

8. ACKNOWLEDGEMENTS

This work has been supported by the Commission of the European Communities DGXIV, by the UK Ministry of Agriculture Fisheries and Food and by the Department of the Environment. Special thanks are due to the staff of the Netherlands Marine Mammal Rehabilitation Centre at Zeedierenpark Harderwijk for access to the two young porpoises studied. The model description was refined with assistance from Marc Goodson and Howard English. Thanks are due to Ted Cranford and to Mats Amundin for use of their tomographic images and for their advice on the tissue histology and morphology. Special thanks are due to Harry Ross, Vic Simpson and Paul Jepson for dissections carried out at the DOE harbour porpoise autopsy workshops held at the Sea Mammals Research Unit in Cambridge and at the Zoological Institute in London.

9. REFERENCES

[1] M KLINOWSKA. 'Dolphins Porpoises and Whales of the World'. The IUCN Red Data Book.. pub: IUCN, Gland, Switzerland and Cambridge UK. ISBN 2-88032-936-1, p429. (1991)

[2] A D GOODSON, R A KASTELEIN, & C R STURTIVANT. 'Source Levels and echolocation signal characteristics of juvenile harbour porpoises' (*Phocoena phocoena*) in a pool. in: P.E.Nachtigall, J.Lien, W.W.L.Au & A.J.Read (eds) Harbour porpoises - Laboratory studies to reduce bycatch. De Spil, Woerden. 41-53. (1995)

[3] C KAMMINGA. 'Research on dolphin sounds'. Doctoral Thesis, Technische Universiteit Delft, Netherlands. (1994).

[4] B MØHL & S. ANDERSEN. 'Echolocation: high frequency component in the click of the Harbour porpoise (*Phocoena phocoena*)'. J.Acoust.Soc.Am. 54, 1368-1373. (1973)

[5] C KAMMINGA & H WEISMA. 'Investigations on cetacean sonar II. Acoustical similarities and differences in odontocete sonar signals'. Aquatic Mammals 8.2, 41-62. (1981)

[6] W W L AU. 'The sonar of dolphins'. Springer-Verlag NY. 277p.
Aquatic Mammals 21.1, 19-42. (1993)

[7] A D GOODSON, M KLINOWSKA & P BLOOM. 'Enhancing the acoustic detectability of gillnets'. SC/090/G16. in: Rep.Int.Whal.Commn.(Special Issue 15). Cambridge UK. 585-595. (1994)

[8] P BLOOM, A D GOODSON, M KLINOWSKA & C R STURTIVANT. 'The activities of a wild, solitary bottlenose dolphin (*Tursiops truncatus*)'. Aq.Mamm. 21(1) 19-42. (1995).

[9] S Andersen. 'Auditory sensitivity of the Harbour porpoise, *Phocoena phocoena.*' In: G.Pilleri (ed). Investigations on Cetacea vol.II. Institute for Brain Research, Bern, 255-259. (1970).

[10] T AKAMATSU, Y HATAKEYAMA, T KOJIMA, AND H SOEDA. 'Echolocation rates of two harbour porpoises (Phocoena phocoena)'. Mar.Mamm.Sci. 10(4), 401-411. (1994).

[11] A D Goodson, & C R Sturtivant. 'Sonar characteristics of the harbour porpoise, *Phocoena phocoena*, Source Levels and spectrum'. ICES J.Mar.Sci. 53: 465-472. (1996)

[12] J L AROYAN, T CRANFORD, J KENT & K S NORRIS. Computer modelling of acoustic beam formation in *Delphinus delphis.* J.Acoust.Soc.Am. 92(5): (1992).

[13] K S NORRIS & G W HARVEY. 'Sound transmission in the porpoise head'.
J.Acoust.Soc.Am. 56: 659-664. (1974).

[14] T W CRANFORD, M AMUNDIN & K S NORRIS. 'Functional morphology and homology in the odontocete nasal complex: Implications for sound generation.' Journal of Morphology 228:223-285. (1996).

[15] M AMUNDIN. 'Sound production in odontocetes'. Doctoral Thesis, Stockholm University. 144 pp. (1991).

[16] T W CRANFORD. 'Functional morphology of the odontocete forehead: implications for sound generation'. Doctoral Thesis, University of California Santa Cruz. 272 pp. (1992).
Functional Morphology of the Dolphin's Biosonar Signal Generator Studied by

[17] T W CRANFORD. 'High-Speed Video Endoscopy'; Van Bonn W.G., Ridgway S.H., Chaplin M.S., Carr J.A., Journal of Morphology 232(3): 243. (1997).