SHALLOW WATER, VERY SHORT RANGE BIOMIMETIC SONAR CONCEPTS.

P.F. Dobbins[1], A.D. Goodson[2]

[1] Department of Physics, University of Bath, Bath BA2 7AY, UK, p.f.dobbins@bath.ac.uk
[2] Dept. Electronic and Electrical Eng., Loughborough University, Loughborough LE11 3TU, UK.

ABSTRACT

Observations suggest that dolphin sonars function well in the very shallow, reverberant, littoral zone, and significantly out-perform man-made systems in such conditions. The echolocation characteristics of many small cetaceans can be measured directly and the high performance of such bio-sonar systems is not in question, but explanations for their resolution, target detection, localisation and tracking abilities are inadequate and deserve further investigation. This paper explores the physics of such systems using data from various species, as well as models based on established radar and sonar principles. Finally, we consider the implications for applying this approach to a bio-mimetic sonar to solve the problems of shallow water operation.

1. INTRODUCTION

There is a need for small, high-resolution sonars capable of effective short-range operation, to be carried by divers or underwater vehicles in various applications [1]. In current systems; the high frequency used to achieve fine resolution limits the maximum range to about 10m, but it also extends the near field out to several metres. Thus, they have no long-range detection capability, but are inoperative at short ranges!

It is well known, however, that man-made systems can be significantly out-performed by dolphins and other animals using acoustic echo-location, e.g. [2]. There is evidence that the dolphin's lower jaw is a component in the echolocation receive mechanism, and a model has been proposed suggesting the equally spaced rows of teeth form receiving arrays [3]. Such arrays in end-fire mode should exhibit no near field degradation [4]. In addition, combining the rows of teeth in a monopulse configuration would give fine angular resolution but with wide beams for rapid area searching [5].

This model is based on the Atlantic bottlenose dolphin, *Tursiops truncatus* [3,5], but other cetaceans have evolved different solutions to the difficulties of sonar operation in shallow, reverberant and noisy conditions. One obvious difference is the range of transmission waveforms employed by various species. Another is the very different tooth and jaw structure of the river dolphins, *Platanista gangetica* and *P. minor* [6]. The aim of this paper is to compare some of these different approaches and consider which, if any, might be applied in a bio-mimetic sonar to solve the problems of shallow water operation.

2. THE TOOTH ARRAY CONCEPT

The model proposed by Goodson and Klinowska [3] is based on the observation that the teeth of the lower jaw are divided into two essentially straight rows of equally spaced teeth. It is postulated that the teeth act as passive resonant receivers, which are combined as two equi-spaced line arrays with the tooth nerves introducing progressive propagation delays which emulate a delayline beamformer. The system is shown schematically Fig. 1.

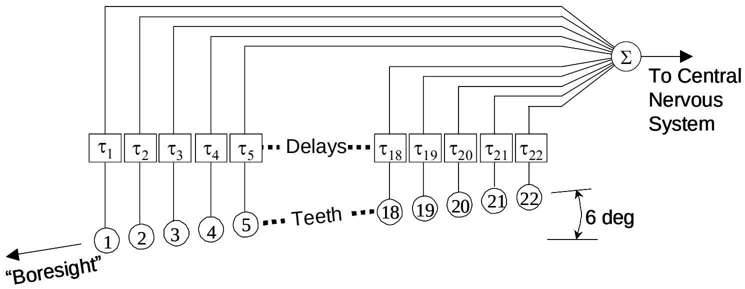

Fig.1: Sketch showing principle of row of teeth acting as endfire array.

The principle of operation is simply that the teeth act as pressure transducers. Signals representing the sound pressure are passed to the central nervous system along mandibular nerves with propagation delays (τ in the diagram) such that an echo arriving from a direction along the row of teeth (boresight) results in all signals arriving at the central nervous system simultaneously and adding constructively. Signals from other directions will not arrive simultaneously, resulting in a reduced response. Thus the array has directivity, with maximum sensitivity in the boresight direction.

The biological mechanisms involved are not considered here, but the involvement of the tooth nerves is not essential. Feasibly, the teeth act simply as passive resonators, with conduction through the jawbone providing appropriate delay paths. Many passive end-fire arrays based on such principles exist, e.g. the TV crew's "shotgun" microphone [7].

2.1 Endfire Directivity

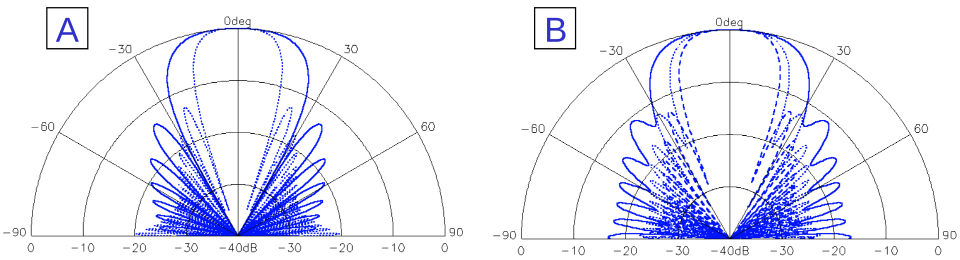

Fig.2: Endfire array directivity patterns for Tursiops tooth geometry. A shows far field patterns at 50kHz and 130kHz (dotted). B shows 120kHz patterns at ranges of 0.1m, 0.3m (dotted) and 1m (dashed).

The Tursiops lower jaw has 2 rows of 22 teeth, spaced at approx. 1cm and separated by an angle of 12°. Beam patterns for a single row in endfire mode are shown in Fig. 2. Far field patterns at frequencies of 50kHz and 130 kHz, the extremes of *Tursiops'* echolocation bandwidth, are shown in A as solid and dotted lines respectively. Patterns at 120kHz for ranges of 1m (dashed), 0.3m (dotted) and 0.1m (solid) are shown in B. The beamwidth reduces with increasing frequency from 40° at 50kHz to 25° at 130kHz, and close to the array, increases with reducing range. However, the far field pattern is reached at just 1m, and even at a range of 10cm the pattern is maintained, although beamwidth is 45°. Interestingly, a conventional broadside array of this size at 120kHz has a near field extending to 3.5m, where effective operation is not possible without special processing.

2.2 Monopulse localisation

The proposed model suggests that the 12° separation between rows of teeth gives angular localisation using monopulse [8]. This is achieved by taking the difference in response of two beams separated in angle and normalising by their sum (a “sum and difference” pattern). The result is proportional to the direction of arrival of a signal over a defined field of view, and limited in accuracy and resolution only by the noise level.

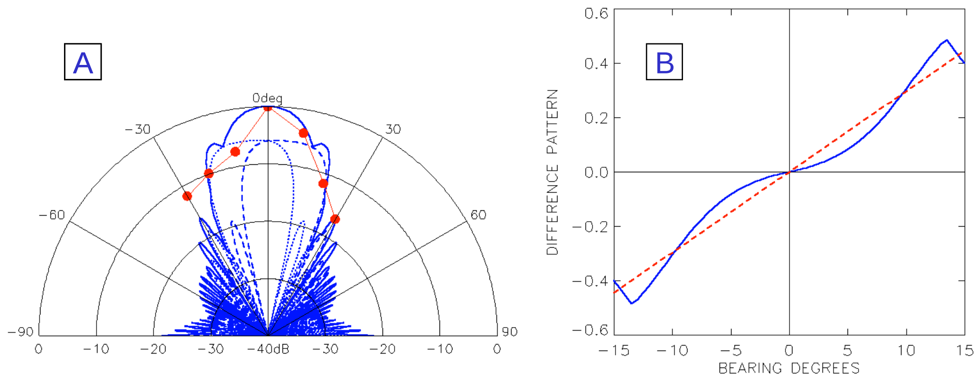

Fig.3: A: Endfire beams rotated ±6° (dashed and dotted lines) and sum pattern (solid) compared with measured *Tursiops* receive directivity [9] (symbols), B: sum-and-difference pattern (solid) with linear approximation (dashed line).

This is demonstrated in Fig.3. In 3A, the two endfire patterns at 120kHz rotated to ±6° are plotted as dashed and dotted lines. The response obtained by summing the two arrays, which represents the animals effective receiving directivity is shown as the solid line, compared with a measured reception pattern from [9]. The agreement is reasonable. In 3B, the sum and difference pattern is shown as the solid line. It is clear that over a field of view covering roughly ±13°, the response is an unambiguous, monotonic function of angle, passing through the origin, although not quite linear (a linear fit is shown as the dashed line).

This is an ideal response for homing on a target, with a distinct left, right or dead ahead indication. The field of view is wide enough to avoid losing moving targets, and is wider than the 10° transmit beam [10] so ambiguity outside the linear range is not a problem.

3. THE RIVER DOLPHIN ALTERNATIVE

The teeth of many dolphin species are linearly arranged with a constant inter-tooth dimension that appears related to the peak frequency of their sonar. It is worth comparing this with the different structure developed by some river dolphins. *Plantanista gangetica* and *Plantanista minor* [11], the small dolphins of the Ganges and Indus rivers, possess a long and slender rostrum and jaw which support an unusual array of teeth which are longer and more closely spaced towards the tip. A precise description of the tooth arrangement is not available, but from images, e.g. Fig 4, and some inexact field measurements [12], there is a suggestion of a log-periodic distribution.

Reverberation limits sonar performance in shallow water, and any sonar receptor needs to be well optimised. Antennas based on log-periodic geometries are well understood and offer wideband performance with low sidelobes to reject off-axis multipath signals [13].

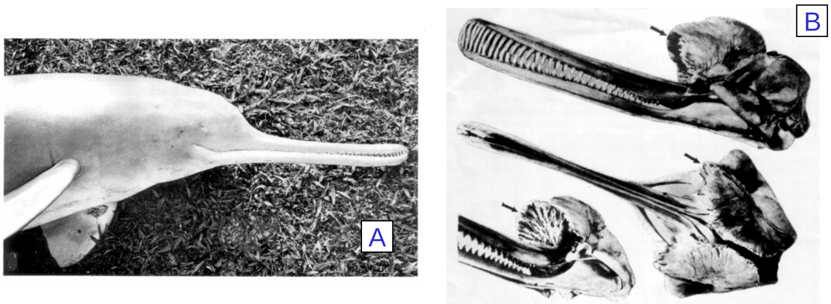

Fig.4: Photographs of (A) *Platanista* head (from [14]) and (B) skull (from [15]).

3.1 Log-Periodic Arrays

The principle of the log-periodic antenna is that an expanding active region, comprising dipoles nearest resonance, moves along the array with changing frequency, as shown in Fig.5A. The result is a constant beampattern and gain over a wide bandwidth. In the antenna implementation [13], the lengths ***l*** and spacings ***s*** of adjacent elements are related by a scaling constant ***k*** so that $\boldsymbol{l_{n+1}/l_n = s_{n+1}/s_n = k}$.

The apex angle α is also related to ***k*** and the spacing in wavelengths, $\boldsymbol{s_\lambda}$. Specifying any 2 of these parameters determines the third, and the relationship is displayed in Fig.5A, with the optimum design line giving the maximum gain for a given value of ***k***.

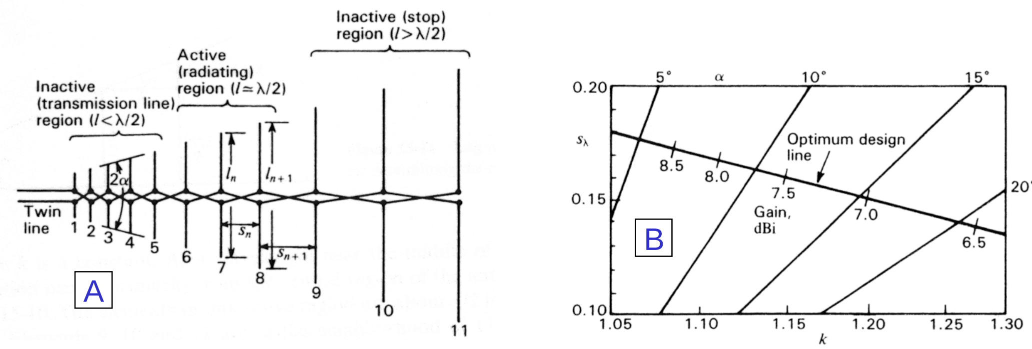

Fig.5: (A) Log-periodic antenna and (B) optimum design parameters (from [13]).

The length of the elements defines the λ/2 resonance frequency. The situation is different for acoustic arrays, and for a preliminary evaluation it is adequate simply to scale resonant frequency along the array. For *Plantanista*, there are approximately 26 teeth in a row, with an overall length of about 14cm [12,14,15]. The bandwidth of echolocation pulses has been reported as 15-60 kHz [15], setting the minimum spacing at <1.25cm (λ/2 at 60 kHz). *Plantanista'*s tooth spacings are not known, but these factors combine to determine a value for ***k*** that can be used to evaluate a speculative log-periodic tooth array.

A value of 1.01 for ***k*** was chosen, with a minimum tooth spacing of 5mm. A model was implemented based on these values, with element resonance represented as a simple first order constant Q filter. Q was 0.3, giving a bandwidth of about 15kHz at the centre of the array.

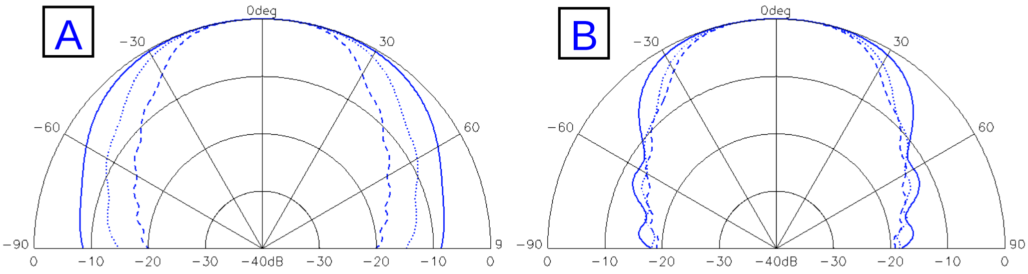

Fig.6: Log-periodic array directivity patterns based on *Plantanista* jaw geometry. A shows far field patterns at 15kHz, 30kHz (dotted) and 60kHz (dashed). B shows 60kHz patterns at ranges of 0.1m, 0.3m (dotted) and 1m (dashed).

Fig.6 shows beampatterns produced using this model for comparison with Fig.2. Frequency was varied over the river dolphin bandwidth of 15-60 kHz in A, and range varied from 0.1m to 1m. It is immediately obvious that the beamwidths are much wider than the endfire array of Fig.2, with a maximum of 100°, but this is expected, partly because the frequency is lower and partly because only part of the array is operating. What is also obvious, however, is that the beamwidth does not change significantly, and nor are there any sidelobes.

This is a promising result, and what is not shown here because of space is that the beampattern is maintained with increasing frequency to beyond 120kHz – that is a 3 octave band – and there is a very high back-to-front ratio for these patterns. It is also likely that this performance can be improved with further development.

4. DISCUSSION AND CONCLUSIONS

The aim of this paper was to examine concepts derived from biological sonar with a view to their suitability for implementing in biomimetic systems. Thus, the ideas may have deviated a little from what is known of cetacean physiology, but some potentially useful proposals for improving the performance of man-made sonar can be seen in the results.

The angle between the rows of teeth in *Tursiops* suggests monopulse localisation. This is not a new concept, and is widely employed in homing systems. What is new, however, is combining monopulse with endfire arrays. This immediately gives a system that is operational at practically zero range. Another promising idea is to base this endfire array on the log-periodic antenna. This gives additional advantages of a frequency invariant pattern and zero sidelobes, albeit at the cost of wider beams.

How useful such ideas might be depends a lot on the operating environment. Dolphins generally operate in noisy, reverberant locations, and any systems they have evolved must give advantages in such a setting. To combat generally diffuse ambient noise, sonar requires a receiver with a high DI. To combat directional noise or reverberation, however, it is necessary to reduce directivity in the direction of the interference, but as the direction is probably not known, this implies low sidelobes generally and a good front-to-back ratio.

With this in mind, a monopulse system using log-periodic arrays may be capable of development to give precise localisation down to very short ranges in reverberant conditions.

ACKNOWLEDGEMENT

The subject matter for this paper was suggested by Dave Goodson shortly before his death in January 2004. Sadly, this has meant that much of the material he intended contributing was not available, but it was felt that the paper should be completed anyway, even if it has turned out more speculative than originally intended.

REFERENCES

[1] Johnson, BM and Pedersen, A, Acoustical Imaging with Compact Sensors for Mine Countermeasures Applications, *Oceans 2001 MTS/IEEE Conf. Proc*. Vols 1-4, 1-5 (2001).

[2] Sigurdson, J.E., ‘Analyzing the Dynamics of Dolphin Biosonar Behaviour During Search and Detection Tasks’, *Proc. Inst. Acoust.,* 19(9), 123-132 (1997).

[3] Goodson, A.D. & Klinowska, M, A Proposed Echolocation Receptor for the Bottlenose Dolphin (Tursiops truncatus): Modelling the Receive Directivity from Tooth and Lower Jaw Geometry, in Thomas & Kastelein, eds, *NATO ASI Series A: Sensory Abilities of Cetaceans*, V196, 255-267, Plenum NY (1990).

[4] Berktay, H.O. and Shooter, J.A., Nearfield Effects in End-Fire Line Arrays, *J. Acoust. Soc. Am*., 53(2), 550-6 (1973).

[5] Dobbins, P.F., Modelling Dolphin Echolocation Reception, *Proc. Inst. Acoust*., 23(4), 123-132 (2001).

[6] Martin, A. R., (ed), *Whales and Dolphins*, Salamander Books Ltd, 180-183 (1990).

[7] Sank, J.R., Microphones, *J. Audio Eng. Soc*., 33(7/8), 514-547 (1985)

[8] Rhodes, D.R., *Introduction to Monopulse*, McGraw-Hill (1959).

[9] Au, W.W.L. and Moore, P.W.B., Receiving Beam Patterns and Directivity Indices of the Atlantic Bottlenose Dolphin *Tursiops Truncatus*, , *J. Acoust. Soc. Am*., 75(1), 255-262 (1984).

[10] Au, W.W.L., Floyd, R.W. and Haun, J.E., Propagation of Atlantic Bottlenose Dolphin Echolocation Signals, *J. Acoust. Soc. Am*., 64(2), 411-422 (1978).

[11] Lal Mohan, R. S,. Dey, S. C. and Bairag, S. P., On a resident population of the Ganges river dolphin *Platanista Gangetica* in the Kulsi River Assam, a tributary of the Brahmaputra, *J. Bombay Nat. Hist. Soc*. 95(1), 1-7 (1998).

[12] Adloff, D. and Schnapp, D., *Operation Platanista*, private report, Copenhagen (1986).

[13] Kraus, J.D., *Antennas*, 2nd. Edn., McGraw-Hill, 1988.

[14] Pilleri, G., *Wissenschaftliche Expedition des Berner Hirnanatomischen Institutes nach Westpakistan und Assam im Jahre 1969 zur Erforschung des Gangesdelphins (Platanista gangetica)*, Buchdruckerei und Verlag Leemann AG, Zurich (1970).

[15] Herald, E.S., Brownell, R.L., Frye, F.L., Evans, W.E. and Scott, A.B., Blind River Dolphin: First Side-Swimming Cetacean, *Science*, 166, 1408-1410 (1969).