MODELLING DOLPHIN ECHOLOCATION RECEPTION.

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1. ABSTRACT

The teeth of many cetacean species form more-or-less straight lines, are invariant in shape and size, and are uniformly spaced at about half a wavelength in water at the highest frequency the animal uses for echolocation. Informed by these observations, models of dolphin echolocation reception based on end-fire line arrays produced by the animal's teeth are gaining credibility. The end-fire array configuration has a number of characteristics that would be of advantage in dolphin echolocation. This paper explores the physics of such systems and considers the implications for cetacean echolocation.

KEY WORDS: dolphin; teeth; echolocation; biomimetic; sonar

2. INTRODUCTION

The characteristics of operational sonar systems are in general highly classified. It is no secret, however, that they can be significantly out-performed by the many members of the animal kingdom that use acoustic echo-location. In particular, the capabilities of bottlenose dolphins (Tursiops truncatus) trained to rapidly search an area of seabed for an identifiable target and home in on it have been convincingly demonstrated (eg [1]). A sonar with this level of performance, besides a superior detection capability, requires high accuracy and fine resolution in spatial localisation. The present paper focuses on this latter requirement and specifically on angular localisation.

2.1 Localisation modelling

Angular localisation performance depends upon many factors, but analysis is commonly idealised as a source signal in the form of a single plane wave arriving from some specific direction and an array of two or more sensors whose precise positions and sensitivities are known. The outputs from these sensors are then fed to some processor where all gains, delays and other relevant factors are also known. It is argued that such idealisations, often in the form of numerical computer models, represent the "essence" of the system behaviour. However, the real physics of signal propagation and detection is often ignored.

By real physics is meant the noisy environment, the randomly fluctuating propagation medium, scattering and reverberation, uncertainties in the position and sensitivity of receiving elements, errors and tolerances in the processor, and all the other problems inflicted on sonar systems when they go to sea. Thus, what follows is based initially on a simple analytical model of a receiving system, but one that will allow the effects these various degrading factors to be examined.

2.2 The receiver

There are at least two potential candidates for the dolphin's echolocation receiving system [2], and in this paper that proposed by Goodson and Klinowska [3] will be followed. This is primarily because a superficial analysis [2] suggests that its performance can more closely approximate the observed characteristics of the dolphin echolocation system than the alternative based on two forward facing rectangular apertures [4].

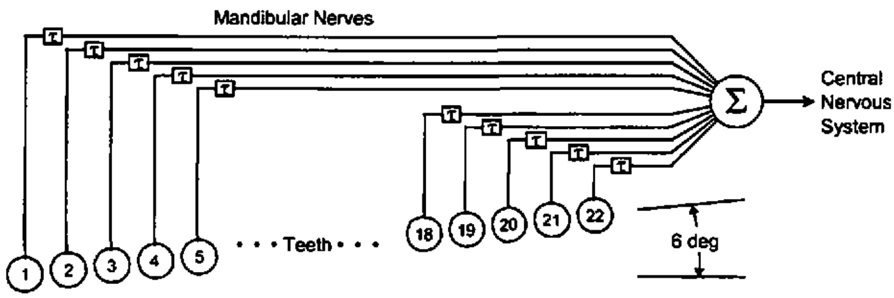

Fig. 1 Sketch showing operating principle of row of teeth acting as an end-fire array.

In this model, an array is formed by the animal's uniformly spaced teeth and it is assumed that some "beamforming" mechanism exists that allows an endfire beam to be generated for each of the more or less straight rows of teeth. Exactly what that beamforming mechanism might be is the subject of some discussion and is examined in two companion papers in this volume [5,6]. However, in the present context, it is not necessary to understand the nature of the mechanism, and its existence will simply be assumed.

3. THE END-FIRE LINE ARRAY

The model proposed by Goodson and Klinowska [3] postulates that the teeth of the lower jaw act as passive resonant receiving elements, which are combined as two equi-spaced line arrays with the tooth nerves introducing progressive propagation delays which emulate a delayline beamformer with a neural network processor. The system is shown schematically Fig. 1. The biological mechanisms involved will not be considered here, and it may be repeated that the details are not important in the present context.

The operation of such an array was outlined in [2], and an exact closed form solution for the acoustic field has been derived by Berktay and Shooter [7]. The geometrical configuration sketched in Fig. 2. The normalised directivity pattern of a continuous line array of simple omnidirectional receivers, phased to give maximum sensitivity in the endfire direction, can be computed from the equation

$$D(R,\theta)=\left(\ln\frac{R}{R-L}\right)^{-1}\int_{v_1}^{v_2}\frac{1}{v}\exp(-jv)dv \qquad (1)$$

where $D(R,\theta)$ is the directivity function, R is range to the source, θ is the source bearing relative to the axis of the array and L is the length of the array. Note that the origin is at the rear end of the

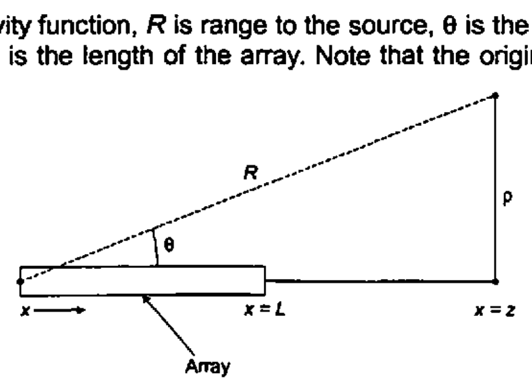

Fig. 2 Geometry of end-fire array.

array, so both range and bearing are measured from the rear of the array. The integration limits v_1 and v_2 are given by

$$\left.\begin{aligned} v_1 &= kR(1-\cos\theta) \\ v_2 &= k\left[\left(R^2 + L^2 - 2LR\cos\theta\right)^{1/2} - (R\cos\theta - L)\right] \end{aligned}\right\} \qquad (2)$$

here k is the acoustic wavenumber, and $k = 2\pi f/c$ or $2\pi/\lambda$ where f is frequency λ is wavelength and c is sound speed.

Example beampatterns for an endfire array computed using (1) and (2) are shown in Fig. 3. In this case the array is broadly representative of a single row of dolphin teeth with 22 omnidirectional receiving elements at 1.0cm spacing, giving an overall length of 22cm. The frequency is 80kHz, where the spacing is approximately half a wavelength, and patterns are computed for ranges of 0.22, 0.3, 0.4, 1.0, 1.6 and 20m. The outer patterns represent the greater ranges, and it is clear that the beampattern changes little from a range of 20m, or 100 times the array length down to less than 1m, or 5 times the array length. Even at 0.4m, only 1 array length from the tip of the array, the beamwidth is still half its long range value, and at 0.22m, effectively touching the end of the array, there is still a well formed main beam.

This behaviour is quite different from most forms of planar or linear receiving array forming broadside beams, where generally the beampattern will degrade dramatically within a near field range given approximately by L^2/λ, and where the sensitivity within this near field oscillates wildly [8]. Fig. 4 shows sensitivity on the array axis plotted against range, and this is compared with the line given by L/R. It is easily seen that, although the sensitivity rises sharply as the range approaches the tip of the array for the endfire configuration, over all ranges beyond about 0.5m the sensitivity plot approaches this smooth line.

These observations show the endfire array has particular advantages at very short ranges, and is especially suitable as a sensor for an animal that must track prey from a large distance right into its jaws.

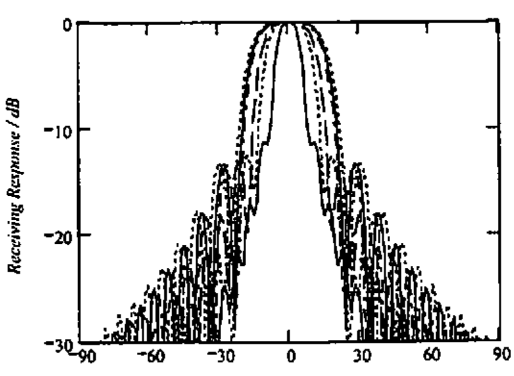

Fig. 3 Beampatterns for 22 element end-fire array with 1.0cm spacing, frequency 80kHz and ranges of 0.22, 0.3, 0.4, 1.0, 1.6 and 20m.

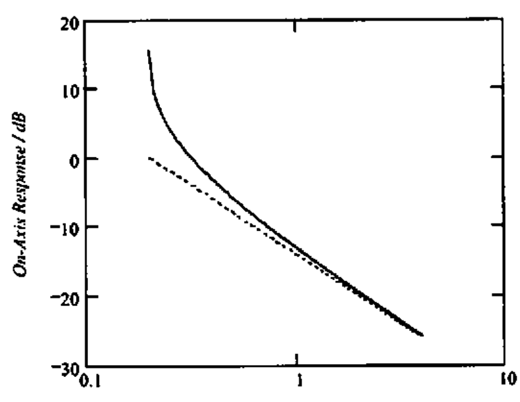

Fig. 4 On axis sensitivity of 22 element end-fire array plotted against range (solid line). For comparison, the dashed line shows L/R.

4. ANGULAR LOCALISATION

The simplest means of measuring the direction of arrival of a propagating wavefront is to rotate a directional receiver until a maximum in the response is observed. However, with beamwidths of greater than 10° it is clear that this approach cannot provide the angular localisation thresholds of less than 1° observed in *Tursiops* [9].

At this point, a comment on the meaning of resolution is in order. The concept of Rayleigh diffraction limit, or beamwidth, approximately λ/L in radians, is appropriate if resolution is taken to mean the angular separation at which two sources can be discriminated if their signals arrive simultaneously. However, it says nothing about the precision with which a single signal can be localised in bearing, and nor does it say anything about determining the angular separation between two signals arriving at different times.

The term 'different times' here is crucial for species like the Bottlenose Dolphin that employ very short, but also very wide bandwidth transmissions. If a typical pulse length, T, is 50μs with a bandwidth, B, of 100kHz then, superficially, the time resolution is T, but with suitable processing [10] the information is present in the signal to reduce this by the BT product, a factor of 5 in this case, to 10μs. This represents a distance of 1.5cm in water and, in practice, it is unlikely that two targets of relevance to a dolphin will be within 1.5cm in range and a few degrees in angle at the same time. Thus, although separate highlights on a single target may cause problems, it will generally be possible to discriminate between all discrete targets of interest.

Thus, the problem is simply one of the precision of localisation in angle of a single source. Noting that it is possible to identify two tooth arrays in either the upper or lower jaw, separated horizontally by an angle of about 12 degrees [3], then there are two classes of techniques commonly employed in sonar and radar:

a. Measuring the phase or time difference at two spatially separated but otherwise similar receivers, loosely known as interferometry.

b. Measuring the amplitude difference at two receivers, usually co-located, with similar directivity patterns pointing in different directions. This is called monopulse localisation in radar terminology.

Such approaches are known to be employed by many species, many of which are much simpler in neurological capabilities than dolphins (see eg [11]), and approach (b) seems most applicable to the two rows of teeth that are 'squinted', or separated by a small angle.

4.1 Monopulse sum and difference localisation

Monopulse is a concept referring to precision direction finding with a pulsed source of radiation that was developed for radar during the 1940's, and the terminology implies that the directional information can be extracted from a single pulse rather than relying on triangulation over a number of separate transmissions.

Amplitude monopulse, as described by Rhodes [12], relies on a comparison between two beams, and in the form generally referred to as 'sum and difference monopulse' the angle output α is given by

$$\alpha(\theta)=\frac{D(\theta)-D(-\theta)}{D(\theta)+D(-\theta)} \qquad (3)$$

where $D(\theta)$ is the directivity function one of the pair of beams. This equation relies on three basic postulates:

1. *Angle information is in the form of a ratio,*
   This implies that the result depends only on the angle of arrival and is independent of the absolute signal amplitude.
2. *The ratio for a positive angle of arrival is the inverse of the ratio for an equal negative angle.*
   This implies that the system is symmetrical about the boresight (dead ahead).
3. *The output is an odd real function of the angle of arrival*
   This implies that the system senses both the magnitude and sense of the angle of arrival.

An example of the endfire beampatterns from two 22 element arrays, separated by 12 degrees, at a frequency of 150 kHz, is shown in Fig. 5, and a group of results obtained by applying (3) to a pair of such beams is shown in Fig. 6.

These results, which show sum and difference response calculated from (3) plotted against source bearing over ±15 degrees for frequencies of 80kHz and 150kHz, and for ranges of 10m and 0.3m. Again this includes the array length, so the target is just 0.2m from the end of the array.

It is apparent from Fig. 6 that for all frequencies and target ranges considered, the sum and difference response has a central region of about ±5 degrees where the output approximates to a linear function of bearing, and beyond that, the response curves back towards zero but, most importantly, remains the same sense. These regions are described as a linear field of view, where the target bearing can be accurately determined, and an unambiguous field of view, where the direction, left or right, is known, but the precise bearing is not. Beyond the angle range shown in the plots the response may possibly cross the zero axis, giving an ambiguous response. Two important points should be noted here:

- The transmission beamwidth for these animals is in the order of 10 degrees, so for practical purposes, targets are only insonified within the linear field of view.
- Within the linear field of view the response is monotonic and continuous. It does not depend upon the signal strength and there is no form of quantisation, so there is no resolution limit.

Because these responses depend upon the shape of the receiving beampatterns, they do vary with frequency. However, with appropriate processing, combined with the broadband signals, this may have advantages in distinguishing genuine targets from frequency dependent effects due to scattering, reverberation and ghost reflections. In the same way, the responses also vary with range but, as with the beampatterns, this is only significant within one or two array lengths of the receiver.

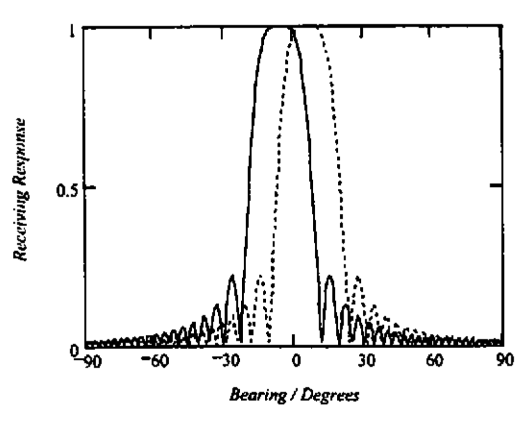

Fig. 5 Pair of beams produced by two endfire arrays, separated by 12 deg., at 150kHz

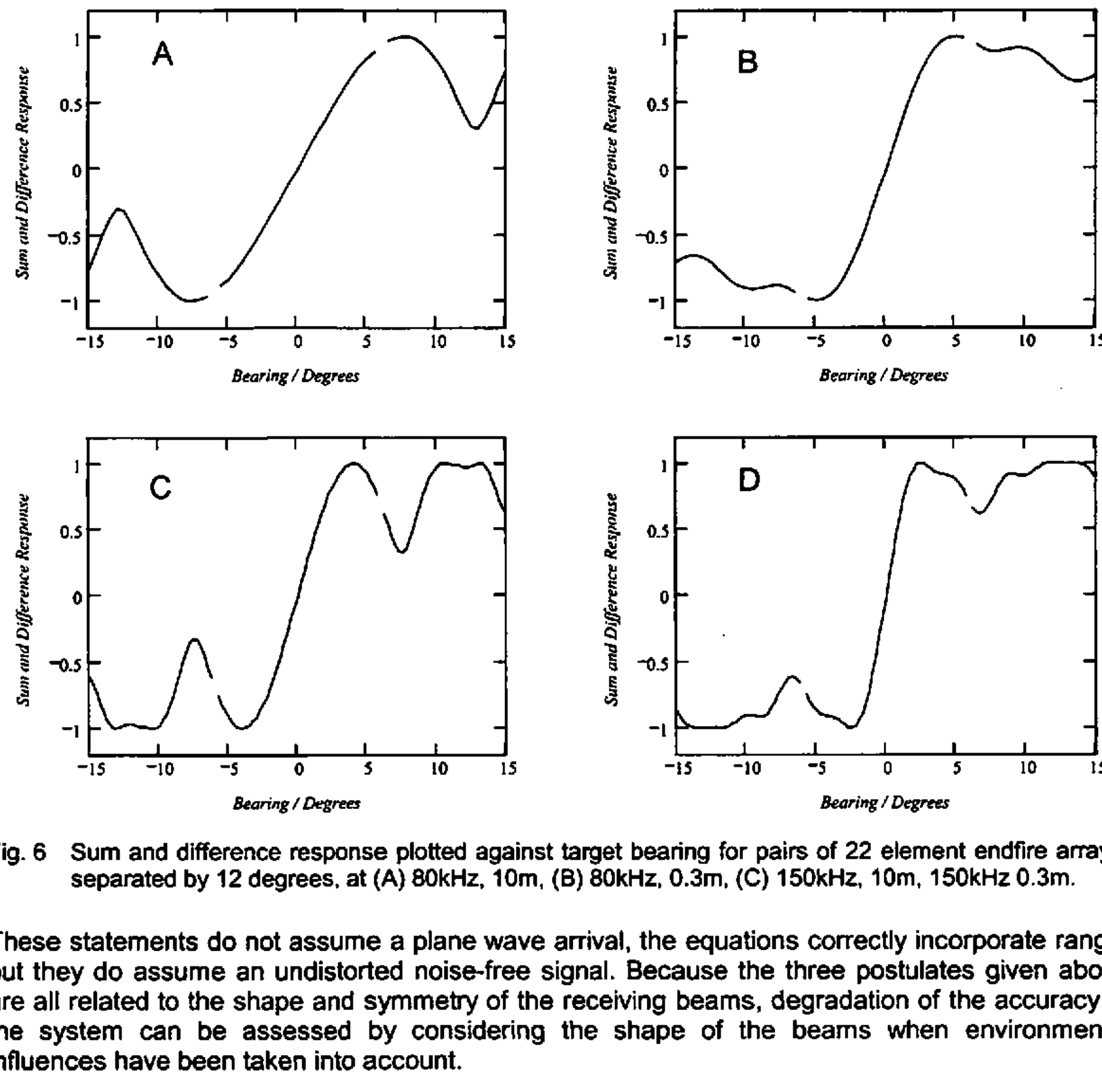

Fig. 6 Sum and difference response plotted against target bearing for pairs of 22 element endfire arrays, separated by 12 degrees, at (A) 80kHz, 10m, (B) 80kHz, 0.3m, (C) 150kHz, 10m, 150kHz 0.3m.

These statements do not assume a plane wave arrival, the equations correctly incorporate range, but they do assume an undistorted noise-free signal. Because the three postulates given above are all related to the shape and symmetry of the receiving beams, degradation of the accuracy of the system can be assessed by considering the shape of the beams when environmental influences have been taken into account.

5. BEAMPATTERN DEGRADATION

The discussion so far has been limited to ideal arrays. It is clear, however, that there are many potential sources of degradation. Some of these relate to noise, some to interference from scattering and reverberation and some simply to variations from the ideal in the response of various components in the system. Space is not available here to discuss all these in detail. However, it is likely that the most significant contribution to uncertainties in angular localisation comes from the final factor, which in a man-made system would be referred to as "component tolerances". Nevertheless, all these factors will be considered briefly.

5.1 Noise

The angular uncertainty introduced by noise was considered previously the present author [2], and it was found that a peak to peak error of less than 1 degree could be achieved with a signal to

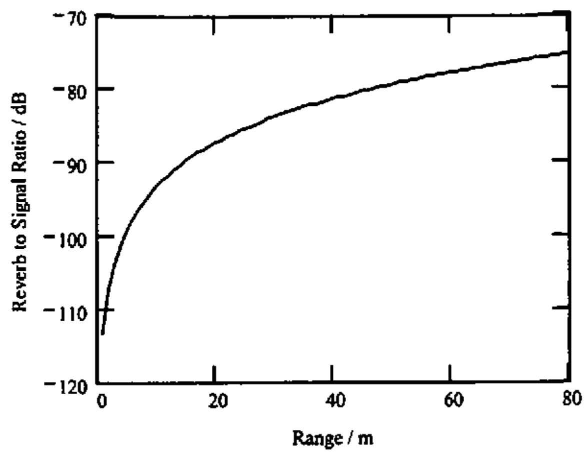

Fig.7 Signal to reverberation ratio plotted against range for a dolphin sonar and a 0dB target.

noise ratio of about 10dB. For an echolocation source level of 200 dB re 1μPa pk-pk at 1m, and a -35 dB target strength, this noise level represents a target range of 80 m, so is not a limiting factor.

5.2 Scattering and reverberation

The effects of reverberation are minimised by the dolphin's very short transmitted pulse. Range resolution has already been considered, and it is clear that reflections emanating from discrete sources more than a few centimetres from the target of interest will be separated in time and will not interfere with the target.

General scattering levels are also minimised by the short pulse. Urick [13] gives a basic expression for volume reverberation level RL as

$$RL_V = SL - 40\log R + S_V + 10\log\left(\frac{c\tau}{2}\Psi r^2\right) \qquad (4)$$

where SL is the echolocation source level, R is range, S_v is volume scattering strength for the sea water, c is sound speed, τ is the pulse length and Ψ is the solid angle in steradians of the product of transmitting and receiving beampatterns. Noting that the first two terms on the right hand side represent the two way transmission loss at range R, but without absorption, the signal to reverberation level for a 0dB target can be approximated by the last two terms. This is plotted against range in Fig. 7 for τ and Ψ appropriate to the dolphin system and a typical volume scattering strength of -70dB.

It is apparent that, even with a much weaker target, reverberation from scattering will not present a significant problem.

5.3 Fluctuations

The effects of wavefront fluctuations on the apparent arrival direction of the signal have also been considered previously the present author [2]. The effect is minimal at ranges of a few metres, but increases rapidly with range and the standard deviation may exceeds 1 degree at about 50 m. However, the effects of fluctuating wavefronts extend further than just a matter of accuracy. Targets appear to move about in much the same way as objects seen through a heat haze and, in man-made systems at least, this can lead to instability and failure in tracking and homing algorithms.

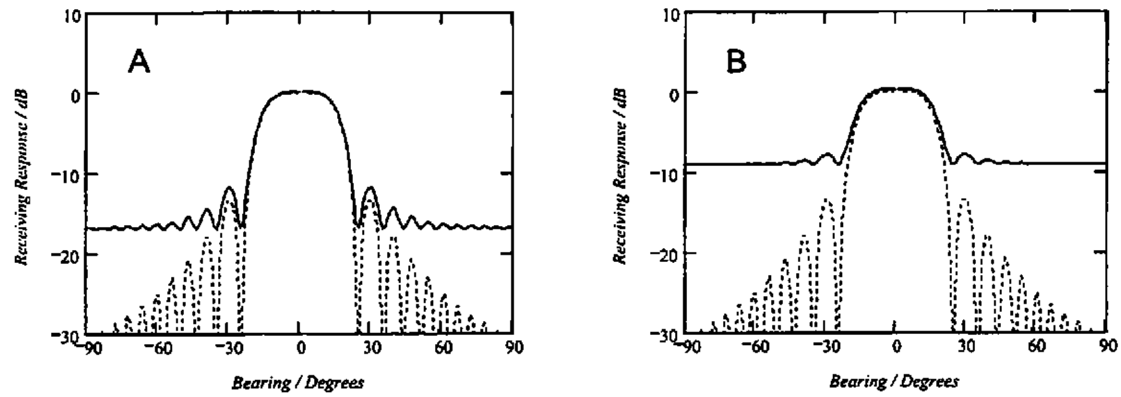

Fig. 8 Average beampatterns with phase and amplitude errors for 22 element end-fire array at 80 kHz at 5m range. A: amplitude error 10% rms, phase error 5 degrees rms, B: amplitude 25% rms and phase 15 degrees rms. Dotted lines are ideal patterns.

5.4 Errors and tolerances

The response of each part of the system is subject to variations in size, exact material composition, positioning and so on. These variations may be from animal to animal, or between, say, different teeth in the same animal.

Many of these variations can be resolved into equivalent errors in amplitude and phase in the response of each individual sensor in the array. It is assumed that, because of the many contributing error sources, the central limit theorem applies and both amplitude and phase deviations are zero mean normally distributed random variables.

The effect on beampatterns of such tolerances are well understood [14]. The normalised average expected beampattern is given by

$$\langle D(\theta)\rangle = \left\{ |D_0|^2 \exp\left(-\delta^2\right) + \frac{\left[1-\exp\left(-\delta^2\right)+\Delta^2\right]}{L_e} \right\}^{1/2} \tag{5}$$

where D_0 is the error free response, δ is the rms phase error (in radians) and Δ is the rms fractional amplitude error. L_e is an effective length, equivalent to the number of elements for an unshaded array.

Fig. 8 shows example beampatterns obtained with this formula. At present, there is no available information about what realistic values for the phase and amplitude tolerances might be. However, it is reasonable to suppose that, for the teeth at least, these are largely related to the resonant frequency and Q, and are dimensionally controlled in the same manner as, for example, ceramic hydrophone elements. In the same way, it might be argued that the anticipated error levels are in the same order as those found in such ceramic hydrophones where no attempt has been made to control errors. Thus, the plots are computed for error values of 10% rms amplitude and 5 degrees rms phase in A, and 25% amplitude and 15 degrees rms in B.

The general effect seen in the plots is a raising of sidelobe levels and a slight broadening of the main beam. It must be remembered that these are average patterns, so individual results may vary about these averages. Nevertheless, the immediate conclusion is that the raised sidelobes may degrade the system noise performance, but the change in shape of the main beam seems to be very small and is unlikely to interfere significantly with the angular localisation process.

6. CONCLUSIONS

In this paper, a rather speculative sonar system has been considered. This system is based on rows of teeth in the Atlantic bottlenose dolphin acting receiving arrays and some biological mechanism, whose exact nature is uncertain, acting as an end-fire beamformer. It was determined previously by the present author [2] that such arrays have beampatterns that closely approximate those measured for the bottlenose dolphin.

The main topic of this paper has been angular localisation, and it has been proposed that if pairs of rows teeth are used in a manner akin to the well established monopulse radar technique for determining the direction of arrival of a signal, then the observed sub-degree angular discrimination is perfectly feasible. This was demonstrated for a limited series of ranges and frequencies with examples of the calculated monopulse response plotted against target bearing.

The secondary topic has been the effects of various degrading environmental factors on this performance. Noise and fluctuations had been considered previously [2], but here reverberation and errors and tolerances were both considered, albeit at a cursory level.

It turns out that the postulated system is remarkably robust. With realistic values for the various parameters it seems that errors are not likely to exceed about one degree at ranges up to at least 50m. This robustness can largely be attributed to the very short broad bandwidth transmitted waveform. Unfortunately, such waveforms have not generally been available to human sonar designers because of the limitations imposed by the available transmitting transducers. However, it may be suggested that this is at least a partial contributor to explaining the dolphin's remarkable sonar performance.

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