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ESTIMATED TARGET LOCALISATION ACCURACY AND RESOLUTION OF DOLPHIN ECHOLOCATION BASED ON HOMING SONAR/RADAR PARADIGMS

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1. INTRODUCTION.

Man made homing systems have evolved independently of any knowledge of biological echolocation systems since the early decades of this century. The prime objectives of homing missiles and torpedoes, however, have much in common with dolphins and other echolocating predators. They need to detect and classify potential targets in all directions over as great a range as possible, localise the most interesting one, then intercept and attack the target despite evasive manoeuvres and potentially distracting alternative targets.

In this paper, experience in modelling and simulating radar and sonar homing systems is combined with a basic knowledge of dolphin echolocation to produce estimates of the potential capabilities of dolphin systems and the degrading effects of various environmental factors such as ambient noise and fluctuations in the seawater medium. Modelling and results are made as general as possible but specific parameters relate to the bottlenose dolphin (*Tursiops truncatus*). However, to estimate the potential performance of the system, the essential components need only be represented as basic acoustic elements. No detailed knowledge is required of specific biological mechanisms and, conversely, no support for any particular model of these biological mechanisms is implied. Nevertheless, it is hoped that the insights gained may suggest fruitful lines of future experimentation.

2. TARGET INFORMATION.

An echolocation system obtains information about a target by comparing the received echo with the transmitted signal. The availability of an echo indicates the presence of a reflecting target, but knowing a target is present is of little use by itself. Something more must be known. A homing system must provide the location of the target as well as its presence, and it must provide information about the type of target.

The basic target localisation parameters are range, determined from the elapsed time between transmission and reception of a reflected signal, and bearing, determined from the apparent direction of arrival of the signal. Target relative velocity may also be determined from the Doppler shift in the received echo.

The ability of the system to extract this information is fundamentally limited by noise, and depends largely on the size of transmitting and receiving apertures, the nature of the transmitted pulse, and any processing carried out by the receiver. On the other hand, the fidelity of the information carried by the signal depends on how it may have been degraded by the propagation environment, principally by variations in the propagation speed or by interference between multiple transmission paths.

Theoretical analyses of these phenomena and estimates of the accuracy of parameter measurements in the presence of noise are well established. Reviews will be found for sonar in the book by Urick [1] and for radar in the book by Skolnik [2]. In the present application, however, it will be more informative to demonstrate the behaviour of a dolphin echolocation system with examples of signal waveforms obtained from simple time-series simulations. The first step in this procedure is to define a model of the dolphin system.

3. THE DOLPHIN MODEL.

Three components of the echolocation system are relevant here: the transmitter, the receiver, and the signal waveforms:

3.1 The Transmitter.

Characteristics of the *Tursiops* sound projector are summarised by Au [3] in terms of a 'composite' broadband directivity pattern, with an associated 3dB beamwidth in vertical and horizontal planes of 10° and a directivity index (DI_T) of 26dB. The meaning of the term 'composite' is not clear, and neither frequencies nor bandwidths are quoted. Furthermore, only the main beam of the beampattern appears to have been measured, so the behaviour in other directions not known.

Au [3] also suggests that the projector can be represented by an equivalent uniformly illuminated planar circular aperture of 4 cm radius. This is a more appropriate description for the present application, and will be adopted as a model, if only on the grounds that its behaviour is well understood (eg [4]) and also that new parameters are easily substituted should those chosen here prove to be in error.

To predict the waveforms of arbitrary signals as functions of range and bearing, the impulse response of the transmitter will be needed. This is well known for planar apertures, and will be found for various uniformly illuminated geometries in [5].

3.2 The Signals.

Several examples of recorded dolphin clicks are presented in [3] and a typical example for *Tursiops* is shown as the top trace in Fig. 1. This curve represents the far field sound pressure in the water on axis, or dead ahead relative to the longitudinal axis of the animals head. The click shown here has an overall duration of 70µs, a 3dB bandwidth of 50kHz and a centre frequency of 120kHz. Dolphins are known to use other click waveforms [3], but this one will be used in the examples that follow. It may be noted that such broad band signals do not carry significant Doppler information, so target velocity cannot be determined from the echoes.

The waveform at other bearings is obtained from the convolution of this signal with the impulse response of the aperture, and this is shown for bearings of 10° and 20° in the lower two traces. These plots have been normalised so that they all appear to be the same amplitude, but the magnitude of the signal actually decreases rapidly as the bearing is increased, as well as becoming more spread out in time as is apparent from the graphs.

The effective directivity of the transmission may be computed from the peak to peak sound pressure level of these signals as a function of bearing, or from the energy in the pulse, estimated by integrating the square of the pressure. Both are shown in Fig. 2 and compared with the data taken from Au [3], presumed to represent peak to peak measurements. For practical purposes the agreement can be accepted as satisfactory. However, it is clear that a more sophisticated model is required to truly represent the behaviour at bearings greater than about 20°. This might be achieved simply by applying

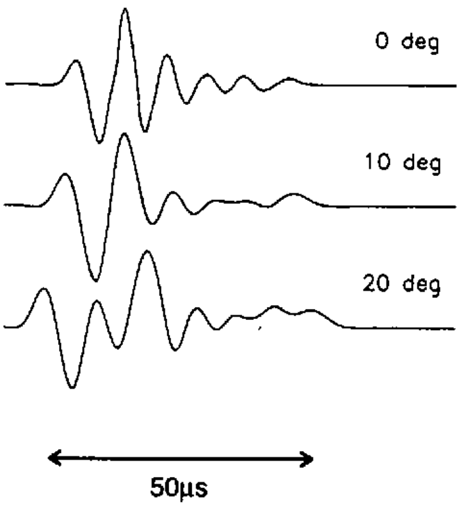

Fig. 1 Typical on axis Tursiops click (top trace) convolved with the aperture impulse response for bearings of 10° and 20°.

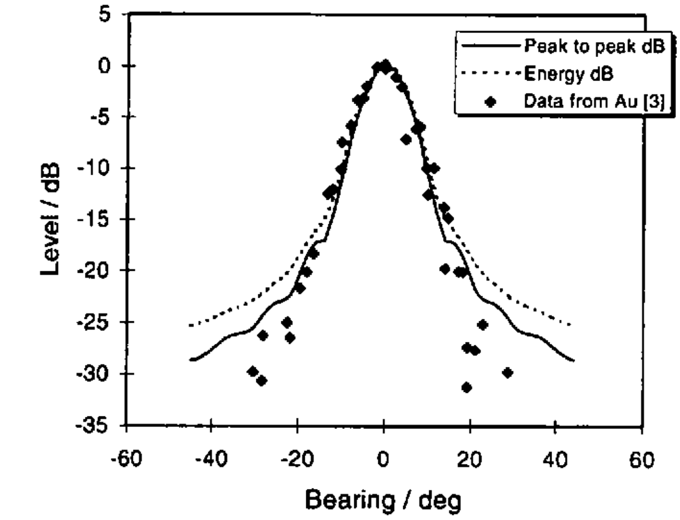

Fig. 2 Estimated Tursiops transmission directivity pattern computed as peak to peak (solid line) and energy (dashed line). Symbols are from measured beampatterns in Au [3].

a radial shading function to the circular aperture, but better results would almost certainly be obtained by formally modelling the lens formed by the varying refractive index of the skull and melon.

3.3 The Receiver:

Two models of the animals receiving system will be considered here. The first is the two point cochleal receiver represented by a pair of forward facing rectangular apertures suggested by Au [3], and the second is the array formed by the uniform, evenly distributed teeth, as proposed by Goodson and Klinowska [6]. It should be stressed that the second model is not 'hearing' in the conventional sense.

3.3.1 Two point cochleal receiver.

Au [3] models the *Tursiops* receiver as two rectangular apertures lying in a vertical plane transverse to the axis of the animal's head, each 2.6 cm wide by 3.1 cm deep, with 12 cm separation between their centres. This description is accompanied by measured directivity patterns for narrow band continuous wave (cw) signals at frequencies of 30, 60 and 120 kHz. However, it is the directional response to the broadband click waveforms that is required here, and this is obtained in exactly the same way as the transmission directivity.

The impulse response of a rectangular aperture is similar to that for a circular aperture [5], and the effective broadband directivity, computed from the convolution of this impulse response with the on-axis click signal, is shown as the solid line in Fig. 3. Also shown is the theoretical cw response for 150 kHz [1] and the measured response at 120 kHz from Au [3]. 150 kHz is the highest frequency present in the signal, while 120 kHz is the highest frequency measured by Au [3] and also the peak in the spectrum of the click signal.

The broadband response and the 150 kHz response are very similar in the main lobe region, but diverge at wider angles as should be expected. These predicted patterns, however, do not fit the measured data well. Nevertheless, there is reasonable agreement over about ±20°, and this model will

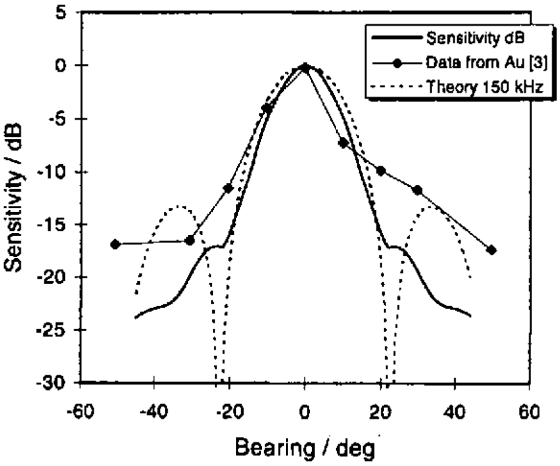

Fig. 3 Tursiops receiving directivity pattern for rectangular aperture model (solid line), theoretical pattern at 150 kHz (dashes) and data from Au [3] for 120 kHz.

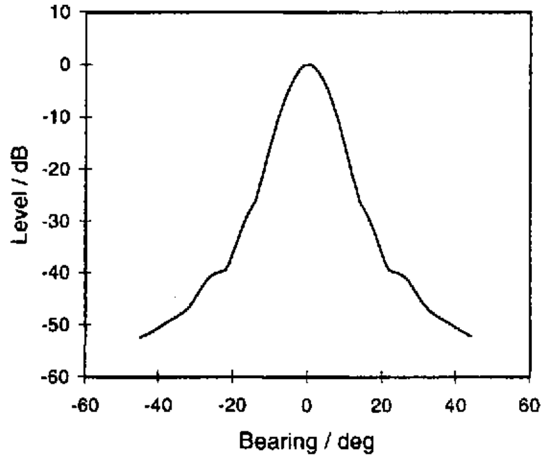

Fig. 4 Combined transmit/receive directivity pattern computed from convolution of on-axis click with transmit aperture and receive aperture impulse responses.

be considered further when angular localisation of targets is examined. When the overall system performance is considered, the combined directivity of both transmitter and receiver will be required. This is obtained simply by convolving the on-axis click with the impulse responses of both the transmitting aperture and the receiving aperture, and is shown in Fig. 4.

3.3.2 End-fire array receiver.

The model proposed by Goodson and Klinowska [6] 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. 5.

The biological mechanisms involved will not be considered here, but the principle of operation is simply that the teeth act as pressure transducers. Signals representing the sound pressure at each tooth are passed to the central nervous system along individual mandibular nerves. The propagation delay in each nerve (τ in the diagram) is such that an echo arriving from a direction along the axis of the row of teeth (end-fire) will result in the signals from all teeth arriving at the central nervous system

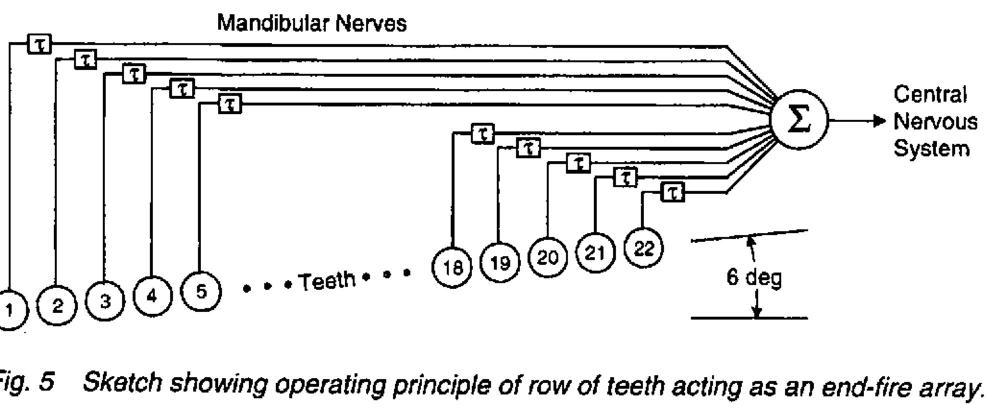

Fig. 5 Sketch showing operating principle of row of teeth acting as an end-fire array.

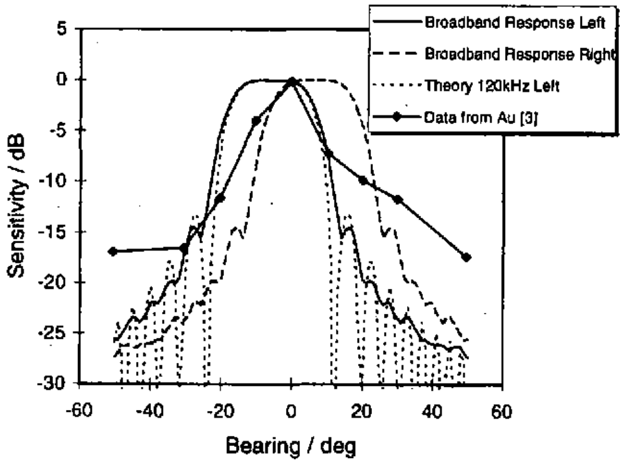

Fig. 6 Receiving directivity patterns for end-fire array model (left, solid line and right, dashes) and left hand theoretical pattern at 120 kHz (dots).

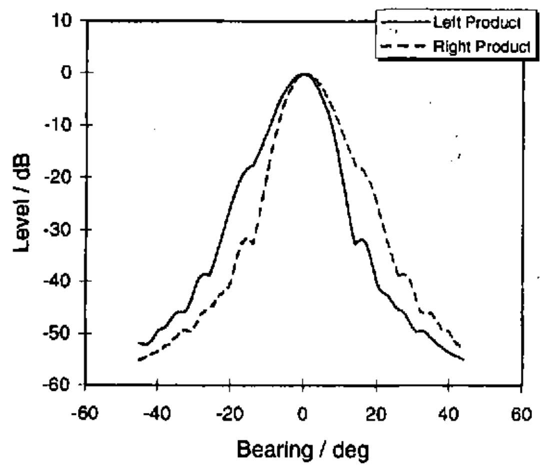

Fig. 7 Combined transmit/receive left and right directivity patterns for end-fire array model.

simultaneously so that they add together constructively. Signals from echoes from other directions, however, will not arrive simultaneously, resulting in a reduced total response. Thus the array has directivity, with its maximum sensitivity in the end-fire direction. The two rows of teeth subtend angles of about 6° to the longitudinal axis of the jaw.

The response of such arrays is well known for narrow band cw signals [1], but is easily modelled for broadband pulses by adding together copies of the pulse, one for each sensor, each of which is delayed by a time equal to the sum of the propagation delay through the water from the target to the tooth plus the delay in the mandibular nerve. The resulting left and right directivity patterns are shown in Fig. 6, along with the theoretical cw pattern at 120 kHz. Again the measured response at 120 kHz from Au [3] is shown and, again, it is noted that the model does not fit these data well when the individual beampatterns are considered. There is reasonable agreement, however, between the data and the overlapping portion of the left and right beams. This might be interpreted as suggesting that the animal only registers a detection when there is an adequate signal level in both beams. The combined transmit and receive responses are shown in Fig. 7.

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* [7].

More sophisticated techniques fall into two classes:

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.

From the descriptions given above, it appears that method (a) is most appropriate for use with the two point cochleal receiver model whilst method (b) is ideally suited to the end-fire array model. These combinations will be used in what follows, but this does not imply that amplitude differences could not be used by the cochleal receiver, nor that phase or time differences could not be used by the end-fire array receiver.

4.1 Time difference angle measurement with the two point cochleal receiver.

For a signal arriving from a bearing θ, the time of arrival difference, τ, between two sensors with a spatial separation s is easily shown to be $\tau = (s/c)\sin\theta$, where c is the speed of sound. The accuracy and resolution of the angle measurement are directly related to the accuracy and resolution of the time measurement, and the relationship varies as $\sin\theta$. Similar relationships exist for phase differences, but phase does not have any meaning for broadband signals unless some form of spectral analysis is carried out before the difference measurement.

Referring to the click waveform in Fig. 1, it can be seen that locating the peak of the pulse envelope would result in a temporal resolution of about 1μs. However, with the spatial separation of 12cm assumed for the two point cochleal receiver model [3], and a sound speed of 1500 ms^{-1}, angular resolution on the order of 1° requires time resolution of about 0.2μs. More precise time measurement can be achieved by cross-correlating the echo with the transmitted pulse, known as match-filtering in sonar and radar. This leads to a resolution improvement roughly equal to the time-bandwidth product of the signal, a factor of about 6 for the signal of Fig. 1. This suggests that the reported angular resolution [7] is achievable with this model in the absence of noise and other degrading factors.

4.2 Amplitude difference measurement with the end-fire array.

The difference between the amplitudes of signals received in the left and right beams of Fig. 7 is plotted against bearing in Fig. 8. The response shows a linear region over a range of about ±7°, beyond which the slope reverses, so leading to ambiguity. This however is beyond the width of the transmitter beam, so no echoes would be returned from these directions.

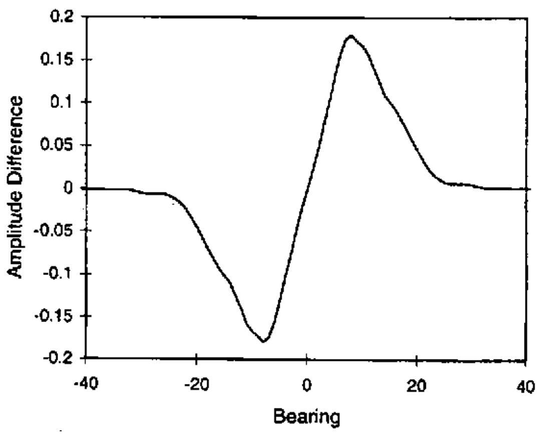

Fig. 8 Difference between left and right combined transmit /receive directivity patterns of Fig. 7.

The accuracy and resolution with which this amplitude difference could be determined is not known, but it is noted that 1° in bearing is represented by about one tenth of the amplitude difference range and discrimination on this order seems quite feasible. Again, the proviso is made that this is in the absence of noise and other degrading factors.

5. NOISE AND FLUCTUATIONS.

Noise degrades the angle measurement when it is uncorrelated and acts differently on the two sensors. Fluctuations in the propagating signal are effectively distortions of the wavefront, and

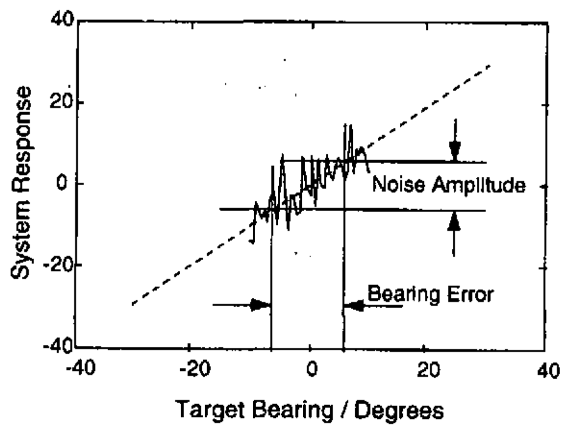

Fig. 9 Effect of noise on angular localisation.

lead to the apparent direction of arrival of the wavefront differing from the true target direction.

5.1 Noise

Because all localisation systems present an output that, within the linear field-of-view, is proportional to target bearing, the angular uncertainty introduced by noise is simply the noise amplitude at the output divided by the slope associated with the bearing/output relationship. This is shown schematically in Fig. 9, where the dashed line represents an idealised system output response and the solid curve is the output with noise added.

The noise performance of the two receiver models is easily evaluated by carrying out Monte Carlo simulations with sequences of random numbers with the correct noise-like statistics added to the click signals. Typical results are shown in Fig. 10 and Fig. 11 for the amplitude difference and time difference methods respectively. The noise had the spectral shape for isotropic ambient noise in the sea [1], and the solid lines represent the situation where the noise was band-limited to the same frequency range as the click signals, while for the dashed lines no bandwidth limitation was imposed. The signal to noise ratio (SNR) is the ratio of the effective rms signal sound pressure level (9 dB below the peak-to-peak level) to the true rms sound pressure level of the noise. Accuracy in these plots refers to three times the standard deviation in the angle measurement.

It is clear that the combination of amplitude difference measurement and the end-fire array model produce better performance than the alternative time difference and two point sensor model. In the first case an accuracy of 1° is achievable with a band-limited SNR of about 10 dB, whilst the time difference approach requires about 30 dB. For a source level of 200 dB re 1μPa pk-pk at 1m, and a -35 dB target strength, these noise levels represent target ranges of 80 m and 30 m respectively.

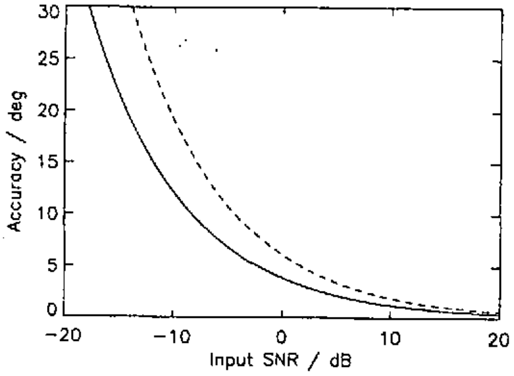

Fig. 10 Angular accuracy plotted against SNR for amplitude difference measurement with band-limited (solid line) and broad-band noise (dashes).

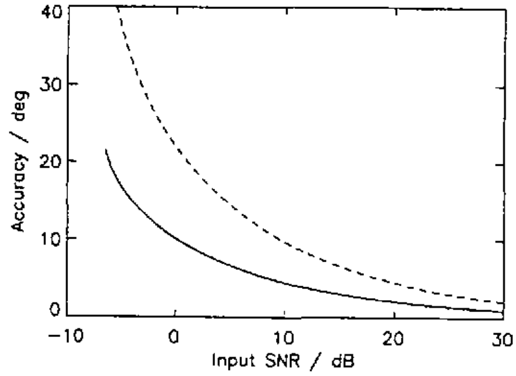

Fig. 11 Angular accuracy plotted against SNR for time difference measurement with band-limited (solid line) and broad-band noise (dashes).

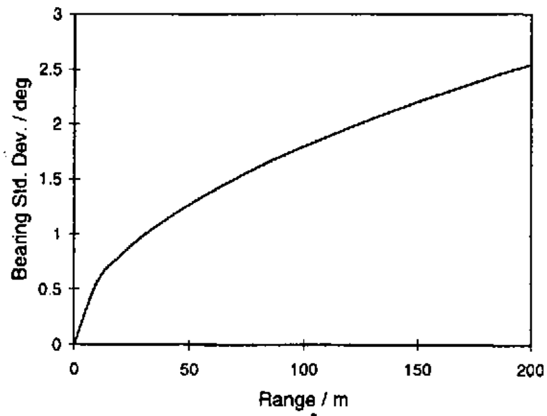

Fig. 12 Estimate of click signal direction of arrival fluctuations in a typical coastal environment.

5.2 Signal Fluctuations

At high frequencies, fluctuations in the phase and amplitude of acoustic signals in the sea are brought about primarily by turbulence. These fluctuations have spatial correlation scales down to a few cm and temporal scales down to about 100 ms [8]. This implies that there are likely to be distortions of the wavefront on smaller scales than the sensor separations considered here, but these distortions will be frozen over the 50 μs duration of a click.

An estimate of the standard deviation of the apparent direction of arrival of a click signal has been calculated using methods described in [8] for a depth of 10 m in a typical coastal environment and a 12 cm sensor separation. This is shown as a function of target range in Fig. 12. It will be seen that the effect is minimal at ranges of a few metres, but increases rapidly with range and the standard deviation exceeds 1° 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.

This represents an extreme situation. Fine scale fluctuations near the surface in coastal environments are far worse than would be expected at greater depth or in the open ocean. However, it does make it clear that in some conditions the accuracy of an performance localisation system may be limited by environmental fluctuations rather than noise, and because this is a feature of the medium rather than the system it cannot generally be corrected with processing.

6. IN CONCLUSION.

The performance of a dolphin echolocation system has been evaluated in much the same way as a sonar or radar homing system might be treated, given only a limited knowledge of the characteristics of the hardware and signals, and knowing nothing about the processing. The treatment presented here has been limited by the space available, but it is still possible to draw some interesting conclusions.

The first general conclusion is that the *Tursiops* system is capable of achieving the angular localisation performance characteristics published in the literature, whichever model for the receiver is chosen. This is not a trivial conclusion. It confirms that neither the models examined nor the published experimental data are grossly in error, although it does not necessarily support the validity of any of the models.

The second conclusion is that performance may be limited by noise, but in some environments it might be constrained by signal fluctuations. This may be of strategic importance because a noise limitation on localisation will generally be accompanied with a noise limitation on detection, so generally implies simply failure to detect targets. Fluctuations, however, may not inhibit detection but will lead to erroneous localisation and degradation of angular resolution.

The final conclusion is that although both receiver models considered seem adequate, the end-fire array is probably capable of better performance in the presence of noise than the two point cochleal sensor. Time or phase difference localisation has not been considered for the end-fire array model, but because the effective centres of the two arrays are closer together than the postulated cochleal receivers, it is also likely to prove superior in this mode of operation.

7. REFERENCES.

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