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INSTITUTE OF ACOUSTICS
UNDERWATER ACOUSTICS GROUP

PROCEEDINGS OF THE
SPECIALIST MEETING

ACOUSTIC SURVEYING OF FISH POPULATIONS

HELD AT THE FISHERIES LABORATORY OF
THE MINISTRY OF AGRICULTURE, FISHERIES AND
FOOD, LOWESTOFT

:7th DECEMBER 1975

ACOUSTIC SURVEYING OF FISH POPULATIONS

This was the first meeting of the Underwater Acoustics Group (UAG) of the Institute of Acoustics. It was a one-day meeting held at the Fisheries Laboratory of the Ministry of Agriculture, Fisheries and Food, at Lowestoft, its aim being to highlight problems in acoustic methods used for the estimation of fish stocks.

Dr.D.H.Cushing of the Fisheries Laboratory, Lowestoft, was Chairman of the first session which was concerned with fish target strength and five papers dealing with different aspects of the subject were presented.

Professor J.W.R.Griffiths, of the University of Technology, Loughborough, acted as Chairman for the second session which dealt with survey methods in five papers.

More than 40 people attended and the Underwater Acoustics Group were particularly pleased at the support from overseas.

The steering committee of the UAG wish to record their appreciation of the support and facilities made available by Mr.A.J.Lee, D.S.C., M.A., Director of Fisheries Research.

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THE ACOUSTIC TARGET STRENGTH OF LIVE FISH

RESULTS OF THE 'EASDALE' PROJECT AND SOME THEORETICAL CONSIDERATIONS

by V. G. Welsby

University of Birmingham

Introduction

The description of the 'Easdale' fish target strength project given here is necessarily a brief one. For fuller information see reference (1). The purpose of the present paper is to summarize the 'Easdale' work and then go on to discuss some general acoustic field theory which is relevant to measurements of this kind.

Brief description of project

The NERC 'Easdale' project (1969-1973) produced punched-tape records of over a million separate acoustic echo pressure-amplitude readings on live fish. Each quoted target strength figure was obtained by taking the mean of 1000 successive 'pings'. 174 specimen fish were used, of four different species (cod, haddock, saithe, dogfish), each individual specimen being measured at sonar frequencies of 10, 30 and 100 kHz and at two different angles of incidence, namely, vertical (i.e. dorsal with respect to the fish) and 22.5 degrees to the horizontal. The fish were free to swim about within a cage of netting approximately 2m x 2m x 1m high, at a depth of 10 metres in the water.

Because the fish had to be kept at a constant depth it was necessary to move the transducers to vary the angle of incidence. A steel structure was erected which enabled the transducers to be towed on a trolley moving on an inclined railway (see fig.1). The sonar beamwidth was 25 degrees, giving a sensitivity which was uniform over the whole of the cage to within ± 1 dB, even when the transducers were at the minimum distance from the cage. The acoustic pulse length was about 200 microsecs., corresponding to a length of about 0.3m in the water. Time-gating of the receiver excluded reverberation from ranges outside the limits of the cage. The frequency bandwidth of the receiver was restricted to 1 kHz, thus reducing the range resolution of the sonar so that the whole of each target fish was represented by a single echo pulse. The sonar pulse repetition rate was 100 per minute, which allowed adequate time for reverberation to die away between pulses. The signal at the output of the receiver was sampled by a peak detector and the results for about 1200 successive echoes for each measurement were punched in digital form on paper tape. Subsequent processing by computer produced the amplitude distribution histogram for the first 1000 of these data points and also their mean and standard deviation. The mean values of echo pressure amplitude were converted into target strength figures by making use of system calibration information stored in the computer memory. The data were finally reduced, by means of a linear regression analysis, to a set of empirical equations showing target strength as a function of fish length and acoustic wavelength (see Table 1) T is the target strength relative to that of a 2 metre radius sphere, i.e. to a scattering cross-section of $4\pi m^2$. The technique is that used by previous authors on the subject of fish target strength measurements. The target strength, expressed as an area, is normalized by the square of the wavelength and is regressed on the fish length normalized by the wavelength. There is no obvious justification for the use of a linear regression but this is found experimentally to lead to a high correlation coefficient.

Fig 2 shows, as an example, one of eight similar charts (the other seven will be found in the full Report on the 'Easdale' project(1)) in which measured values of target strength have been plotted in the form of a 'scatter diagram', with the corresponding regression line drawn in for comparison.

In addition to the main work with individual fish a subsidiary experiment was carried out to find out how the mean target strength of a fish would be affected by the presence in the cage of other specimens of the same species. It was found most convenient to use haddock, with lengths ranging from 30 to 35 cm, for this purpose and a number of measurement runs were made using groups containing 1,2,4,8,16 and 32 fish at a time. In the absence of any interaction between the fish the target strength would be expected to rise by 3 dB each time the number of fish was doubled. It turned out however that the actual figure consistently exceed 3 dB by a small but statistically significant amount. The results for three acoustic frequencies and two different aspect angles varied between 3.31 and 3.55 dB, with an average value of 3.27 dB per doubling of fish number. The cause of this effect is not known. A rough calculation suggests that multiple scattering could hardly account for it while 'shadowing' of one fish by another would be expected to reduce the target strength below 3 dB per doubling, rather than increase it.

Discussion of results

The relationship between mean-power and mean-amplitude values of sonar signals depends on the probability distribution of the pressure-amplitude readings. If, for example, the distribution is of a 'Rayleigh' type then the mean-power level is known to be 1.05 dB higher than the mean-amplitude level. A study of all the histograms of the pressure-amplitude results obtained in the 'Easdale' project showed that the fit to a 'Rayleigh' type curve was quite good provided the fish length/wavelength ratio (L/λ) was greater than 20. This applied for all species and wavelengths used. For (L/λ) less than 5 the 'Rayleigh' model appeared to be quite unappropriate. For (L/λ) intermediate between 5 and 20 the fit to a 'Rayleigh' curve was sometimes reasonably good but sometimes very bad. Much effort was devoted to attempts to find any kind of empirical relationship which could be applied when (L/λ) was small. The conclusion eventually reached was that there simply was not sufficient constancy of statistical parameters to enable this to be done. A theoretical discussion of the problem will be given in the next Section but the matter can be put briefly as follows. When (L/λ) is large the sonar echo fluctuates rapidly as the fish moves about so that 1000 successive pings in 10 minutes provided a large enough ensemble of samples to enable statistically stable results to be obtained. For small values of (L/λ) however there are fewer maxima and minima in the directional scattering pattern of the fish and less likelihood that even as many as 1000 samples over 10 minutes will be enough to 'randomize' the result. In other words, the smaller the value of (L/λ) the more the observed result is likely to depend on the exact <u>behaviour</u> of the specimen fish in the cage. It might be mentioned, in passing, that the value of (L/λ) for the specimens in the 'multiple-fish' experiments varied from about 2.0 to 20. The evidence of the results seems to suggest that the echoes were however all satisfactorily 'randomized'. This is not incompatible with the above argument because it is very likely that the fish swam about more vigorously when in a group than they would have done as individuals.

Theoretical consideration of echo fluctuations

The way in which the strength of sonar echoes from fish varies from ping to ping is obviously of fundamental importance in any survey work on fish populations. It will therefore be appropriate to include here some theoretical considerations, from an acoustics point of view, concerning the nature of the echo fluctuations. It is suggested that the reader should discard any preconceived notions about the echoes from real fish and should consider instead certain principles which must apply to <u>any</u> target object, no matter what its shape and constitution. In the first instance we shall simplify the problem by assuming that the object, although it may change its orientation with time, does at least retain the same configuration while this is happening. The special case of live fish, where the target is also able to deform its own shape, can then be discussed as a separate problem.

Imagine that the orientation of the object is varied, by some external means, and that the pressure amplitude of the echo from it is measured, as a function of the direction of some convenient reference axis associated with the object. The result, for any particular plane of rotation, can be plotted either as a polar diagram (see fig. 3a) or as a linear curve (see fig.3b). The complete polar diagram of the object, for all possible planes of rotation, is three-dimensional and can be visualized roughly as a ball with 'spikes' or 'lumps' projecting in various directions. Fig. 4 illustrates a useful trick to help in producing a mental picture of what happens to the echo strength as the target rotates. Instead of the conventional plot in which a moving point traces out a fixed polar curve, imagine that the complete curve has been drawn and is now made to rotate so that the magnitude appears as an intercept on the fixed OX-axis. The advantage of this method of representation lies in the fact that the axis of the complete three-dimensional pattern can be thought of as being linked to that of the object itself; as the object rotates, in any plane, the polar echo-strength pattern rotates with it and the strength at any instant is always represented by the intercept of the pattern on the OX-axis. Looked at in this way it is easy to see just how the echo strength is 'modulated' by rotation of the target object. At first sight it might seem to be a hopeless task to draw any meaningful conclusions from this because it begins to look as if there might be practically an infinite number of different results for different planes of rotation. But there is in fact one important basic parameter which is common to all of them; that is the minimum angular spacing of any two successive lobes of any of the patterns for a given object. There is no need to be too precise here in defining terms; the essential idea to grasp is that a fundamental property of such patterns has something to do with the 'closeness' of the lobes, and hence with the rate at which successive maxima and minima of the object occur as it rotates. Note that this statement refers to the minimum spacing that ever <u>can</u> occur between two successive lobes of the pattern; it does not imply that there will necessarily be lobes in all possible positions in any particular case. A suitable term to describe this might be 'maximum angular frequency' of the lobes of the pattern.

Think for a moment about the acoustic field conditions at the interface surface between the object and the water. Because the object has been introduced into the water the field will not be the same as it would have been without it. One way of expressing that fairly obvious fact would be to say that something has been added (in the general algebraic sense) to the original acoustic field. This added component is called the perturbation field of the object. It has the general form of waves radiating outwards from the target object. The latter appears to be extracting a flow of energy from the passing incident waves and to be re-radiating the energy in the form of the perturbation field. The proportion of this which happens to be directed back towards the source of the incident waves contributes to the observed sonar echo. Now, because the re-radiated field has emerged through the surface of the object the latter can be regarded as the 'aperture' of an 'array' of virtual sources situated at the surface itself. The significance of this is seen when it is remembered that there is a basic rule connecting 'beamwidths' of directional patterns with sizes of 'apertures', measured in wavelengths. It will not be surprising to find that there is some kind of tie-up between the size of an object in wavelengths and the 'maximum angular frequency' of its echo pattern. Put even more simply; the more wavelengths there are in the target the more lobes there are likely to be on its echo pattern. It is this simple truth which lies behind much of the cumbersome mathematics which has to be brought into this subject as soon as any attempt is made to obtain exact formulations of the ideas stated. But is quite possible to look at the patterns shown in figs. 5a and 5b and to say, with confidence, that (b) must have come from an object which is larger, in wavelengths, than that relating to (a). Note that it is the size of the object in acoustic wavelengths which counts, not its absolute size. A very interesting corollary to the above argument is that the echo behaviour of any object can always be referred to the conditions at its surface, no matter whether it contains real discrete scatterers inside it or not. Unless the distant sonar observer has some a priori knowledge about the target object he cannot tell whether the observed behaviour is caused by surface effects or discrete scatterers, or any combination of these. (All this assumes that the effective sonar pulse length is greater than the largest dimension of the target). It can be shown mathematically that (a) any physical set of scatterers can always be represented by a set of virtual point sources distributed over the interface surface, and (b) the total number of independent virtual sources can be closely estimated by the following procedure, (see Fig.6). Draw an imaginary grid of lines on the surface of the object, crossing each other at right-angles and spaced, as nearly as possible, at a distance of one half-wavelength apart. The maximum number of independent sources is then given by the number of intersections of the network of lines. Put another way, no matter how many physical scatterers there really are inside the object, their effect can always be represented by the number of independent samples given by the above rule. This is obviously a very rough-and-ready rule but it leads to conclusions which are surprisingly close to those obtained by exact and tedious mathematical analysis, in the few cases where the shape of the object is sufficiently close to some canonical geometrical form to make exact analysis possible.

Probability distribution of echo amplitude

If the target object happened to rotate continuously and uniformly the result would be a periodic modulation of the sonar echo and it would be an easy matter to determine the mean and r.m.s. values of the echo fluctuations. We are only discussing hypothetical targets here but there are important implications when real fish are considered. It will be realized for example that if the pattern happened to have pronounced lobes in certain directions but if the orientation behaviour of the target were quite unknown then it would be impossible to make accurate predictions about the probable target strength, whether expressed as a mean-amplitude or a mean-power or, indeed, in any way at all.

Target with time-varying shape

So far we have deliberately considered only objects which change their orientation but retain their shape. But live fish are not like this so the next step must be to imagine that the reference axis of the object is held stationary but that the shape of its surface, and possibly its internal structure as well, can vary with time. It has already been explained that anything happening acoustically inside the object can always be referred to its surface. So all we have to do is to go back to fig. 6 and to imagine that both the shape of the surface and the magnitudes of the virtual sources distributed over that surface are time-varying. A live fish is thus able to impress on the echo amplitude another kind of modulation; one which is a function of its body movement, as distinct from the average orientation of its axis. A significant thing about this modulation is that the rate at which it occurs is not necessarily linked to the size of the fish in wavelengths. As an extreme example to illustrate this point suppose that the fish remained generally stationary, as far as orientation was concerned, but rapidly changed the acoustic properties of, say, its swim-bladder.

Change of acoustic frequency

Finally, note that the 'size' of a target in wavelengths can be changed simply by changing the acoustic frequency. This changes the number and spacing of the lobes of the echo pattern. Theoretically therefore, even if the target remained absolutely static, changing the frequency causes the echo amplitude to fluctuate. Furthermore, the rate of fluctuation of echo amplitude, expressed as a function of frequency, contains information about the size of the object. For the present purpose it will suffice to draw attention to this possibility. There are obvious implications relating to the future use of wide-band frequency-scanning sonars.

Reference

1. G.C.Goddard and V.G.Welsby: "Statistical measurements of the acoustic target strength of live fish". University of Birmingham, Department of Electronic and Electrical Engineering Memorandum No.456, Jan.1975. (In course of publication in "Journal du Conseil").

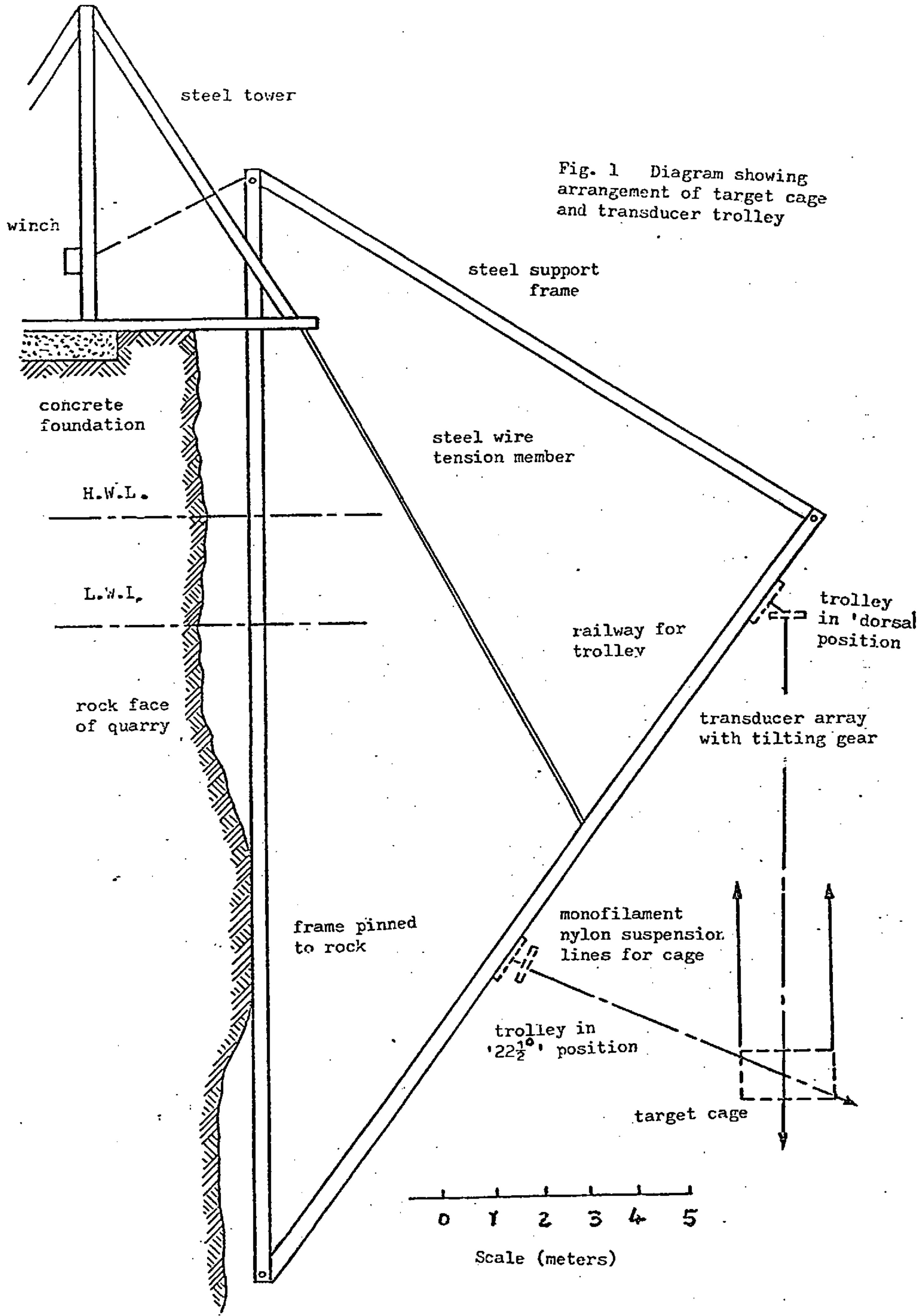

Fig. 1 Diagram showing arrangement of target cage and transducer trolley

1.0

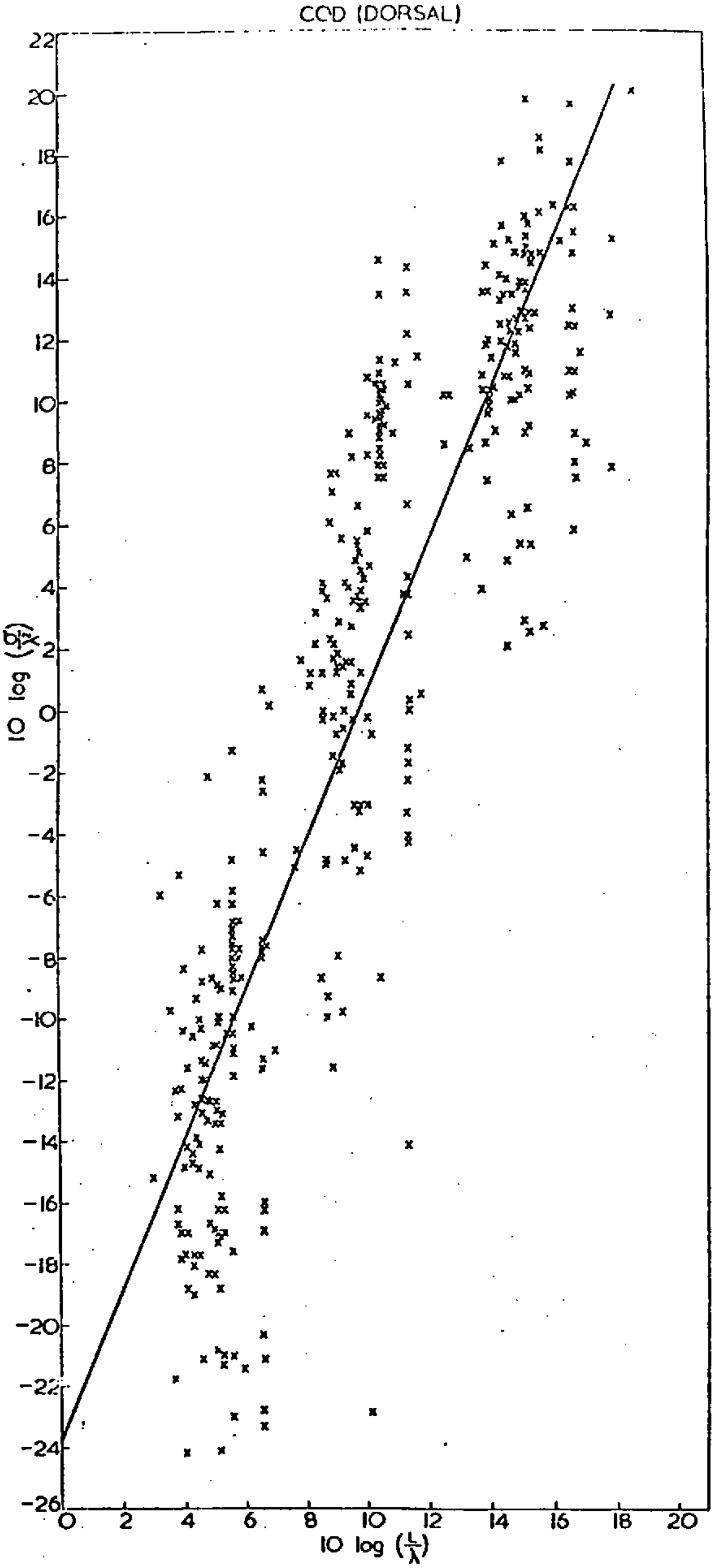

Fig. 2 Example of scatter diagram of measured target strength results

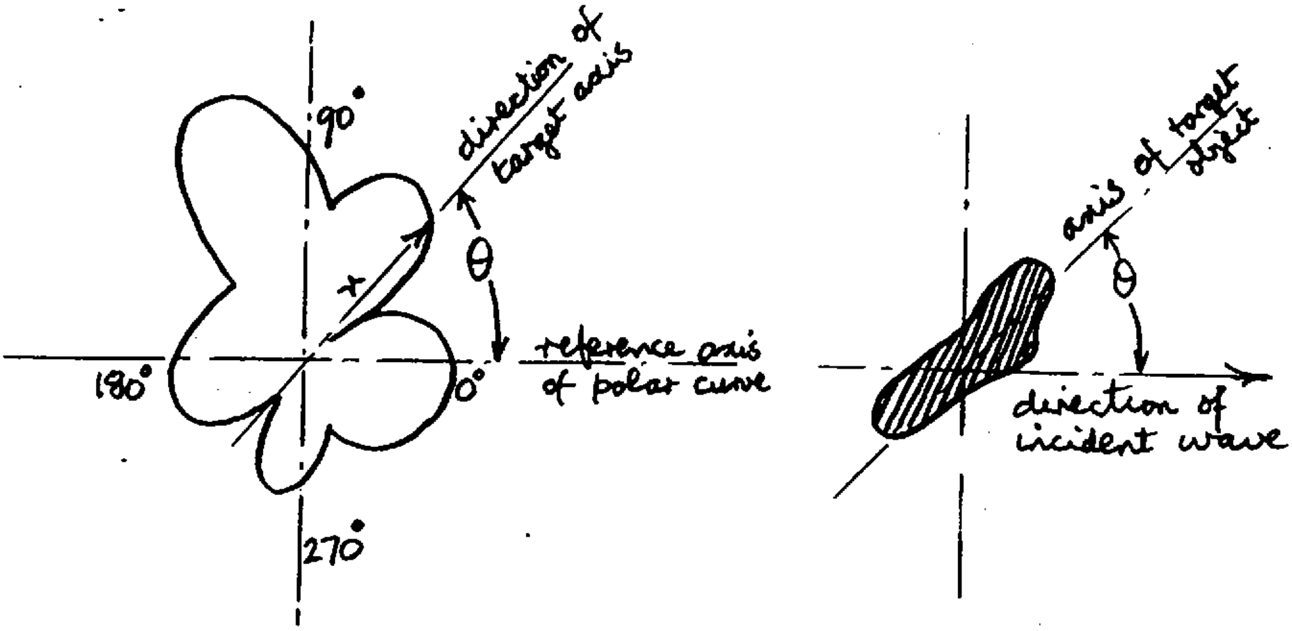

Fig 3a. Polar diagram obtained by plotting the echo pressure in the back-scatter direction as a function of the angle of rotation of the target.

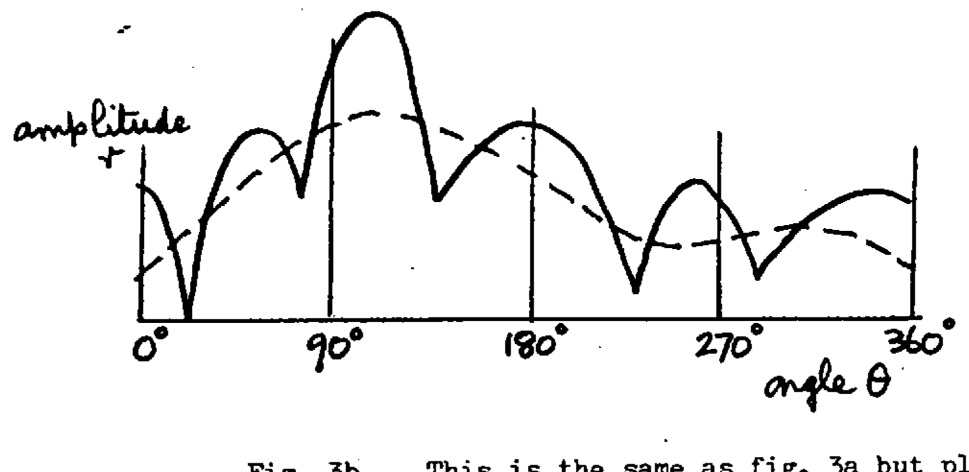

Fig. 3b This is the same as fig. 3a but plotted on a linear scale of angles. The dotted line indicates how the mean value of the fluctuating amplitude may vary.

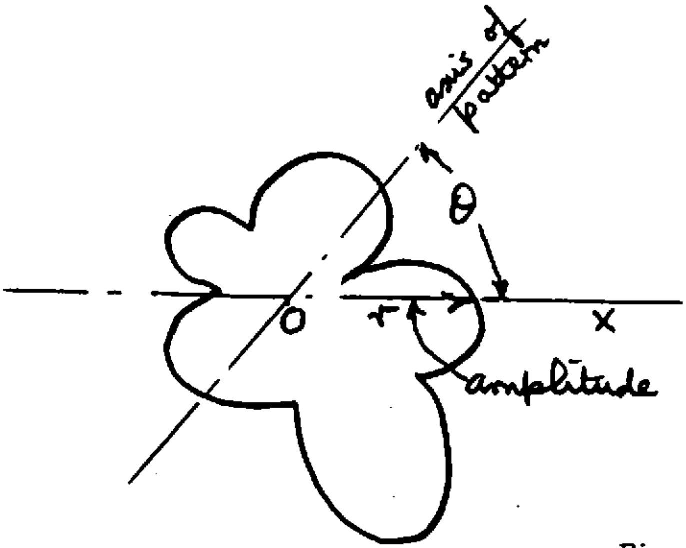

Fig. 4

Polar curve of fig. 3a, replotted so that amplitude r appears as intercept on OX-axis when the reference axis of the pattern is aligned with that of the target.

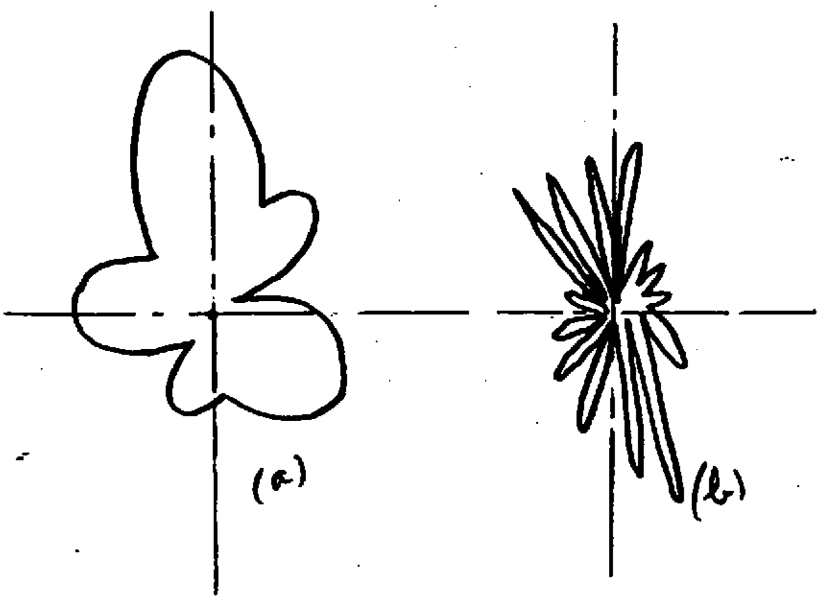

Fig. 5

Sketches to illustrate patterns with low (a) and high (b) 'angular frequencies'.

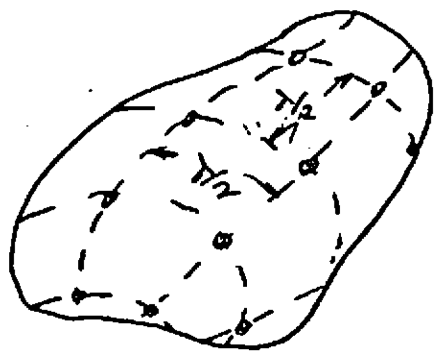

Fig. 6 Sketch to illustrate method of estimating number of independent virtual sources.

TABLE 1

COD	Dorsal $22\frac{1}{2}^{\circ}$	$T = 24.5 \log L - 4.5 \log \lambda - 34.7$ dB $T = 21.0 \log L - 1.0 \log \lambda - 34.9$ dB
HADDOCK	Dorsal $22\frac{1}{2}^{\circ}$	$T = 22.5 \log L - 2.5 \log \lambda - 34.2$ dB $T = 19.5 \log L + 0.5 \log \lambda - 36.0$ dB
SAITHE	Dorsal $22\frac{1}{2}^{\circ}$	$T = 25.1 \log L - 5.1 \log \lambda - 37.0$ dB $T = 17.7 \log L + 2.3 \log \lambda - 31.6$ dB
DOGFISH	Dorsal $22\frac{1}{2}^{\circ}$	$T = 22.5 \log L - 2.5 \log \lambda - 48.4$ dB $T = 19.4 \log L + 0.6 \log \lambda - 47.0$ dB

σ is the scattering cross-section of the fish in m^2

T Target strength, in dB relative to 2 metre radius sphere

$$T = 10 \log \sigma / 4\pi$$

L Overall length of fish (metres)

λ Wavelength (metres)

DISCUSSION FOLLOWING THE PAPER BY DR.V.G.WELSBY :

The acoustic target strength of live fish, results of the 'EASDALE' project and some theoretical considerations.

MR.R.E.CRAIG: Table 1 of Mr.Forbes' summary represents in effect half the results from Easdale and the second half was, in fact, a conclusion that the variability of echoes in a ping-to-ping sense from a single fish was approximately a Rayleigh distribution.

DR.WELSBY: When the fish length was greater than 20 the distribution was closely Rayleigh. When it was less than 5 it was definitely not Rayleigh. If the fish was between these limits the approximation to a Rayleigh distribution was sometimes good and sometimes bad. If there are a large number of lobes on the pattern and the fish is swimming around fast enough and randomly and you take 1000 pings, this is enough to give a statistically stable result; to randomise the result to the right extent, then a Rayleigh distribution will appear. When the fish is small and there are only a few lobes on the pattern and the fish is not swimming around quickly then 1000 pings might not be enough. You can only get a Rayleigh distribution if there is a pattern which is swinging to and fro between something and nothing.

DR.R.W.G.HASLETT: You set out to do statistical probabilities and have shown the results achieved. Although there were lots of variations and the results may be to some extent subjective, nevertheless the experiments set out to use frequencies, pulse lengths and directions which were realistic as seen from fishing vessels. There is a large mass of results which can be analysed in different ways which have close analogy to the real environment. Do you suggest that the results are not good ?

DR.WELSBY: No, but the difficulties have to be mentioned. The results are presented in the form of a diagram showing $10 \log \frac{\sigma}{\lambda^2}$ normalised against L/λ. A further analysis on the results has been carried out by Mr.Forbes and you will hear about these later.

DR.HASLETT: If you are going to analyse the back scattering polar diagrams then you need not necessarily use a statistical approach but take a single fish under carefully controlled conditions - not even moving.

DR.WELSBY: If you are on a ship looking at an unknown situation the polar diagram will be of no use. All that can be done is to take statistical measurements and even when you have the average figure and go to apply it in real life you do not know what the fish is doing down there and the echo that comes back depends on which way it is turning.

DR.McCARTNEY: I would like to make a plea for publication of the report of the Easdale results.*

* This was later arranged to be in the Journal du Conseil pour l'Exploration de la Mer.