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The Counting of Fish with an Echo Sounder

by

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I. Introduction

Echo survey (Cushing, 1952) is a method of estimating the abundance of fish traces based on the presence or absence of fish within a given transmission. Abundance is estimated as the number of presences recorded per unit of distance steamed. Richardson et al. (1959) showed that abundance of cod in the Barents Sea could be well estimated from the sums of signals (as amplitudes) from single and multiple fish targets per unit distance steamed. Mitson and Wood (1961) have shown that an automatic counting equipment can achieve the same result. This paper is concerned with the possibility of counting fish within a size range and within the depth range covered by a particular gear. Within these limits absence of signal will mean absence of fish.

We will consider firstly the target strengths of fish of different sizes. Secondly, we will consider how to count single fish within a size range and depth range with the use of an ordinary wide beamed echo sounder. Lastly, the limits of such a system with an ordinary wide beamed echo sounder will be contrasted with the virtues of doing the same thing with a sector scanner (Tucker et al., 1958).

II. Measurements of target strength

The target strength of a single fish is measured in decibels with reference to a sphere of 2 m radius (for which the target strength is calculable), at a range of 1 m.

$$T = 10 \log_{10} \frac{I_r}{I_o} r^2$$

where I_o is the incident energy on the target;
" I_r is the reflected energy from the target;
" r is the range in m;

or $$T = 20 \log_{10} \frac{V_r}{V_o} r,$$

where V_o and V_r are the voltages in the instruments corresponding to I_o and I_r, respectively (UCDWR, "The Physics of sound in the sea").

Figure 1 shows the measurements in target strength of individual fish of different lengths, the latter being on a log scale (Cushing, Harden Jones, Mitson, Ellis and Pearce, 1963). The measurements were made at 3o kc/s on dead cod, herring, plaice and perch. In three out of four series of experiments, false Onazote air bladders were placed in the body of the fish to simulate the acoustic properties of the normal swim bladder (Jones & Pearce, 1958). The line drawn to the data is Haslett's (1962) empirical curve, derived from a large series of measurements on scaled down models. The best observations are those marked with a circle. The high variance in the measurements on cod can be attributed to three sources of experimental error (a) the difficulty of suspending the fish in the right and steady attitude, (b) slight differences in aspect between targets, (c) measurements being made in the middle zone of frequency (8-100 L/λ, L being the length of the fish in cm and λ being the wavelength of sound used, in cm). In the experiments on perch, aspect was shown not to generate error, the fish were rigidly suspended and the measurements were not made in the middle zone. Yet the measurements are variable. They were made in an "acoustic hole" in a tank 6 m x 3 m x 3 m; it is possible that the fish of different sizes generated differences in reverberation in the "acoustic hole".

Figure 2 is based on the measurements on cod made by Midttun and Hoft (1962). The measurements on perch are shown on the figure, as are the four best measurements from Figure 1. It is immediately obvious that the error in the Norwegian experiments is considerably less than that shown in Figure 1. The main difference between the two series is that the Norwegian fish were rotated about their lateral horizontal axes whereas the British fish were not so rotated. The maximum signal found by rotation takes into account small differences in aspect. So the British measurements may include a component of variance that will be found in any series of measurements on wild targets, but the Norwegian measurements are the more reliable for deriving the relationship between target strength and fish size. Another difference between the two sets of experiments is that the Norwegian fish were acclimatized to lo m, killed and then returned to that depth, whereas the British fish were long dead and stuffed with Onazote air bladders. It is possible that some artificial components of variance were included in the British series from this procedure.

Both series of measurements show a tendency for the larger fish (> 5o cm) to yield relatively lower target strengths for their size than the smaller fish. This is probably because these measurements on larger fish were made in the middle zone of frequency. When the target is small compared with the wavelength, it varies inversely by the fourth power of wavelength; when it is large, it varies inversely by the square; in the middle zone, when the target is of about the same dimension as the wavelength, signals are highly variable. From Haslett's work (1962) on scaled down models, we provisionally define the middle zone as 8-100 L/λ ; at 3o kc/s it ranges from about 40 cm to 500 cm. In the middle zone, a series of maxima and minima would be expected with increasing size of fish. Using both series of measurements (Figures 1 and 2), we might expect such a minimum between 70 and 100 cm.

It may be concluded from the two sets of measurements that there is a clear relationship between the size of fish and its target strength. To make true estimates of the error of a single observation, considerably more work is needed. This does not prevent us from finding how far the relation can be exploited. The rest of this paper is concerned with an examination of this problem.

III. The estimation of the sizes of a single target

The beam angle of a transducer is expressed as an angle θ from the axis at an angle ϕ in azimuth from a reference direction. Let us suppose that the transducer is symmetrical in ϕ. At a range r from the transducer, but at angle θ from the axis, the signal from a fish on the axis V_r is reduced by a directivity coefficient δ .

There is a low limit in signal, MRS, the minimum recordable signal, which is set conventionally at three times the noise level. Let the maximum range at which the MRS can be recorded on the axis, necessarily, be r_T. At any lesser range, the signal received from a single target is greater than or equal to the MRS out to an extreme angle, θ_T. Given r_T, θ_T can be calculated for different ranges from

$$\frac{MRS}{V_r \cdot \delta} = \frac{\sin\left(\frac{2\pi a}{\lambda} \cdot \sin\theta\right)}{\frac{2\pi a}{\lambda} \cdot \sin\theta}$$

where a is the width of the transducer in cm,

" λ is the wavelength of sound in cm.

At low ranges, θ_T corresponds to the first minimum in the directivity pattern, ignoring side lobes, but at middle and at long ranges, θ_T decreases until finally at maximum range it is zero. Such a curve of θ_T with range is calculable for each size of target.

In any one transmission, the volume sampled in a range slice is given by

$$\frac{2}{3}(r_2^3 - r_1^3)\ (1 - \cos\theta_T),$$

where $r_2 - r_1$ is any range difference greater than one pulse length, where θ_T is the limiting angle at which $V_r \cdot \delta$ falls below MRS.

The volume sampled is a spherical section of the surface skin of a sphere, $r_2 - r_1$ being the thickness of the skin in m. In many commercial transducers, the volume examined is not a sphere, but is more like an ellipsoid because θ changes in the azimuthal angle ϕ.

With a wide beamed echo sounder, the position of a target in the volume sampled is unknown. But the most probable position of the target is on the circumference of the spherical slice described by the solid angle θ_T. Yet the probability of detection decreases from θ_o to θ_T as a function of δ. The two probabilities may be combined. For example, with a transducer with the first minimum at 3o°, the most probable angle of detection, θ_m, is 15.9°, with a standard deviation of 5.9°. So, at sea the average values of echo signal, V_r, will be reduced to 40% (with a standard deviation of + 32.5%, - 24.0%); this value is $V_r \cdot \delta_m$.

For a simple transducer, the shape of curve of the directivity coefficient is the same however narrow the beam. So from the point of view of estimating the size of fish from the echo signal, $V_r \cdot \delta_m$, the narrow beam is of no advantage. The sampling volume is sharply reduced as the beam is narrowed and for counting, this is a disadvantage. At 100 m range, the volumes sampled by different beam angles are:-

1°	2°	5°	10°	15°	30°	
9.8	19.5	78.0	293.0	674.0	2618.0	m^3

Figure 3 shows the volumes sampled in ranges for fish of different sizes (x 2 in length, 2o db in target strength). For a single target, θ_m decreases with range, very slightly at short ranges and then rapidly with increasing range. At a long range where θ_m is small, θ_m is dependent on size. Therefore the size of a single target cannot be specified precisely. At a short range, where θ_T is at the first minimum, θ_m is nearly constant with range, so θ_m is independent of size. Consequently, the size of a single target can be specified fairly well. The variation of θ_m with range is shown in Table 1, expressed as the percentage decrease in $V_r \cdot \delta_m$ with range for a target with a maximum axial range of 300 m.

Table 1. Downward bias in $V_r \cdot \delta_m$ at different ranges due to the changes in θ_m with range (r_T = 300 m).

Range (m)	θ_m	Sampled volume (m^3)	% decrease (in θ_m)	% decrease weighted by sampling volume
0	15.99°	0	0.0	
50	15.88°	71.7	0.6%	3.0%
100	14.85°	293.0	6.0%	3.0%
150	13.15°	630.0	15.0%	11.2%
200	11.10°		29.4%	
250	7.95°	984.0	51.3%	
300	0.0 °	0.0	100.0%	

From this table, we may accept conventionally a decrease in $V_r \cdot \delta_m$ of 3.0%. Hence we must use 1/3 of the maximum axial range of the smallest target. For some purposes, we might accept a decrease of 11.2% in $V_r \cdot \delta_m$, which would mean using ½ of the maximum axial range of the smallest target. To obtain a size range of x 2 in length (or 20 db in target strength), the range of the biggest target would be over 3 times that of the smallest. Hence we would be restricted to using 1/6 to 1/9 of the sampling volume available. Hence to achieve the required size distribution in the top 100 m of the ocean, the echo sounder has to be powerful enough to pick up a single fish of the largest size at 600 m or 900 m.

The large volume in which the size of the single target cannot be determined is really an effect of the directivity coefficient δ, shown as function of θ in Figure 4. If this curve was rectangular with a flat top out to about 2o° and a sharp and final cut off, the change in θ_m with range would take place effectively at much greater ranges (see Table 1). Then the curves in Figure 3 would be much more pear-shaped. Such a beam is difficult to make, but a linear array approaches it; unfortunately, as the number of elements increase, the signal-to-noise ratio increases sharply (personal communication, Dr. V. G. Welsby). So by altering the beam pattern, we might improve the sampling volume from ½ of the maximum axial range of the smallest target to perhaps 2/3.

However, it is possible to use the whole envelope of the sampling volume for the smallest target. This is done with a sector scanner (Tucker et al., 1968). A wide beam is transmitted from a single element of the transducer and the echo from a target is received from an array of many elements. Between elements there are phase differences which are resolved so that the bearing of the target is found. A typical presentation is given in Figure 5, of bearing on range for a single transmission of the sector scanner.

Because the position of the target in the beam is known in each transmission, the directivity coefficient for the given bearing is known and so the target can be sized directly. Moreover, as it crosses the beam, independent estimates of size can be made continuously. With the simple beam described above, δ_m would be derived from the mean of a number of observations, which is not so satisfactory. The most important thing, however, is that the limit set out in Table 1 for the simple beam no longer applies. Sampling in any one bearing can continue in range until the signal, by convention, is three times the noise level. So the volume sampled is then only a function of the degree of size discrimination required - for a difference of ten times in target strength we require a range difference of ten times in the maximum axial range between the smallest and largest targets. If we wish to examine the top 100m of the ocean, with a target discrimination of x 10, the range of the largest target would be 300m. Another advantage of the sector scanner is found when the ship rolls. With the simple beam, θ_m is increased when the ship rolls because it must be derived from observations taken in successive transmissions. With the sector scanner, resolving in range as well as in bearing, the rolling of the ship makes no difference unless the aspect of the target in the water becomes important. Measurements of the aspect of perch (Jones & Pearce, 1958) suggest that within 20° of the vertical, aspect is of little importance; but some model experiments (Cushing 1955, Haslett 1962) suggest that the aspect of the target might become an important source of error.

Combining the evidence from Figures 1 and 2 with the scope of the sector scanner, it appears that within the limits imposed by noise, single targets can be sized adequately up to the maximum range of the largest target. If the directivity coefficient were built into the scanner's computer alongside a time-varied gain, the scanner would present the results in the quantities given in Figures 1 and 2.

IV. The estimation of the sizes of individuals and their number in multiple targets

At a given range, ${}_nV_r \propto \sqrt{n}$, where n is the number of fish in a multiple target and ${}_nV_r$ is the voltage received in a single transmission from the multiple target composed of fish of a given size. The main difficulty here is that the multiple target may be composed of many small fish or of few large fish. The simplest way of resolving this difficulty is to split the multiple targets into single targets. The commonest multiple target is the well-known hyperbolic, comet or crescent shaped trace, which is smaller than the conic section of the sound beam. The sound beam can be split up in two ways, firstly in sectors of the angle as in the sector scanner, and secondly in range in units of pulse length. The pulse length of commercial echo sounders is about ½ ms; with higher frequency machines it is possible to reduce the pulse length to 50 μs (at 100 kc/s). This corresponds to a range slice of 7.5 cm and so there is a good chance that fish greater than lo cm are recorded as single targets with such equipment. So the ideal counting equipment is one with high angular resolution and a very short pulse length. Angular resolution depends on the number of sectors in the array of the transducer. Pulse length tends to be shorter at higher frequencies. Hence a sector scanner at 100 kc/s (or higher in frequency) with many sectors and a very short pulse length would have the best chance of splitting multiple targets into single targets.

At high frequencies (100 kc/s or more), attenuation of the propagated sound becomes important (50 db/kiloyard at 100 kc/s and 100 db/kiloyard at 500 kc/s). This sets a limit in range to the use of high frequency equipment; it may be that 100 m is somewhere near the limit in useful range. It is/fortunate accident that in the sea smaller animals live near the surface and bigger animals live deeper. Coupled with this is the fact that it is the smaller animals that live in shoals and the bigger animals that live singly. So the best counting equipment would consist of a number of transducers in descending order of frequency, increasing order of pulse length and increasing order of range capacity. One might arrange them like this:-

Range slice	Frequency	Pulse length	Number of sectors
0-50 m	500 kc/s	0.01 ms	5o
50-100 m	100 kc/s	0.05 ms	20
100-300 m	30 kc/s	0.5 ms	5

It is not known whether this is a practical arrangement in detail, or whether another set of frequencies might not achieve the same result. But the three transducers would be of about the same dimensions - perhaps three feet long. The three transducers could work off the same electronic system with the use of a frequency changer. And it would be possible to resolve fish no bigger than sprats in the top 50 m and at the same time the system could cope with fish of the size of cod from 100-300 m.

In order to keep the transducers of a reasonable size the number of sectors has been reduced with reducing frequency. Using Figure 3, it can be seen that volume sampled down to 300 m increases considerably with range. So high angular resolution has been discarded when a large sampling volume has been obtained. Again this is lucky because many observations will be taken in each sector, giving good estimates of $V_r \cdot \delta_s$ (where δ_s is the directivity coefficient appropriate to a given sector.. If multiple targets are characteristic of shallow water, the same quality of information can be obtained simultaneously from the different sectors or range segments. Each is corrected by the appropriate directivity coefficient and range factor. So good estimates of V_r are found from multiple targets in shallow water by simultaneous observation in small sampling volumes, the shoal being split down to single targets; good estimates of V_r are made in deeper water by collecting observations in a time series in one sector from a large volume, the targets probably being single fish in any case.

It is possible that one might consider the use of an ordinary wide beamed sounder within one third or one half of the maximal range of the smallest target. Here the multiple targets might be split with a narrow beam. But there is an added ambiguity in that θ_T may increase with numbers even in the restricted range. If this is so, there is some confusion between target strength and abundance. This confusion is an added reason for using a sector scanner, in which such confusion does not arise.

In summary, it is likely that multiple targets can be split into single targets with the high angular resolution of the sector scanner combined with the very short pulse lengths associated with high frequencies. A multiple target that is not split in the resolution of theequipment, because the fish are smaller than the range of sizes desired, could be readily rejected. Hence, within a specified size range, not only single targets, but also multiple targets, can be sized and counted.

V. The use of fish counting with an echo sounder

Cushing (in Richardson et al., 1959), Mitson and Wood (1961) and Burd (mimeogr.paper to this meeting) have described clear relationships between catch per effort and signal strength. In this work, the catches were primarily taken to identify the fish. Because fish of the same size can be of different species, catches must be made frequently enough to establish identity. For example, within the narrow range slice of 7 fathoms sampled by the East Anglian drift nets, a complete count within a specified size range could be made; but sampling with drift nets will remain necessary to maintain identification. The purpose of the echo counting is to provide great quantities of information and further to provide an independent estimate of abundance. Given identification, such an estimate of numbers, prudently limited, provides a basis for analysing the catch per effort as index of abundance.

When catch per effort is a true index of abundance, echo counting could serve to give research vessel sampling some of the power of the sampling by a commercial fleet. When catch per effort is biassed by an effect of availability, echo counting is useful so long as fish are being caught, providing evidence of identification. For example, the East Anglian drift nets are selective. So long as herring are caught, an echo counting device could provide a true estimate of numbers when the drift net would give an underestimate. But if some herring are too big or too small to be caught at all by the drift nets, an identification cannot be made. Hence the echo counter can only be used to investigate availability, when the fish can be caught.

Another use of an echo counter is to provide an estimate of sizes and numbers in the top 300 m of the ocean. Here no identification is necessarily attempted, for perhaps many species live together. Given the analysis by size and numbers, the use of non-selective gears may be used after the survey is over. This is perhaps the best method of using the echo counter in oceanic exploration.

Summarizing, there are three main uses for the echo counter:-

(1) to support research vessel sampling;

(2) to analyze some of the simpler forms of availability;

(3) to provide a rapid form of oceanic exploration.

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TARGET STRENGTH VS. FISH LENGTH

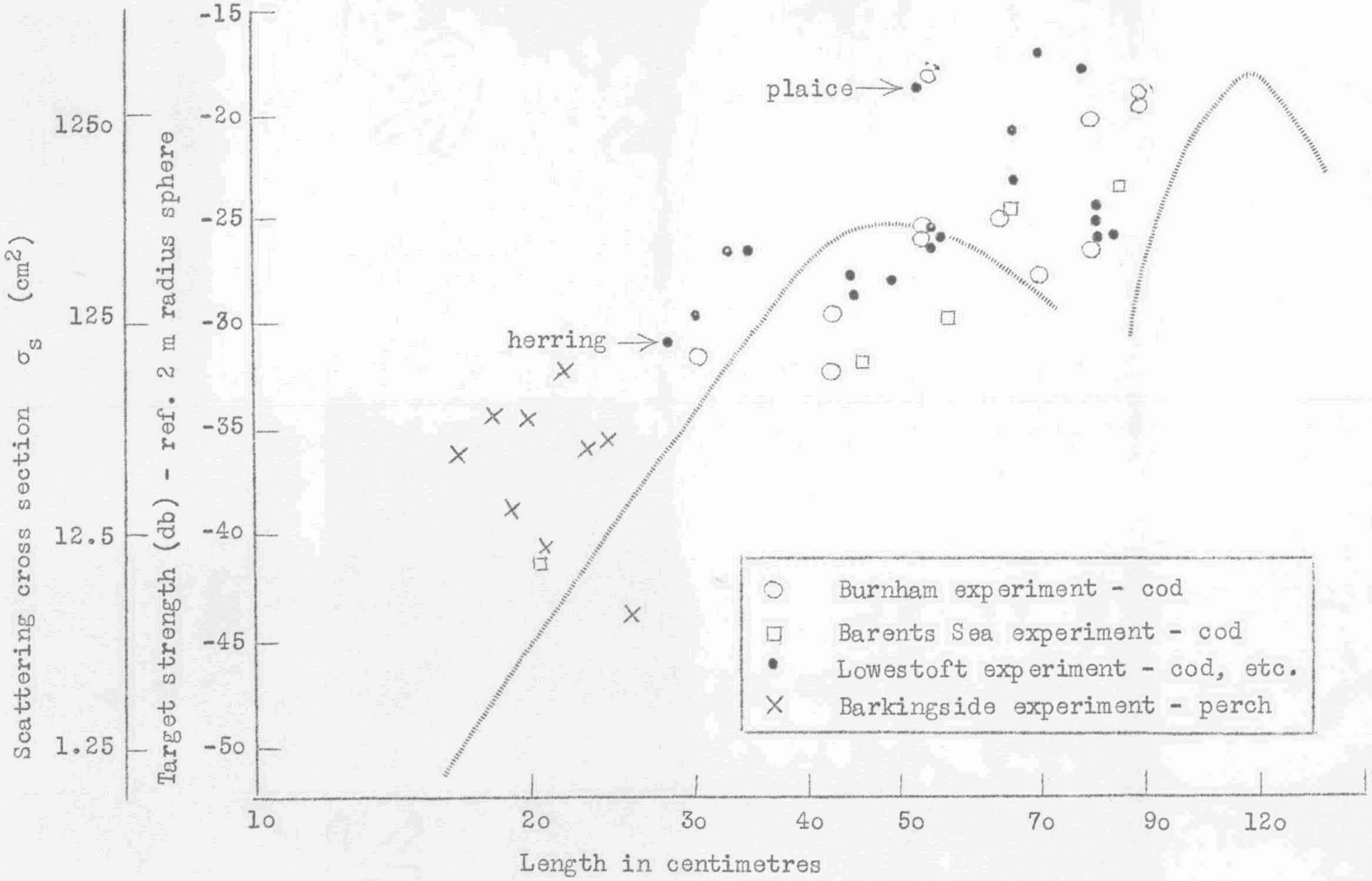

Figure 1. Target strengths of fish. The circled points represent the best observations. The fish were suspended at more than 10 m from the transducer; the mean of a large number of maximal signals was used as the measure of target strength.

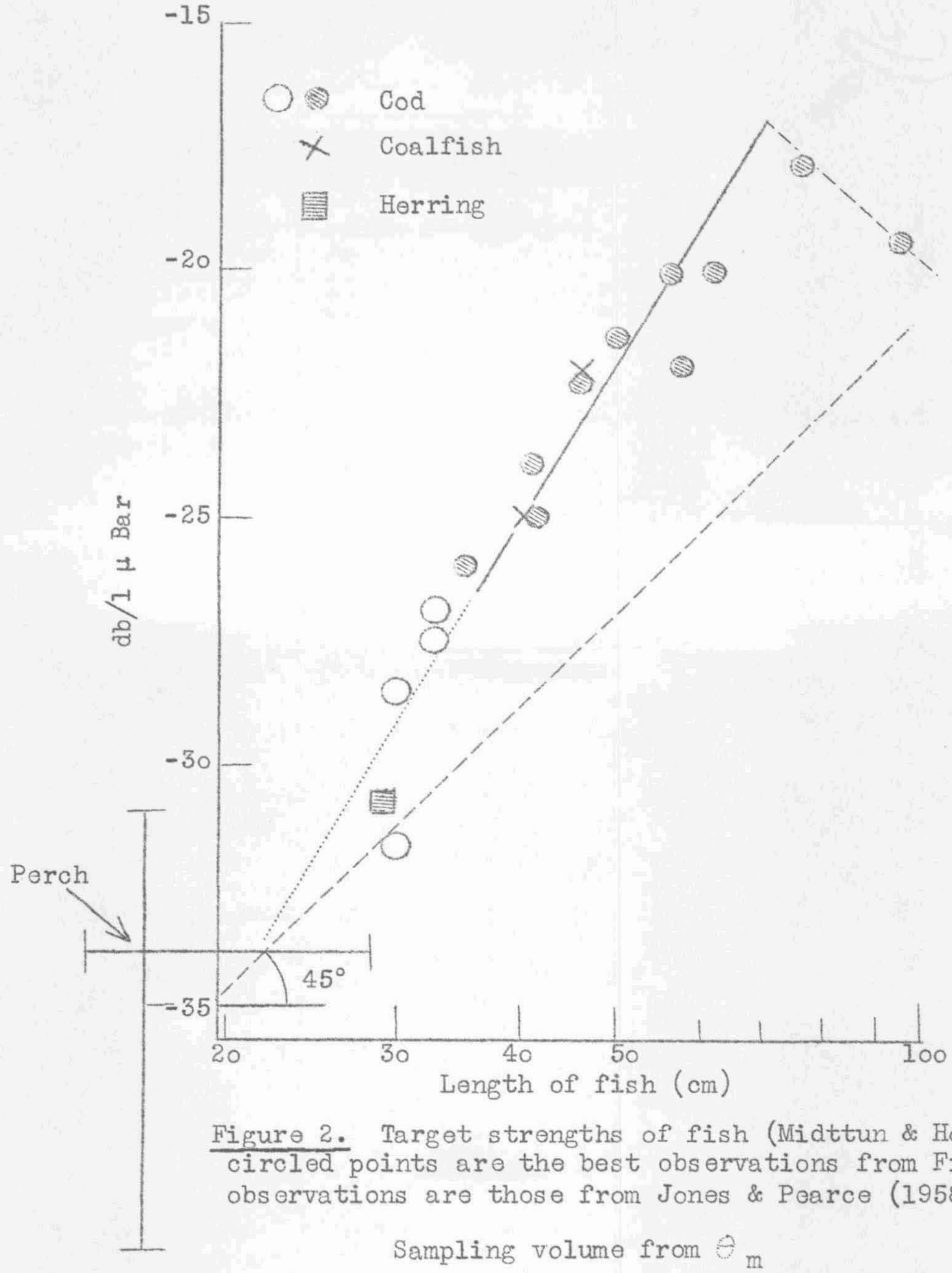

Figure 2. Target strengths of fish (Midttun & Hoft,1962). The circled points are the best observations from Figure 1; the perch observations are those from Jones & Pearce (1958).

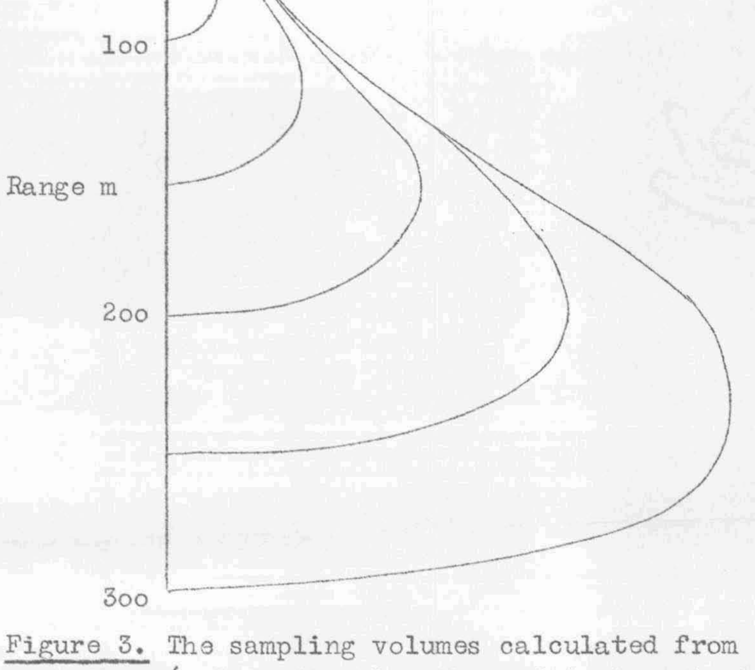

Figure 3. The sampling volumes calculated from θ_m for a range (x 2 in fish length, x 9 in target strength) of fish sizes.

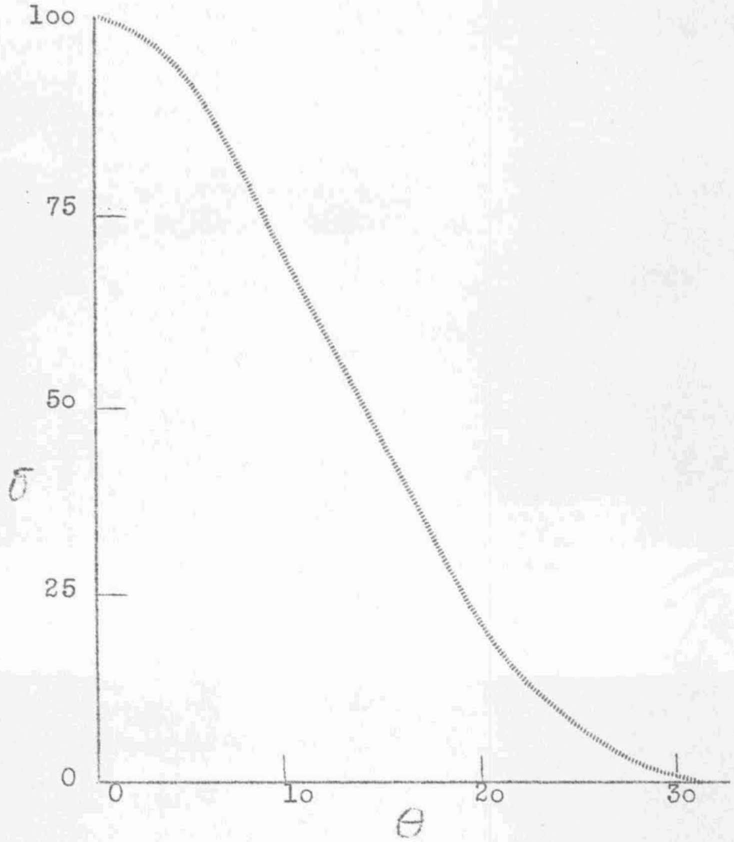

Figure 4. The directivity pattern of a simple transducer (9 x 14½ cm at 3o kgs).

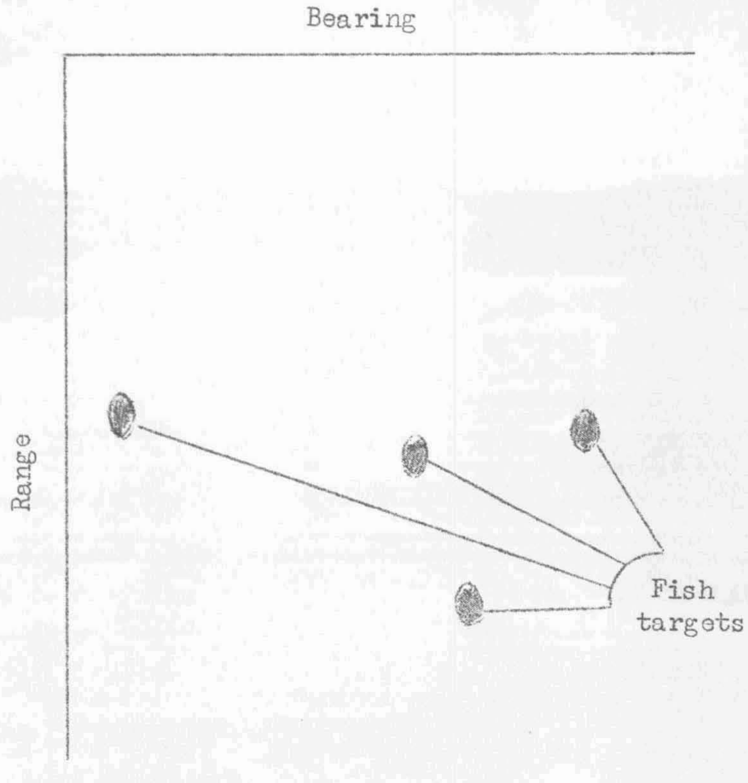

Figure 5. The presentation of target position in a single transmission from a sector scanner.