THE ACOUSTIC TARGET STRENGTHS OF MARINE ORGANISMS.

J.D.Penrose and N.G.Sofoulis, Physics Department, Western Australian
Institute of Technology, South Bentley, Western Australia 6102.

G.T.Kaye, Marine Physical Laboratory,
Scripps Institution of Oceanography,
University of California, San Diego.
San Diego, California 92152.

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INTRODUCTION

The work described in this paper forms part of a program of research in marine acoustics which has been undertaken at the Physics Department of the Western Australian Institute of Technology over the past five years. The major field of activity has been a study of the role of echo sounding in the Australian prawning industry. This has resulted in the development of a modified sounder installation for use in one of the major Australian fisheries. Part of the program has recently been described in the industry journal "Australian Fisheries" (May 1978).

During the prawn research program, attention was given to the target strengths of several of the commonly encountered species. This work is described in this paper and the results obtained are compared with those for some other species of marine organisms. These topics concern the relationship between target size and acoustic target strength. Some initial work has also been undertaken in an attempt to relate the distribution of received echoes from a monospecific population to the acoustic target strength of an individual target. A summary of this work is also included.

A number of investigators have examined the target strength of fish, usually by undertaking laboratory studies on single animals. Much of this work has been reviewed by Love (1971), who draws attention to the important acoustical role attributed by several investigators to the gas filled swimbladder, in those fish possessing this organ. Recently Clay and Medwin (1977) have reviewed the theory of scattering from gas bubbles in the sea and have applied their treatment to fish with swim bladder and gas bubble carrying macroplankton, such as Physonectae siphonophores.

Relatively little attention has been given to the acoustic properties of crustacea of greater than zooplanktonic sizes. The habitat of many large crustaceans renders them inaccessible to active acoustic detection and the absence of a swim bladder in Crustacea suggests that these animals should have relatively low target strengths. As a consequence, however, of interest in the acoustic backscatter from aggregations of zooplankton organisms, both in the deep scattering layers and elsewhere, some investigators have examined the acoustic target strengths of the smaller marine crustaceans. Limited information is available for Crustacea with characteristic dimensions exceeding one centimeter.

In the present work, attention has been given to the acoustic target strengths of several species of penaeid prawns, adult specimens of which may grown to a total length in the range 20 to 30 cm. Further, several of these species spend at least part of their adult life in a benthopelagic environment. When this occurs, echo sounding techniques may provide discernible acoustic returns, resolved from the sea bottom echo, from such targets.

TARGET DESCRIPTION AND MEASUREMENT

Measurements have been made of the acoustic target strengths of penaeid prawns of lengths 16 ± 2 cm and over the frequency range 50 kHz → 1200 kHz. The length cited here refers to the dimension from the tip of the rostrum extension to the end of the tail, with the animal in a fully extended position. Specimens were obtained from trawler catches in South Australian and Western Australian fisheries.

Three species have been examined: tiger prawns (Penaeus esculentus), banana prawns (Penaeus merguiensis), and the western king prawn (Penaeus latisulcatus). No significant variation in target strength between these species was found which could not be directly attributed to differences in animal weight and length. Accordingly in the discussion which follows target strength values are assigned to these species collectively.

The values of Target Strength, T, were evaluated according to:

$$T = 20 \log (P_1/P_0) \qquad (1)$$

where P_1 is the backscattered sound pressure at one metre from the target subject to an incident sound wave described by pressure P_0. This approach has been used by a number of investigators. Haslett (1962a, 1962b, 1964, 1965, 1969) has described the technique employed in such a program in a series of publications which have been used in establishing the methods employed in the present work.

Fig.1 shows in schematic form the equipment developed for the prawn measuring program. The targets were suspended by monofilament lines in a freshwater filled tank of six cubic metres capacity. Fresh water is commonly used in such target strength work, and offers considerable working advantages over sea water. Since, however, target animals used were directly frozen after capture and thawed out immediately prior to measurement, it was necessary to allow the prawns to stabilize for about four hours to achieve a quasi-equilibrium osmosis state in the fresh water, as indicated by acoustic monitoring during this period. Once this had taken place, target strength measurements did not vary over target immersion periods of up to two days, after which variation occurred which we presently attribute to tissue degradation. Before insonification all animals were inspected to check for bubbles forming under the exoskeleton. If formed, such bubbles were removed by manipulation of the exoskeleton segments to allow the gas to escape.

Sound pressures were linearly related to voltages from a suite of piezoceramic transducers. All measurements were made in the far field regions of the transducers used and, because of the short range employed throughout, no significant absorption corrections were needed even at the highest frequencies used. Insonifying pulses were generated within the pulse generator, function generator and pulse amplifier sequence, which allows variation in pulse frequency, repetition rate, and duration. The reflected signal P_1 was measured using a single transducer with combined transmit-receive functions. Incident sound pressure P_0 was measured at the target location using an identical transducer to the transmit-receive unit. Overall system calibration was checked by using the air-water interface in the tank as a reference reflector. The transducer to target spacing allowed the target echo to arrive at the receiver before the first echoes from the tank boundaries, which were gated out.

In general pulses of 200 μsec were employed in tank tests. The reflected estimate was made from a 50 μsec segment gated out of the centre section of the returning pulse. The gated signal output from the transmit-receive switch was demodulated and converted to a slowly varying envelope voltage in the signal conditioner, the output of which was applied to the cathode ray oscilloscope, chart recorder and digital voltmeter-printer, and interfaced with a PDP 11/10 computer. Each of these output devices also received information regarding the angular position of the target rotation frame.

TARGET STRENGTH RESULTS

The use of different specimen mounting geometries allowed target prawns to be rotated along roll, pitch and yaw axes during insonification.

In what follows pitch or dorsal plane results are used throughout. Three measures were used to describe the magnitude of the received signals: peak reading, average reading over the dorsal plane and the average taken over an angular excursion of $\pm 40^{\circ}$ to the normal to the animal axis in the dorsal plane. Averages were at first determined graphically, and later by using an on-line computer processing technique.

Fig.2 shows the peak target strength values from seven specimens at a variety of frequencies. The straight line least squares fitted to the data has the form;

$$T = -44.4 - 2.52 \times 10^{-3} f \qquad (2)$$

T in dB re 1 m, f in kHz.

An important feature of this result is the observed small dependence of target strength on frequency, amounting to a decrease of 2.9 dB over the range 50 kHz to 1200 kHz.

Target strength values averaged over the dorsal plane are described by:

$$T = -51.2 - 1.68 \times 10^{-3} f \qquad (3)$$

The frequency dependence is again small, corresponding to a decrease of 1.9 dB over the 50 kHz to 1200 kHz frequency range.

Target strength values averaged in the ± 40° angular excursion range were essentially constant over the frequency range, at -47 dB.

THE DEPENDENCE OF TARGET STRENGTH ON FREQUENCY

Because of the complex scattering characteristics exhibited by biota, data interpretation as well as target strength prediction have proven difficult. Several attempts have been made to present a unifying treatment of fish target strengths, which would account for the dependence of target strength upon frequency and scatterer size and shape. These have their origins in different models of the scattering process such that the target may be represented as either a quasi geometric solid or merely as an energy intercepting area presented to the sound wave.

The scattering of sound from simply shaped objects has been treated extensively and, in a number of publications, considerable agreement between theory and experiment has been achieved. Because, to a first approximation, fish swimbladders or even entire fish in the geometric scattering region may be viewed as finite length cylinders, scattering from this shape has had particular interest as a possible guide to the target behaviour of fisheries targets. A recent experiment of interest has been carried out by Andreeva and Samovol'kin (1976) who measured the backscatter in water from air and metal cylinders of finite length. Here $k = \frac{2\pi}{\lambda}$ and a = cylinder radius. The metal cylinders provided, over the ka range 1 to 8, general increases in target strength of 6 to 10 dB, depending on target material. The air cylinders were obtained using rubber envelopes and over the ka range 1 to 10, the measured acoustic cross sections followed a simple linear dependence on frequency, providing a 10 dB increase in target strength. This is consistent with the simple formulation for the acoustic cross section of a cylinder of finite length L and radius a:

$$\text{i.e. acoustic cross section } \sigma \text{ proportional to } \frac{L^2 a}{2\lambda} \qquad (4)$$

This result was derived for the case of the scattering of short radio waves by Kerr and Goldstein (1951). Andreeva and Samovol'kin used this relationship in the interpretation of their results, as have some other workers dealing with the acoustic properties of fish.

Most target strength measurements on fish have involved the geometric scattering region, in which the characteristic dimensions of the target are larger than the insonifying wavelength. This is a consequence of the fish sizes and sound wavelengths which, being of practical concern to fisheries, have been utilized in most target strength measurements. The difficulties of using long wavelengths in the laboratory test tanks commonly employed in acoustic measurements on fisheries targets have also tended to restrict such work to higher frequencies and, thus, to the geometric region.

Many fisheries targets have been treated, to a first approximation, as simple geometric solids. Hashimoto and Maniwa (1957) have used a finite length circular cylinder to approximate the entire fish target and Haslett (1962a) has used this geometry to model the dorsal aspect backscatter from fish swimbladders and backbones. Haslett distinguished between the dorsal and side aspects, claiming that the fish body, modelled by an ellipsoid, would be of greatest importance for side aspect backscatter. However, for dorsal viewing Haslett predicted that at high frequencies, the swimbladder and backbone components would predominate. He further modelled the acoustic behaviour of these elements by an equation of the form of (4) above thus predicting a geometric region dependence of target strength on frequency increase of 10 dB per decade. This prediction is also cited by Forbes and Nakken (1972) and Clay and Medwin (1977).

Love (1971), in a review of the target strength measurement programs of a number of researchers, collected the results on fish from up to 16 families, ranging in length from 1.5 cm to almost 1 m, insonified with frequencies ranging from 8 kHz to 1.5 MHz. From this compilation he calculated regression lines to fit the data:

$$T = 19.4 \log L + 0.6\lambda - 21.9 \text{ (dorsal aspect} \quad (5)$$

$$T = 22.8 \log L - 2.8\lambda - 22.9 \text{ (side aspect)} \quad (6)$$

where T is target strength in dB re 1m and target length. L and wavelength λ are in metres. It should be noted that a single length dimension is used to characterize the target and that little variation of target strength with frequency is provided by equations (5) and (6).

Further, since:

$$T = 10 \log \left(\frac{\sigma}{4\pi}\right) \quad (7)$$

equations (5) and (6) imply that the acoustic cross section σ is nearly proportional to L^2, as would be expected if the scattering process is simply area dependent. More recently Love (1977) has expanded these results to include an approximation of target strength for fish at any aspect for L/λ ratios from 1 to 100. He has shown that ignoring the frequency dependence of target strength introduces only small errors in prediction, typically 1 to 4 dB. Love reduced his data to a series of expressions:

$$\sigma_m = a_m L^2 \quad (8)$$

where σ_m is the acoustic cross section at a particular target aspect. For peak target strengths in the dorsal plane, equation (8) becomes

$$\sigma = 0.042\ L^2 \quad (9)$$

Thus the literature on fish target strengths shows the influence of several models of the scattering process. The use of geometric solids to approximate biological scatterers has led, in the case of the finite circular cylinder, to a projected increase of geometric region target strength with frequency, which is not observed in the synthesized data presented by Love, although Andreeva and Samovol'kin have clearly shown such a trend in artificial targets approximating in form to a fish swimbladder. The empirical formulations of Love suggest that the combined results of many laboratory measurements of fish target strengths are best represented by expressions which involve no frequency dependence and a direct proportionality between acoustic and geometric cross sections as is appropriate, in the simplest formulation, for scattering dimensions in the geometric region.

The two interpretations of the scattering process have been compared with the peak target strength values for the penaeid prawns in Fig (3). If the prawns are regarded as finite cylinders, of radius 1 cm and length 16 cm, dimensions which are approximate to the animals studied, then the peak target strengths for normal incidence in dorsal aspect may be represented by a modification of Equation (4) i.e.

$$T = 10 \log \frac{aL^2R^2}{2\lambda} \qquad (10)$$

where R is the pressure reflectivity.

A series of curves of this form and for various R values have been superimposed on the prawn results in Fig.3. It is clear that, while some agreement at high frequencies exists for reflectivities of around 3%, the low frequency behaviour predicted by the finite cylinder model is not observed.

For L = 0.16 m, the peak dorsal aspect target expression developed for fish by Love, Equation (9), provides T = -40.7 dB, constant with frequency. Figure 3 includes this result. It is clear that the present results are better fitted in terms of frequency dependence by the Love formulation for fish targets than by the finite cylinder approximation. The prediction due to Love provides a target strength value 5 to 6 dB stronger than that found for the penaeid prawns. Since many of the fish used to form the data compiled by Love possessed swimbladders, it is to be expected that the acoustic reflectivity implied by Equation (9) would exceed that associated with the penaeid prawns.

The extent to which Love's empirical formulations, developed from results on fish, are applicable to the penaeid prawn results cited here, suggests that the target strengths of some other marine organisms may be approximately predicted in a similar fashion.

THE TARGET STRENGTHS OF CRABS, SQUID AND ZOOPLANKTON

Samovol'kin (1975) reported target strengths of crabs of length 3 and 5 cm at six frequencies ranging from 30 to 200 kHz. For the 3 cm crabs, target strengths were around -66, -61 and -58 dB for L/λ values of 0.6, 2.4 and 4.0, respectively; for the 5 cm crabs values of approximately -66, -55, and -56 dB for L/λ of 1.3, 2.6, and 5.3 respectively were found. Thus, for both examples, target strength values increased significantly with L/λ, for L/λ values near unity, suggesting that these measurements involve the transition range between the Rayleigh and geometric scattering regions. Samovol'kin used both live and formalin preserved targets, noting that, in the case of crabs, for the most part, no variation in scattering cross section was thereby introduced.

Matsui et al. (1972) measured backscatter from 11 squid with mantle lengths of 11-13 cm. Total body lengths were not reported. At frequencies of 50 and 200 kHz (L/λ of 4.3 and 17.2) maximum target strengths were -45 and -42 dB, respectively.

Some measurements of zooplankton target strengths have been made. Beamish (1971), using an in situ method determined the target strengths of euphausiids at 102 kHz and more recently Greenlaw (1977) has measured the target strengths of three zooplanktors over the frequency range 220 kHz to 1100 kHz using a laboratory based method. Because of the small target sizes involved, these measurements sometimes fall in or near the Rayleigh scattering region for which ka or kr are significantly less than unity. Both investigators have modelled the zooplanktonic scatterers by spheres and have made use of the fluid sphere model due to Anderson (1950) and in Greenlaw's case, that of Johnson (1977) who has described a simplified fluid sphere scattering model appropriate to biological targets. Greenlaw has shown strong frequency dependence from copepods in the ka region 0.7 to 3.5. He describes this by:

$$T = -150.6 + 23.4 \log f \qquad (11)$$

where frequency f is in kHz.

Equation (11) corresponds to an acoustical cross section which is proportional to f^2 rather than to f^4 as would be expected for targets well into the Rayleigh scattering region. This result, together with the values of ka used, suggest however, that some Rayleigh region interactions were involved.

Greenlaw also measured the target strengths of euphausiids for which ka ranged from 1 to 20, and found little overall frequency dependence over this wavenumber range although considerable fluctuations within the range were observed. The euphausiid results were interpreted as lying primarily in the geometric scattering region. The measurements reported by Greenlaw were made on preserved specimens.

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The transition from Rayleigh to geometric region scattering is difficult to define for fish and similar targets. Some, however, of the results cited above, and summarised in Table (1), involve target dimension/wavelength ratios less than those normally associated with geometric region scattering. Some of the results also show a frequency dependence of target strength which is consistent with the transition to Rayleigh scattering, rather than geometric region behaviour.

In order to compare the target strength values for the various organisms listed in Table (1), with the predictions emerging from Love's empirical relationships, it is necessary to use only values involving geometric region scattering.

It should be noted that the values listed in Table (1) are those for peak target strength values, where applicable, in the dorsal plane. Peak values are used here in order to facilitate the comparison of target strength data from the various measurement programs cited.

Fig.4 shows a plot of target strength values, taken from Table 1 but involving only those results for which $L/\lambda > 2$. Fig.4 also shows (full line) the appropriate prediction for fish obtained using Love's formulation (equations 9 and 10). Love's equations have been computed from targets in the length range 1.5 cm to almost 1 m. Fig.4 shows the equation 9 prediction extrapolated down to 1 mm.

With the exception of the euphausiids, the results lie within about 5 dB of the trend computed by Love for fish. The euphausiid results as reported by Greenlaw showed little overall frequency dependence over the experimental range considered, but did show considerable detailed variation with a frequency,more in fact, than the associated copepod results measured in a different way in the same work. The euphausiid specimens were mounted on a support in the beam, but were also large enough to provide interference patterns in the backscatter diagrams and as a consequence backscatter signals would be expected to vary markedly with specimen orientation in the beam. Therefore some measurements made on the euphausiids would return low values, since specimens were apparently not rotated in the beam, but measured in one orientation at a time. It is possible that the wide range of target strength values, if not the generally low figures reported are a consequence of the experimental difficulties involved in making backscatter measurements on targets whose small size makes specimen handling difficult, but which are large enough to provide backscatter which is strongly influenced by target orientation.

Overall,however, the degree of agreement seen between most Fig.4 values and the empirical Love formulation for fish suggest that the latter is a useful predictor for some species other than fish, and that provided sound frequencies are high enough to permit geometric region interactions to occur, such predictions may be extended to targets of planktonic dimensions. Further measurements of the target strengths of plankton are needed to consolidate this conclusion.

The use of equation (9) implies that many marine organisms may be usefully modelled as simple energy-intercepting areas, areas which may be regarded as collections of reflecting Huygens sources. In the geometric scattering region, the acoustic cross section will be linearly related to the physical cross-sectional area of the target and will be essentially independent of frequency. If the sources were assumed to have varying amplitudes and to be distributed spatially in a random manner, we would expect the distribution of echo amplitudes to be Rayleigh in form. Several experiments have shown this to be approximately the case, provided the target size to wavelength ratio is considerably greater than unity.

THE DISTRIBUTION OF ECHO AMPLITUDES

The average L/λ values for the prawns described in this paper ranged from 5.3 to 128. This ensured that the backscattered pressure signal varied markedly with changes in target orientation to the sound beam. Large echoes occurred for only a few specific orientations and the bulk of the returns had amplitudes considerably less than the maximum value. Fig.5 shows the echo signals from a 200 kHz (L/λ = 21) dorsal plane record presented in an amplitude versus frequency of occurrence format. Two thousand returns were recorded and sorted into 16 amplitude intervals, while the target was rotated over the angular excursion -50° to $+ 50^{\circ}$ about the normal to the dorsal axis in the dorsal plane. This angular excursion ensured that a substantial number of the backscatter lobes were included during the data acquisition.

Fig.5 shows, in histogram form, the results of two runs on the same animal, using slightly different roll mode orientation in each case. The resulting histograms show that most returns occur at relatively low amplitudes, and provide an approximation to the probability density function appropriate to received signals for this scattering regime.

The large L/λ values involved suggest that the target may be modelled as a collection of incoherent Huygens sources, as discussed for fish by Peterson et al. (1976). The reflected pressure waves from the various source elements which form the prawn acoustic topography will interfere to an extent governed by the detailed structure of the target and its orientation to the sound beam.

It is the vector sum of each signal element which provides the backscattered signal observed at any particular target orientation. The resultant of the incoherent addition of a large number of signals of equal amplitude has as a characteristic probability density function, the Rayleigh distribution (Rayleigh 1896). The function has the form;

$$f = 2/n \; r e^{-r^2/n} \qquad (12)$$

This function gives the proportion f of returns of amplitude r which would be expected as a result of the incoherent addition of a large number n of oscillations, each of unit amplitude. Other signal amplitudes call for appropriate normalization. Equation 12 is still applicable if, as is probable in the case of a prawn or fish target, the scatterer provides sources of varying magnitudes, provided large numbers of sources of each magnitude exist.

Peterson et al. (1976) in adopting the Rayleigh distribution for their model of acoustic scattering from fish targets, have cited evidence from Cron and Schumacher (1961) and Bergmann (1969) in support of this step. Neither reference, however, concerns the fluctuations from a single quasi-point scatterer. Cron and Schumacher deal with surface and volume reverberation and the Bergmann data are derived from transmission experiments. In both cases the number of scattering centres is unknown and probably large. The extent to which the statistics of large distributed targets may resemble those from quasi-point scatterers has not been established in the literature.

Some guidance as to the applicability of the Rayleigh distribution as a descriptor of the backscatter statistics from the present targets may be obtained by fitting a suitably normalized distribution to the data shown in Fig.5. The full line in Fig.5 has been fitted to the most common amplitude value of the histograms. The fitted line thus follows approximately the low amplitude returns but underestimates the proportion of higher values found in the experiment. It should be noted, however, that as the experimental results were taken over only one plane in the dorsal hemisphere, some high amplitude enhancement compared to the field situation is to be expected. Considerations of likely animal orientation and usable beam geometries in field echo sounding suggest that a full suite of experimental returns should involve not only dorsal plane data. Sampling undertaken over more orientations in the dorsal hemisphere would be expected to enhance the proportion of low amplitude returns.

Under these conditions the Rayleigh distribution would more closely approximate the experimental results.

Laboratory measurements of the distribution of backscatter pressure amplitudes have been made by Kung (1977). Kung used live 12 cm long fish (Notropis cornutos) insonified at 220 kHz. The L/λ value involved was thus approximately 18. For targets supported in the beam in such a way that changes in orientation were possible, the distribution of backscattered echoes was, again, approximately Rayleigh in form.

Goddard and Welsby (1975), in a program to determine the acoustic target strengths of live fish, used single and group targets swimming freely in a net cage in a sea flooded quarry in Scotland. Their conclusions regarding the PDF shape to be expected from single targets stress the difficulty of obtaining statistically significant data, but indicate that for L/λ > 20, the Rayleigh distribution gave a useful fit. For L/λ values less than this, the fit was very variable, and below L/λ = 5, quite inadequate.

MODELLING FIELD ECHO BEHAVIOUR

The echo received in the field from an individual target depends on, amongst other factors, the product of two random functions. These are; the position of the target in the beam and its orientation to the insonifying wavefronts. The position of the target involves the range, which can be deduced from time measurements, and the location of the scatterer with respect to the beam directivity pattern. We here assume that the target is large enough to be in the geometric scattering region and that the two random functions may properly be regarded as independent. For targets with L/λ > approx. 20 the Rayleigh distribution appears to offer a useful approximation to the distribution of fluctuations which arise because of random target orientation. If the transducer beamshape in transmission and reception is known, the analysis of a sufficiently large ensemble of echo returns from many isolated similar targets permits an assessment of the acoustic target strength of the individual targets.

This approach has been used by Peterson et al (1976) who calculated a PDF in this way and compared the computed curve with the experimentally recorded PDF from echo sounding carried out in Lake Michigan. The fish, believed to be a nearly monospecific population of Lake Michigan alewives (Alosa pseudoharengus) were about 15 cm long. The results were then used to calibrate an echo integration system, the results of which given an estimate of the range of <N> values encountered in the survey. Here <N> refers to N, the number of targets contributing to a single sampling of the echo return, averaged over substantial regions of the survey volume, <N> ranged from 0 to about 36 at the depths used in Peterson's analysis. In the PDF comparison method, however, only returns for which N = 1 are useful. The authors selected the ensemble of N = 1 returns by inspection of the graphic record accumulated during the field data acquisition. The effectiveness of this selection process is an important factor in the successful interpretation of the PDF comparison method, and depends to a large extent on the detailed spatial distribution of the targets. One method of determining the N = 1 echoes relies on estimating the duration of the return pulses, and rejecting those of greater than some minimum length. A number of errors are associated with this process, as discussed by Ehrenberg and Lytle (1977) so that some N = 2,3 and higher value returns, each involving pulse overlap, will be counted in with the N = 1 samples. This problem is clearly reduced when the targets have an overall low spatial density,such that the N>1 cases are improbable. In this case, however, large survey areas are required in order to provide enough returns to assemble a statistically significant ensemble. This requirement may, in many areas, conflict with the need to interrogate a monospecific population, and will often make the method difficult to apply to a fish school. Ehrenberg (1974) has considered the errors caused in echo counting as fish density varies and defines a mean number of scatterers per sample $\lambda_o\tau$ where λ_o is the expected number of echoes per unit time. Sampling at intervals of τ ensures that, within a one pulse process, individual samples are statistically independent. Under these conditions, $\lambda_o\tau = N$. Ehrenberg defines a region, extending $0.5<N<20$, in which both echo counting and echo integration give high errors. For smaller N, counting is effective and the method of analysis employed by Peterson et al is in this sense usable. For $N>20$ echo integration becomes necessary, with consequent loss of the information associated with echoes from individual fish.

As part of the prawn research program described in this paper, a computer model of selected field echo distributions was developed. We use some of the results of this work to comment on the effect of variations in fish spatial density on a recorded PDF.

The model uses Monte Carlo techniques to calculate the pressure amplitude from targets each with PDF described by a Rayleigh distribution, placed randomly within the known beam pattern of a transducer, and at a specified range D. The target density is such that N targets appear in the range slice volume at D. Specifically, the results cited here have been computed as follows:- The model has:

(i) Computed a target strength for each target, from a Rayleigh distribution of echo amplitude. The average value of the Rayleigh distribution corresponded to a target strength of -47 dB re 1 m.

(ii) Located N such targets within a range slice $c\tau/2$ thick (τ = 100μs) at range D = 20 m. The beam pattern effects in transmission and reception have been computed for a circular transducer of diameter 9.3 cm. operating at 200 kHz. (7.6° between the 3 dB points). The model includes the main and first side lobes in the calculation.

(iii) The resultant echoes from each of the N targets were then added randomly with respect to phase.

(iv) The process (i) → (iii) was then repeated for a total of 1000 iterations, the signals being sorted in 1 dB bins to form an estimate of the appropriate PDF.

Fig. (6) shows the model result for N = 1. The echo amplitudes are expressed in terms of an effective target strength at range 1 m, and have been filtered with a running mean filter of 2 dB width.

The bulk of the returns lie below -120 dB, because of the high probability of targets being in the side lobes, coupled with the low response there. Inclusion of second and higher and higher side lobes in the model would expand the low amplitude returns, most of which would provide echoes below the noise levels appropriate to field operation. The detection of the targets modelled would depend in practice on the relatively few high amplitude returns forming the "leading edge" of the PDF seen in Fig.6. It is the shape of this leading edge which has been used by Peterson et al (albeit with a log-log plot rather than the linear-log format shown here) in their comparison of experimental and computed PDF curves.

Figs. 7, 8 and 9 show PDF results calculated for N values of 3,9 and 15 respectively. These show the rapid change in the PDF shape as N increases, a consequence of the increasing probability that some of the N targets will always be found in the main lobe.

The importance of the N>1 PDF calculations in the present context is that their inclusion in the accumulated amplitude values from N = 1 returns, as a result of imprecision in the selection of N = 1 echoes, will distort the experimentally produced PDF. The extent of this effect depends on:

(i) The probability that N>1 assemblies will occur. This depends on the spatial distribution of targets and the volume v associated with the insonifying range slice. Such probabilities will increase with fish density.

(2) The effectiveness of the N = 1 selection process, normally based on measures of return pulse duration. This in turn involves the relationship between spatial distribution and the distribution of return pulse lengths.

Further work on these areas is proceeding.

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TABLE I

Target Parameters

Target	Characterising Dimension (cm)	Frequency Range (kHz)	Range of ka kr or L/λ	Source
Squid	Mantle length L = 12.9 cm	50, 200	4.3–17.2	Matsui et. al. (1972)
Prawn	Total length L = 16 cm	50 - 1200	5.3 - 128	Sofoulis (1977)
	Cylinder radius r = 1 cm	50 - 1200	2.1 - 50	
Crab	Carapace diagonal L = 3 cm	50 - 200	0.6 - 4.0	Samovol'kin (1975)
	Carapace diagonal L = 5 cm	40 - 160	1.3 - 5.3	
Euphausiid	Sphere radius a = 0.32cm, length L= 2.3 cm	64 - 1100	.85 - 16 1.0 - 17.2	Greenlaw (1977)
Copepod	Sphere radius a = .08 cm length L = 0.3 cm	220 - 1100	0.7 - 3.5 0.44 - 2.2	Greenlaw (1977)

FIGURE LEGENDS

Fig. 1.	Measuring System.
Fig. 2.	Peak Target Strength vs Frequency.
Fig. 3.	Peak Target Strength vs Frequency. Dotted Lines show the Cylinder Approximation (Equation 10).The upper full Line shows the appropriate prediction due to Love (Equation 9).
Fig. 4.	Peak Target Strengths vs Lengths for Various Organisms. Full line calculated using Equation 9.
Fig. 5.	Frequency Distribution of Backscatter Amplitudes for a 100° Target Rotation in the Dorsal Plane,with a Theoretical Rayleigh Distribution (Full Line) Superimposed.
Fig. 6.	Model Results for $N = 1$ Target.
Fig. 7.	Model Results for $N = 3$ Targets.
Fig. 8.	Model Results for $N = 9$ Targets.
Fig. 9.	Model Results for $N = 15$ Targets.

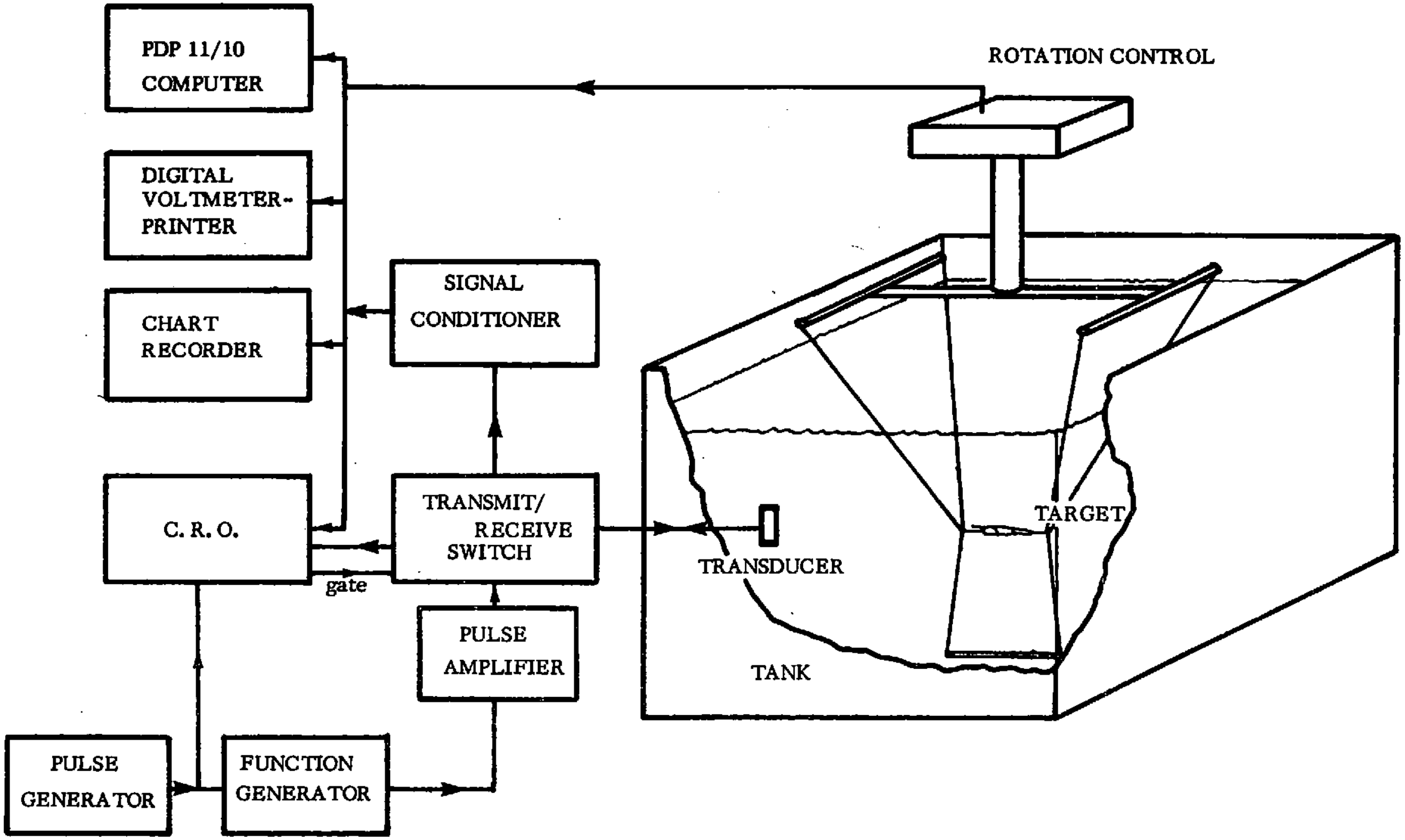


FIG. 1 MEASURING SYSTEM

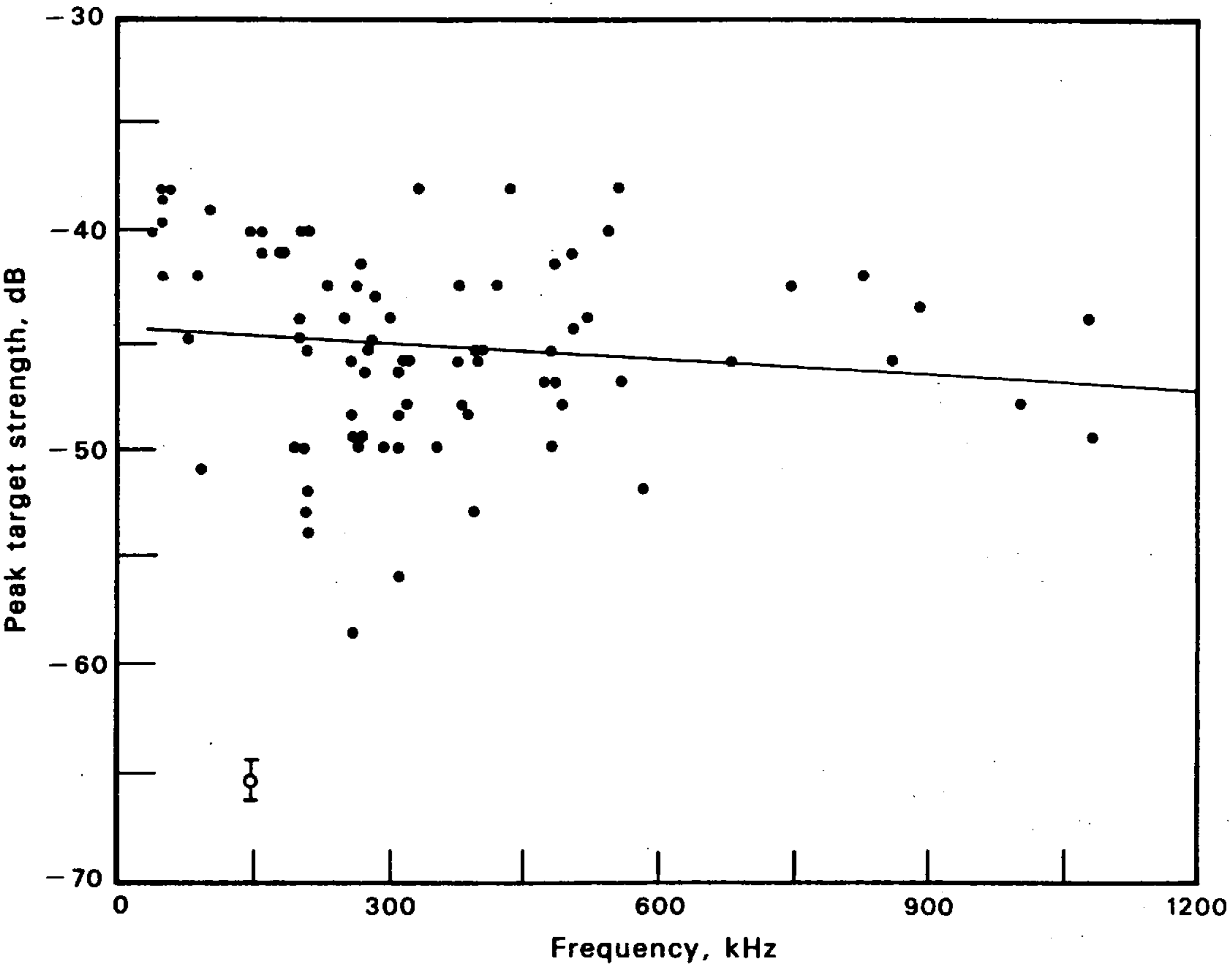


FIG. 2. PEAK TARGET STRENGTH vs FREQUENCY .

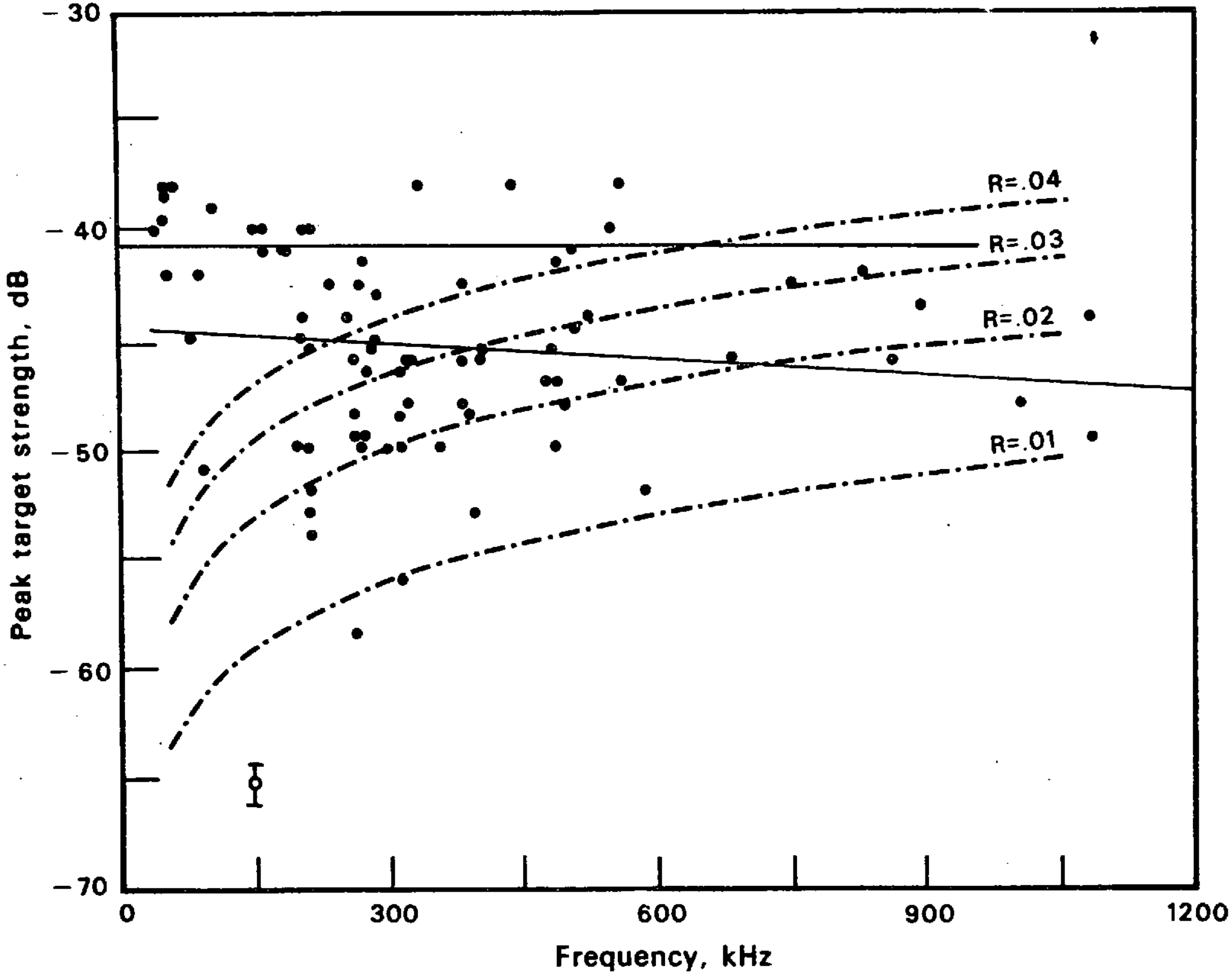

-30
-40
-50
-60
-70
Peak target strength, dB
0
300
600
900
1200
Frequency, kHz
R=.04
R=.03
R=.02
R=.01

Fig. 3.

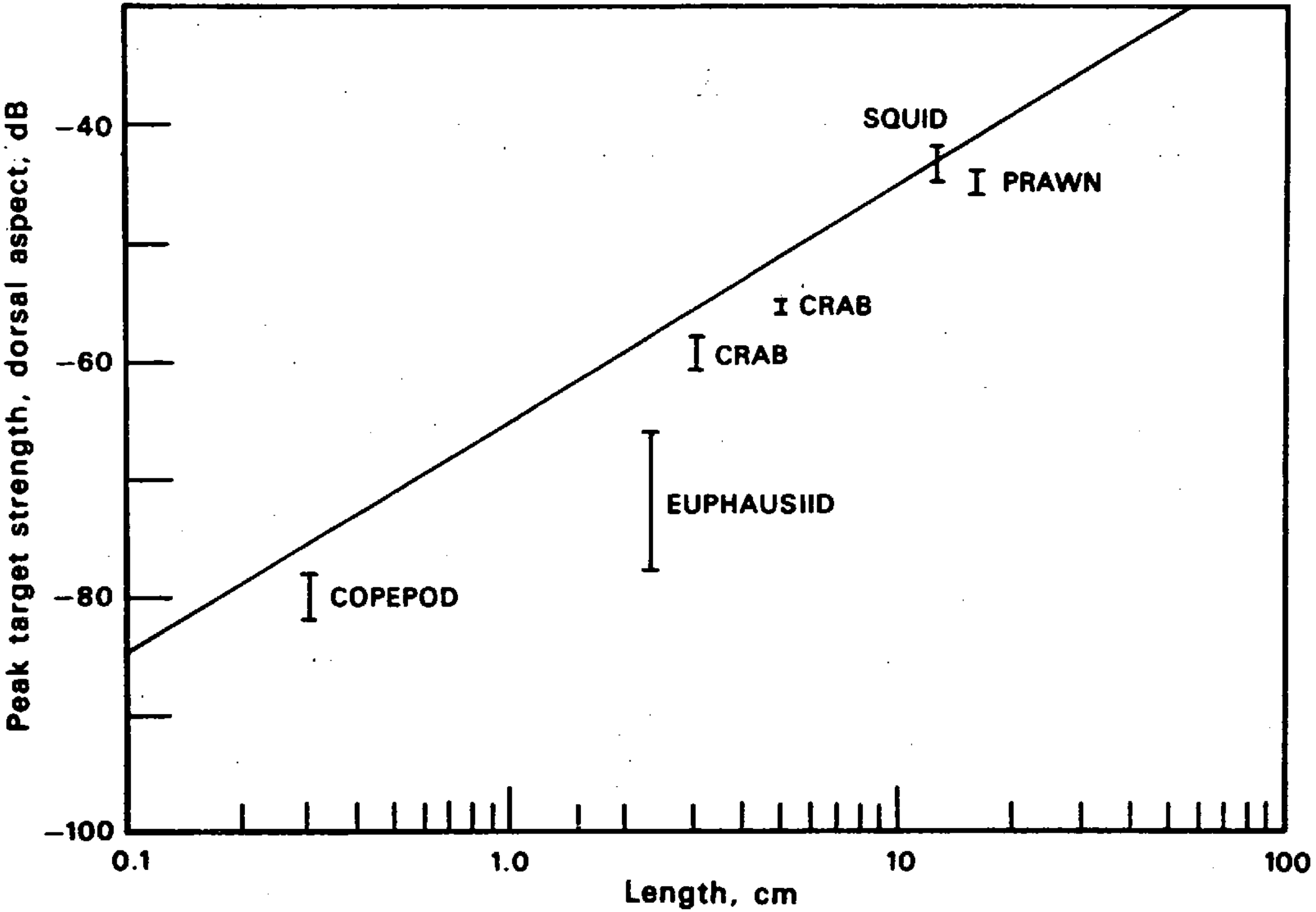
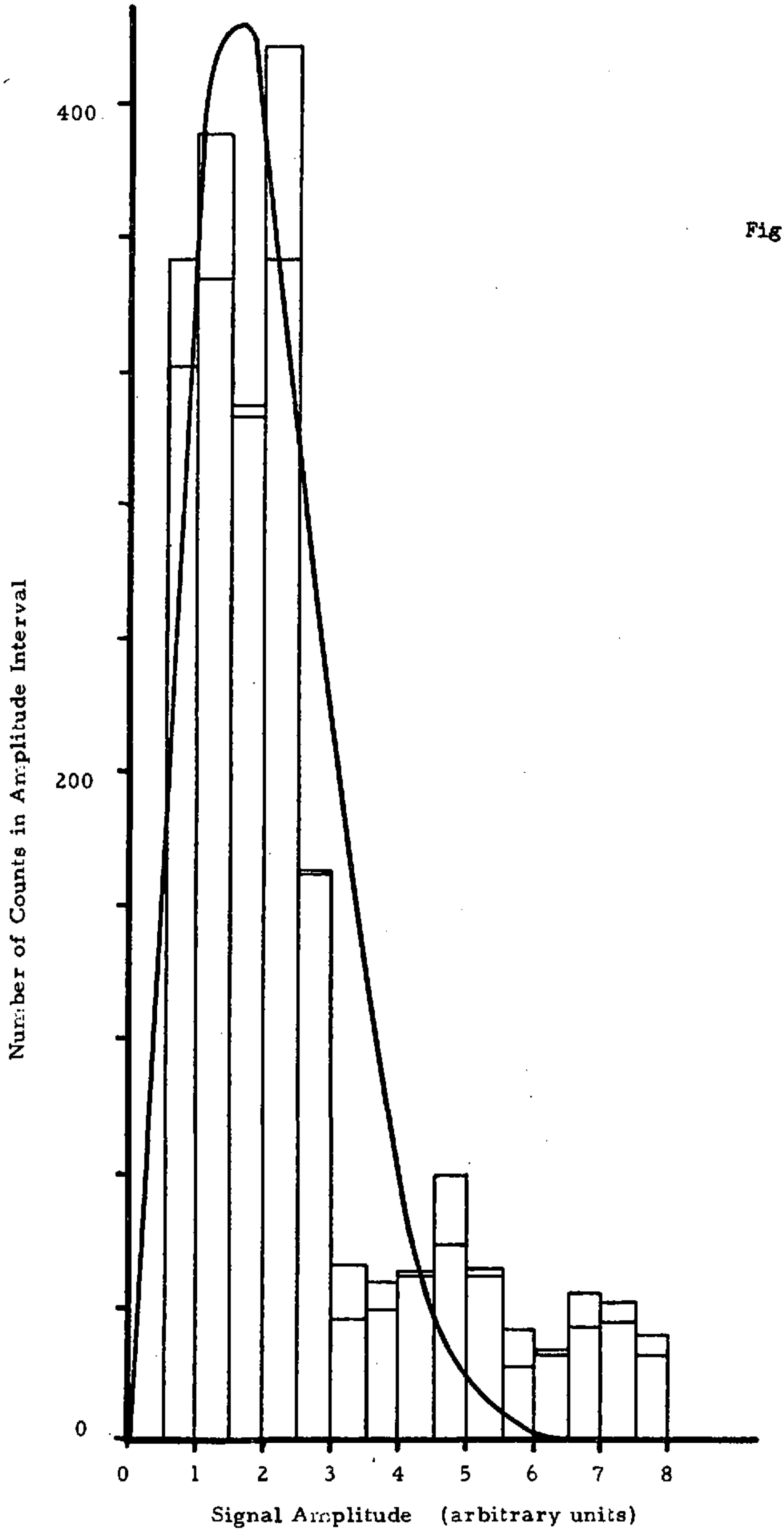

Peak target strength, dorsal aspect, dB
−40
−60
−80
−100
0.1
1.0
10
100
Length, cm
SQUID
PRAWN
CRAB
CRAB
EUPHAUSIID
COPEPOD

Fig. 4.

1.6

Fig. 5.


400
200
0
Number of Counts in Amplitude Interval
0
1
2
3
4
5
6
7
8
Signal Amplitude (arbitrary units)

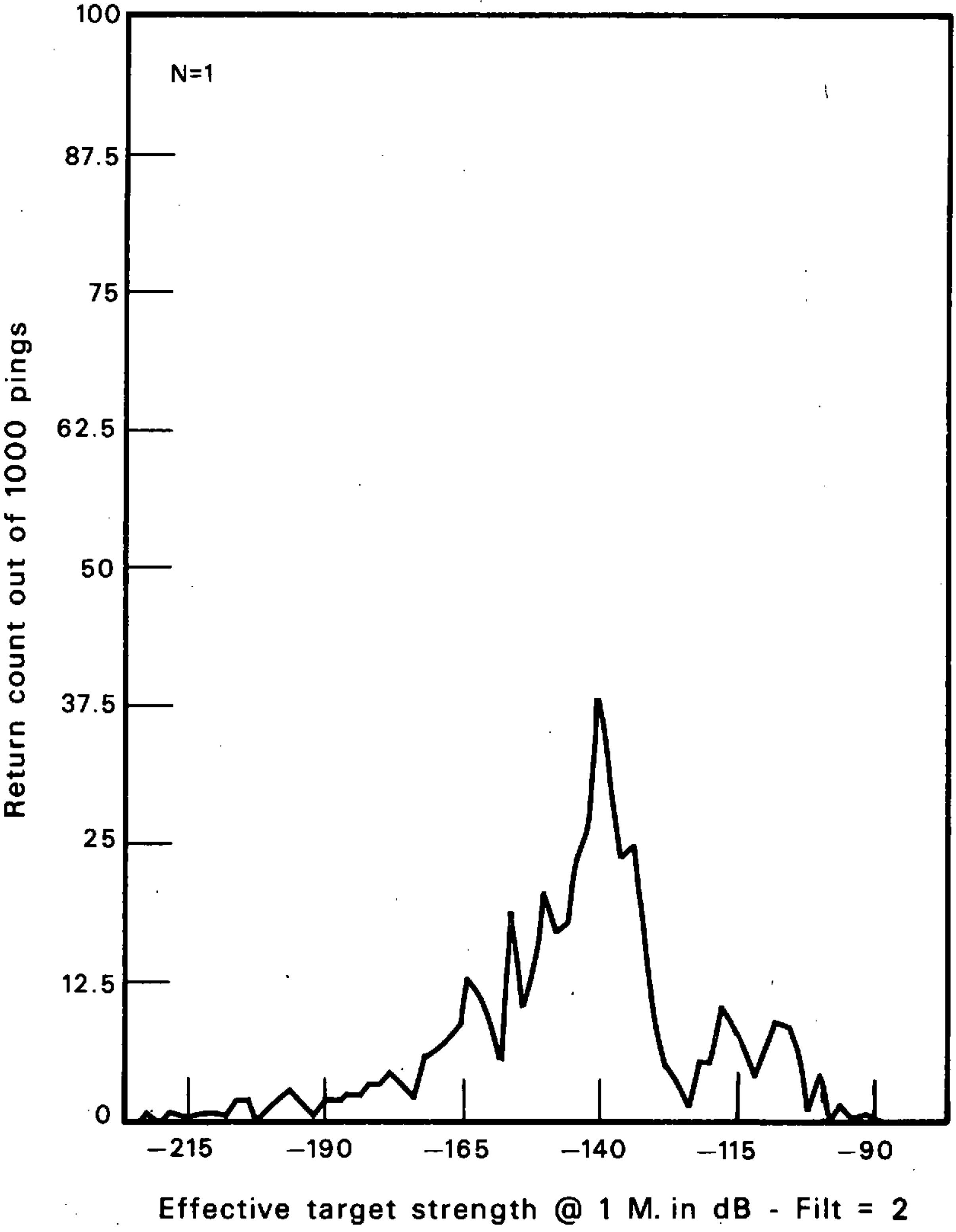

N=1
100
87.5
75
62.5
50
37.5
25
12.5
0
Return count out of 1000 pings
−215
−190
−165
−140
−115
−90
Effective target strength @ 1 M. in dB - Filt = 2

Fig. 6.

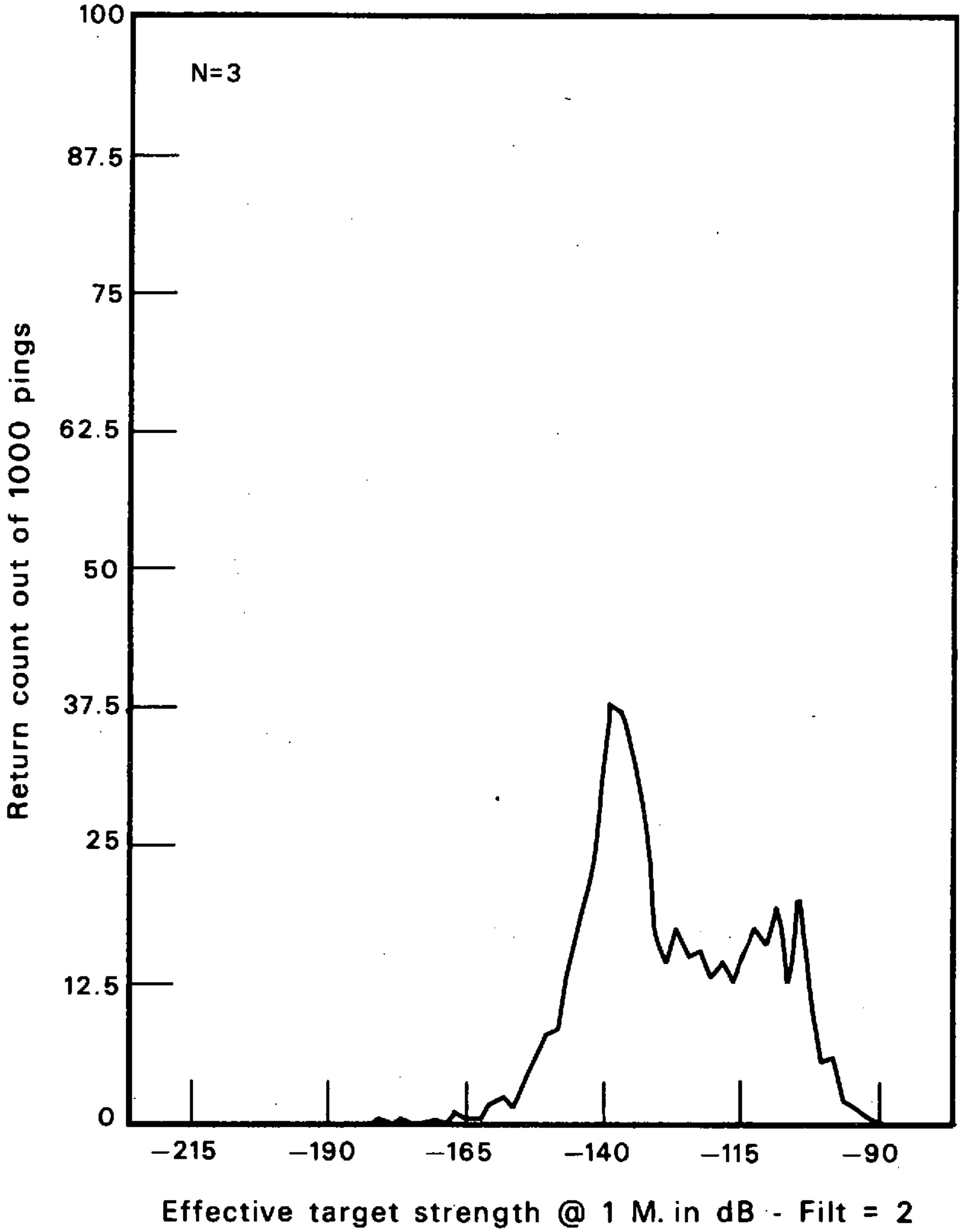

100
N=3
87.5
75
62.5
50
37.5
25
12.5
0
Return count out of 1000 pings
−215
−190
−165
−140
−115
−90
Effective target strength @ 1 M. in dB - Filt = 2

Fig. 7.

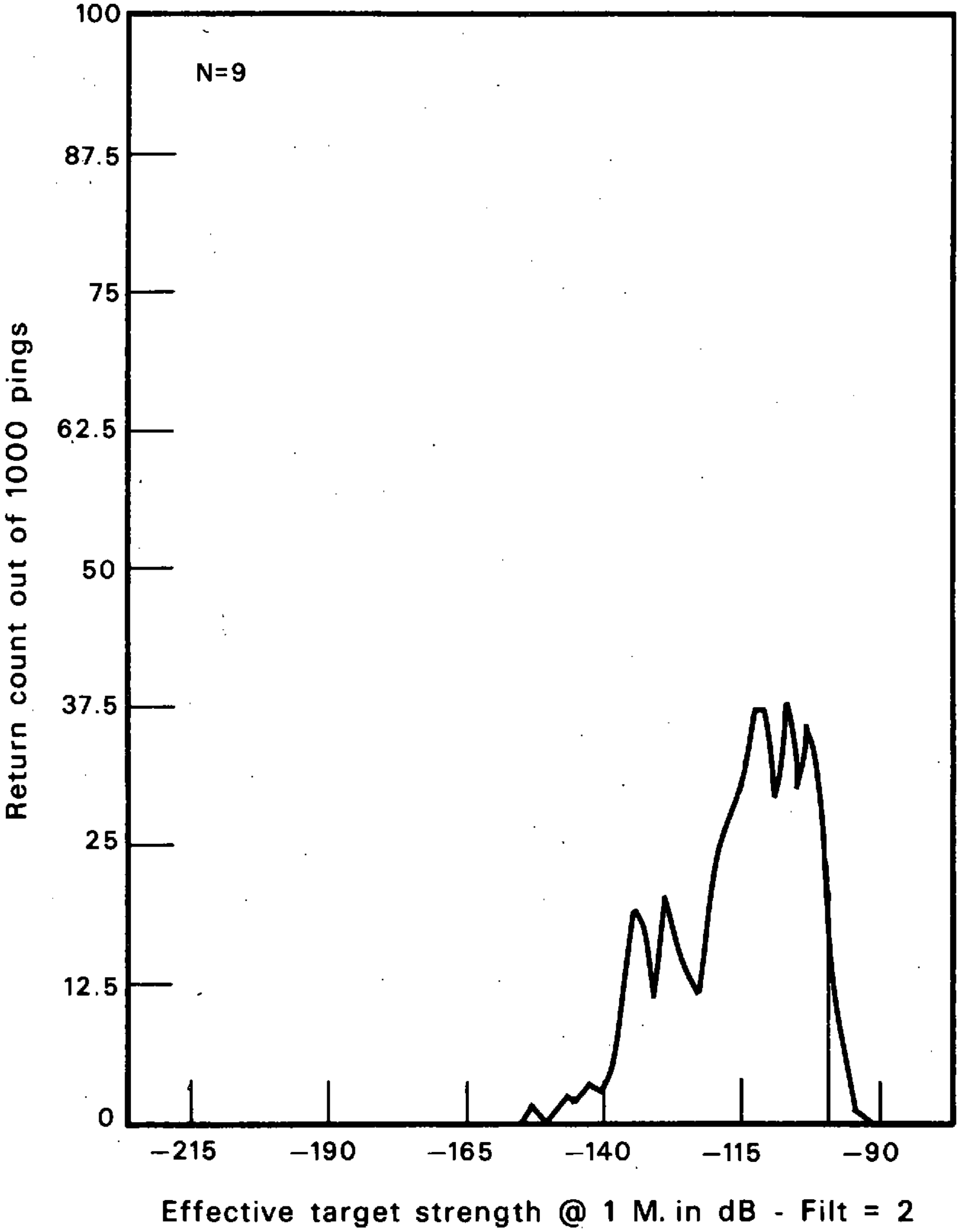

N=9
100
87.5
75
62.5
50
37.5
25
12.5
0
Return count out of 1000 pings
−215
−190
−165
−140
−115
−90
Effective target strength @ 1 M. in dB - Filt = 2

Fig. 8.

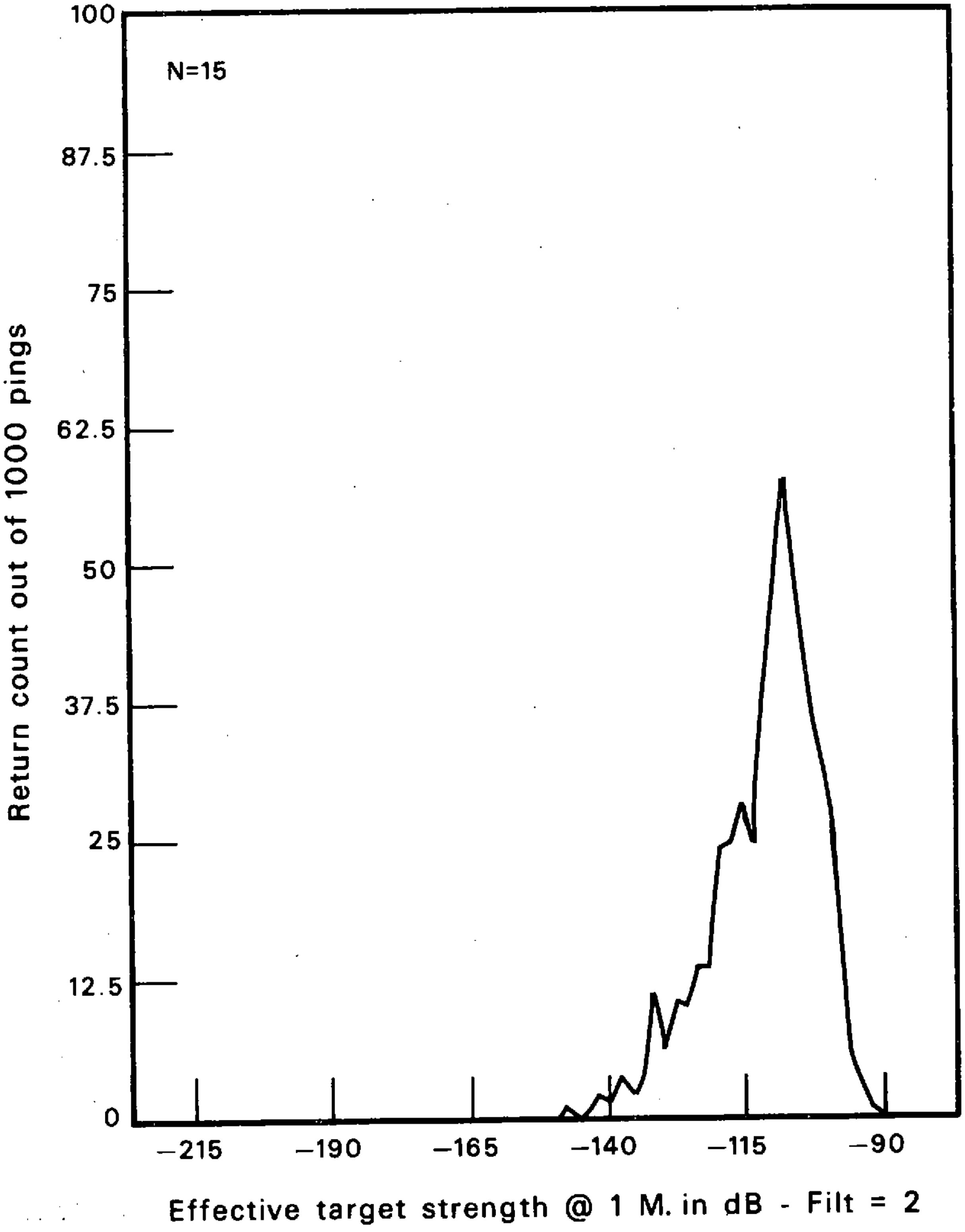

N=15
100
87.5
75
62.5
50
37.5
25
12.5
0
Return count out of 1000 pings
−215
−190
−165
−140
−115
−90
Effective target strength @ 1 M. in dB - Filt = 2

Fig. 9.