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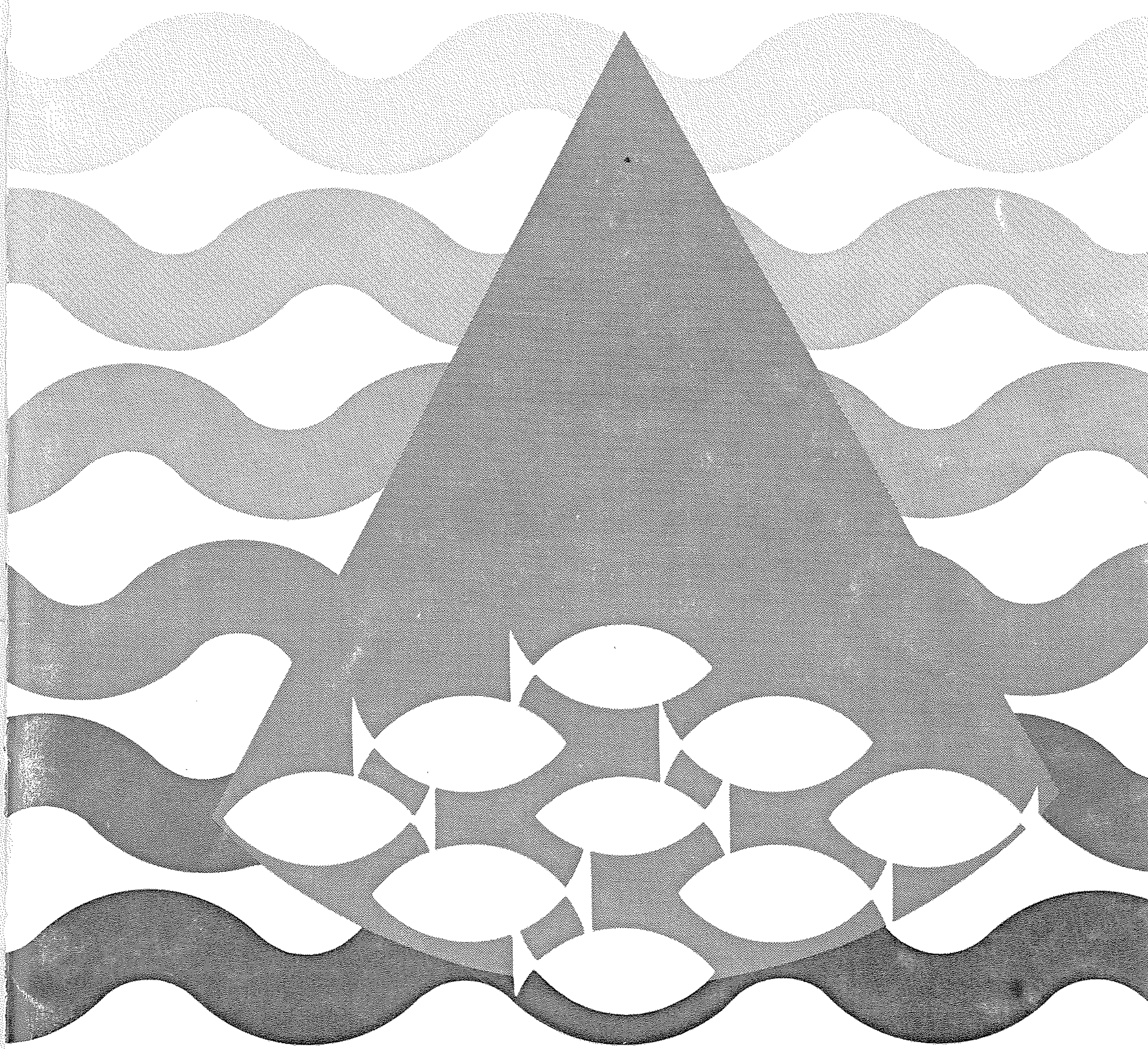

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ACOUSTIC ABUNDANCE ESTIMATION OF THE SPAWNING COMPONENT OF THE LOCAL HERRING STOCK IN LINDAASPOLLENE, WESTERN NORWAY

By

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ABSTRACT

AKSKLAND, M. 1983. Acoustic abundance estimation of the spawning component of the local herring stock in Lindaaspollene, western Norway. *FiskDir. Skr.Ser. HavUnders.*, 297–334.

During 1978–1980 yearly acoustic surveys were carried out in the spawning area of a small herring stock in the semi-enclosed bay area Lindaaspollene, approximately 30 km north of Bergen, using the Simrad EY-M echo sounder system. Absolute abundance estimates have been calculated by means of echo integration of the survey data and controlled acoustic measurements of anaesthetized single fish at tilt angles between $-45°$ and $45°$. The stock size may roughly be set at 150,000–250,000 individuals in 1979, while in 1980 the number was 100,000–200,000 older fish and 150,000–300,000 recruits.

INTRODUCTION

The present paper presents some results from acoustic investigations of the "Lindaas herring stock", which is a small local stock living in the Lindaas poll system shown in Fig. 1. The investigations are part of a larger program originally started in 1971 as a result of the 1961 ICES meeting, "Herring population studies", in Copenhagen, which recommended intensive studies of small, self-contained stocks.

A description of the Lindaas poll escosystem is found in DAHL, ØSTVEDT and LIE (1973) and description of the local herring stock in LIE, DAHL and ØSTVEDT (1978). A detailed study of the egg and larval stage of the herring stock has been performed by A. Johannessen parallel with the acoustic investigations. He also gives estimates of the spawning stock based on egg surveys (JOHANNESSEN 1982).

Before spawning, which takes place in late March or early April, the stock concentrates in the spawning area northeast of Bjørnøy (see Fig. 1.). This

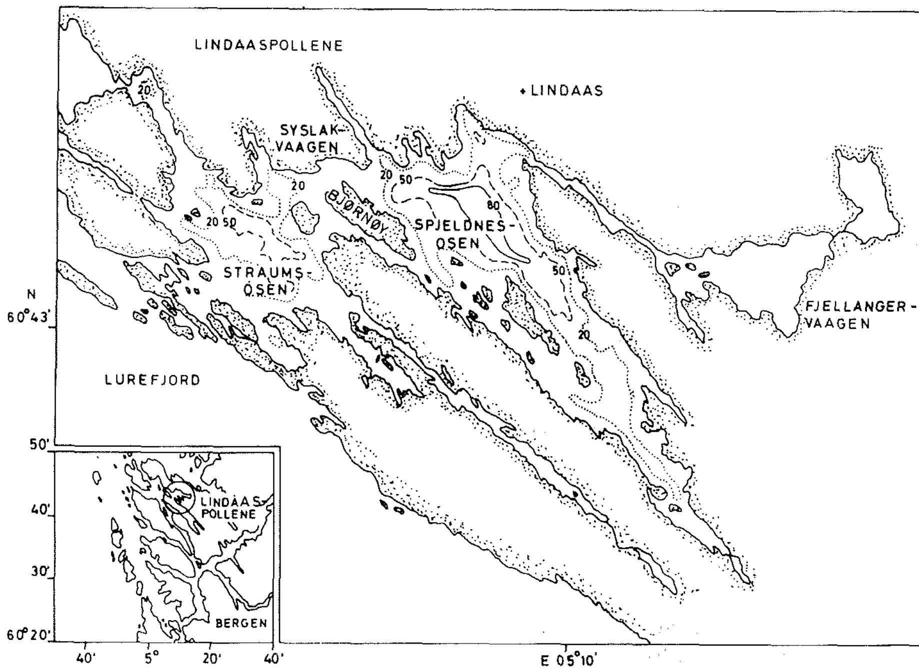


Fig. 1. The Lindaas poll system.

situation is excellent for acoustic surveying since the stock is distributed within a well-defined region where mixing with other sound scattering organisms is negligible.

To obtain yearly estimates of the size of the spawning stock, night-time surveys along zig-zag nets were performed in 1978, 1979 and 1980 with a small boat equipped with radar, a portable echo sounding system and analog cassette tape recorder for storing the acoustic data. Estimates are computed by means of the echo integration technique, where the integrator data are referred to controlled acoustic measurements on anaesthetized single fish by the same echo sounder, thus precluding the need for parameters such as source level, voltage response and target strength.

The data from both measurements and surveys were detected, digitized and stored on digital tapes and further processed on a general Nord-100 computer system by means of programs written in Fortran. Since the signal was sampled each 66 μs, the data contained fine details, and each received single echo consisted in roughly 17 values.

Since the estimates depend on the tilt angle distribution of the stock, which has not been observed, stock sizes in numbers of fish for different tilt angle distributions are given in a table. All computations have been performed ashore on general computers.

The paper gives a short description of the theory behind the method and a straightforward report of the computer processing.

MODEL AND NOTATIONS FOR THE ACOUSTIC PROPERTIES OF FISH

As in FOOTE (1980) each fish is assigned a function $\sigma(\tau,\varrho)$ as a measure of the ability to backscatter sound energy transmitted by an echo sounder. The arguments τ and ϱ are the apparent tilt and roll angle of the orientation of the fish relative to the direction of sound such that $\tau = \varrho = 0$ when the dorsal aspect direction of the fish passes through the transducer and τ is positive when the fish is frontally oriented towards the transducer. The function $\sigma(\tau,\varrho)$ is here defined slightly differently from the absolute scattering cross section concept in the acoustic litterature and is called the relative scattering cross section (r.s.c.s.) function. The following explanation leads to its definition.

Consider an echo sounder with "20 log r" time varied gain (TVG). The TVG function is proportional to texp($2c\beta t$), where c is the sound speed, β the absorption coefficient, and t the time measured from transmission of a sound pulse.

The echo from a point scatterer at distance r from the transducer generates, after detection of the received signal, a pulse of voltage V(t) with center at time 2r/c after transmission of the center of the sound pulse (t = 0). The relative intensity of the pulse is defined as

$$I = k \int_{\frac{2r}{c}-\varepsilon}^{\frac{2r}{c}+\varepsilon} V^2(t)\, dt \qquad (1)$$

where ε is large enough to make $\frac{dI}{d\varepsilon}/I \approx 0$ in the absence of noise, and k is a user-defined constant. In this paper, however, k depends on the recorder gain setting of the echo sounder.

Let a fish with apparent tilt and roll angles τ and ϱ be on the acoustic axis at distance r from the transducer. The r.s.c.s. function is defined by

$$\sigma(\tau, \varrho) = r^2 I \qquad (2)$$

where I is the measured intensity (1) of the received pulse. Equation (2) is used for experimental measurement of σ. For fish beyond the acoustic axis, positions are given in the usual transducer-fixed spherical reference system (θ,ϕ,r) as shown in Fig. 2. The relationship between I and σ for fish at position (θ,ϕ,,r) is simply:

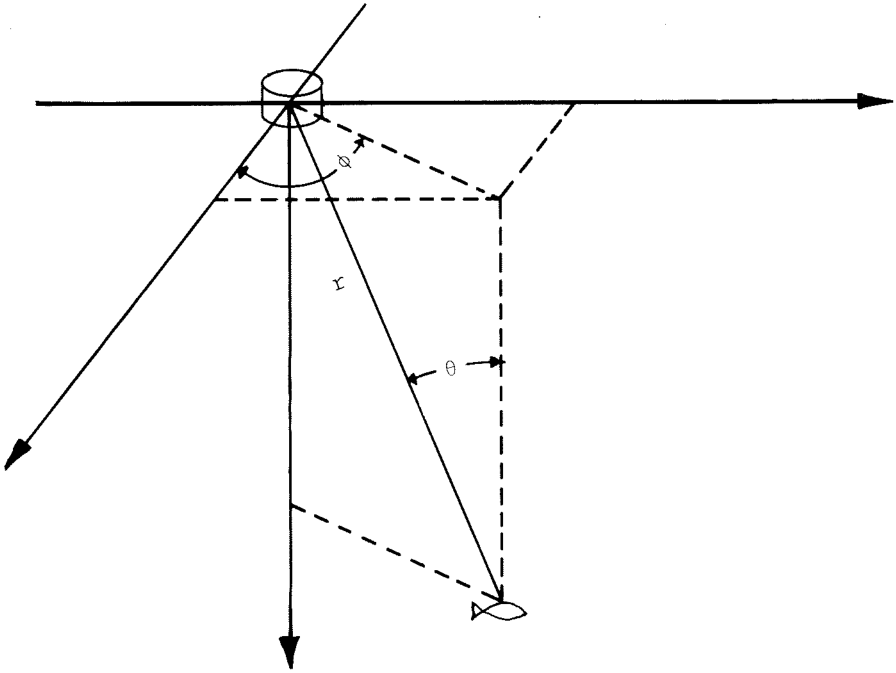


Fig. 2. Transducer-fixed reference system.

$$\sigma(\tau, \varrho) = \frac{r^2 I}{b^2(\theta, \phi)} \tag{3}$$

where $b^2(\theta,\phi)$ is the product of the transducer transmit and receive beam functions. It follows from (3) and substitution of $r = ct/2$ in the TVG function that

$$\frac{I}{\mathrm{TVG}(r)} \propto \frac{b^2(\theta, \phi)\ \sigma(\tau, \varrho)}{r^4}\ e^{-2\beta r} \tag{4}$$

This is the sonar equation expressed by the r.s.c.s.

The basic acoustic quantity assigned to single fish, as used in this paper, is given by the echo-value E (AKSLAND 1976).

$$E = \int_{\theta<\theta'} I\, dA = \int_{\theta<\theta'} \frac{b^2(\theta, \phi)\, \sigma(\tau, \varrho)}{r^2}\, dA \tag{5}$$

where dA is the area differential and the integral is over all the positions of the transducer in a horizontal plane above the fish within the circle $\theta = \theta'$. The integral can also be thought of as being over all positions of the fish in a horizontal plane beneath the transducer restricted by $\theta \leq \theta'$, but since it is the transducer which moves in a horizontal plane during acoustic surveys, the first explanation is preferred by the author.

Substitution of $dA = r^2 \, tg\theta d\theta d\phi$ leads to the following equivalent expression

$$E = \int_{\theta=0}^{\theta'} \int_{\phi=0}^{2\pi} b^2(\theta, \phi) \, \sigma(\tau, \varrho) \, d\phi \, tg\,\theta \, d\theta \tag{6}$$

Thus it is seen from (6) that if $\sigma(\tau,\varrho)$ is independent of the depth of the fish, then E is also depth independent.

For the echo-value to be uniquely defined, a value for θ' must be given, and σ must be expressed as a function of θ and ϕ. At first we give the echo-value of a fish with fixed orientation in the sea.

Since the data underlying the computation in this paper only contain measurements of $\sigma(\tau,\varrho)$ in the range $\varrho = 0$ and $-45° \leq \tau \leq 45°$, we assume that $\sigma(\tau, \varrho) \approx \sigma(\tau,0) = \sigma(\tau)$ for small roll angles, where the ϱ-argument is now supressed, and that apparent roll angles where this approximation does not hold have negligible probability.

From the general discussion by FOOTE (1980), or simply by geometrical considerations, the following relationship for the apparent tilt angle may be deduced:

$$\tau = tg^{-1} \; [x/ (1-x^2)] \tag{7}$$

where $x = \sin\theta\cos\alpha\cos(\phi-\gamma) + \cos\theta\sin\alpha$ and α and γ are the tilt and azimuth angles in relation to the sea.

Further, we introduce the special case of common circular symmetrical transmit and receive beam functions $b(\theta)$, since the transducer of survey use had this property.

Thus, the echo-value may be written

$$E = \int_{0}^{\theta'} b^2(\theta) \, \sigma_\theta(\alpha) \, tg\,\theta d\,\theta \tag{8}$$

where $\sigma_\theta(\alpha) = \int_{0}^{2\pi} \sigma(\tau) \, d\phi$ with τ given by (7).

That $\sigma_\theta(\alpha)$ is independent of the azimuth γ follows from the 2π periodicity of $\cos(\phi-\gamma)$. The determination of θ' is discussed below.

Normally E increases rapidly with θ' within the transducer main lobe, after which it flattens out and remains approximately constant until $\theta' \approx 90°$ where

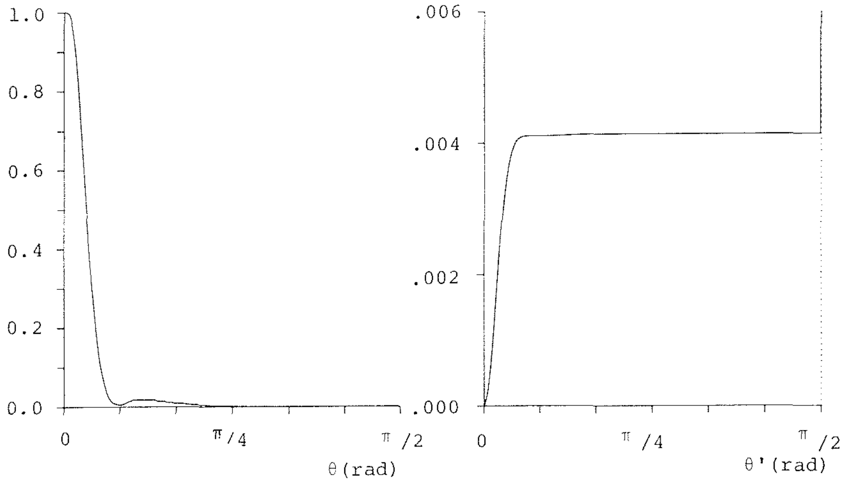


Fig. 3. Diagrams of b(θ) and $\int_0^{\theta'} b^2(\theta)tg(\theta)d\theta$

it diverges if $\sigma(90°)$ and $b(90°) >$. When $\sigma_\theta(\alpha)$ is replaced by unity, the flat region has a range from the angle of − 10dB on the main lobe to more than 89° for most transducers. The corresponding curve, generated by beam function of the transducer we used, is given in Fig. 3.

For normal fish distributions, $\sigma_\theta(\alpha)$ will be small compared to its maximum for all θ above a certain value, and it may be assumed that (8) has a similar shape as shown in Fig. 3, except perhaps for fish oriented near the vertical.

Let us define the echo-value to be that value on the flat region which, for practical purposes, can be assumed constant. The exact value for θ' may then be conveniently chosen within the flat region, but for computational reasons a small value would be advantageous. A value of 13° was used in the present work. It is seen from (8) that for fixed θ', E is a function of α alone. For free-swimming fish, the orientational behaviour is modelled by a probability distribution for α (FOOTE 1980).

Now, if α is a random variable, so is E, and the "mean echo-value" is simply defined as the expected value for E. Denoting the probalility density of α by $f(\alpha)$, the mean e ho-value is given by

$$\bar{E} = \int_0^{\theta'} b^2(\theta)\, \bar{\sigma}_\theta\, tg\, \theta d\, \theta \tag{9}$$

where $\bar{\sigma}_\theta = \int_{f>0} \sigma_\theta(\alpha)\, f(\alpha)\, d\alpha$

Two even more generalized echo-value concepts are needed. These are the length regression of mean echo-value, i.e. the expectation of (9) for a random fish of given length defined as

$$\hat{E}_l = \int_0^{\theta'} b^2(\theta)\, \sigma_\theta(l)\, \mathrm{tg}\, \theta d\theta \tag{10}$$

and the overall mean echo-value which is defined from (10) for given length distribution (probability density) h(l) by

$$\hat{E} = \int_{h>0} \hat{E}_l h(l)\, dl \tag{11}$$

Generalization to length-dependent tilt angle distributions is straightforward, but is not used in this paper. The estimation of these several quantities is done from measurements of r.s.c.s. on anaesthetized fish tilted by a tilting apparatus.

To complete the list of fishery-acoustic concepts used in this paper, the relative echo-abundance of a sea region will be defined.

After transmitting a sound pulse at position (x,y) relative to a Cartesian reference system on the sea surface, a vertical downward-looking echo sounder receives a signal which, after detection, generates a voltage signal, her denoted $V_{x,y}(t)$. As in (1), the time is zero when the center of the transmitted sound pulse is emitted. In analogy with (1) we call

$$I_{x,y}(t_1, t_2) = k \int_{t_1}^{\min(t_2, t_b)} V^2_{x,y}(t)\, dt \tag{12}$$

the relative echo intensity at position (x,y) in the time interval (t_1,t_2). To avoid contribution from the bottom echo in (12), t_b must equal the time when the bottom echo begins to rise.

Let D be a region of the sea surface. We call

$$M(D) = \int_D I_{x,y}(t_1, t_2)\, dA \tag{13}$$

where dA is the differential area dxdy, the echo abundance within D in the time interval (t_1,t_2). A more generalized version of (13) where t_1 and t_2 are functions of (x,y) will also be used.

The relative echo intensity and hence the echo abundance contain, in addition to energy from fish echoes, also some unwanted noise energy. It is assumed that noise, caused both by external sources and echoes from planktonic organisms, is a negligible part of the echo abundance provided that the mean fish density is not too low.

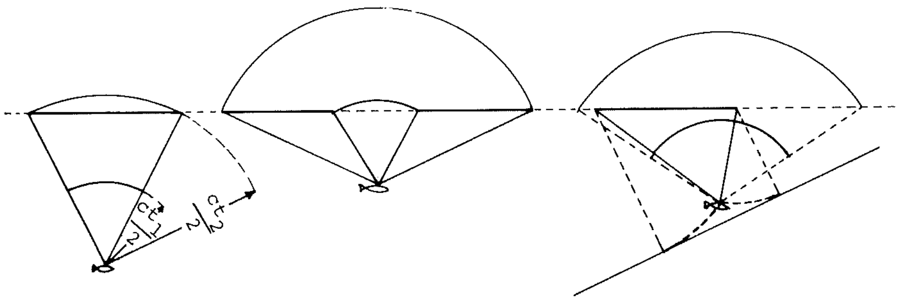


Fig. 4. The solid lines at transducer level indicate the positions where the fish echo is received in time-channel $[t_1, \text{min.} (t_2, t_b)] \cdot t_b$ is the time when the bottom echo is received.

Now, consider the echo abundance within a region D in a constant time interval (t_1,t_2). Since the energy in time-overlapping echoes, according to the random phase hypothesis, is the sum of the energies from the single echoes, it follows from (1) and (13) that M(D) is approximately equal to the sum of the random echo-values. Thus, because of the law of large numbers, M(D) is also the sum of the mean echo-values for the fish in region D and confined in depths between $ct_1/2$ and $ct_2/2$ where c is the sound speed.

However, as is seen from Fig. 4a, a fish at depth z contributes its echo-value which is given by (8) with $\theta' = \cos^{-1} (2z/ct_2)$. For fish at depths near $ct_2/2$ this will be smaller than the echo-value given by a proper value for θ'. On the other hand, as is seen from Fig. 4b, fish at depths $z > ct_1/2$ do contribute to the echo abundance at angles exceeding $\cos^{-1}(2z/ct_1)$ from the acoustic axis. Further, when a fish is near enough a flat or sloping bottom, its contribution to the echo abundance may be considerably smaller than its echo-value since many transducer positions with $\theta < \theta'$ may have a shorter distance to the bottom than to the fish (Fig. 4c). The errors caused by the effects illustrated in Fig. 4 depend of course on the transducer beamwidth and hence on the lowest value for θ' which can be used in (8).

For our purposes, it is assumed that the echo abundance from fishes within a region can be set equal to the sum of their mean echo-values. This implies the following relation between fish number N, echo abundance M and the overall mean echo value $\hat{E}$ for those fish:

$$M = N\hat{E} \tag{14}$$

Equation (14) is used to estimate fish number in this paper through estimation of M and $\hat{E}$.

THE FIELD WORK

A necessary condition for application of the theory outlined in the previous section, without calibration of acoustic instruments, is to use the same instruments for measurement of r.s.c.s. functions and for acoustic surveys. Constant performance in all functions of the equipment during the complete investigation must, of course, be assumed. The acoustic equipment consisted of a portable 70 kHz echo sounder and a ceramic transducer with a beam function as shown in Fig. 3.

The source level and pulse duration was given by the manufacturer Simrad a/s, as 112 dB//1 μBar at 1 m and 0.6 msec. The echo sounder had 10 settings of receiver gain 3 dB apart, and TVG settings of 20 log r and 40 log r. Pulse repetition rates of 90 and 180 pulses per second (pps) were available. The cabinet had two sets of outputs for trigger pulse and received signal, and a marker button, which in addition to marking the paper also switched the output trigger pulse off when pushed.

The output echo signal was converted to 10 kHz in order to facilitate recording on analog tape. During operation the outputs were connected to an oscilloscope and to a conventional high-quality portable cassette recorder. The trigger pulse and acoustic signals were recorded on separate tracks. The echo sounder had a test setting in which a constant test signal was fed to the TVG amplifier. The test output was always recorded on the tape as reference for the acoustic signal, thus making superfluous an exact and known recorder gain setting. The system was powered by a 12 v storage battery.

Measurements of absolute target strength on herring at 70 kHz did not exist at the start of this project so it was decided to incorporate such measurements. However, since it was natural to use the same echo sounder and transducer both for measurements and acoustic surveys, relative values were sufficient, and the measurements were done without calibration.

The field work is classified into three parts:

1. Measurements of the r.s.c.s. function of single fish.
2. Acoustic reconnoitering and surveying along zig-zag nets.
3. Catching of herring in gill-nets for analysis of the length distribution and other biological parameters.

Measurements under part 1 were done during 2–8 September 1978 at the location shown in Fig. 5. The location was chosen for its sheltered environment and its sufficient depth of 10–12 m.

The experimental setup was similar to that of NAKKEN and OLSEN (1973) with the exception that a smaller float was used, and that data were recorded in analog form on to the cassette recorder. The transducer depth was approximately 10 m, and the distance between target and transducer 8.35 m. The pulse repetition rate was 3 per sec giving 170 pulses over one rotation of tilt angle

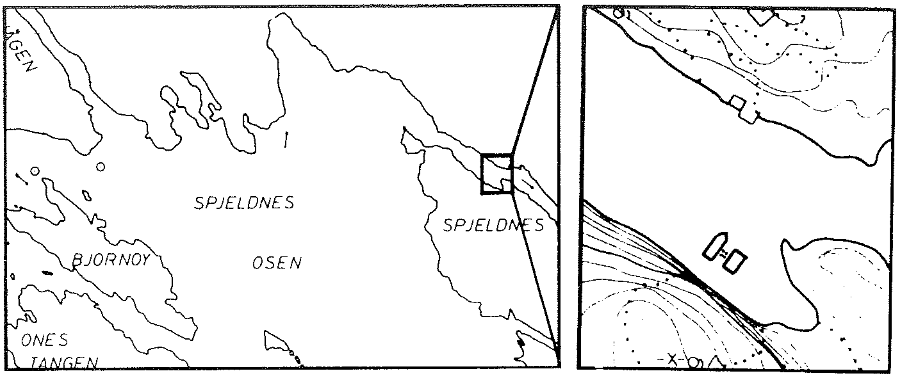


Fig. 5. Location used for the measurements of relative scattering cross-section functions.

from $-45°$ to $45°$. The different measurement series were separated in the recordings by time intervals without trigger pulse produced by depressing the marker button a second or so before and after each measurement series.

A total of 118 fish consisting og 15 sprat of lengths 7.3–12.9 cm, 92 herring of lengths 7.9– 36.5 cm and 11 fish of others species were measured. Of these, only herring and sprat will be used in this paper. The sprat are included for the analysis of autumn surveys where a mixture of sprat and 0-group herring were found. This is, however, not reported here.

The fish were caught by purse seine and transported to the location of measurement in net cages. However, although the smallest fish were caught the night before they were measured, most of them did not survive and had to be measured dead.

A 40 mm steel sphere was used to test the setup and included a series of measurement at each receiver gain setting.

A target depth of approximately 1.65 m was chosen as the separation of target and surface echo was excellent there. However, some of the measurements were later disturbed by echoes from air bubbles near the surface which occasionally were brought into the measurement position by local currents.

Acoustic surveys across the area of distribution of the spawning stock were done by the same method in late March 1978, 1979 and 1980. A 30-foot motor boat equipped with navigation radar was used, and the transducer was mounted on a special frame approximately 1 m in front of the bow as shown in Fig. 6.

The date of the first survey each year was determined from estimates of the degree of maturation of herring in gill net catches taken regularly from the middle of March. The spawning stock aggregated in the same area each year, and it was found that the best time for survey was just before spawning since the fish distribution was then concentrated and relatively stabilized.

When most of the herring in the catches was fully matured, the geographic

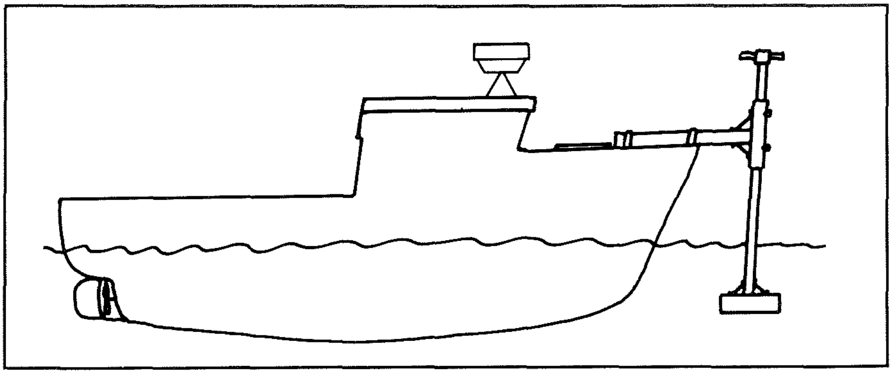


Fig. 6. Transducer setup.

distribution of the stock was determined from reconnoitering surveys. These showed that the stock concentrated in one or a very few large schools during the day, which at night spread out slightly into one connected layer of variable, but high density. The layer always covered less than 50 acres as is seen from Fig. 13 and 14 in the next section. The echoes from mature herring in this layer were always dominant in relation to echoes from other sources.

When the state of maturation indicated a possible spawning within a week or so, the surveys were commenced the same evening. A zig-zag net was designed, and care was taken to ensure that the courses could be followed in the dark by radar. Thanks to the radar, the actual courses followed could be traced relatively accurately on a map after each survey.

Before each survey the receiver gain was set by adjusting peaks of the strongest echo signals slightly but safely below the clipping level of the output amplifier. The recording level on the cassette recorder was further adjusted to just accept the clipping level without causing tape saturation, and so after recording the test-signal for 30 seconds, the survey could start. In order to obtain a relationship between every part of the acoustic signal and the corresponding position on the survey net, the boat was held at constant speed throughout the survey, and the marker button was depressed during each turn to a new course. Trigger pulses were thus stored on the straight part of the courses only.

In 1978 two repetitive surveys were carried out around midnight 28–29 March. The survey nets are shown in Fig. 13. The depth distribution can be read from Fig. 7 where it is seen that most of the herring was found between 10 and 25 m depth.

In 1979 three repetitive surveys were done before midnight on 27 March. Although the herring distribution was geographically similar to that of 1978, the depth distribution was different. As can be seen from Fig. 7 the herring was found from surface to 18 m and this may be the reason why it reacted so

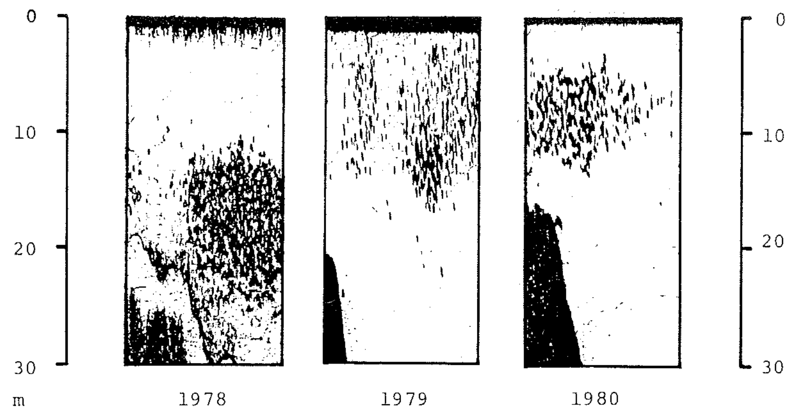


Fig. 7. Illustration of depth distributions.

strongly to the boat. Fig. 14 shows that between survey 1 and survey 3 the herring moved southeast off Bjørnøy.

In 1980 the survey was conducted two hours before midnight on 30 March. The geographical distribution was slightly different this year since the herring were closer to Bjørnøy and stretched farther to each end of the island as compared to the two previous years. The depth distribution was from 4 to 15 m.

Two additional surveys were conducted the next evening, but by then most of the herring had migrated out of the region, and as such only the first survey will be used.

Apart from fish caught by purse seine for measurement of r.s.c.s., all fish samples were caught by gill nets at the positions shown in Fig. 8. The catch for length-distribution analysis of the spawning stock were done over 3 to 4 nights terminating the first day after the acoustic survey. Since the acoustic signal from 1978 could not be used, as is explained in the next section, the gill net samples from this year will not be discussed.

In 1979 and 1980 gill nets with mesh sizes 21, 24, 26, 29 and 31 mm were used. Apart from the 26 mm net, the areas of the gill nets are proportional to the mesh sizes. The 26 mm gill net was larger than the others and was only used in the preinvestigations for determination of the degree of maturation.

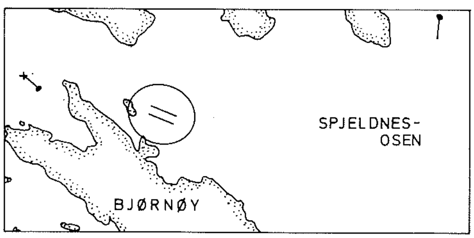


Fig. 8. Gill net position.

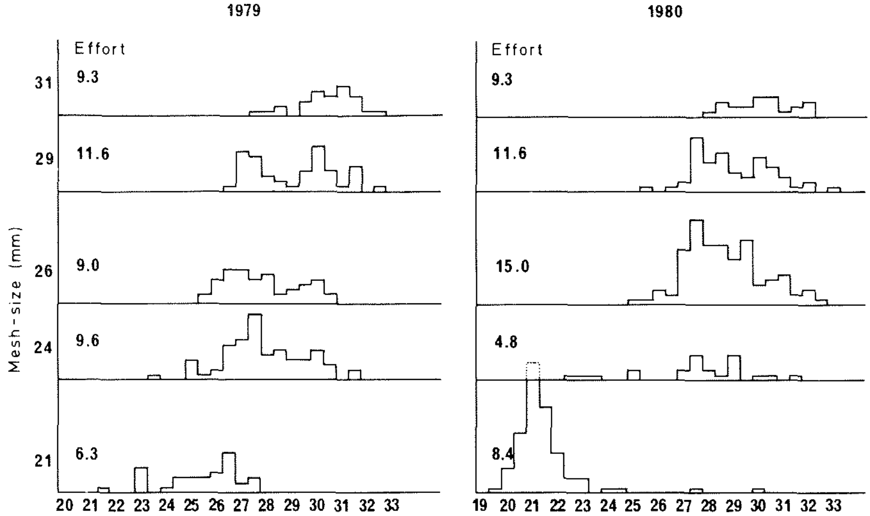


Fig. 9. Length distributions in the gill net catches. The lowest bars corresponds to one fish.

The last of these catches, however, is used together with the others for length distribution analysis. The length distributions for each mesh size are shown in Fig. 9. The measure of relative effort is proportional to the product of gill net area and the number of nights with catching.

DATA PROCESSING AND ANALYSIS

Since no existing equipment for processing of acoustic signals according to the method presented in the first section were suitable, the analog signals had to be digitized and stored for later processing by general computers. This was done on board the R/V "G. O. Sars" in Bergen in June 1980 on a system consisting of an A/D converter, a Nord 10 computer and a digital tape station.

A 10 kHz bandpass filter with 4 kHz bandwidth was used between the cassette recorder and the system input to lower the signal-to-tape noise ratio. Actually this reduced the noise level by as much as 10 dB for the weakest parts of the signals. The signal was converted to 12 bit numbers at a rate of 15150 Hz, and all numbers from one sound pulse were stored in one block. The digitized part of the signal extended from the surface to a given depth which was set as small as possible for each new digital tape without losing any fish echoes. Further, the time of a computer clock was stored as the first number in each block in order to be able to detect separations between series of pulses (produced during the recordings by depression of the marker button). The input gain was held constant throughout the digitizing, giving a value of

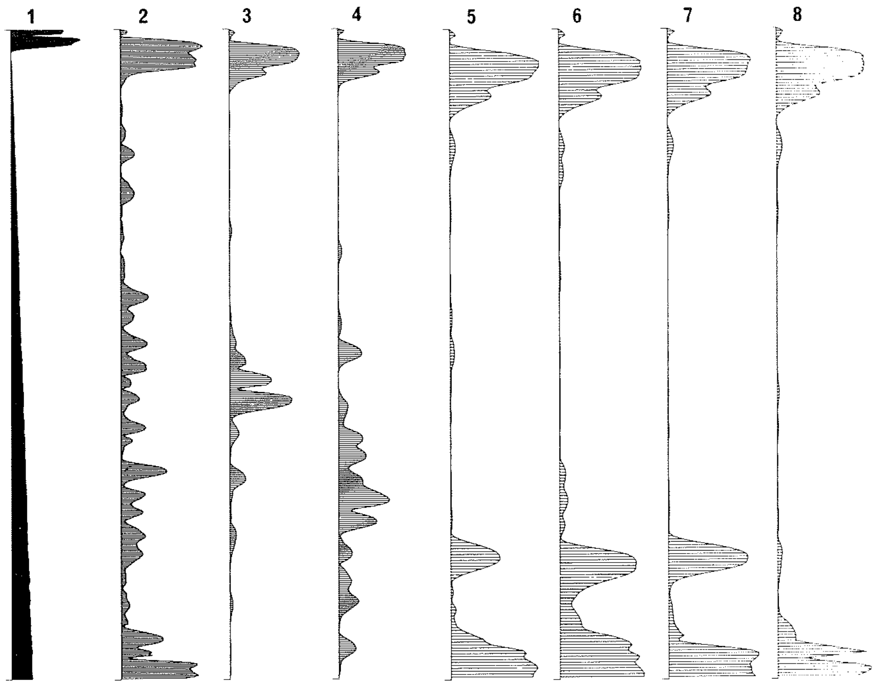


Fig. 10. 1. Test-signal; 2. Signal with transmit and bottom echo; 3 and 4. Signals from spawning stock 1979; 5–8. Echoes from the measurements r.s.c.s. showing transmit pulse and surface echo; 5. Good echo; 6. Strong echo with air bubble noise; 7. Strong but good echo; 8. Weak echo.

approximately 2400 for signals corresponding to tape saturation. The noise readings had digital values between 0 and 6. Some of the digitized signals are shown in Fig. 10. There is 66μs between successive readings, shown as horizontal lines, giving 20 lines, per m depth.

The designing of computer programs for processing the data constituted the most time-consuming part of the present project and was performed mainly on Nord 100 computer system at the Institute of Marine Research. Because special software was needed, some routines were also run at the computer center at the University of Bergen.

As the natural addressing on the tapes is by block number and within blocks by "sequence number", a correspondence to the actual geographical positions on the surveys and for the r.s.c.s. data, a correspondance to the measured fish numbers had to be established. Establishing this constituted the first step of the data processing.

The time between successive trigger pulses obtained from the stored computer clock times were tested against the time given by the used pulse repetition rate. When this was sufficiently exceeded, the last block read was the first in a new series of pulses. To pick out false series caused by possible weak trigger pulses, reset of the computer clock and some stops during the digitizing, two special routines were included. One of these examined each block for a bottom echo. As tests on any bottom echo level could not be used because of the limited dynamic range on the analog tapes, the sum of between 20 and 30 sequential sequence numbers scanned over the block was tested against a value which as a rule was exceeded when a bottom echo was hit, but very seldom when hitting echoes from fish concentrations. If a bottom echo was found, the sequence number of its center was plotted at a line printer, otherwise, the block was checked for the presence of a test signal. If present, pertinent information was written on the line printer. If not present, a star was written to indicate that the bottom echo was beyond the range of digitized values. In fact, the output of the program showed the bottom contour of those parts of the survey where the bottom was above a certain depth. Further, each single series of pulses, usually corresponding to a leg of the survey net, was separated by written information about the number of blocks in the previous series and the block number of the first pulse in the next series. The other routine, written for the r.s.c.s. data, differed from the first one only in that the peak values of the target echoes were plotted instead of the position of the bottom echo.

For a more detailed examination of the data, an interactive program, here called "the investigation program", was designed. With a tape mounted on the tape station the program is able to perform the following upon input of proper codes and parameter values:

1. Advance or backspace to a given block number and read its content into memory.
2. Display the voltage readings within a given interval of sequence numbers on the terminal screen by their actual number.
3. Plot the selected voltage readings by means of stars on the terminal screen.

The programs described hitherto were necessary for obtaining information such as addresses for any part of the data in terms of block numbers and sequence numbers. The investigation program was also used to check the quality of the data. In fact, some defects were found which could be remedied. These are described later.

The most serious defects, however, were found in the 1978 survey data, which had to be rejected for the following reason: The transmit pulse and bottom echo as shown in Fig. 10.2, which should be fairly constant because they are clipped in the echo sounder, varied considerably. Since large parts were at the tape saturation level, these defects could not be compensated for. The echo sounder was changed the following summer, but as similar variations, although smaller, were also found in data from the new echo sounder, there is reason to beleive that they were caused by the tape recorder.

It was, however, not necessary to reject any of these data since the defects could be compensated for.

The data processing was continued by analysis of the test signal series. Examination of test-signals recorded with "20 log r" TVG showed that they were fairly linear functions of the depth, at least above 30 m where the majority of fish echoes could be found (Fig. 10.1). This was accepted since absorption is negligible at small depths.

Because all parts of the data should be referred to their appropriate test signal series, a measure of the test signal strength had to be calculated. It was chosen to base this measure upon the maximal signal over the signals in each series since individual variations within a series were mainly caused by drops in the strength. A straight line was fitted by hand to the maximized signal and the squared ordinate of this line at the depth of 12 m was used as the measure of test signal strength.

To perform echo integration for the survey and r.s.c.s. data, the voltage readings have to be squared. However, when checking the analog tape recorder, the linear relationship between voltage in and voltage out was found to have broken down for input intensities approximately 8 dB below the lowest value causing complete tape saturation. Because parts of the signals had values above this linear domain, a routine was written which squared a voltage reading after compensating for possible nonlinearity during analog recording.

Investigation of the r.s.c.s. data showed that no fish echo contained more than 17 sequence numbers (Fig. 10. 5–8). However, the location of the echoes was not quite constant possibly due to small variations in the depth of the fish during tilting and also variations in the form and location of the trigger pulses. The smallest fixed interval containing all echoes had to consist of more than 30 sequence numbers, and to avoid the integration of noise, a routine was written which located the echo and summed its squared voltages over just 17 sequence numbers. Also, since some of the data contained air bubble noise, which is seen in Fig. 9.6, and which most often was at the echo-tail nearest the surface, the routine was able to adjust the interval of integration slightly away from the noise. Further, if both tails were badly mixed with noise, the squared peak value of the echo was calculated and multiplied by the factor 7.1, which was obtained as the mean of the ratios between summed squared values and the squared peak value of 2500 echoes with negligible noise.

After rejection of measurements containing defective data, a total of 93 measured fish with length range 7.3–32 cm was picked for computation of the r.s.c.s. function (2). The measured echoes from these fishes were integrated by the routines just described, and the corresponding r.s.c.s. functions computed by use of the associated test-signal strengths and receiver gain levels. Some of the calculated functions are shown in Fig. 11.

Next, a program for computing mean echo values for a set of tilt angle

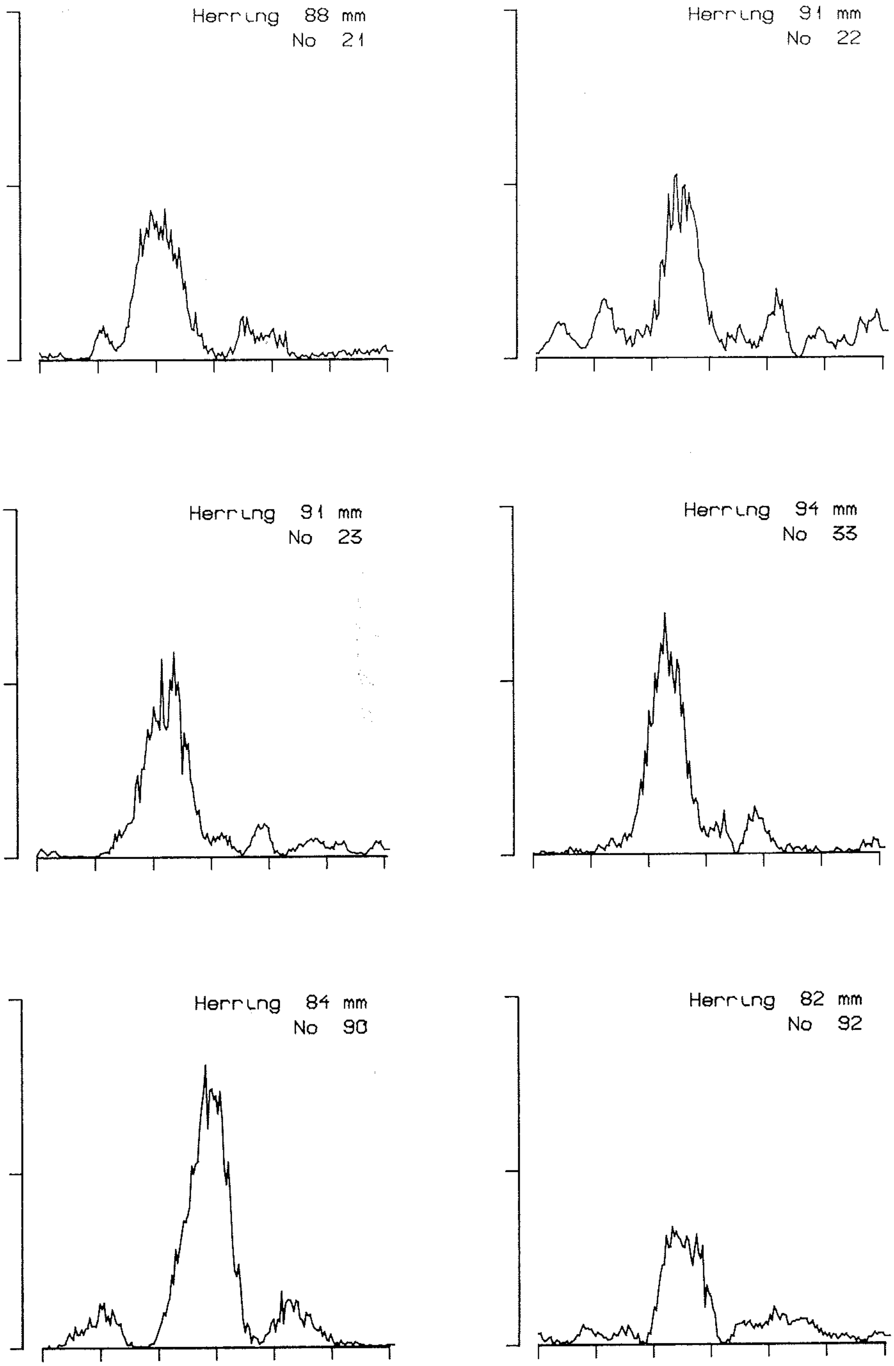


Fig. 11. 42 relative scattering cross section functions between −45° and 45° of fish of different sizes. The y-axis is linear with the same arbitrary chosen unit between the ticks.

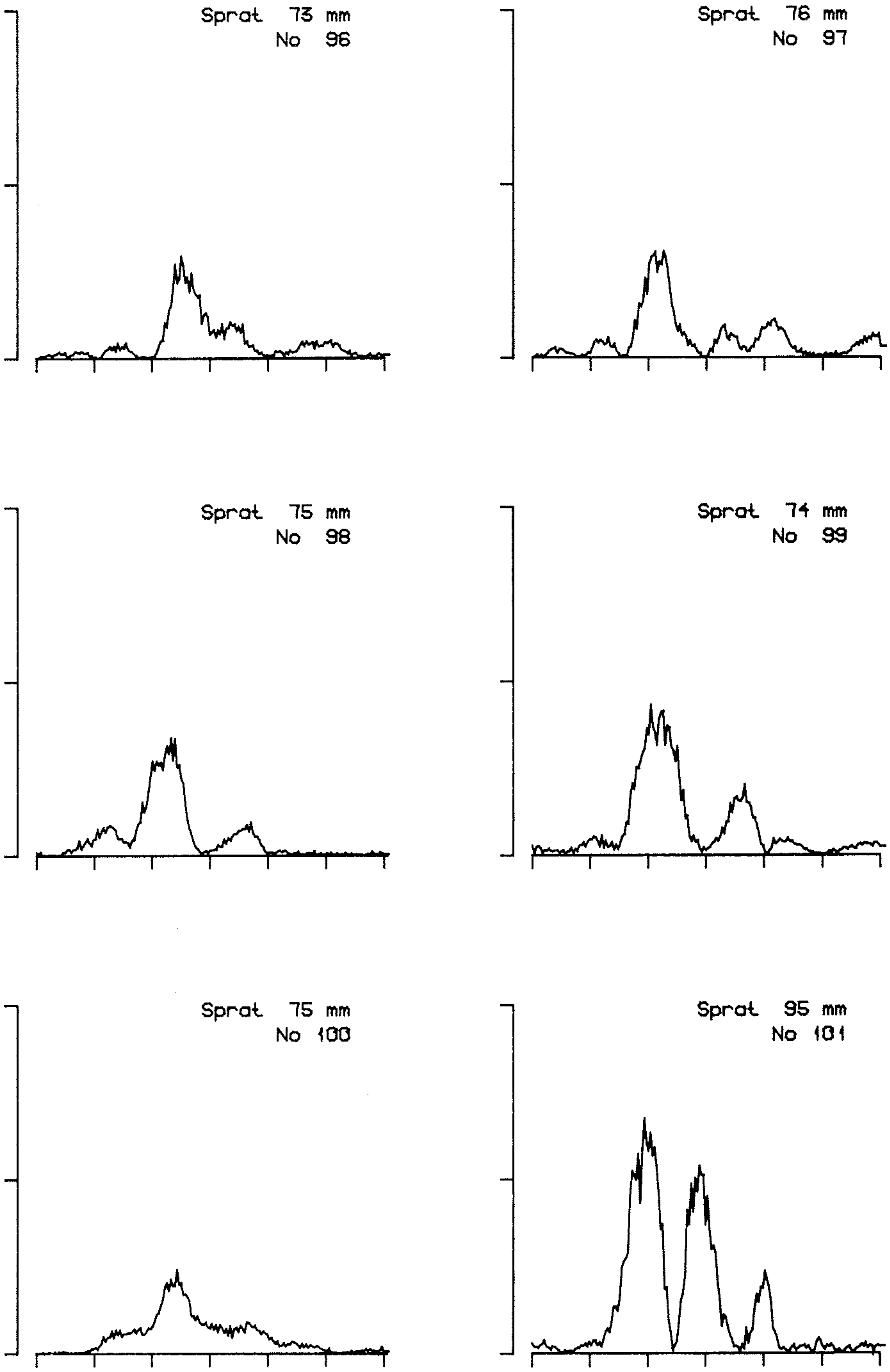

Sprat 73 mm
No 96
Sprat 76 mm
No 97
Sprat 75 mm
No 98
Sprat 74 mm
No 99
Sprat 75 mm
No 100
Sprat 95 mm
No 101

Fig. 11. Cont.

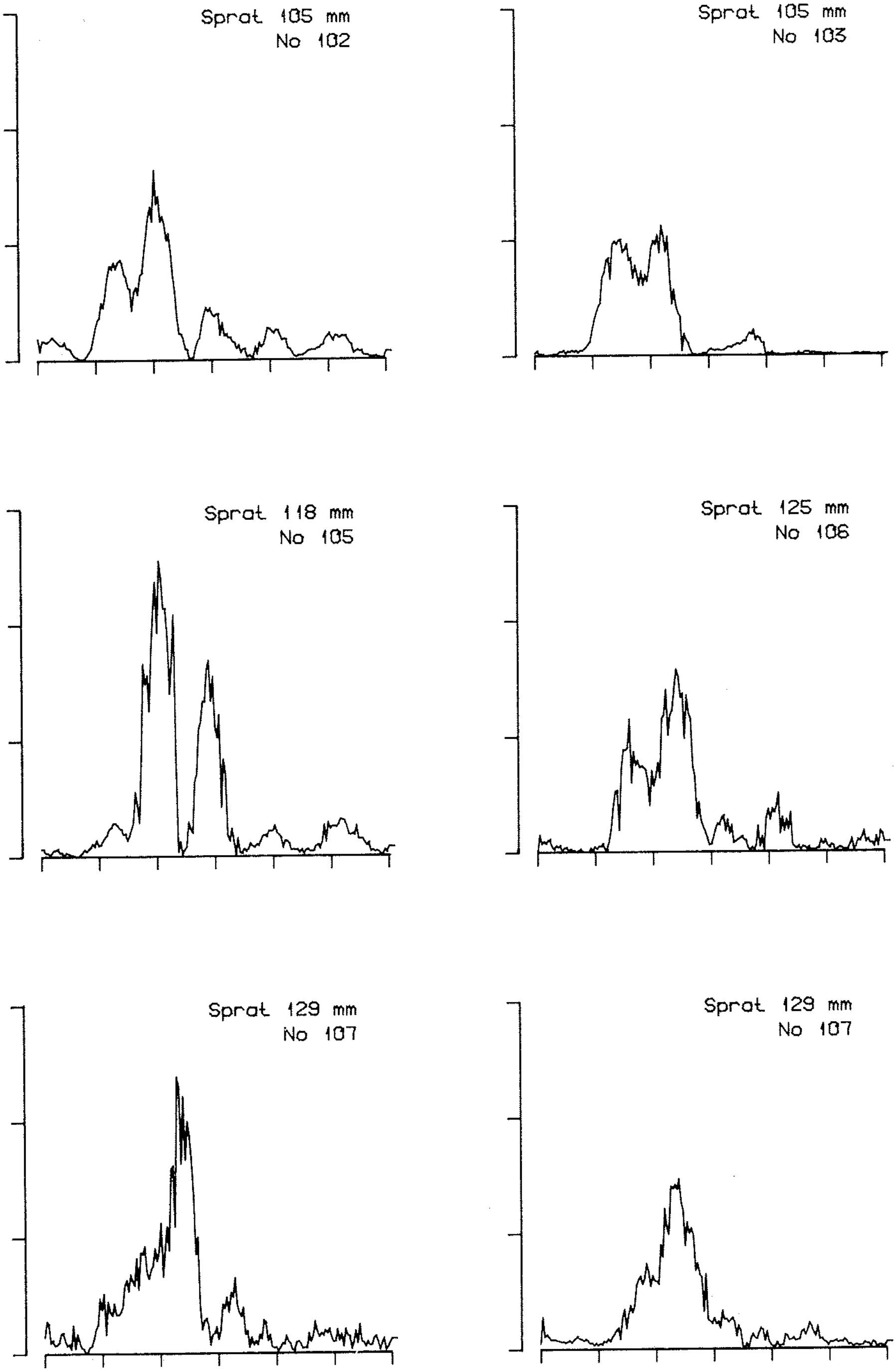

Sprat 105 mm
No 102
Sprat 105 mm
No 103
Sprat 118 mm
No 105
Sprat 125 mm
No 106
Sprat 129 mm
No 107
Sprat 129 mm
No 107

Fig. 11. Cont.

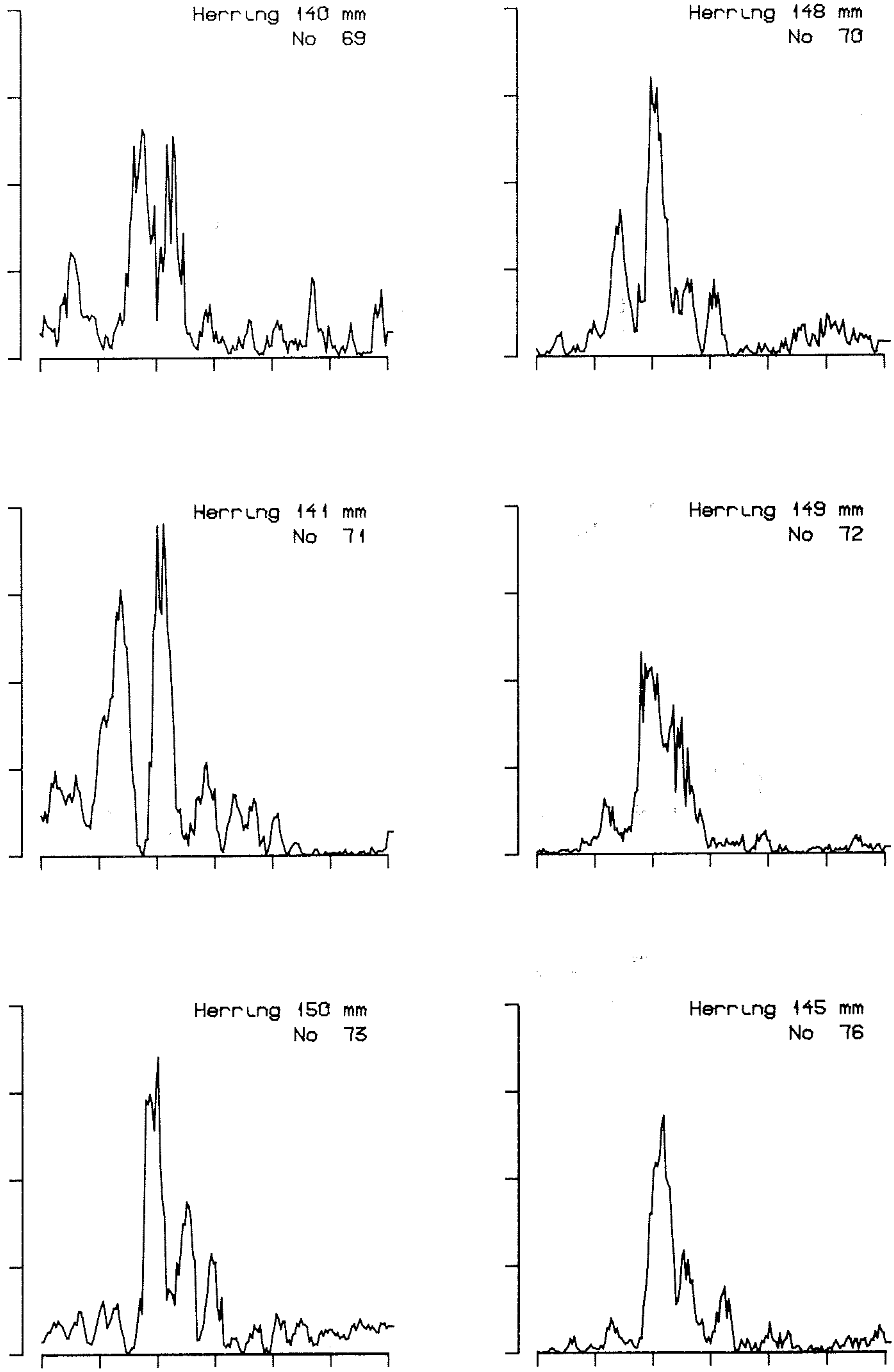

Herring 140 mm
No 69
Herring 148 mm
No 70
Herring 141 mm
No 71
Herring 149 mm
No 72
Herring 150 mm
No 73
Herring 145 mm
No 76

Fig. 11. Cont.

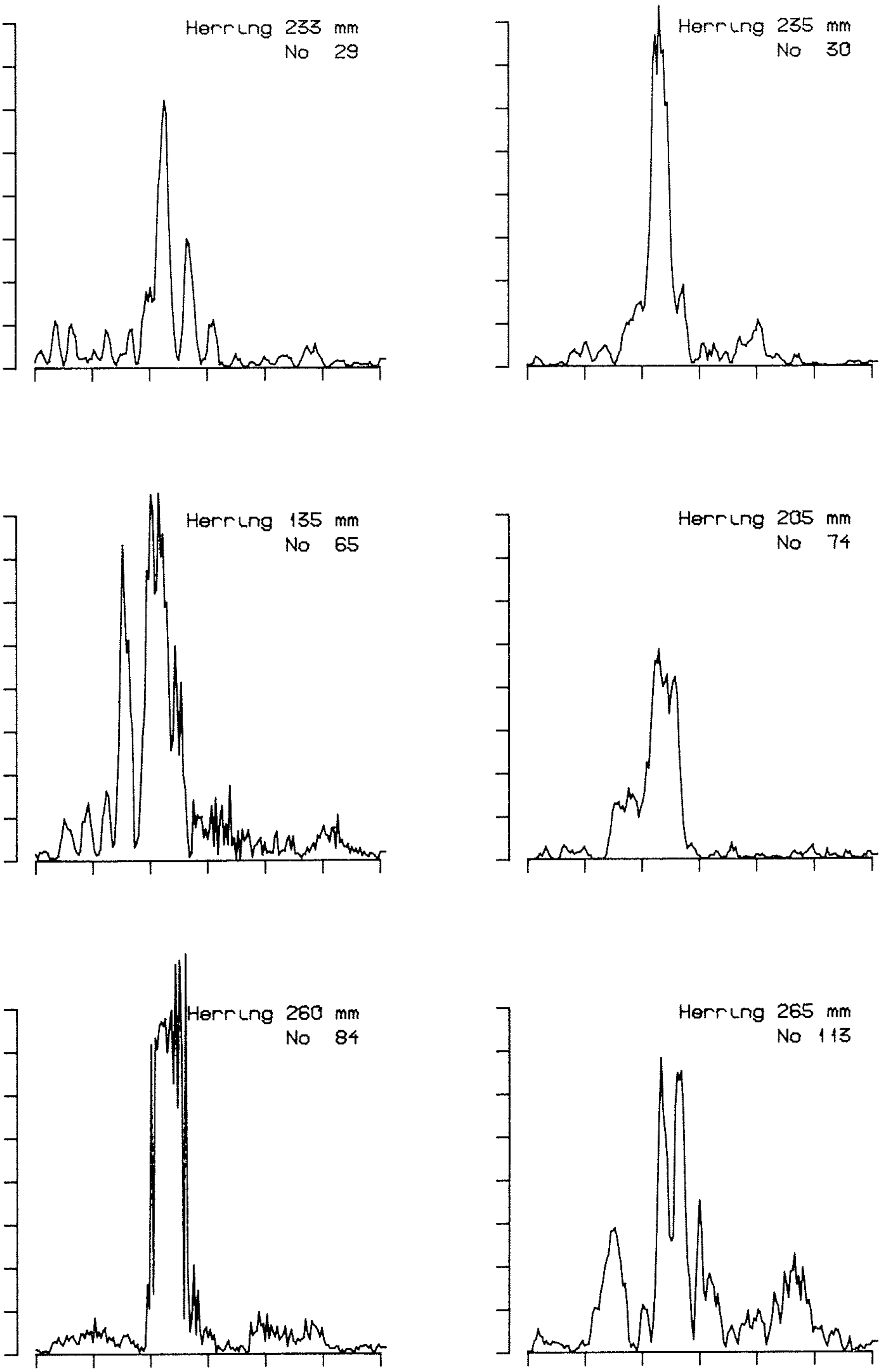

Herring 233 mm
No 29
Herring 235 mm
No 30
Herring 135 mm
No 65
Herring 205 mm
No 74
Herring 260 mm
No 84
Herring 265 mm
No 113

Fig. 11. Cont.

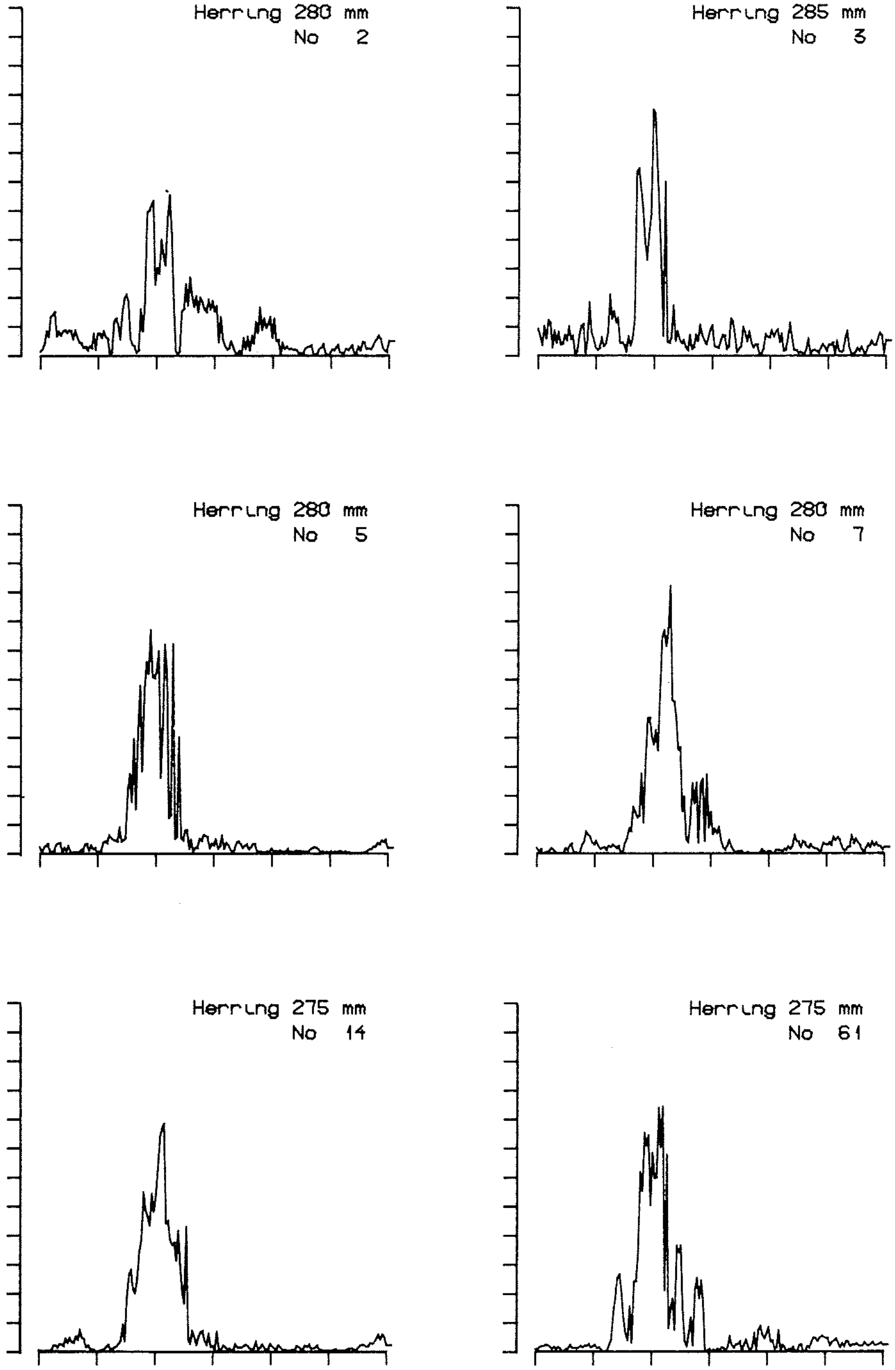

Herring 280 mm
No 2
Herring 285 mm
No 3
Herring 280 mm
No 5
Herring 280 mm
No 7
Herring 275 mm
No 14
Herring 275 mm
No 61

Fig. 11. Cont.

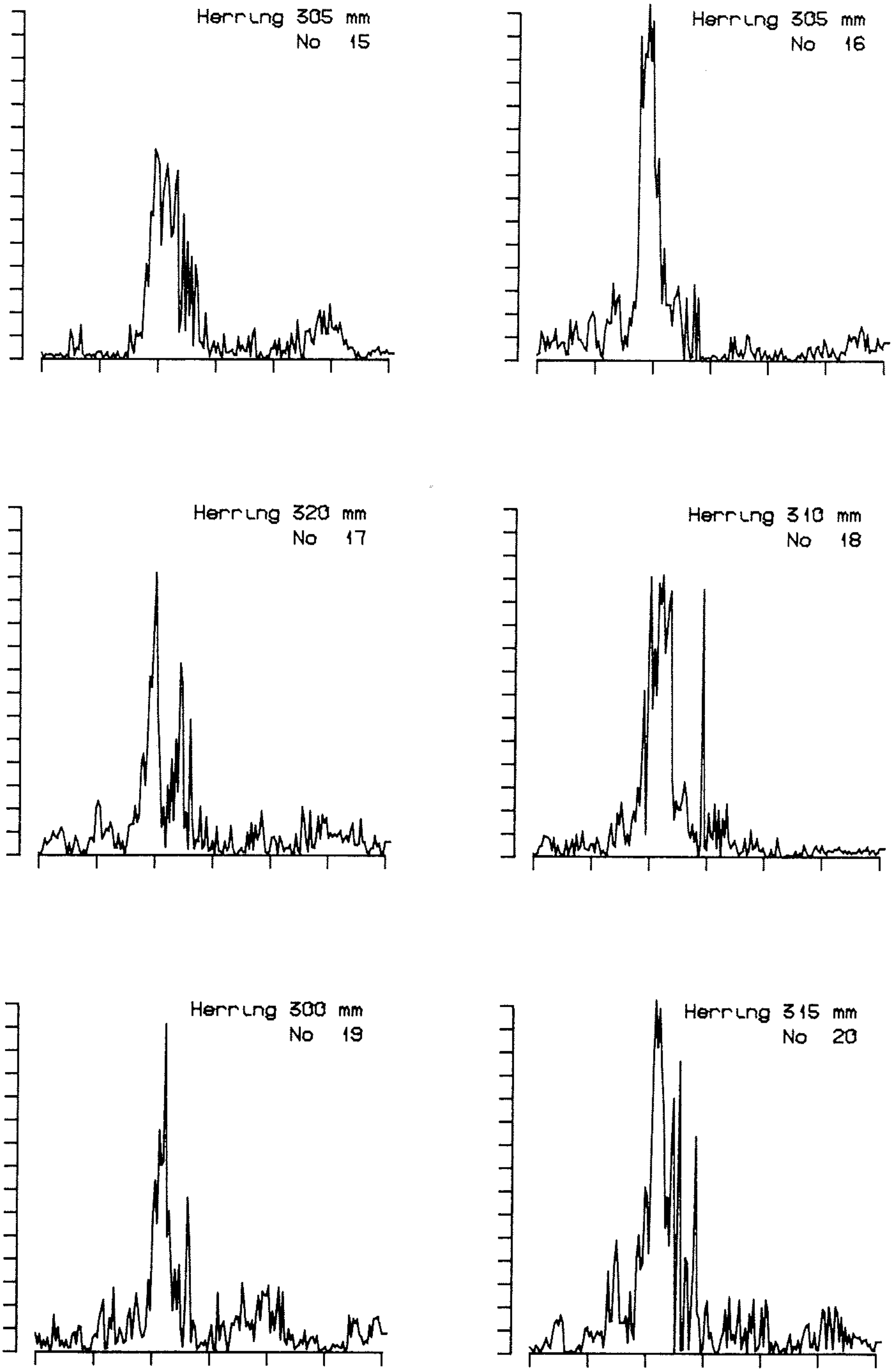

Herring 305 mm
No 15
Herring 305 mm
No 16
Herring 320 mm
No 17
Herring 310 mm
No 18
Herring 300 mm
No 19
Herring 315 mm
No 20

Fig. 11. Cont.

Table 1. Tilt angle distributions used for calculation of abundance estimates.

Mean (degrees)	Standard deviation (degrees)	Behaviour
10	10 20	Mean upward-looking fish.
0	10 20 30	Various activities, but mean horizontal orientation.
−10	10 20	Mean orientation of swim-bladder approximately horizontal.
−20	10 20	Slightly downward-looking fish.
−30	20	Avoidance behaviour.
−40	20	Strong avoidance behaviour.

distributions was written. Normal tilt angle distributions truncated four standard deviations from their mean, and further specified in Table 1, were used. The program performed numerical integration of (9) for all selected r.s.c.s. functions and each tilt angle distribution.

Foote (1980) found that his averaged fish target strengths were linearly related to the logarithm of fish length. As the scattering cross section is an exponential function of target strength, the mean echo values may be regressed on fish length l by the relation Al^B, for some constants A and B depending on the tilt angle distribution. In fact, 11 relations

$$A_i l^{B_i} + C \qquad i = 1, 2, \ldots, 11 \tag{15}$$

were fitted by the least squares method to the computed mean echo-values corresponding to the 11 distributions given in Table 1.

More precisely, denoting the mean echo-value for the j-th measured fish with i-th distribution by E_{ij}, and it's length by L_j, the constant A_i, B_i, $i = 1,2, \ldots, 11$ and C were determined to minimize

$$Q = \sum_{i=1}^{93} \sum_{j=1}^{11} \frac{(E_{ij} - C - A_i L_j^{B_i})^2}{L_j^2} \tag{16}$$

where C will be interpreted as the mean contribution from noise sources. The minimization program also had a routine which plotted the regression curves

$$A_i \, l^{B_i}$$

together with the mean echo-value data as shown in Fig. 12. Since C, which was estimated as 4, represents noise, it was subtracted from the data points and (15) before plotting.

To compute an estimate of the overall mean echo-value per fish in the spawning stock, an estimate of the length distribution of the stock is needed in (11).

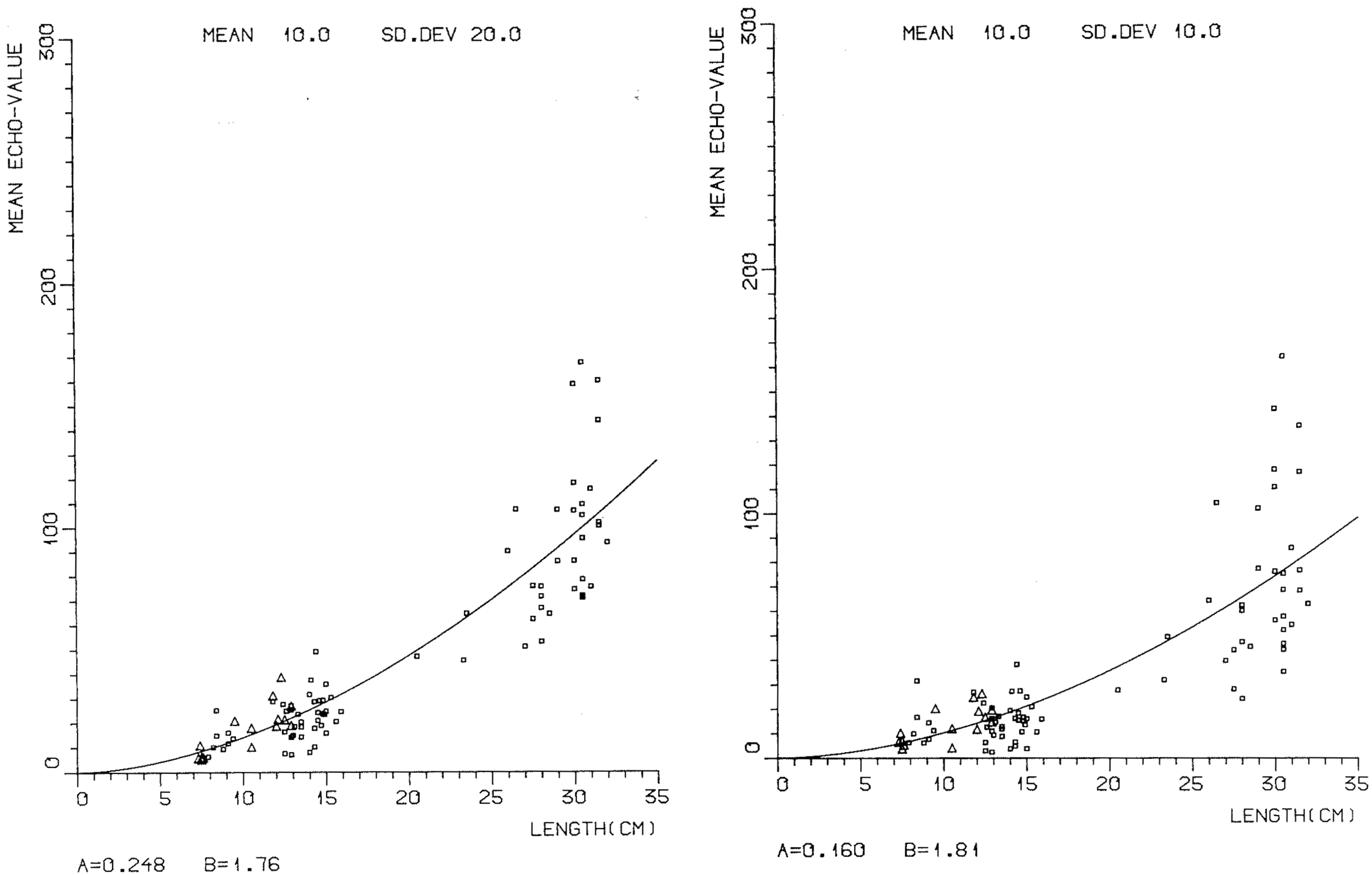
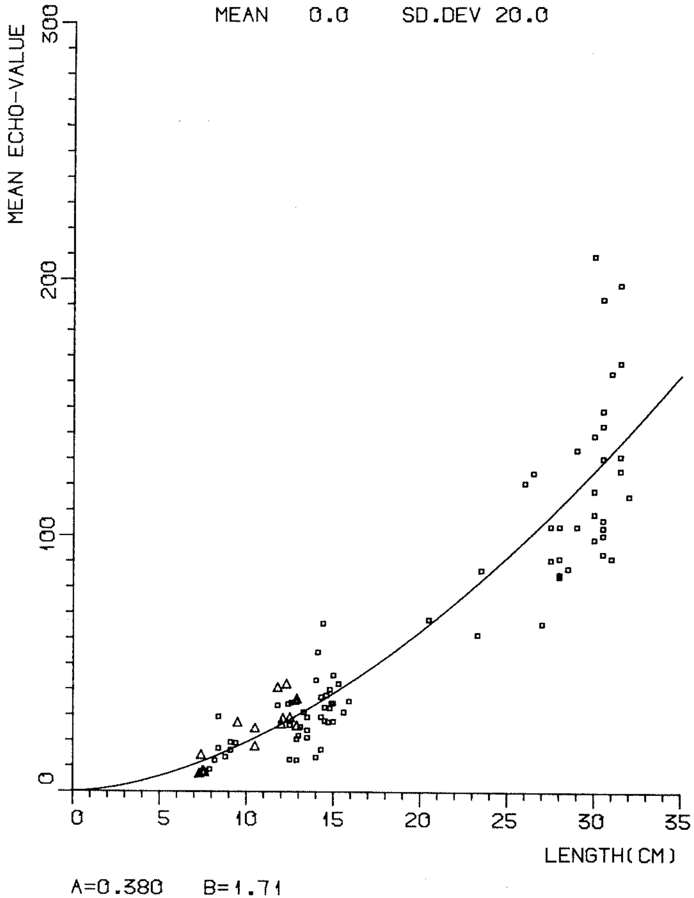


Fig. 12. The computed length regression given by A (LENGTH)^B of the mean echo-values at 11 tilt angle distributions. The data points are marked with □ for herring and △ for sprat.


MEAN 0.0 SD.DEV 20.0
MEAN ECHO-VALUE
LENGTH(CM)
A=0.380 B=1.71

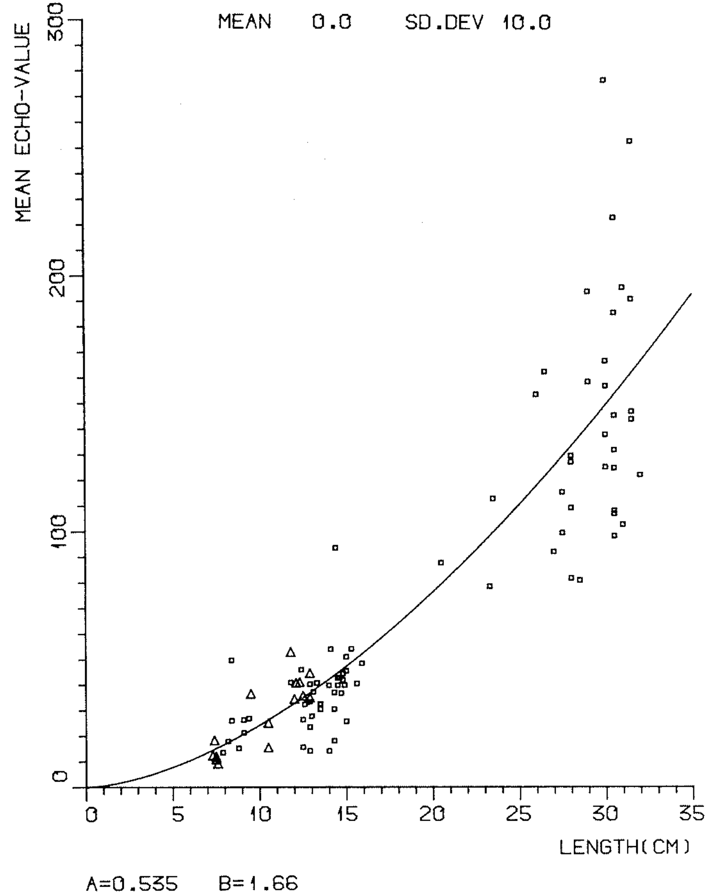

MEAN 0.0 SD.DEV 10.0
MEAN ECHO-VALUE
LENGTH(CM)
A=0.535 B=1.66

Fig. 12. Cont.

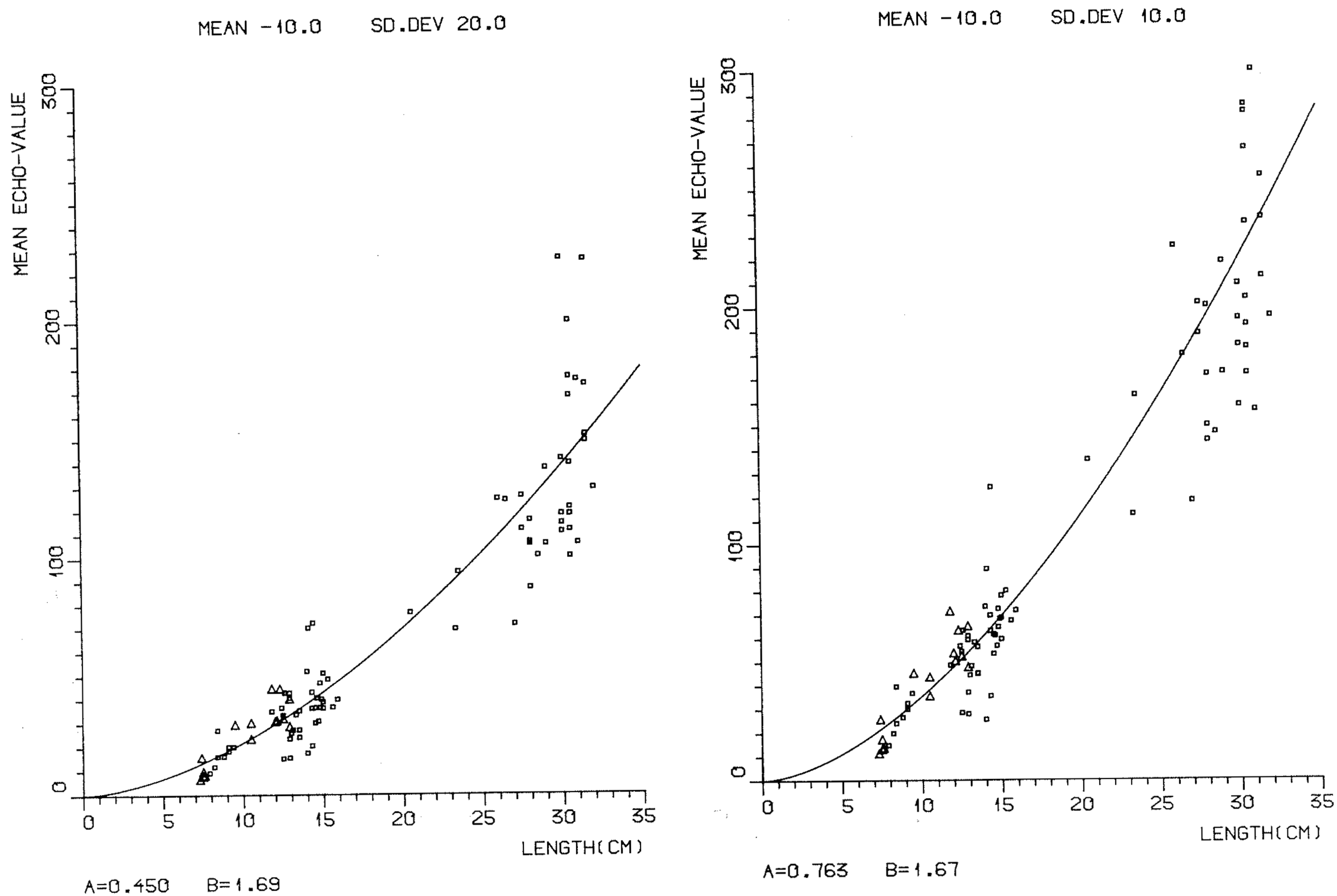

MEAN -10.0 SD.DEV 20.0
MEAN ECHO-VALUE
0
100
200
300
0
5
10
15
20
25
30
35
LENGTH(CM)
A=0.450 B=1.69
MEAN -10.0 SD.DEV 10.0
MEAN ECHO-VALUE
0
100
200
300
0
5
10
15
20
25
30
35
LENGTH(CM)
A=0.763 B=1.67

Fig. 12. Cont.

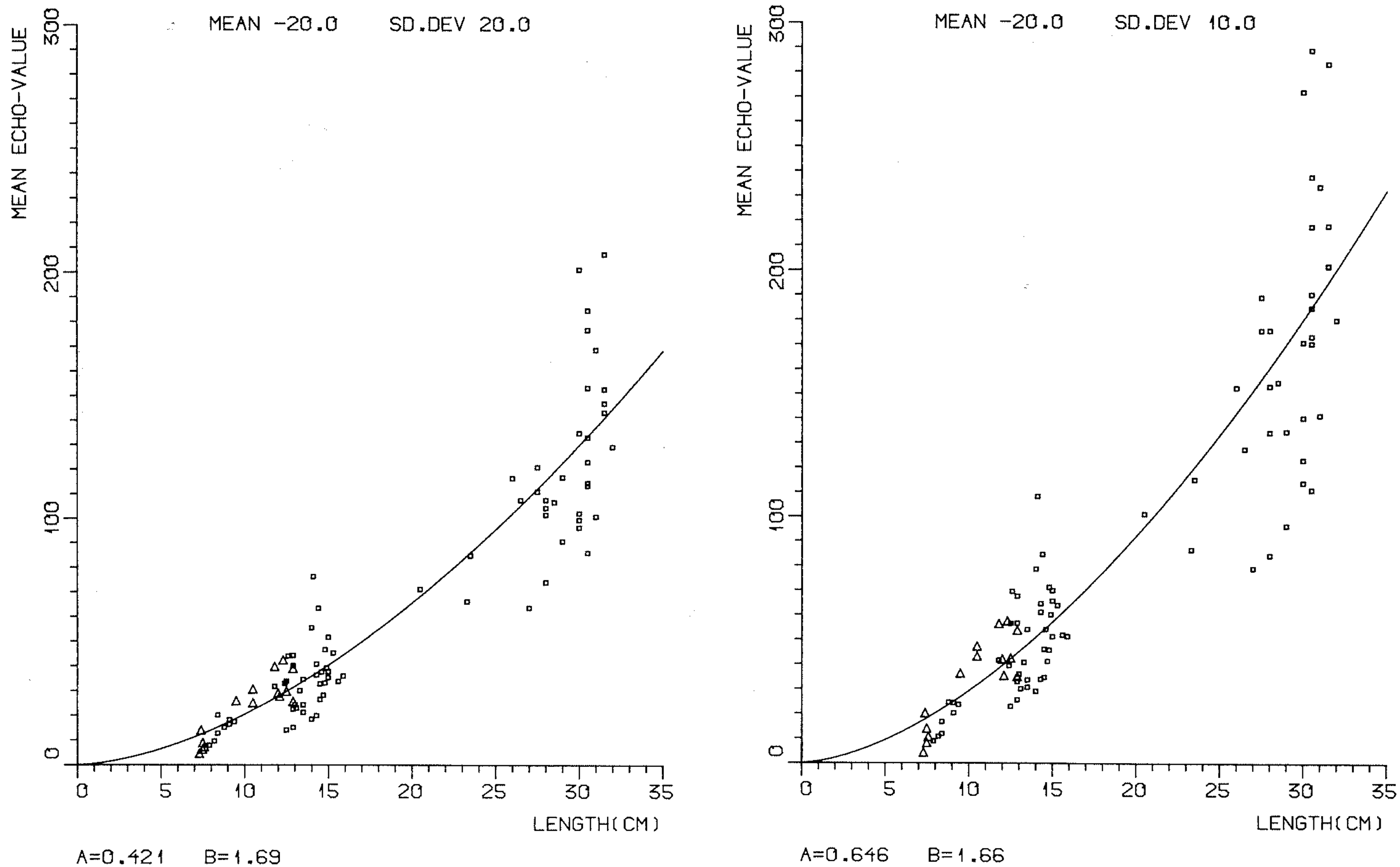

MEAN -20.0 SD.DEV 20.0
MEAN ECHO-VALUE
LENGTH(CM)
A=0.421 B=1.69
MEAN -20.0 SD.DEV 10.0
MEAN ECHO-VALUE
LENGTH(CM)
A=0.646 B=1.66

Fig. 12. Cont.

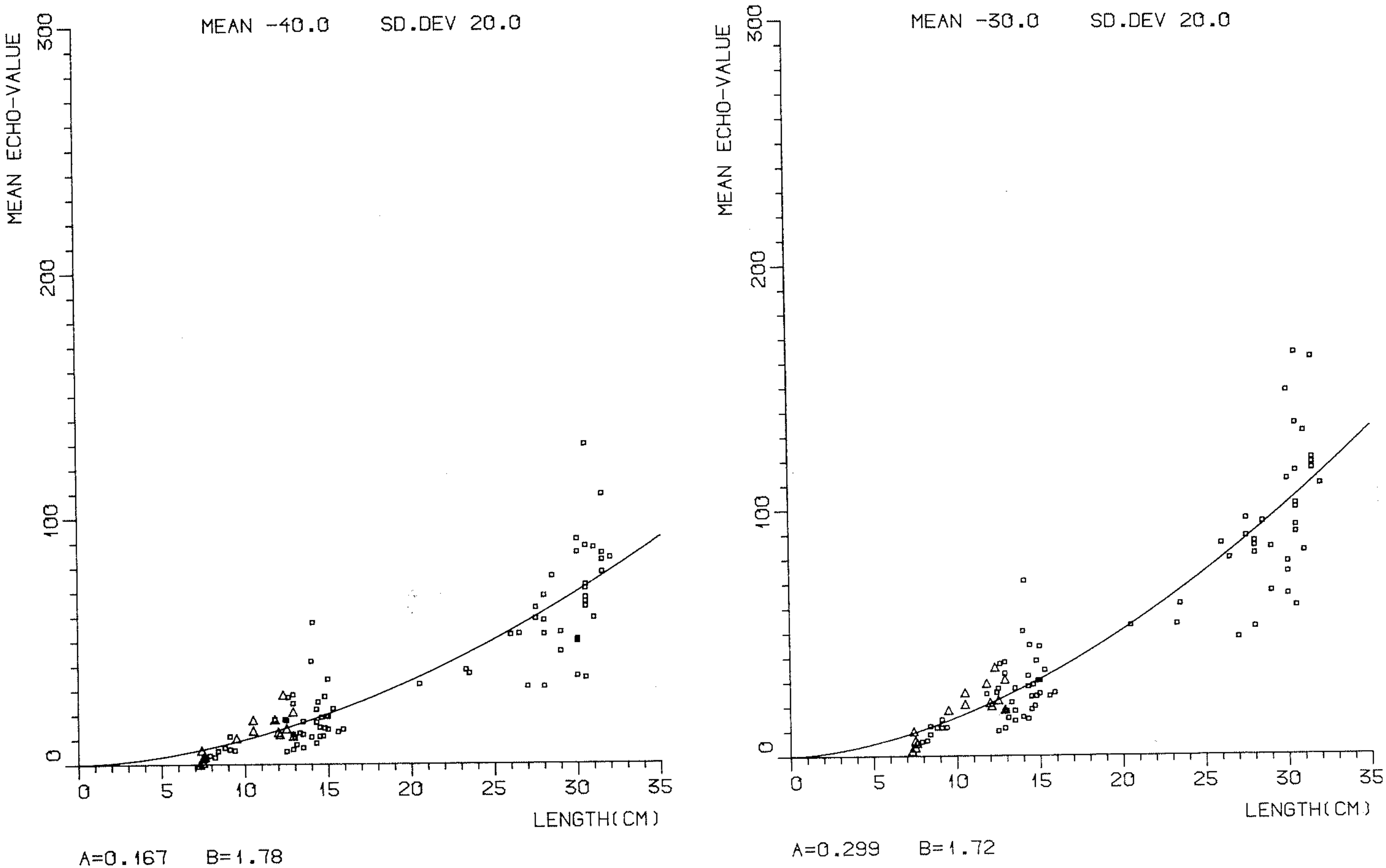

MEAN -40.0 SD.DEV 20.0
MEAN ECHO-VALUE
300
200
100
0
0 5 10 15 20 25 30 35
LENGTH(CM)
A=0.167 B=1.78
MEAN -30.0 SD.DEV 20.0
MEAN ECHO-VALUE
300
200
100
0
0 5 10 15 20 25 30 35
LENGTH(CM)
A=0.299 B=1.72

Fig. 12. Cont.

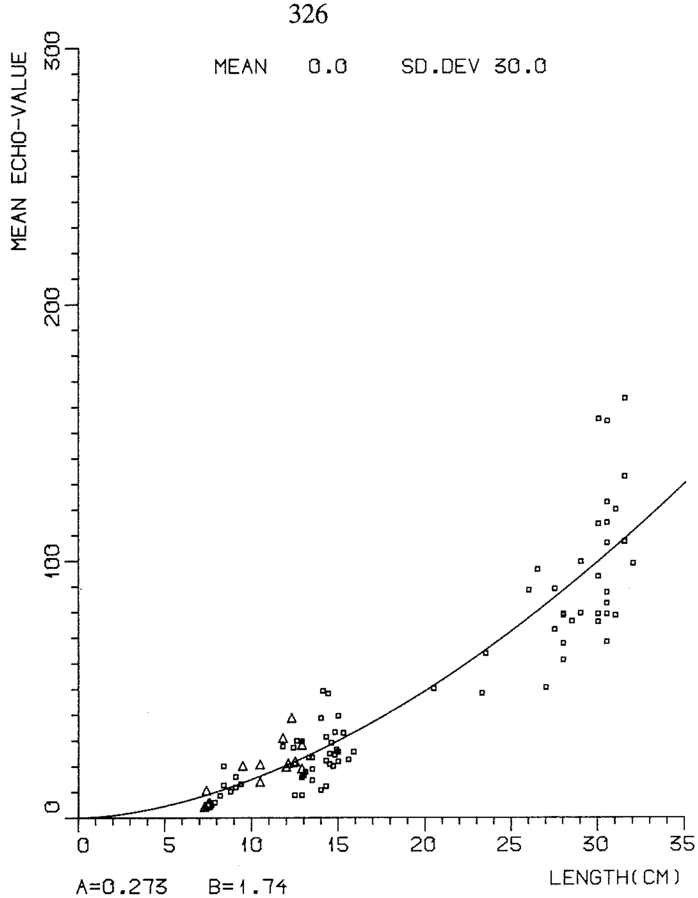


Fig. 12. Cont.

The length distributions in the gill net samples are shown in Fig. 10, and for estimation of the length distribution of the stock from these, the gill net selection curves are needed. Models underlying methods for determining selection curves based on catches with different mesh sizes assume a known relationship between curves apart from some unknown parameters. Moreover, each length group of the unknown length distribution has to be represented by a sufficient number of fish in the catches from at least two mesh sizes (HAMLEY 1975). It is also known that selection curves may have two maximums, especially for fish with small head girth in relation to maximum girth, as for herring (HAMLEY 1975). In addition, many experiments have shown that selection curves have generally larger maxima for large mesh sizes than for small.

Inspection of our data shows that these give inadequate information about the selection curves. Thus, to avoid the difficulties of estimating selection curves, the following simple method to estimate the over all mean echo-value (10) was adopted:

The approximation

$$\int_{h>0} \hat{E}_l \, h(l) \, dl \approx \hat{E}_{\bar{L}} \tag{17}$$

for (11), where $\bar{L}$ is a rough and subjective estimate, from Fig. 10, of the mean length per fish in the stock, was used. This is justified because (17) yields exact equality when $\hat{E}_l$ is a linear function of l, and because inspection of the regression curves in Fig. 12 shows that these are fairly linear within the range of fish lengths in the spawning stock. Also, even without knowing the exact selection curves, the error in $\bar{L}$ will hopefully not be serious.

The spawning stock in 1980 is divided into two groups, the new recruits and the older fish. The mean fish lengths were determined as 27.5 cm in 1979 and as 21 and 28 cm, respectively, for the new recruits and the older fish in 1980. The overall mean echo-values were computed and are given in Table 2.

Table 2. Overall mean echo-value pr fish (eq. 11) in the spawning stock in 1979 and 1980 for different tilt angle distributions.

Tilt angle distribution		1979	1980	
Mean	Standard deviation	All	Older fish	New recruits
10	10	64.5	66.6	39.6
10	20	84.7	87.4	52.7
0	10	131.1	135.5	83.8
0	20	109.9	113.4	69.3
0	30	87.2	90.0	54.6
–10	10	193.3	199.2	123.2
–10	20	121.8	125.6	77.2
–20	10	158.3	163.1	101.2
–20	20	114.0	117.5	72.2
–30	20	89.4	92.2	56.2
–40	20	60.9	62.9	37.7

The survey data were next processed by computing the relative echo intensity (12) from each sound pulse along the different survey nets. For the time interval (t_1, t_2) in (12), a constant value of t_1 was used, while t_2 was varied in steps to separate bottom and herring echoes. The computed echo intensities were averaged over intervals of 20 subsequent sound pulses to reduce the amount of data.

The data processing was concluded with computation of estimates of the total echo abundance (13) and plotting of the geographical distribution of the relative echo intensities for the different surveys in 1979 and 1980 as shown in Fig. 14. a), b) and c). The distribution of the stock in 1978 as shown in Fig. 13 is obtained from the echograms.

There exists no theory for statistically estimating the integral of a

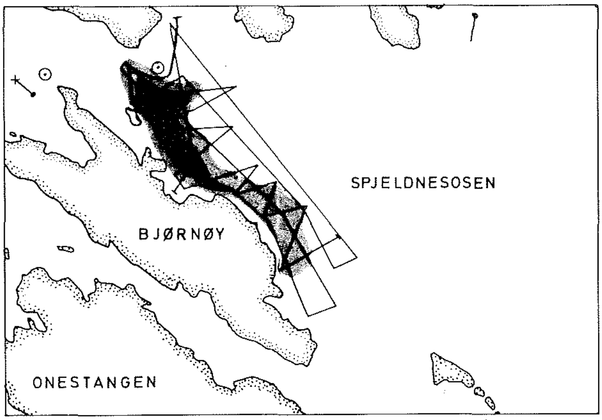


Fig. 13. The geographical distribution of herring in 1978 as judged from the echograms together with the two survey nets used.

two-dimensional function based on observations along a non-random system of lines. Although subjective methods such as hand-drawing isolines in a map where the data values are written, and estimating the integral from the areas between those isolines are usual in fisheries biology, a different method was used in the present analysis.

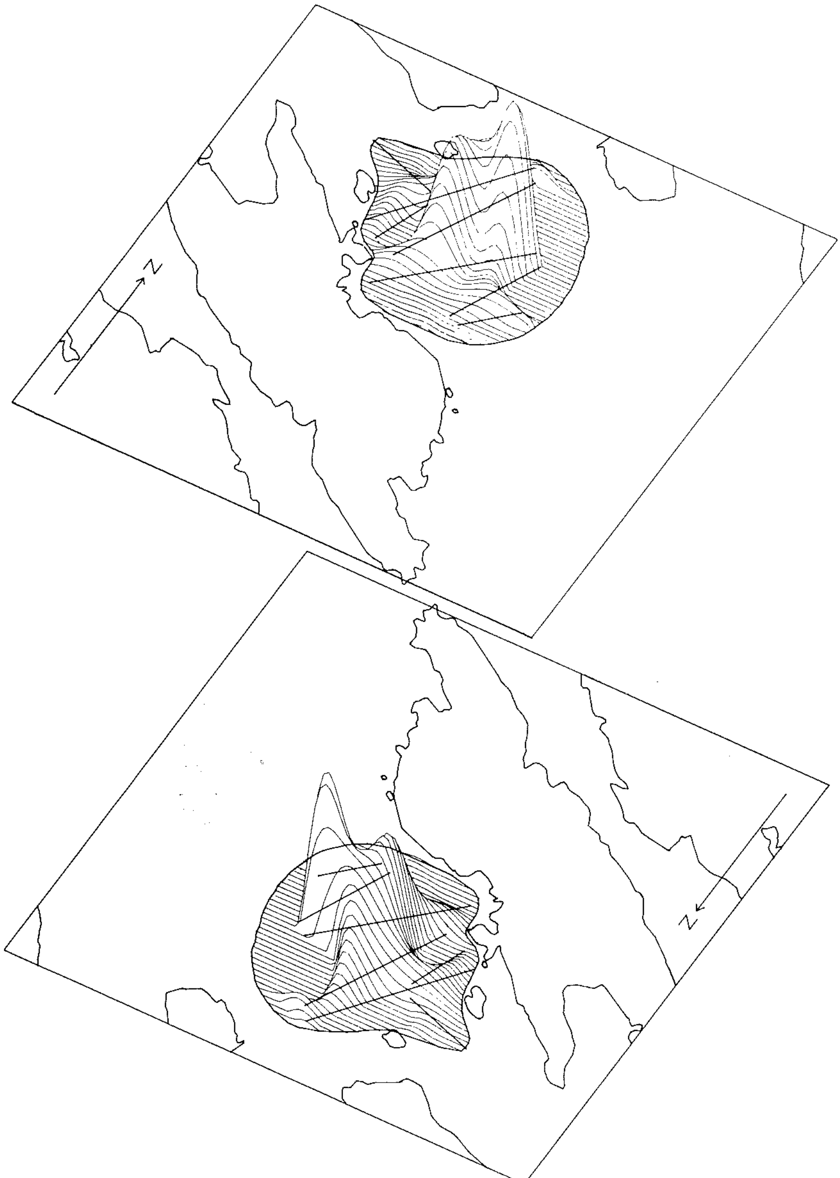
The subroute package NAG (Numerical Algorithm Group) contains a routine which fit a bivariate normalized spline function to the values of arbitrary data points in the plane (HAYES and HALLIDAY 1974). Experimentation with this routine showed that the input echo intensity data had to be supplemented by a set of zero values along an assumed edge of the fish distribution; otherwise the spline function did not perform satisfactorily. The fitted spline functions are shown in Fig. 14 a), b) and c) which are 3-dimensional perspective plots made by routines from the subroutine package "Surrender" under GPGS (ZACRISEN 1979).

Estimates of the echo abundance (13) were computed by simply summing the spline values over a regular grid. The results are given in Table 3.

Table 3. Echo abundance (eq. 13) for the different surveys.

Survey	1979–1	1979–2	1979–3	1980
Echo abundance	20.6 10^6	16.9 10^6	15.1 10^6	44.5 10^6

Since the new recruits in 1980 were only caught in the left tail of the 21 mm mesh selection curve as shown in Fig. 10, their ratio, R, to the number of older herring cannot be determined. Hence, estimates for a given set of such ratios are given.



a)

Fig. 14. Perspective plots of the distributions of echo abundance in 1979 and 1980 from different directions. The distance between the lines is 10 m. The view is from 50° above the horizontal for the surveys 1979–1 and 1980, while the same for 1979–2 and 3 is 40° and 30° respectively. a) Survey at 1030 p.m. 27 March 1979; b) Survey at 1115 p.m. (above) and 1200 p.m. (below) 27 March 1979; c) Survey at 100 p.m. 30 March 1980.

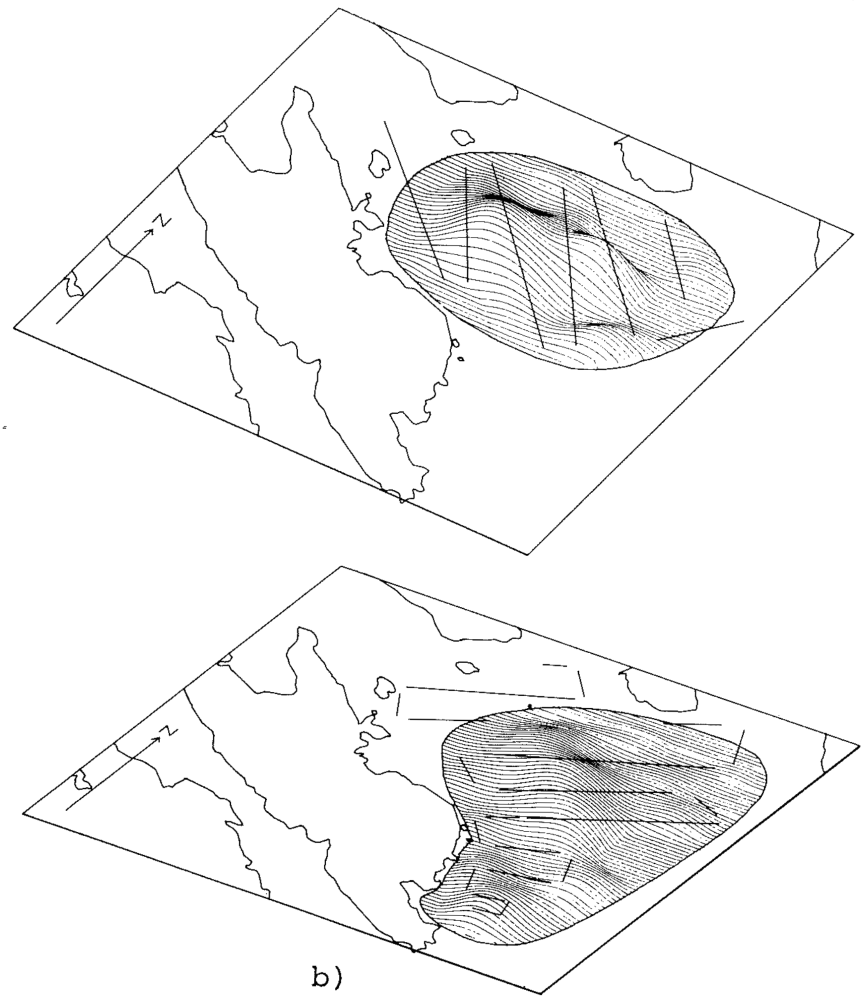


Fig. 14. Cont.

Denoting the echo abundance by M, the mean echo-value for recruits and older fish by C_R and C and their numbers by N_R and N respectively, we have

$$N_R C_R + NC = M$$

$$R = N_R/N$$

from which N_R and N were calculated at the values 0.6, 0.8, 1.0, 1.2, 1.6, 2.0 and 2.5 for R.

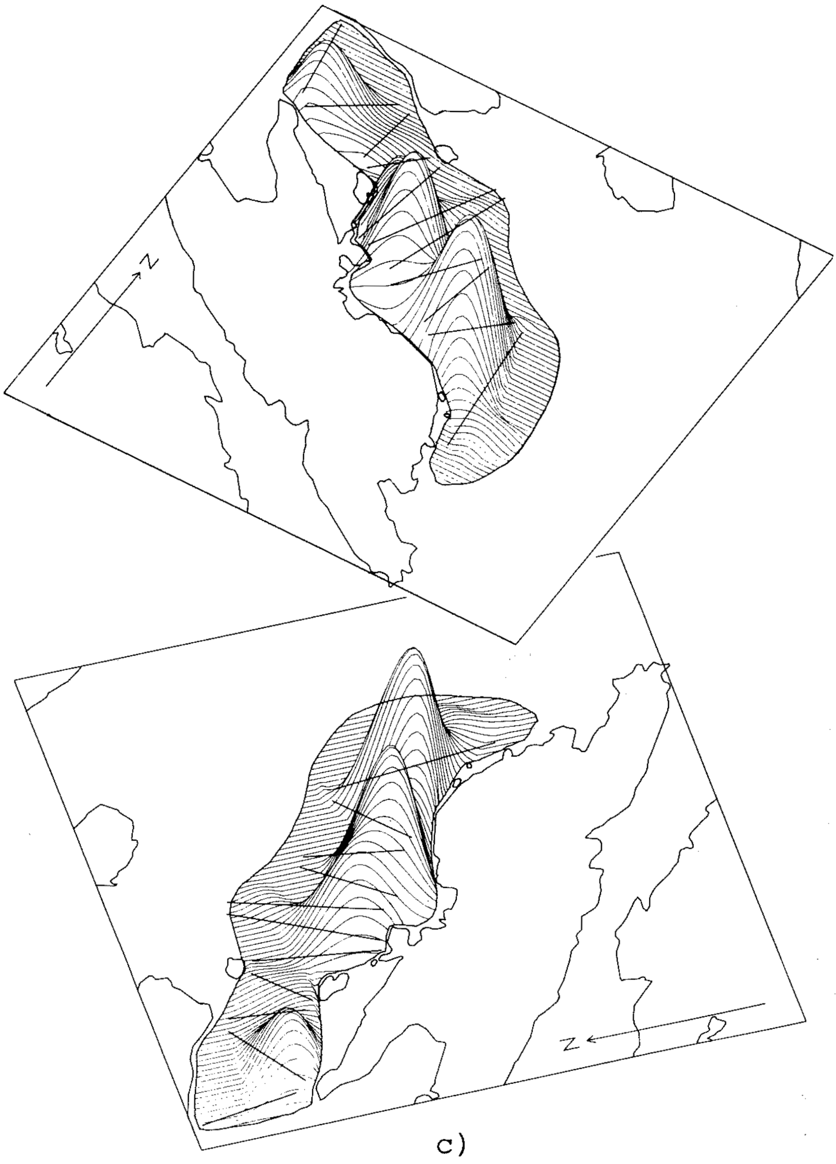


Fig. 14. Cont.

Apart from many programs and routines not mentioned, this completed the data processing, and the following estimates given in Table 4 are based on the computations.

The table gives estimates of number of herring in thousands. For the 1980 survey number of older fish and new recruits are given beneath each value of R (see text).

Table 4. Estimates of number of herring in thousands for the different tilt angle distributions. For the survey in 1980, number of older fish and new recruits are given beneath each value of R which is the ratio between the numbers.

Tilt angle distribution	1979 survey			1980 survey						
	1	2	3	R 0.6	0.8	1.0	1.2	1.6	2.0	2.5
0 10	152	129	115	240 144	220 176	203 203	189 226	165 264	147 294	129 322
0 20	182	153	138	287 172	264 211	244 244	226 272	198 317	177 353	155 388
0 30	229	193	173	362 217	333 266	308 308	286 343	251 401	223 447	196 491
−10 10	103	87	78	163 98	149 120	138 138	128 154	112 180	100 200	88 219
−10 20	165	136	124	259 155	238 190	219 219	204 245	179 286	159 318	140 349
−20 10	126	107	96	199 119	182 146	168 168	156 188	137 219	122 244	107 267
−20 20	175	148	133	2.77 166	254 203	235 235	218 262	191 306	170 340	149 373
−30 20	224	189	169	353 212	324 260	300 300	279 334	244 391	217 435	191 478
−40 20	328	276	248							

DISCUSSION

The given estimates may be influenced by a set of non-random errors which are shortly discussed. In 1979 avoidance behaviour took place due to the depth distribution which extended nearly to the surface. If the avoidance reaction did not cause any serious reduction in the fish density below the transducer, it may be described by a tilt angle distribution with negative mean, but the reduction in echo abundance from survey 1 to 3 in 1979 is, however, most probably explained by a combination of geographical spreading to regions beyond the area covered by the survey nets and a decrease in the mean of the tilt angle distribution. As seen from Tables 2 and 3, the reduction in echo abundance from survey 1 to 3 corresponds to the reduction induced by replacing tilt angle distribution (−20, 20) by (−30, 20).

In any case it may be assumed that the echo abundance of survey 1 is not a serious underestimate caused by avoidance-induced reduction in fish density. It is, however, difficult to give an estimate of the tilt angle distribution, but according to the observed disturbance of the herring, an overall mean echo-value larger than that given by the (−20, 20) tilt angle distribution in Table 2 is doubtful. The larger echo abundance in 1980 may be explained by the considerable recruitment to the spawning stock that year, but also in part by less avoidance reaction since it is seen from Table 4 that under the assumption of the same tilt angle distribution as in the first survey in 1979 and the survey in 1980, the number of recruits has to be at least twice the number of older fish to account for any mortality between those surveys.

Another possible source of error is that of the r.s.c.s. measurements. These may not be representative of the surveyed fish. An experiment by Foote (1982) has shown that the averaged backscattering cross section of anaesthetized fish is representative of that of similar, but free-swimming fish, when the tilt angle distribution is known. If the anaesthetized and free-swimming fish are dissimilar, then the connection may not be valid. This is a concern here since the r.s.c.s was determined for non-spawning herring, while the survey was performed on spawning herring. Ona's description of the effect of large gonads on the swimbladder form (ONA 1982) strengthens the suspicion of acoustic differences. The likely effect of this is underestimation of the stock, although by unknown magnitude.

The analog storing process on the conventional tape recorder may also give rise to errors due to high sensitivity to factors such as variations in tape quality, variations in head cleanness and possible dust particles between tape and head. Errors of this kind were observed in our data as drops in the stored signal, but its resultant effect is assumed to be negligible. Although the use of high quality instrument recorders will almost eliminate this, its cost would be unreasonably high.

The possibility that parts of the herring stock were beyond the region covered by each survey net is judged to be small since reconnoiterings showed no sign of this at times close to the surveys.

The purpose of the present investigations was, however, to obtain the first rough estimates of the size of the herring stock for use in a more extensive study of the Lindaaspoll ecosystem. It is hoped that the estimates in Table 4 at least specify the order of magnitude of the stock.

ACKNOWLEDGMENT

I want to thank those colleagues and students at the Department of Fisheries Biology, University of Bergen, and colleagues at the Institute of Marine Research, Bergen, who took part in the field work, for their outstanding help in preparing and performing the different field activities. I wish particulary to thank Kenneth G. Foote, Institute of Marine Research, for valuable discussions and for taking part in the measurements of scattering cross section and also in some of the surveys. Per Eide, Institute of Marine Research, is also specially thanked for designing a program to store the digitized signals.

REFERENCES

AKSLAND, M. 1976. Estimators in acoustic surveying of fish populations. *Coun.Meet.int. Coun. Explor. Sea, 1976* (B:36):1–19.

DAHL, O., ØSTVEDT, O. J. and LIE, U. 1973. An introduction to a study of the marine echosystem and local herring stock in Lindaaspollene. *FiskDir. Skr. Ser. HavUnders., 16*: 148–158.

FOOTE, K. G. 1980. Averaging of fish target strength functions. *J. Acoust. Soc. Am., 67*: 504–515.

FOOTE, K. G. 1980. Linearity of Fisheries Acoustics, with Addition Theorems. *Symp. on Fisheries Acoustics, Bergen 1982* (43): 1–18.

HAMLEY, J. M. 1975. Review of Gillnet Selectivity. *J. Fish. Res. Bd Can., 32*: 1943–1969.

HAYES, J. G. and HALLIDAY, J. 1974. The Least-squares Fitting of Cubic Spline Surfaces to General Data Sets. *J. Inst. Math. and its Appl., 14:* 89–103.

JOHANNESSEN, A. *Studies on the ecology and population dynamics of eggs and larvae of herring (Clupea harengus L.) in Lindaaspollene, western Norway, during 1977–1980.* (Dr. scient. Thesis, in prep.)

LIE, U., DAHL, O. and ØSTVEDT, O. J. 1978. Aspects of the life history of the local herring stock in Lindaaspollene, western Norway. *FiskDir. Skr. Ser. HavUnders., 16*: 369–404.

NAKKEN, O. and OLSEN, K. 1977. Target Strength Measurements of Fish. P.52–69 in MARGETTS, A. R. ed. *Hydro-Acoustics in Fisheries Research. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 170.*

ONA, E. 1982. *Kartlegging av svømmeblærens form og formstabilitet for teoretiske beregninger av akustisk refleksjon fra fisk.* Thesis cand. real. University of Bergen, Norway (in press, in Norwegian).

ZACHRISEN, M. 1979. Surrender – A bivariate subroutine package for rendering bivariate surfaces. *SINTEF report no. STF14 A79020, RUNIT Univ. of Trondheim, Norway.*

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STANDARD CALIBRATION OF ECHO SOUNDERS AND INTEGRATORS WITH OPTIMAL COPPER SPHERES

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ABSTRACT

FOOTE, K.G., KNUDSEN, H. P. and VESTNES, G. 1983. Standard calibration of echo sounders and integrators with optimal copper spheres. *FiskDir. Skr. Ser. HavUnders., 17*: 335–346.

Calibration of fisheries echo sounders and integrators by means of optimal copper spheres is reviewed. The standard procedure is elaborated. Maintenance of 0.1 dB precision is described for a wide range of temperatures and for untuned equipment. The method is illustrated by reference to a calibration exercise of R/V "Michael Sars". The long-term stability of quoted, cumulative calibration results for the same vessel witnesses to the reliability and precision of the method.

INTRODUCTION

In essence, calibration of hydroacoustic equipment by spherical targets is simple. The target is placed at a known position in the transducer beam, ensonified, and the properties of the echo related to the known scattering characteristics of the target. Specification of the relationship between the target and response of the acoustic equipment, including signal processing hardware and software, constitutes the calibration.

In practice, however, calibration is seldom a simple matter. Getting a 130 g, 30 mm-diameter sphere to hang virtually motionless in the center of an 8° beam, 20 m beneath the hull of a 1500 ton research vessel is not undertaken lightly. Yet the success of this operation is absolutely essential to even an ordinary calibration, not to mention precision calibration with expected 0.1 dB accuracy.

Appreciation of this fact has prompted the present contribution, a sequel to FOOTE *et al.* (1981). It is with design, therefore, that the method of calibration with spherical targets is described in detail. In order that any possibility of performing a precision calibration be seized, the particular application of optimal copper spheres to the routine is elaborated. The abstractions of the method and theory are offset by a practical example: calibration of R/V

"Michael Sars". Data from both an individual calibration exercise and from the semi-annual series of calibration exercises are presented. In addition to commenting on these, the problem of intercalibration and the improvement of present procedures are discussed.

THE METHOD

The general process of large-system calibration is now described. This is oriented towards the ocean-going research vessel, but may be applied whenever and wherever echo sounders or echo integrators must be calibrated.

1. PRELIMINARY PERFORMANCE MEASUREMENT AND ADJUSTMENT OF EQUIPMENT

Six basic tasks are enumerated here. These should precede the physical part of the calibration. They may be conducted expeditiously while the vessel is underway, for example, when sailing to its calibration anchorage.

(i) Measure and record transducer insulation and impedance.

(ii) Check and adjust, as necessary, the mains voltage and all critical voltages in the transmitter and receiver.

(iii) Check and record the two time-varied-gain functions; namely, the $20 \log r + 2\alpha r$ and $40 \log r + 2\alpha r$ functions.

(iv) Check and record total gains, bandwidths, and accuracy of the −10 and −20 dB attenuators.

(v) Measure and record the various effects for all combinations of transmitters and pulse durations of common or possible use during the preceding or following cruise program, for which the calibration is being undertaken.

(vi) Confirm the echo integrator performance by playing in a known signal and observing, hence recording, the output. Adjust the electronics as necessary to meet specifications. Confirm the vessel log compensation.

2. RIGGING FOR SPHERE MEASUREMENTS

The vessel is anchored in calm and sheltered water. The depth must be sufficient for separation of sphere and bottom echoes. It is desirable, moreover, to work in water as deep as possible, consistent with maintaining a stable platform. Both bow and stern anchoring or tying are recommended. This is illustrated in Fig. 1.

Winches to guide and steer lines to the sphere for its centering in the echo sounder beam are affixed to the deck railing. This is done in accordance with detailed ship drawings. The first winch is placed in the transverse plane of the ship running through the transducer. The second and third winches are placed

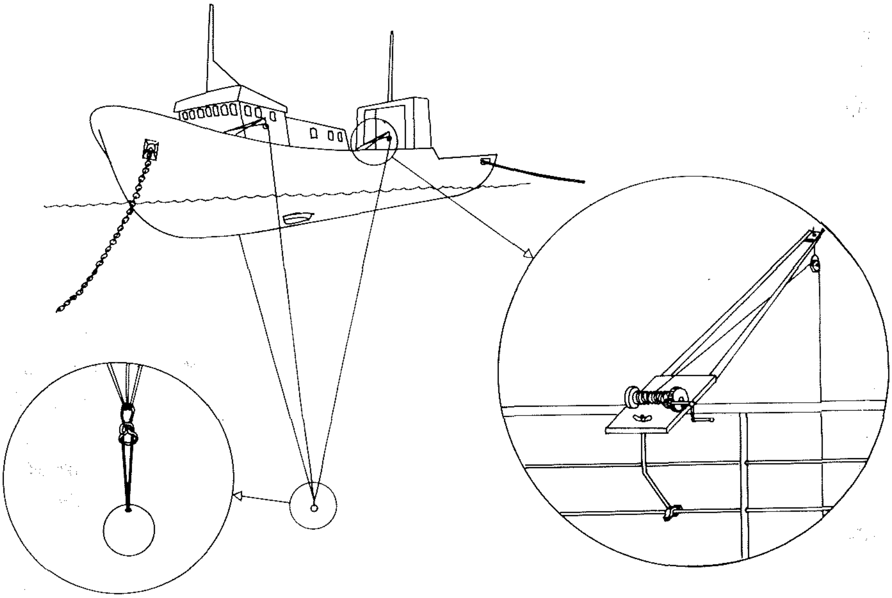

Fig. 1. Rigging of a research vessel for calibration.

on the opposite boat side and at equal distances from the transverse section containing the transducer and first winch. Each winch is provided with a long spool of 0.60 mm-diameter monofilament nylon, which is marked with small lead weights at five-meter intervals, beginning 10 m from the loose end.

Prior to commencing the sphere measurements, the lines from the two winches on the same side of the boat are drawn beneath the hull to the other winch by means of a line passed under the keel before anchoring. The appropriate sphere, with affixed loop, is attached to the three suspension lines, cf. Fig. 1. It is then immersed in a solution of soap and fresh water and lifted overboard by the fastened lines without being touched. The sphere is lowered beneath the vessel to the desired depth, for example, 25 m, which is determined roughly by counting the lead marker-weights on each line.

The sphere depth or range from the transducer is determined by several considerations. The minimal allowable range to the sphere is the greater of the Rayleigh distance, or square of the largest transducer dimension divided by the acoustic wavelength, which defines the nearfield/farfield transition, and the least range for which the sphere echo does not saturate the electronics, e.g., the preamplifier. Two further practical considerations in choosing the range are the transducer beamwidth and vessel geometry. The physical width of the beam, which increases linearly with range, should be sufficiently great so that the sphere echo is unaffected by the small, perhaps pendular movements to which it is inevitably subjected. The minimal range must also be convenient with respect to the boat geometry. In particular, if the suspension lines do not hang freely, then control of the sphere may be hindered by friction or possible obstructions on the hull. Despite the number and variety of these considerations, it is seldom difficult in practice to find a suitable range which satisfies all of the above criteria.

3. *HYDROGRAPHY*

During the anchoring and rigging operations, the temperature and salinity profiles should be taken. These will allow computation of the sound speed both at discrete depths and cumulatively to the depths of possible sphere suspension. The second computation will allow determination of the exact depth of eventual sphere suspension from the echo time delay. When this depth is applied in the first computation, the temperature correction to the target strength of the calibration sphere may be obtained from a reference graph or table.

4. *CENTERING*

The purpose of this crucial operation is to move the immersed, suspended sphere onto the acoustic axis of the transducer. Movement of the sphere occurs by turning of the various hand-winches, always singly and upon specific command by the director of this procedure, who is guided by constant observation of the echo waveform on the oscilloscope. The two principles guiding the search for the beam center are (i) preliminary exploration of the beam to ensure location of the sphere in the main lobe, and (ii) further probing to find the position of strongest echo. In the case of highly directional transducers, determination of the ultimate axial location is made when any movement of any winch, in or out, cannot increase the echo amplitude.

5. *COMPUTATIONS FOR ECHO SOUNDER CALIBRATION*

The sphere range is measured in units of milliseconds from the echo on the oscilloscope. The range r in meters is then given by $r = ct/2$, where t is the measured echo time delay and c is the average speed of sound from transducer to sphere depth. The approximate root-mean-square (rms) echo amplitude u_{rms} is determined from the peak-to-peak amplitude u_{pp} by assumption of a rectangular echo pulse, hence $u_{rms} = u_{pp}/2 \cdot 2^{\frac{1}{2}}$. This is converted to logarithmic units by the definition: $U = 20 \log u_{rms}$, where u_{rms} is expressed in volts. The sum of source level SL and voltage response VR is now determined from the target strength TS of the calibration sphere, after appropriate fine adjustments. The specifying equations are

$$SL + VR = U_1 - TS + 20 \log R_1 + 2\alpha R_1 - G + 20 \log r$$
for "20 log r" TVG,

and

$$SL + VR = U_2 - TS + 40 \log R_2 + 2\alpha R_2 - G$$
for "40 log r" TVG,

where U_1 and U_2 are respective echo levels with "20 log r" and "40 log r" TVG functions, r is the sphere range, R_1 and R_2 are the respective cutoff ranges of the two TVG functions, α is the absorption coefficient used in the TVG functions, and G is the attenuator setting. The units of the various quantities are stated in Table 1.

Table 1. Units of quantities in calibration equations.

Quantity	Symbol	Units
Source level	SL	dB//1μPa
Voltage reponse	VR	dB//1v/μPa
Echo level	U_1, U_2	dB//1v
Target strength	TS	dB
Ranges	r, R_1, R_2	m
Absorption coefficient	α	dB/m
Gain or attenuator setting	G	dB//1v

6. *READINESS OF ECHO INTEGRATOR*

The echo sounder is adjusted to its normal cruise settings. For the Simrad EK-38 echo sounder, for example, these might be the following: selected transducer: 30 × 30, transmitter: external, pulse duration: 0.6 ms, TVG: "20 log r", attenuator setting: –20 dB, bandwidth: 3 kHz, range scale: 0–250 m. The vessel speed is simulated as 10 knots and the observation time chosen to be six minutes, corresponding to a sailed distance of 1 n.m. Three 5 m-thick echo integration channels or layers are defined: the central channel is centered at the sphere depth and the others are placed immediately above and below, thus sharing common limits with the central channel. No threshold is used. The middle channel will thus contain the contribution from the sphere echo; the others will measure noise including volume reverberation.

7. *COMPUTATIONS FOR ECHO INTEGRATOR CALIBRATION*

The echo energy from each of a large number of pings is computed. The largest of these, if within about 10% of the average, is extracted. If the deviation is larger, then the centering operation should be repeated and the acoustic measurements performed anew. The product of the largest echo energy finally selected and the total number of pings in its sequence is expressed in terms of the arbitrary, historical units of millimeters of pen deflection per meter of sailed distance at 10 knots speed and the ping rate of most common use, for the given target referred to 1 m range. Despite the *a priori* oddity of this conversion, the fact of all pertinent calibration data being stored guarantees the possibility of intercalibration with other echo integrators, on other research vessels, by citation of the peak echo energy, for example.

8. DOCUMENTATION.

Special preprinted forms are filled in during the entire course of measurements. Collateral documentation in the form of oscilloscope photographs and hydrographic measurements are attached to these forms, all of which are identified for future reference. Copies are left onboard, distributed otherwise as necessary, and the originals are filed in the archives of the institute.

PRESERVING PRECISION

As mentioned above under "Computations for echo sounder calibration", the calibration value of target strength is adjusted for the temperature. In more general terms, the target strength depends on the hydrography, or temperature and salinity of the immersion medium at the depth of sphere suspension. This is clearly seen in the first paper on acoustic scattering by solid elastic spheres, FARAN 1951, as well as in many later works, e.g., HICKLING 1962, VOGT *et al.* 1975, FLAX *et al.* 1978, MACLENNAN 1981. In each of these, the hydrographic dependence appears implicitly through the density and sound speed of the medium. The connections between these parameters and the hydrography are well known. Two standard references are DIETRICH (1952) and Del GROSSO (1974).

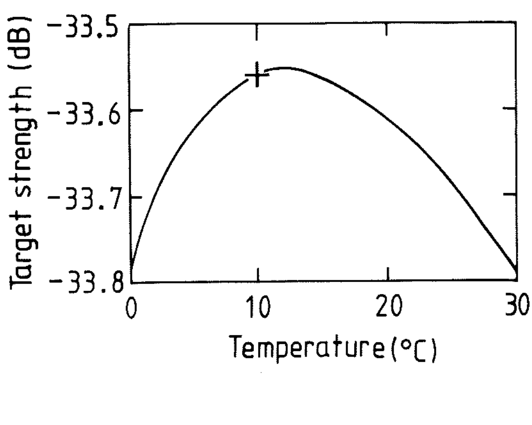

Fig. 2. Effects of temperature variations on the target strength of the 60 mm copper sphere for calibration of the EK-38 echo sounder. The plus indicates a common datum with the other computations, which are represented here by the constant center frequency of 38 kHz and pulse duration of 0.6 ms.

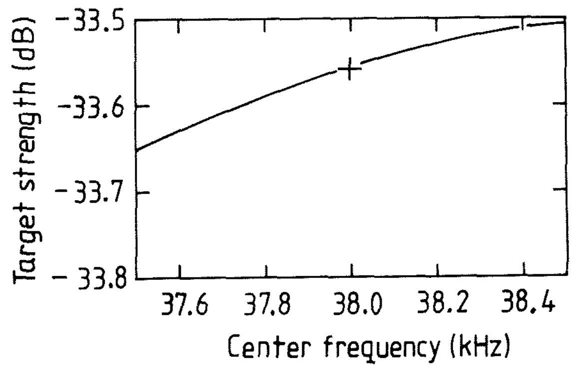

Fig. 3. Dependence of the target strength of the 60 mm copper sphere on the transmitter center frequency of the EK-38 echo sounder. The plus indicates a common datum with Figs. 2 and 4.

The influence of temperature on the target strength of the 60 mm copper sphere has already been investigated (FOOTE 1981, 1982b). The result of this is presented in Fig. 2 for marine calibrations of the Simrad EK-38 echo sounder, when operated under the following nominal conditions: 38 kHz center frequency, 0.6 ms pulse duration, and 3 kHz receiver bandwidth. The temperature is varied from 0 to 30°C, assuming a constant salinity of 35 ppt.

Evidently, use of a target strength of –33.7 dB will ensure a precision calibration over the entire 30°C range, without requiring temperature compensation. This is a direct consequence of the method of determining the sphere diameter, given its composition of electrical-grade copper (FOOTE *et al.* 1981, FOOTE 1982). Application of the temperature-correted target strength will, however, contribute to the overall control of potential calibration errors, hence is recommended in the general case. In the present case, use of the nominal target strength of –33.6 dB for temperatures from 4 to 22°C will assist this control, as the single value of–33.7 dB does ot make allowance for rounding errors.

Both the center frequency and duration of the transmit pulse can also influence the calibration value of target strength (FOOTE 1981, 1982, 1983). These dependences are shown in Figs 3 and 4, respectively, for the following nominal

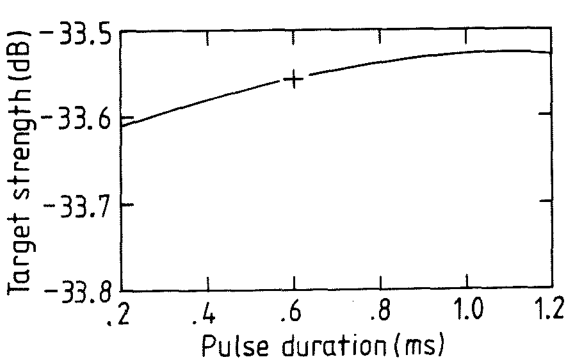

Fig. 4. Dependence of the target strength of the 60 mm copper sphere on the duration of the transmit pulse of the EK-38 echo sounder. The plus indicates a common datum with Figs. 2 and 3.

hydrographic state: temperature of 10°C and salinity of 35 ppt, hence medium density of 1027 kg/m^3 and sound speed of 1490 m/s.

Again, as with the temperature, the dependences are weak, and use of the nominal value, –33.6 dB after rounding, would permit neglect of variations in the two parameters over the considered ranges. However, since both equipment parameters can be measured with high accuracy, control of the calibration process would dictate adjustment of the target strength.

It might be thought that it is best to maintain a tuned condition for the sake of calibration. In fact, this is unnecessary, for the acoustic robustness of optimal copper spheres, a consequence of their design by optimization, allows their use over a wide range of conditions departing from nominality. Thus, equipment that is discovered to be out of tune or that cannot be tuned easily, because of age, for instance, can be calibrated by the same sphere by a slight modification in the target strength.

EXAMPLE

The method of calibration is illustrated by an example derived from the exercise with R/V "Michael Sars" on 5 January 1982. This concerns the Simrad EK-38R echo sounder and attached echo integrator, standard equipment widely used in the acoustic estimation of fish abundance.

The exercise began at 0800 hours with departure of the boat for Skogsvaagen, an inlet on the island of Sotra, about a one-hour sail from Bergen, where the sphere measurements were to be conducted. While underway, the performance of the equipment was measured. This followed the task list of item (1) of the method. No serious deviations from the specifications were discovered, precluding special adjustments. In addition to these preparatory measurements, the three outriggers with hand-winches were attached to the deck railing in their usual positions and the several copper spheres to serve as targets were immersed in a bucket of fresh water and detergent.

At Skogsvaagen the boat was anchored near the northern shoreline of the inlet, hugging a rock wall affording shelter from a light north breeze. Both bow and stern were anchored in water of 100 m depth. Owing to local geography, tidal flow and other submarine currents are completely negligible in the inlet, hence these were not considerations in choosing the anchoring location.

The hydrography was performed immediately upon completion of the anchoring. The temperature and salinity profiles measured by a standard CTD-sonde were logged automatically by the central computer and computations of sound speed and density performed. At the anticipated calibration depth of 24 m, the temperature and salinity were found to be about 6°C and 33 ppt, implying a local sound speed of 1472 m/s and density of 1026 kg/m^3. The average sound speed from the transducer to this depth was found by computation to be 1466 m/s.

Calibration of the 38 kHz equipment generally has the highest priority in this kind of exercise, hence the 60 mm copper sphere was immersed first. Its echo was observed on the oscilloscope immediately upon lowering to approximate 24 m depth, suggesting its location in the main lobe. This was confirmed by routine exploration of the beam.

After fine adjustment, the sphere was assumed to be on the acoustic axis of the transducer and the measurements were begun. These are now described for the "20 log r" TVG function and external transmitter, the standard combination for many acoustic surveys. The sequences of items (5) and (7) of the method are followed below.

The echo time delay t was measured as 25.2 ms on the oscilloscope. Use of the average sound speed $c = 1466$ m/s determined the sphere range $r = ct/2 = 18.5$ m. The peak-to-peak sphere echo u_{pp} was measured with the attenuator setting or gain $G = -20$ dB with the result $u_{pp} = 3.35$ V. This was converted to the echo level $U_l = 20 \log u_{pp}/2 \cdot 2^{\frac{1}{2}} = 1.5$ dB. The cutoff range R_l of the "20 log r" TVG function is 502 m. The absorbtion coefficient α for the particular echo sounder is 0.0105 dB/m. For the exact sphere depth, the hydrography dictated a target strength TS = —33.6 dB, cf. Fig 2. The sum of the source level SL and voltage response VR can now be determined:

$$
\begin{aligned}
SL + VR &= U_l - TS + 20 \log R_l + 2\alpha R_l - G + 20 \log r \\
&= 1.5 + 33.6 + 54.0 + 10.5 + 20.0 + 25.3 \\
&= 144.9 \text{ dB}
\end{aligned}
$$

In practice, reference is generally made to the actual attenuator setting of the measurement, which is also that of greatest use in survey work; namely, G = —20 dB. According to this reference, SL + VR = 124.9 dB.

Following calibration of the echo sounder, the echo integrator was prepared for its calibration. This was performed in the manner described in item (6) of the method. Because of the sphere range of 18.5 m, the central 5 m-thick integration volume was defined as [17, 22] m. The adjacent channels were defined as [12, 17] and [22, 27] m.

The results of integrating the sphere echo for six minutes at the standard ping rate of 48 pings per minute are the following: average echo energy of 6934 mm and maximum echo energy of 7356 mm. The observed excursion of 6% was considered acceptable. Further evidence for the acceptability of the measurement was provided by the measurements of echo energy, viz. reverberation, in each of the adjacent channels. The peak echoes lay between 10 and 20 mm, i.e., about 25 to 30 dB below the sphere echo, which is typical. It was concluded from these measurements that there were no extraneous scatterers such as fish in the integration volume. This was also confirmed by observation of the oscilloscope during the integration: the sphere echo appeared entirely stable.

Calibration of the echo integrator can now be completed by reference of the peak echo energy to a 1 m-sailed distance and 1 m-depth. The calibration value is expressed thus:

$$\text{Integral (mm//1 m-sailed distance} \cdot \text{1 m-depth)} = \frac{7356 \cdot 18.5^2}{1852 \text{ m/n.m.}} = 1359$$

Measurements of the source level and voltage response of the echo sounder were also made for other equipment settings; namely, for other transmitters for both the "20 log r" and "40 log r" TVG functions. Documentation was collected, copied, and the originals deposited at the Institute upon completion of the cruise on the same day.

The derived numbers are compared with previous calibration results for the same boat in Table 2, where the sum of source level and voltage response is referred to the usual —20 dB attenuator setting. The consistency of corresponding numbers witnesses both to the precision of the calibrations and to the long-term stability of the equipment.

Table 2. Summary of calibrations of the EK-38 echo sounder and attached echo integrator on board R/V "Michael Sars".

Date of exercise	SL + VR (dB)	Integral (mm)
January 1980	125.5	1387
July 1980	124.9	1264
January 1981	124.6	1291
June 1981	124.9	1330
January 1982	124.9	1359

DISCUSSION

Calibration of echo sounders and integrators is a straightforward process, but one that requires vigilance at all stages for its success. This evidently has been the case with calibration of the 38 kHz echo sounder and echo integrator of R/V "Michael Sars", as illustrated in Table 2. A detailed analysis of the errors in a routine exercise has suggested a precision well under 0.5 dB, if not approaching 0.1 dB. The consistency of the tabulated numbers for the five cruises supports this, for the greatest excursion from the average sum of source level and voltage response for the echo sounder is 0.5 dB, while the corresponding deviation in echo integral from the average is 5%.

The present procedures can be improved, of course, and the Institute of Marine Research is continuing its work on this. In particular, measurement of the time-varied-gain function has proved to be problematical. To facilitate its measurement, special circuitry for performing the determination automatically is being designed. Eventually, it is planned to incorporate a TVG correction in the software of the echo integrator, to reduce what hardware errors may exist or develop with time.

Another procedure which could be improved is that of centering of the sphere. At present, the angular position of largest echo is sought. This is rather time consuming because of the relative broadness of the main lobe, hence insensitivity of the echo to fine adjustments in position. Were it possible to operate the same or similar transducer in a split-beam mode, in which four quadrant beams are separately formed, then generation of the difference responses in the fore-and-aft and athwartships planes would enable very sensitive minima – ideally sharply defined nulls – to be sought. Not only would this accelerate the alignment process, but it would also effect a demonstrably highly accurate positioning. Additionally, observation of the sphere echo on the oscilloscope during calibration of the echo sounder would enable the data goodness to be confirmed without having to study the statistics.

When and if both improvements are made, it should be easy to establish the accuracy of calibrations of echo sounders and integrators. This is expected to approach 0.1 dB.

Intercalibration is entirely feasible given the present calibration procedures based on the use of optimal copper spheres. To determine the relative performances of two systems, either the same or similar spheres can be used. Different spheres could also be employed, if their target strengths were known with sufficient accuracy.

The significance of the present calibration method to multiple-vessel acoustic surveys of fish stocks is that intercalibration of the several instruments can be effected without requiring the vessels to meet and perform a simultaneous survey of the same fish aggregation. Use of optimal copper spheres is especially advantageous here, for the properties of copper as a standards material are unalloyed, and offer an immediate, potential accuracy of 0.1 dB, with the possibility of further improvements.

REFERENCES

Del Grosso, V.A. 1974. New equation for the speed of sound in natural waters (with comparison to other equations). *J. Acoust. Soc. Am., 56*: 1084–1091.

Dietrich, G. 1952. Ozeanographie. Physikalische Eigenschaften des Meerwassers: Allgemeiner Teil. Pp. 426–441 in Vol. 3, *Landolt-Börnstein Zahlenwerte und Funktionen*, 6th ed. Springer-Verlag, Berlin.

Faran, J.J., Jr. 1951. Sound scattering by solid cylinders and spheres. *J. Acoust. Soc. Am., 23*: 405–418.

Flax, L., Dragonette, L.R., and Überall, H. 1978. Theory of elastic resonance excitation by sound scattering. *J. Acoust. Soc. Am., 63*: 723–731.

FOOTE, K.G. 1981. Constancy in target strength of optimal, elastic calibration spheres. Pp. 11/1–6 in *Proc. IOA Underwater Acoustics Group Conf. 'Advances in Underwater Acoustics'*, Portland, England, 1–2 December 1981. Institute of Acoustics, Edinburgh.

FOOTE, K.G. 1982. Optimizing copper spheres for precision calibration of hydroacoustic equipment. *J. Acoust. Soc. Am., 71*: 742–747.

FOOTE, K.G. 1983. Maintaining precision calibrations with optimal copper spheres. *J. Acoust. Soc. Am., 73*: 1054–1063.

FOOTE, K.G., KNUDSEN, H.P., VESTNES, G., BREDE, R., and NIELSEN, R.L. 1981. Improved calibration of hydroacoustic equipment with copper spheres. *Coun. Meet. int. Coun. Explor. Sea, 1981* (B:20): 1–18. [Mimeo.]

HICKLING, R. 1962. Analysis of echoes from a solid elastic sphere in water. *J. Acoust. Soc. Am., 34*: 1582–1592.

MACLENNAN,, D.N. 1981. The theory of solid spheres as sonar calibration targets. *Scottish Fisheries Research Report* No. 22: 1–17.

VOGT, R.H., FLAX, L., DRAGONETTE, L.R., and Neubauer, W.G. 1975. Monostatic reflection of a plane wave from an absorbing sphere. *J. Acoust. Soc. Am., 57*: 558–561.

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