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Absorption of acoustic energy in dense herring schools studied by the attenuation in the bottom echo signal

by

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Abstract

The absorption of acoustic energy in herring schools is studied by echo integration of the bottom signal under various densities of herring. The investigations were carried out in a fjord in northern Norway, where large schools of adult herring overwinter. The intensity of the bottom signal, expressed by the integrator value (reflected area in square meters per square nautical mile(m^2/NM^2)) of the bottom decreased significantly as the density of herring increased. The bottom integrator value decreased exponentially from 1.39 to 0.36 $\cdot 10^6$ as the area density of herring increased from 0 to 550 $\cdot 10^3$, corresponding to an increase in number of herring per square meter of 0 - 180. A method for correction of this effect is also presented.

Introduction

The basic principle of acoustic abundance estimation of fish by echo integration is that the relationship between the integrated echo intensity and the fish density is linear (Forbes and Nakken 1972, Midttun and Nakken 1971). However, in dense schools extinction of energy may modify this basic principle. The significance of extinction depends upon the density of the scatterers, and it may be supposed that there is a critical density above which the linearity in the proportionality between fish density and integrated echo intensity will not be valid. Density dependence of the echo energy in fish schools is studied in an experiment by Røttingen (1976) and is analysed by Foote (1978). Røttingen found that the integrated energy is proportional to the fish density up to a certain value, after which the energy increases more slowly and may even decrease as the density increases further. The main cause of the non-linearity is the so-called "shadow" effect. When the density is very high, the fish nearest the transducer attenuate the acoustic energy so that more distant fish contribute less to the reflected signal. The weakening, or in many cases even actual loss of bottom signal due to the presence of large, dense schools is the most striking evidence of this phenomenon in practical work. The principle of linear proportionality of total echo energy and density of fish may therefore not apply to dense fish aggregations (Foote 1982, Foote 1983).

Røttingen (1976) also found that the exact density values at which shadowing occurs appear to depend on parameters such as fish species, size, orientation, and vertical extension of the school. However, when analysing 12 cm sprat at 38 kHz and 0.6 ms pulse length, Røttingen determined the critical density at which nonlinearity becomes evident to be 1800 - 2000 fish/m^3, corresponding to an area density of 4300 - 4800 fish/m^2.

Multiple scattering is often discussed in terms of the volume density of targets. According to MacLennan and Forbes (1984) this is unhelpful at least in the case of the shadow effect when the controlling parameter is the number of fish insonified per unit cross section area of the beam. In other words, two schools of different vertical extension but having the same fish density by volume will not suffer shadowing to the same extent.

The aim of this work is to measure the density values at which nonlinearity is evident in the case of adult herring (Clupea harengus L.), by measuring the attenuation of the bottom echo signal under various densities of herring. The final goal is to establish a method and its parameters to correct for this effect in acoustic abundance estimation in general.

Material and methods

The investigations were carried out in a fjord (Ofotfjorden) in northern Norway. Here, dense concentrations of herring have been recorded for the last 3 years. The data used in these investigations were collected on January 7 - 19 1990.

Estimation of the absorption of sound energy in herring schools is carried out by studying the variation of the intensity of the bottom signal while recording various densities of herring. For both variables, bottom and herring, mean integrator values were applied.

In short, the integrator value is proportional to the energy in echoes from scatterers in a depth interval which is computed by integrating the intensity over the same interval (Midttun and Nakken 1971, Dalen and Smedstad 1979). In the process the echo signal voltages are squared, because the signal voltages V are proportional to acoustic pressure p. The density of fish is proportional to the acoustic intensity which is proportional to p^2.

The denomination of the integrator value is square meters reflected area per square nautical mile (m^2/NM^2), an area density index. To convert the integrator values into fish densities, the following target strength (TS) function was applied:

$$TS = 20 \log L - 71.9 \text{ dB}$$

where L is the length of the fish, (Foote 1987, for clupeoids).

Over a distance of approximately 15 NM in the middle of the fjord, the depth is more or less constant (540 m), and the mean bottom integrator values per cable length (1/10 NM) varied within acceptable limits (Table 1).

Where herring were absent the mean integrator value of the bottom was measured. The speed of the vessel was 10 knots.

The instrument specifics were as follows:

Echo Sounder : SIMRAD EK 500
Transducer : ES 38B, $7.6^0 \cdot 7.4^0$
Two Way Beam Angle : 10 log = -20.1 dB
Bandwith : 3.8 kHz
Pulse Length : 1.0 ms
Power : 4 kW
Sv Transducer Gain : 26.9 dB
TVG : 20 log R
Absorption Coefficient : 10 dB/KM
Range : 0-600 m
Depth intervals (layers) : 1 layer covering the herring school, sublayers dividing the herring school in layers of 10 m, and 1 layer covering the bottom.

The EK500 is a digital system and an analog signal output (calibrated output), as found in conventional scientific sounders, does not exist. Saturation of the receiver is unlikely, even from bottom echoes. The calibration of this instrument is carried out with a standard target on axis, but the procedure has slightly been changed from the way this has been done earlier. The integral of the standard target is, now, compared to the theoretically calculated integral, and the instruments are adjusted to attain the correct output from the instruments (Knudsen 1989). The standard sphere represents an area backscattering coefficient (integrator value), normalized to one square nautical mile (NM^2), given by the equation:

$$s_A = \sigma/\psi z^2 \cdot 1852^2$$

where σ = backscattering cross section of the target
z = sphere depth (m)
ψ = solid angle covering the equivalent beam.

The following variables were recorded during the experiment: (1) vertical extension of the herring layer (Z_2-Z_1), (2) mean integrator value of the bottom (M_b), (3) mean integrator-value of the herring school (M_s), and (4) mean integrator values of the herring school divided in sublayers of 10 m (M_i). For the last one, only completely "filled" layers where used. Integrator values were recorded every cable length (1/10 NM), and integrator values of the bottom at the edge of the schools where both the free bottom and the covered bottom was insonified within one cable length, where left out. The bottom layer was also divided in several sublayers to follow the integration of the bottom and to secure integration of the total bottom signal.

The data were treated statistically applying standard statistical methods.

The investigations were carried out both day and night, running four surveys with a time lag of a day or so in between.

Results

A trawl catch was carried out to verify the registrations. The mean length of the herring under study was 32.9 cm and about 90% of the herring was 7 years of age (1983 year class), (Figure 1).

A total of 547 cable lengths or 54,7 NM were covered during the studies. The herring were recorded in a few very large schools of varying vertical extension and varying densities. The mean bottom integrator values per 1/10 NM were divided in groups corresponding to area densities of herring (integrator output in m^2/NM^2) in steps of 50 000. The density groups (by integrator output and by number per m^2), the number of observations, the average integrator output for the bottom and the standard error of the average in each group are shown in Table 1. The mean integrator value for the free bottom was 1388 ± 27 (unit thousands), also given in Table 1.

A plot of the mean integrator values of the bottom under the various density groups of herring is presented in Figure 2. The average integrator output of the bottom in all groups where herring was detected is significantly smaller than the output without herring observations. The bottom integrator output decreases as the area density of herring increases. The first four density intervals of herring are significantly different from one another (mean values are found to be outside the confidence limits of the value it is compared to). However, in these groups, the sample size is more than double the size of the groups of more dense herring registrations. As the density of herring becomes very high (integrator values greater than 250 000 per 1/10 NM, corresponding to a number of about 100 per m^2), the tendency is still clear, but the mean values of the bottom are not significantly different.

Data analysis

Approach no. 1. Bottom value as function of fish value.

An exponential least squares regression correlated the bottom echo signals as expressed by the integrator values (single observations of M_b) to integrator value of the covering area density of herring (M_s). The "linearization" was achieved through logarithmic transformation. The regression resulted in the following parameter values:

$$M_b = e^{7.12 - 2.13 \cdot 10E\text{-}3 \cdot M_s}$$

The fitted curve is shown in Figure 2. The correlation coefficient, r, is -0.75, and the standard errors of the intercept and slope are 0.013 and $7.9 \cdot 10^{-5}$ respectively.

Approach no. 2. Bottom value as function of vertical extension of fish layer.

In theory, assuming uniform distribution of fish in a school, the extinction of acoustic energy is proportional to the vertical extension of the layer and the density within the layer. An outline of this approach is given by Foote (1983), and the following relation applies:

$$M_{b(f)} = M_{b(0)} \; e^{-2\rho\sigma_e \cdot |Z_2 - Z_1|}$$

where $M_{b(f)}$ = bottom integrator value with fish in the water column, $M_{b(0)}$ = free bottom integrator value, ρ = density of fish, σ_e = mean extinction cross section of the fish and $|Z_2 - Z_1|$ vertical extension of the school (m).
An exponential least squares regression related the bottom echo signals ($M_{b(f)}$) to the vertical extension of the herring layer (Z_2-Z_1), resulting in the following:

$$M_b = e^{7.20 - 9.19 \cdot 10E\text{-}3 \cdot |Z_2 - Z_1|}$$

The slope of the curve represents the density in the observed material. The correlation coefficient is -0.72, and the standard errors of the intercept and slope are 0.017 and $3.8 \cdot 10^{-4}$ respectively.

Discussion

Measuring herring acoustically in the range of densities observed during these investigations, the linearity between fish density and echo intensity is not valid. The fall in bottom echo intensity as area density of herring increases indicates severe shadowing effects.

It seems that the relationship between bottom echo signal and fish density is curvilinear and fits negative exponential models. This is according to theory (Foote 1983), and it is also quite reasonable as the cumulative area density increase exponentially with depth.

The intercept in the fitted exponential models does not quite coincide with the mean observed free bottom integrator value (1236 and 1339 vs 1388). However, the observations of the free bottom should be representative, since the number of observations is high and the observations shifted as the herring migrated during the investigations.

The recorded area density approach provided a better fit to the data than the vertical extension approach. The standard error of both intercept and slope is smaller when relating the observed integrator values of fish to the bottom integrator values than relating the vertical extension of the herring layers to the same. This may be due to the fact that data from all schools observed along the section were applied in the regressions and the volume density in the various schools varied quite a lot (Table 2). During night, the schools dispersed and had a wider horizontal distribution, although the vertical extension was about equal to that observed during daytime. The assumption of uniform distribution within a layer of fish is barely valid for one single school and definitely not valid applying data from several schools. One school with a vertical extension of 50 m may attenuate acoustic energy at quite another level than another school with the same extension.

The recorded area density fit may also readily be applied to observations of various densities of herring elsewhere.

Application

Adjustments for the effect of attenuation may be achieved by applying the estimated relationship in recorded area density as follows.

It must be assumed that any registration of fish underneath the "cover" of herring is attenuated in the same degree as is observed for the bottom. The following relationships illustrate this:

$$A = 1 - M_{b(f)} / M_{b(0)}$$

or $$A = 1 - e^{-d \cdot M_{cover}}$$

where A = attenuation in any echo signal under the fish school (cover) giving the observed attenuation in the bottom signal, and d = estimated slope of the regression curve.

While recording herring schools, the schools should be divided into layers. To each layer in the school, a proportion, corresponding to the shadowing effect of the area density of the herring above the layer should be added. In other words, the sum of the densities from the top of the herring school and downwards determines the level of attenuation of the layers in the school and the proportion of which should be added according to the correction factor:

$$C_i = 1/e^{-2.13 \cdot 10E\text{-}3 \cdot M_{cover}}$$

where C_i = correction factor for sublayer i in the school, and M_{cover} = sum of integrator values in the sublayers above the layer to be corrected for (total area density of the covering layer) in units of thousands. The thinner the sublayers, the more accurate the correction.

An example of this method is made for three herring schools, two of them divided in layers of 10 m and one divided in layers of 5 m. The results are given in Table 2. The observed integrator value of each layer in the schools are visualized in Figure 3 a), b), and c).
The observed integrator values in the various layers in the schools is not uniform. In two of the schools, the values increase from the top to a maximum about 30-40 m down the school, decreasing further into the school. In these two schools the integrator values in a few of the layers are very high. The reduction in the observed integrator value output in the deeper layers in the schools may be explained by shadowing effects in the upper layers. In the third school, the observed integrator values are quite uniform throughout the school, but the level is much lower.

For the three schools in the example, the proportion of the total observed integrator output added in correction is 34, 41 and 10 percent respectively.

The strength of this method lay in the application of the observed integrator output and no shaky assumptions are made. On the other hand, more measurements should be carried out to minimize the variance in the estimated parameters and to get more accurate estimates of these.

Applying this method in the acoustic abundance estimation of adult herring, would result in a somewhat higher biomass estimate. This will depend on the density in the survey area. It is reasonable to believe that applying this method in acoustic abundance estimation would lead to more accurate estimates.

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Table 1. Groups of increasing density of herring (M refering to integrator output in m^2/NM^2 (unit thousands), and ρ/m^2 refering to fish per m^2), sample size (number of cable lengths), average bottom integrator values (M_b, unit thousands), and standard error of the average (unit thousands).

M	ρ/m^2	Sample size	M_b	Standard Error
0	0	140	1388.16	27.23
0 - 50	8	112	1120.90	20.79
50 - 100	25	86	1034.13	19.78
100 - 150	41	75	927.29	22.09
150 - 200	57	31	790.07	39.05
200 - 250	75	17	772.12	53.31
250 - 300	91	22	733.36	23.83
300 - 350	107	20	681.35	36.66
350 - 400	123	25	588.12	27.98
400 - 450	141	9	566.67	50.52
450 - 500	157	4	500.00	32.29
500 - 550	179	6	358.33	35.92

Table 2. Area density (integrator values) in layers of three schools (M_i), the sum of the densities in the layers representing the "cover" of the layers (M_{cover}), and the adsusted amount in each layer ($M_{adjusted}$), and volume density (number/M^3) in each layer based on $M_{adjusted}$.

School no. 1. Layers, 10 M.

Layer	M_i	M_{cover}	$M_{adjusted}$	ρ_{vi}
1	14721	14721	14721	0.5
2	31031	45752	32017	1.1
3	41741	87493	46008	1.5
4	44770	132263	53942	1.8
5	47021	179284	62327	2.1
6	48630	227914	71247	2.4
7	42134	270048	68462	2.3
8	33009	303057	58667	1.9
	Σ 303057		Σ 407391	Av. 1.68

School no. 2. Layers, 10 M.

Layer	M_i	M_{cover}	$M_{adjusted}$	ρ_{vi}
1	17755	17755	17755	0.6
2	31577	49332	32797	1.1
3	42891	92223	47640	1.6
4	50165	142388	61051	2.0
5	45572	187960	61820	2.0
6	39457	227417	58889	1.9
7	32328	259745	52473	1.7
8	27139	286884	47188	1.6
9	22826	309710	42056	1.4
10	21787	331497	44095	1.5
	Σ 331497		Σ 465764	Av. 1.54

School no. 3. Layers, 5 M.

Layer	M_i	M_{cover}	$M_{adjusted}$	ρ_{vi}
1	7792	7792	7792	0.5
2	9938	17730	10104	0.7
3	11592	29322	12037	0.8
4	12411	41733	13210	0.9
5	11564	53297	12638	0.8
6	11378	64675	12745	0.8
7	10863	75538	12353	0.8
8	11386	86924	13372	0.9
9	11261	98185	13551	0.9
	Σ 98185		Σ 107802	Av. 0.79

Captions

Figure 1. Length and age distribution of herring in the Ofotfjorden, January 1990.

Figure 2. The mean integrator values (with 95% confidence limits) of the bottom in intervalls of the integrator values of the schools in steps of 50 · 10^3. The curve fitted by regression, $Y = e^{(a + bX)}$, is also shown. The unit of both axis is thousands.

Figure 3. Integrator output in 10 m layers of a herring school. D = vertical extension of the school (m).

Figure 4. Integrator output in 10 m layers of a herring school. D = vertical extension of the school (m).

Figure 5. Integrator output in 5 m layers of a herring school. D = vertical extension of the school (m).

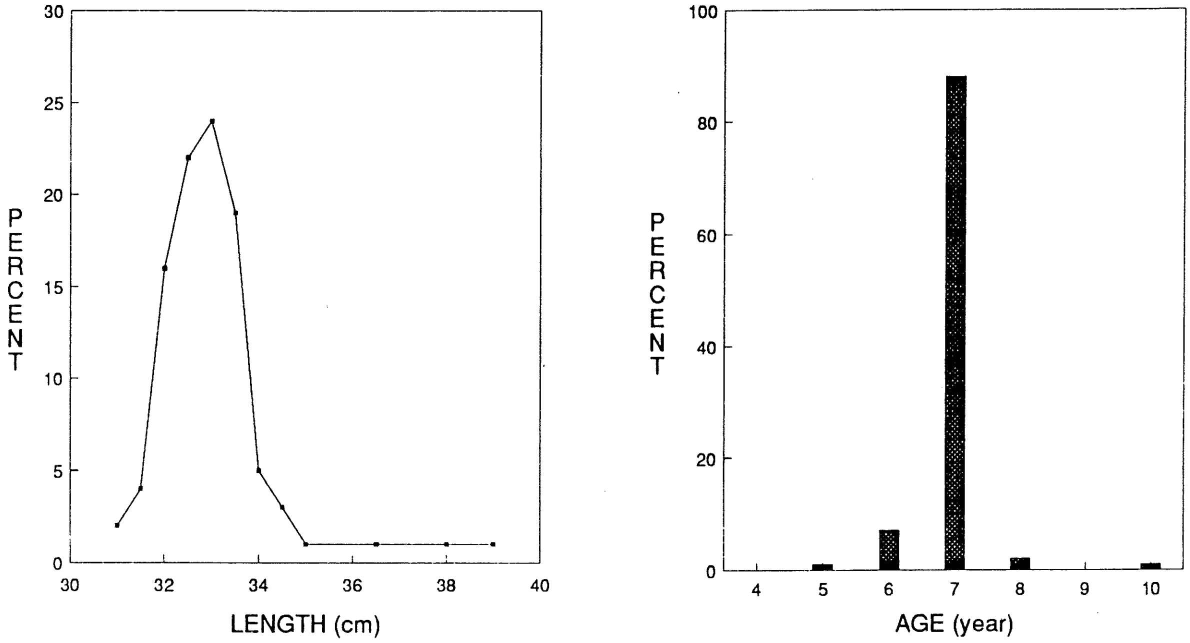

Figure 1. Length and age distribution of herring in Ofotfjorden, January 1990.

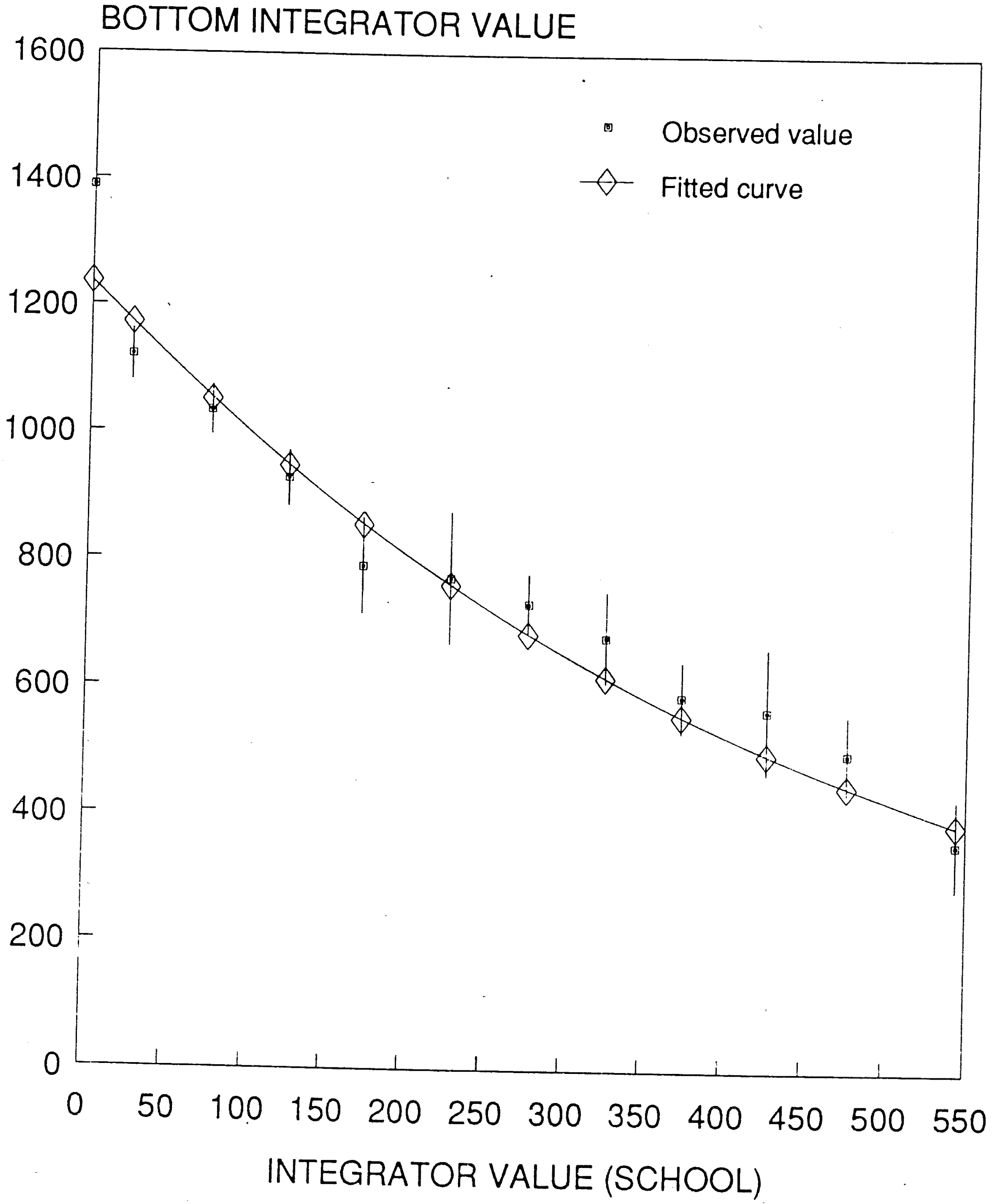

Figure 2. The mean integrator values (with 95% confidence limits) of the bottom in intervals of the integrator values of the schools in steps of 50 x 10 exp 3. The curve fitted by regression is also shown. The unit of both axis is thousands.

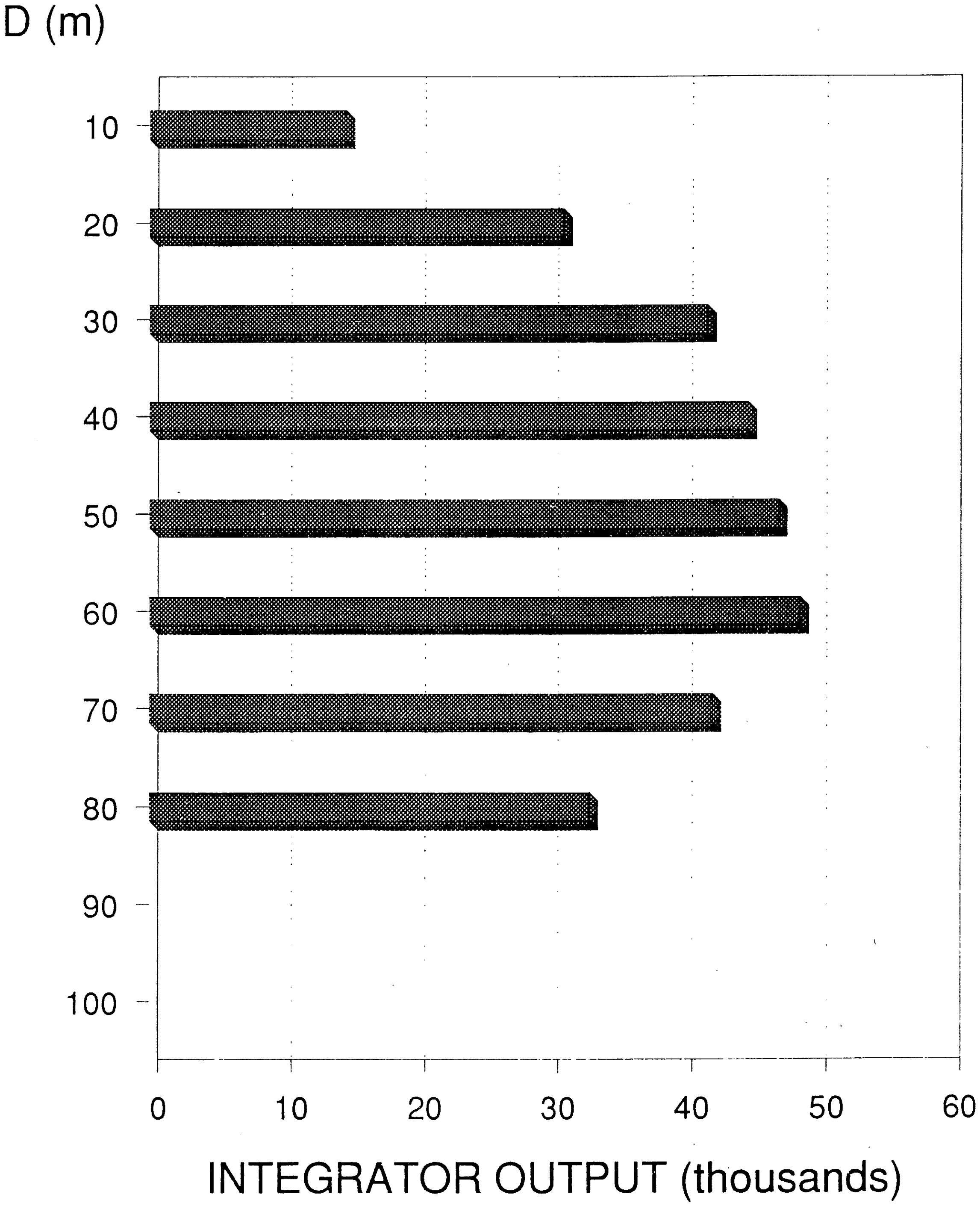

Figure 3. Integrator output in 10 m layers of a herring school. D = vertical extension of the school (m).

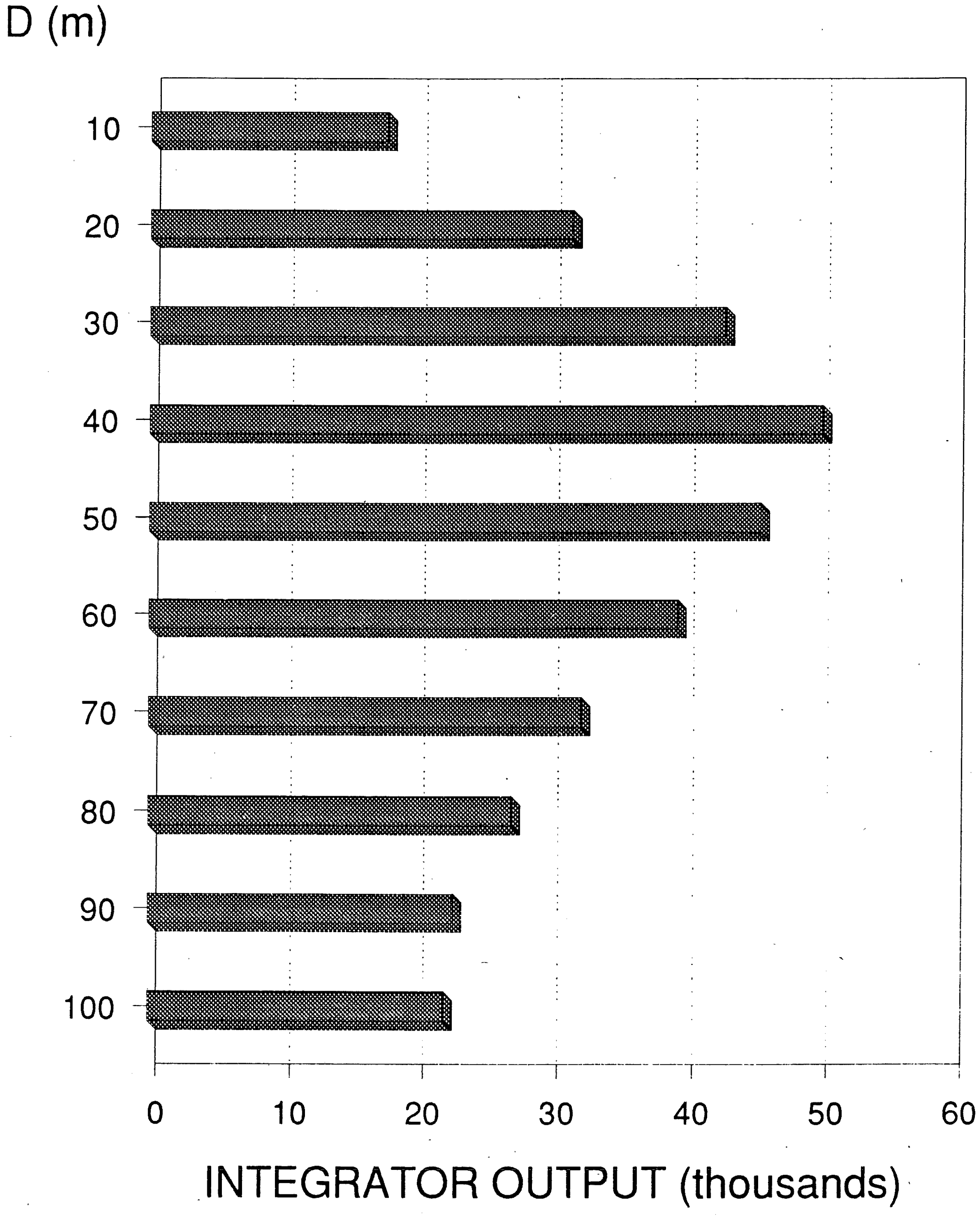

Figure 4. Integrator output in 10 m layers of a herring school. D = vertical extension of the school (m).

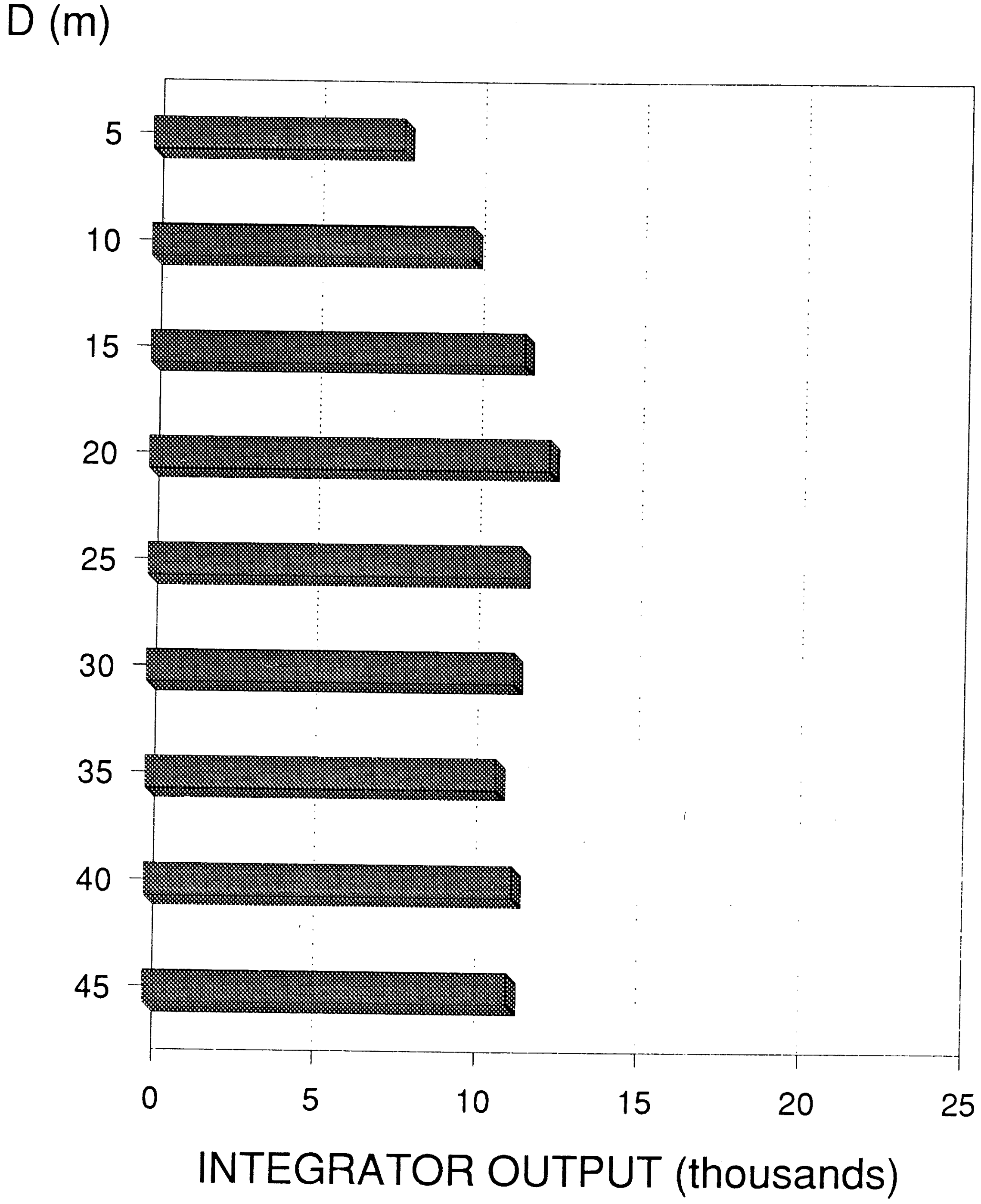

Figure 5. Integrator output in 5 m layers of a herring school. D = vertical extension of the school (m)