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On Estimating the Average Target Strength of Pelagic Fishes *in situ* by Acoustic Methods

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Abstract

Methods for estimating the average target strength of pelagic fish with acoustic data from scattered aggregations of free-swimming individuals are described, and the results of some experiments on blue whiting (*Micromesistius poutassu*) during echometric surveys by the research vessel *Persey III* in different parts of the Norwegian Sea are presented. A compact two-channel echo-integrating and echo-counting device (EI-2) that was connected to the echo-sounder (EK-S-38) was used for target strength measurements and echometric surveying. Simultaneous sampling of blue whiting with midwater trawl was conducted at the depth levels where the acoustic data were obtained. Consistency of the results for scattered aggregations of fish indicates that use of the method in conjunction with other underwater technology (television and photography) may be promising for surveying dense aggregations of fish.

Introduction

Echometric surveys of blue whiting (*Micromesistius poutassu*) were conducted in the Northeast Atlantic in spring during 1982-84. Dense aggregations of immature and postspawning fish were recorded primarily at depths of 300-500 m in the northern Norwegian Sea during March and April. From late April onwards, blue whiting migrated upwards to depths of 150-200 m at night, and fish in the upper parts of the aggregations could be recorded individually by the echo-sounder. When conditions were favorable during May, attempts were made to obtain *in situ* measurements of average target strength of the fish. In July, scattered aggregations of blue whiting were found in depths of 120-150 m during both daylight and darkness. In this paper, a method of determining the average target strength of pelagic fish is described and the results of *in situ* measurements in 1982-84 are presented.

Materials and Methods

The average target strength of fish *in situ* may be estimated if the echo-sounder constant (C_{ES}) and the echo-integrator constant (C_{EI}), both parameters in decibels (db), and the absolute calibration coefficient (C) of echo-integrator readings (M), estimated from aggregations of free-swimming fish, are known (Stephnowski and Burczynski, 1981; Burczynski *et al.*, MS 1982). The formula for calculating the average target strength (TS) of fish is

$$TS=10 \log (3430 \times 10^3)+C_{ES}-C_{EI}+\triangle TVG-\log (C) \quad (1)$$

where $C_{ES}=-(SL+VR) - 10 \log \left(\frac{c\tau}{2}\right) + 20 \log (r_0) + 2\alpha r_0 - \log (\psi)$,

$C_{EI}=10 \log (M) - 20 \log (V_{RMS}) - 10 \log (H)$,

$\triangle TVG$ = difference between theoretical and actual TVG functions at the surveyed depth (db),

SL = transmission level of echo-sounder (db/μPa/m),

VR = sensitivity of echo-sounder (db/V/μPa),

c = sound velocity in water (m/sec),

τ = length of transmitted pulse (sec),

r_0 = maximum depth of TVG function (m),

α = coefficient of sound absorption in water (db/m),

ψ = equivalent width of the directivity diagram of the echo-sounder (steradians),

V_{RMS} = effective voltage at echo-integrator input (V), and

H = thickness of the integrated layer (m).

The average target strength per kilogram of fish may be estimated from the equation

$$TS/kg = TS - 10 \log (\bar{W}) \quad (2)$$

where $\bar{W}$ is average weight of fish (kg).

The constants C_{ES} and C_{EI} may be estimated accurately enough, the first being usually determined with the use of hydrophone (Bodholt *et al.*, 1979) or a calibrated sphere (Foote *et al.*, MS 1982), and the second may be estimated with the use of standard electrical instruments. The coefficient C may be estimated by several methods (echo-counting and photogrammetric methods, use of cages with live fish, catch size within the integrator range), each of which has its shortcoming and advantages (Thorne *et al.*, 1971; Johannesson and Losse, 1977; Midttun and Nakken, 1977; Ermolchev, 1977, 1978, 1979; Hagstrøm and Røttingen, MS 1982). The advantages of the echo-counting method are that coefficient C and target strength are estimated during surveys of real aggregations of free-swimming fish with their natural behavioral and spatial orientation, and that large numbers of measurements can be obtained in short periods of time.

The target strength of blue whiting was estimated by the above method, which is based on simultaneous echo-integration and counting of signals from fish in scattered aggregations, when almost all fish are recorded individually (Ermolchev, 1977, 1979; Ermolchev *et al.*, 1980; Ermolchev and Zafermann, 1983). For the present study, the echo-integrating and counting device (EI-2) implemented the "calibration regime", whereby echoes were divided into those from single fish and those from groups of fish by analysis of echo-length, with simultaneous output of echo-signal measurements: summed echo intensity (M), number of echoes from single fish (K_o), and number of echoes from groups of fish (K_g). The selection criteria for separating single fish echoes from multiple echoes were

$$\tau_o = (0.5 - 1.5)\ \tau_p \quad \text{and} \quad \tau_g > 1.5\ \tau_p$$

where τ_o is echo-length from single fish, τ_g is echo-length from groups of fish, and τ_p is pulse length of the echo-sounder. The thickness of the integrated layer (H) was 20–40 m. Values of M, K_o and K_g were recorded automatically both in digital form by standard electronic pulse-counters and in analog form directly on the sounder echogram (Fig. 1–3).

The M value is registered on the echogram in the first channel (H_1), the "0" line of M is at the beginning of the H_1 channel, the 0.5 jump on the deflection line M denotes half of one complete deflection of M. The registered echo signals from individual fish (K_o) and groups of fish (K_g) are shifted on the echogram relative to each other and to M, with the line at the end of the H_1 channel being the "0" line of K_o and the line at the end of the H_2 channel being the "0" line of K_g. Every full deflection of K_o (or K_g) on the echogram is equal to $2^8 =$ 256 echo signals. Parameter M is measured as number of deflections on the echogram per selected interval of measurement, and it is then referred to the acoustic surveying regime (e.g. 1 mile, 5 miles or 10 miles).

A data-record series comprising one full deflection of M, 13 deflections of K_o ($13 \times 256 = 3{,}328$ echo signals), and 0.64 deflection of K_g ($0.64 \times 256 = 164$ echo signals) is shown in the upper part of Fig. 1. The bottom part of Fig. 1 shows a data-record series comprising 2.5 deflections of M, 34 deflections of K_o ($34 \times 256 = 8{,}704$ echo signals), and 2 deflections of K_g ($2 \times 256 = 512$ echo signals). The data-record series in Fig. 2 comprises 1.8 deflections of M, 13 deflections of K_o ($13 \times 256 = 3{,}328$ echo signals), and 0.94 deflection of K_g ($0.94 \times 256 = 240$ echo signals). Figure 3 shows a data-record series comprising 2 deflections of M, 31 deflections of K_o ($31 \times 256 = 7{,}936$ echo signals), and $K_g \approx 0$. These data-record series may be divided into smaller sections (e.g. for each 0.5 deflection of M).

The density of fish aggregations was determined from readings (K_o and K_g) of the echo-counting system as

$$\rho_s = \frac{(3.43 \times 10^6)\ (K_o + K_g\bar{X})\ (2^8)}{(N_p \times S_A)} \tag{3}$$

where $\bar{X}$ is mean number of fish in the groups, S_A is effective area (m^2) of the cross-section of the sonified volume in the sampled layer at depth r, and N_p is number of pings of the echo-sounder per selected interval of measurements.

The mean number of fish ($\bar{X}$) in groups was determined theoretically from the ratio (K_g/K_o) under the assumption that the fish were Poisson-distributed within the sampled layer. For $K_g/K_o \leqslant 0.5$, it may be accepted that $\bar{X} = 2$, because the error in ρ_s is smallest in this case (Ermolchev, 1979). The effective angle of the directivity diagram (θ) and the diameter (D_E) and section area (S_A) of the sonified layer were determined by the horizontal length (l, mm) of echo-traces from single fish on the echogram at maximum transmission frequency of the sounder (Q_m, pulses/min), maximum tape speed (V_p, mm/min), and constant ship speed (V_s) (3–4 knots), whereby

$$\tan(\theta) = D_E/2r$$

$$D_E = 1852\ (V_s \times l)/60\ V_p$$

$$S_A = \pi\ (D_E)^2/4$$

and

$$\bar{l} = 4l/\pi \tag{4}$$

where l is mean horizontal length of echo-traces from single fish.

Values of ρ_s (Eq. 3) were compared with summed echo intensities (M), and the coefficient C was then calculated by regression analysis. A functional relationship (GM regression) between ρ_s and M was used in order to avoid a possible bias in the estimate of C due to non-uniform distribution of ρ_s in the samples

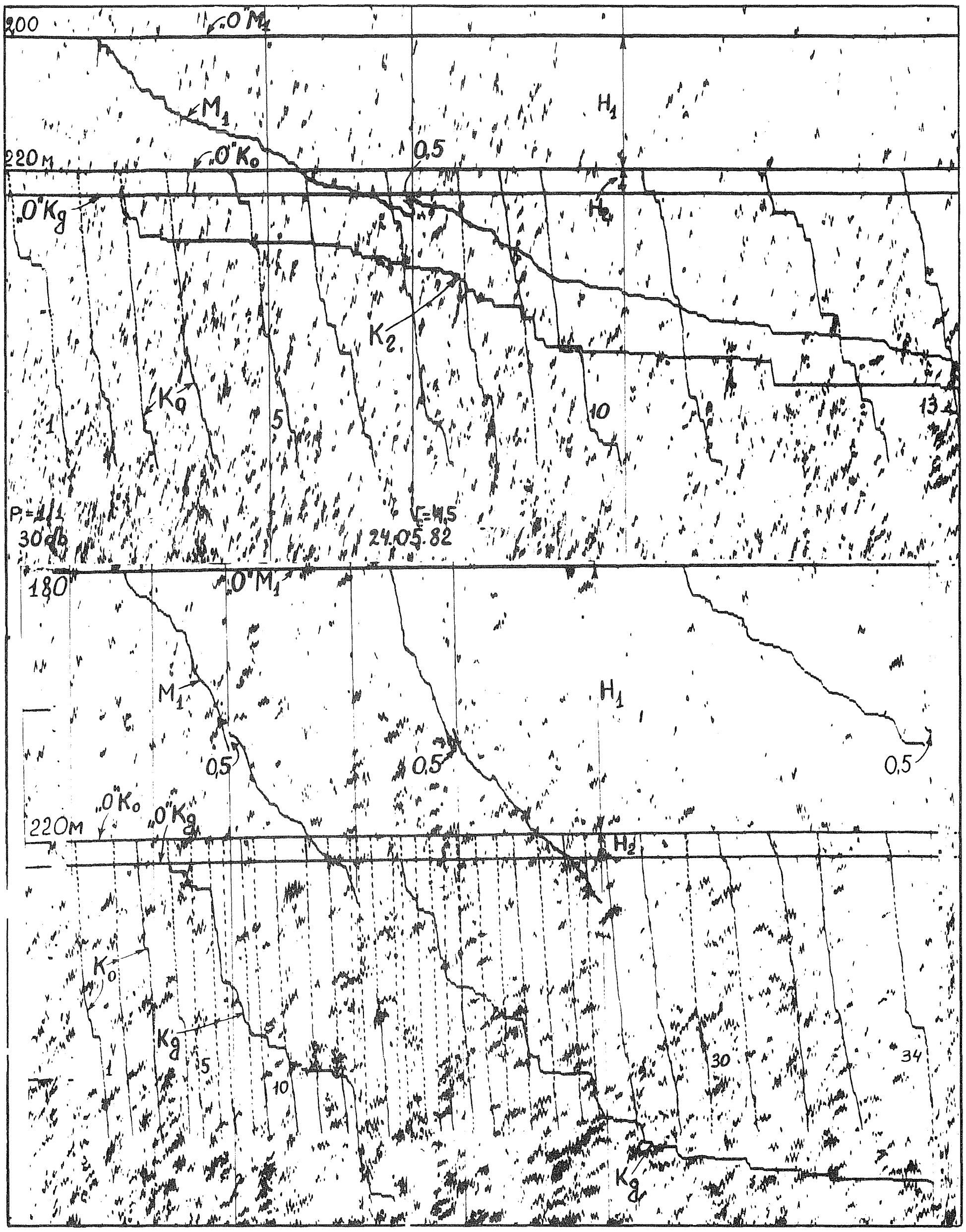

Fig. 1. Echograms of EK-S-38 sounder with recordings of individual blue whiting and summed echo intensity (M), numbers of echo signals from single fish (K_o) and from groups of fish (K_g) in the H_1 layer, measured by the EI-2 echo-integrator, east of Faroes, May 1982.

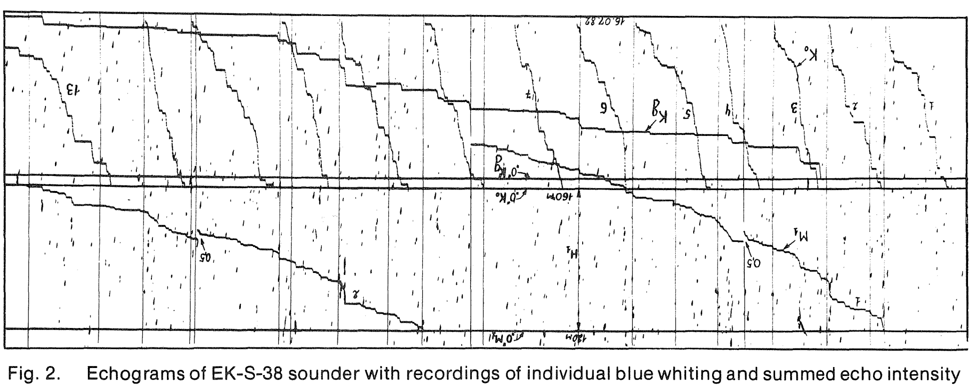

Fig. 2. Echograms of EK-S-38 sounder with recordings of individual blue whiting and summed echo intensity (M), numbers of echo signals from signle fish (K_o) and from groups of fish (K_g) in the H_1 layer, measured by the EI-2 echo-integrator, east of Iceland, July 1982.

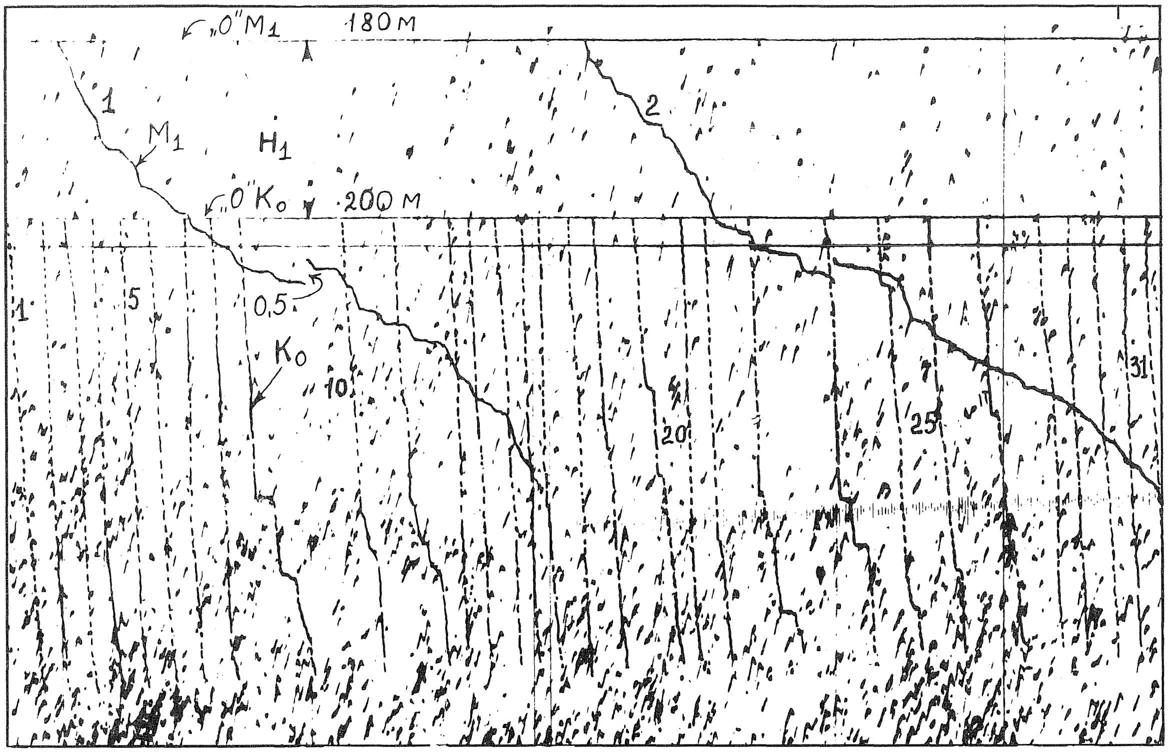

Fig. 3. Echograms of EK-S-38 sounder with recordings of individual blue whiting and summed echo intensity (M), numbers of echo signals from single fish (K_o) in the H_1 layer, measured by the EI-2 echo-integrator, east of Faroes, May 1983.

(Ricker, 1973). Linear relationships between density (ρ_s) of fish aggregation (absolute value) and summed echo intensity (M) at the echo-integrator output (in relative units) per selected distance (e.g. 1 mile, 5 miles or 10 miles), between M and ρ_s, and the functional relationship (GM regression) between ρ_s and M are expressed as follows:

$$\rho_s = C_1M + d_1; \qquad M = C_2\rho_s + d_2; \qquad C = (C_1/C_2)^{1/2}$$

where C_1 and C_2 are the slopes of the linear relationships, d_1 and d_2 are the corresponding intercepts, and C is the slope of the functional GM regression and represents the absolute calibration coefficient of the echo-integrator readings (M) expressed as fish abunance per unit area per unit M for the chosen distance.

The echo-sounder surveys which yielded the measurements for this study were conducted in various parts of the Norwegian Sea mostly in late spring of 1982–84. Simultaneously, the length and weight distributions of blue whiting in the surveyed areas were determined from catches with a midwater trawl which had a small-meshed liner in the codend.

Results and Discussion

The data-record series was comprised of echo signals from single fish (K_o) and groups of fish (K_g) whereby $K_g = (0.1 - 0.5)\ K_o$ (Fig. 1 and 2), as well as signals from single fish only (K_o) whereby $K_g = 0$ (Fig. 3). The number of echoes from single fish (K_o) in each data-record series ranged from 500 to 10,000. Absolute calibration coefficients in both cases appeared to be close in value. The total number of echoes in each calibration of the coefficient C exceeded 10,000. The echo-sounder instrumental constant (C_{EI}) was determined from measurements on a calibrated sphere. An internal integrator with transmitted pulse length of $\tau_p = 1.0$, TBG function of $-20 \log (r)/$"0" db, and 29/25E antenna with directivity angles of $8° \times 8°$ ($10 \log \psi = -19.6$ db) were used in the EK-S-38 sounder. The value of SL+VR, according to measurements on the calibrated sphere was found to be 130.4 db. The value of ΔTVG for different depths in the 3–500 m range was calculated from electric measurements, with α = 8db/km for the Norwegian Sea.

The results of estimating the average target strength of blue whiting of different sizes in various parts of the Norwegian Sea show relatively small variability (Table 1). The length compositions of six catches in May 1984 are shown in Table 2, together with expected errors in the estimates of the calibration coefficient (C) and target strength (TS). The statistical relationships between fish density ($\rho_s \times 10^3$) and summed echo intensity (M) for six typical experiments are given in Table 3 and illustrated in Fig. 4–6.

TABLE 1. Estimates of the average target strength of blue whiting in scattered feeding aggregations at different times and places in the Norwegian Sea, 1982-84. (See text for definitions of abbreviations used.)

		Trawl samples			Calculated values			
Area	Time	Mean L (cm)	Mean W (g)	No. of fish	r (m)	TS (db)	TS/kg (db)	R[a]
North of G. Britain	May 1982	31.7	170	522	260	−39.6	−31.9	0.97
	May 1983	25.1	101	517	190	−44.0	−34.1	0.99
	May 1983	29.0	135	431	250	−41.3	−32.6	0.95
	May 1983	31.4	159	469	250	−40.3	−32.3	0.91
	May 1984	26.0	105	456	140	−41.0	−31.2	0.97[b]
	May 1984	24.6	89	474	260	−41.9	−31.4	0.99[b]
	May 1984	20.2	48	386	250	−43.4	−30.2	0.93[b]
	May 1984	24.5	96	518	260	−42.4	−32.2	0.93[b]
	May 1984	24.2	120	521	260	−42.5	−33.3	0.98[b]
	May 1984	28.5	132	511	220	−40.5	−31.7	0.90[b]
East of Faroes	May 1982	32.0	159	515	270	−40.8	−32.8	0.90
	May 1982	32.0	159	482	210	−40.6	−32.6	0.96
	May 1982	32.3	154	438	210	−39.9	−31.8	0.98
East of Iceland	Jul 1982	31.0	187	531	200	−40.5	−33.2	0.98
	Jul 1982	31.1	198	478	205	−39.5	−32.5	0.88
	Jul 1982	30.5	188	463	135	−40.7	−33.4	0.96

[a] Correlation coefficient relevant to regression of ρ_s and M.
[b] Data sets used in Fig. 4–6.

TABLE 2. Length compositions of blue whiting catches and errors of *in situ* measurements of average target strength from experiments in May 1984.

Fish length (cm)	Length composition of six catches (per mille) 1	2	3	4	5	6
16	—	—	2	—	—	—
17	—	—	90	—	8	20
18	—	—	198	8	44	30
19	—	6	301	11	46	20
20	3	47	68	33	76	14
21	3	19	34	5	22	9
22	9	53	36	38	16	14
23	24	97	90	96	95	53
24	118	268	99	290	144	110
25	299	295	72	339	278	119
26	243	119	5	109	79	50
27	181	35	5	44	63	26
28	42	6	—	8	25	12
29	15	9	—	—	5	3
30	9	6	—	—	5	32
31	6	3	—	—	19	67
32	24	13	—	5	16	117
33	21	9	—	16	19	105
34	3	9	—	3	14	96
35	—	3	—	—	12	57
36	—	—	—	—	8	26
37	—	3	—	—	3	17
38	—	—	—	—	3	3
Mean L (cm)	26.0	24.6	20.2	24.5	24.2	28.5
Mean W (g)	105.1	88.5	47.8	95.7	120.0	131.6
ΔC(%)	4.4	8.3	4.3	8.1	10.4	14.3
TS (db)	−41.0	−41.9	−43.4	−42.4	−42.5	−40.5
TS/kg (db)	−31.2	−31.4	−30.2	32.2	−33.3	−31.7
ΔTS (db)	±0.83	±0.86	±0.83	±0.86	±0.90	±0.96
ΔTS (%)	±21.0	±22.0	±21.0	±21.9	±22.8	±24.8
Var (L)	4.0	5.5	6.7	11.0	13.5	27.9

The parameters needed to calculate the calibration coefficient (C) are the number of echoes from fish (K_o), the summed echo intensity (M), ship speed (V_s), and horizontal extent of echo traces from fish (l). If the standard errors associated with these parameters are $\Delta K_o = 15\%$, $\Delta M = 10\%$, $\Delta V_s = 5\%$, $\Delta l = 10\%$, and $n \geqslant 10$ (number of samples of ρ_s and M), the expected error in C (i.e. ΔC) will be less than 18%. For $n \geqslant 20$, ΔC will be about 12%. This parameter actually ranged from 4 to 14% in the six cases of Tables 2 and 3.

The parameters needed to estimate average target strength are SL+VR, τ_p, C_{EI}, ΔTVG, and C. If the standard errors associated with these parameters are Δ(SL+VR) = 10–12%, $\Delta\tau_p = 5\%$, $\Delta C_{EI} = 10$–12%, ΔTVG = 5%, and $\Delta C = 12\%$, the error in the average target strength (TS) will not exceed 20–25%, but it increases as the varaince in fish size (Var L) increases (Table 2).

This study represents an attempt to estimate the average target strength of blue whiting from *in situ* measurements of the critical parameters on scattered aggregations of free-swimming fish during the post-spawning (feeding) period in late spring. However, the behavior and orientation of the fish remain unknown, and it is also unknown whether the values of TS are constant for other stages of the life cycle (prespawning and spawning) and for other depths. To overcome these problems, the use of hydroacoustic systems in conjunction with other underwater facilities (e.g. photography and television) is promising with regard to

TABLE 3. Linear regression parameters and functional (GM) regression coefficient for relationship between fish density (ρ_s) and summed echo intensity (M) for acoustic experiments in May 1984 (Table 2).

Expt. No.	Number of points	($\rho_s = C_1M + d_1$)[a] Slope (C_1)	Intercept (d_1)	($M = C_2\rho_s + d_2$)[b] Slope (C_2)	Intercept (d_2)	GM regression coefficient (C)[c]	R[d]	Standard error (ΔC)	$\Delta C/C$ (%)
1	10	32.3×10^3	-0.3×10^3	0.03×10^{-3}	+0.03	33.0×10^3	0.97	1.2×10^3	4.4
2	13	11.8×10^3	$+1.2 \times 10^3$	0.08×10^{-3}	-0.08	11.8×10^3	0.99	1.0×10^3	8.3
3	11	15.4×10^3	-1.0×10^3	0.06×10^{-3}	+0.20	16.5×10^3	0.93	0.7×10^3	4.3
4	14	12.2×10^3	-0.4×10^3	0.08×10^{-3}	-0.05	12.3×10^3	0.93	1.0×10^3	8.1
5	19	13.2×10^3	-1.5×10^3	0.07×10^{-3}	+0.14	13.5×10^3	0.98	1.4×10^3	10.4
6	15	7.6×10^3	$+4.0 \times 10^3$	0.10×10^{-3}	-0.20	8.4×10^3	0.90	1.2×10^3	14.3

[a] Line 1 in Fig. 4–6. [b] Line 2 in Fig. 4–6. [c] Slope of line 3 in Fig. 4–6. [d] R = coefficient of correlation.

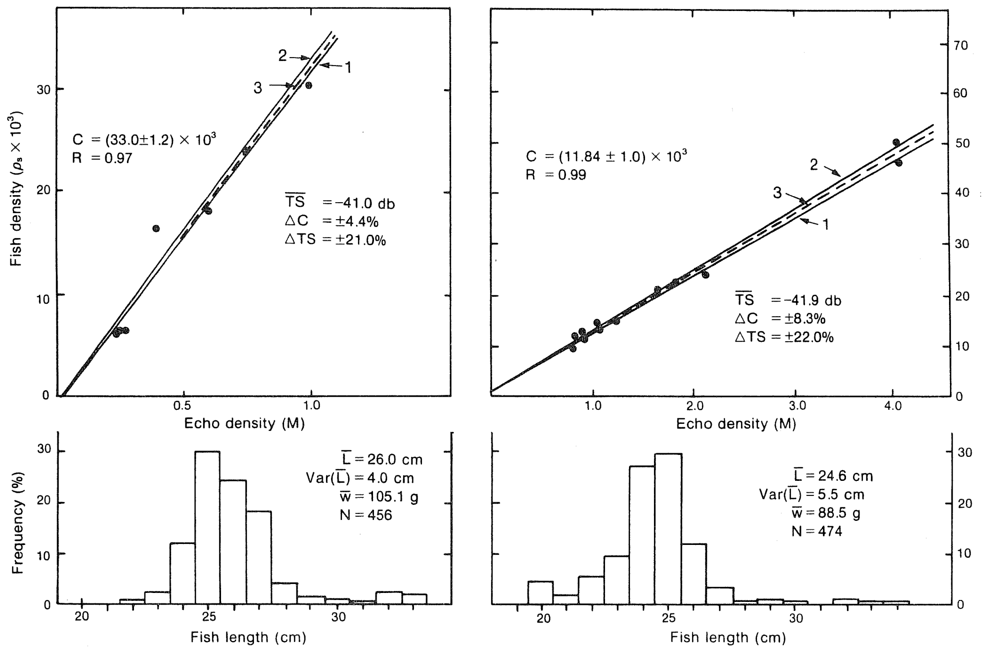

Fig. 4. Statistical relationships between fish density (ρ_s, number of fish per nm^2) and summed echo intensity (M), together with size compositions of fish in catches from the surveyed layer, for two sets of acoustic measurements in May 1984 (col. 1 and 2 in Table 3).

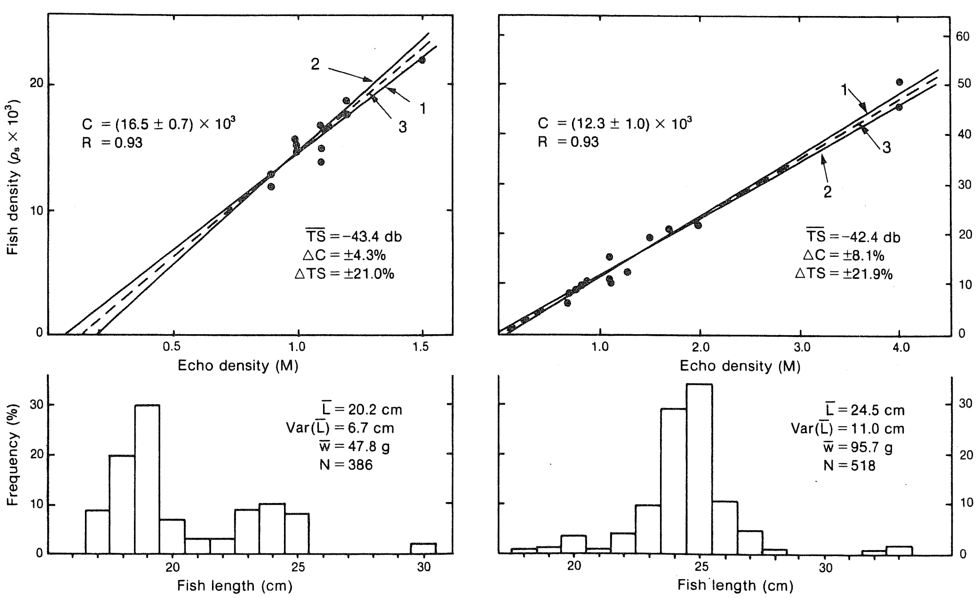

Fig. 5. Statistical relationships between fish density (ρ_s, number of fish per nm^2) and summed echo intensity (M), together with size compositions of fish in catches from the surveyed layer, for two sets of acoustic measurements in May 1984 (col. 3 and 4 in Table 3).

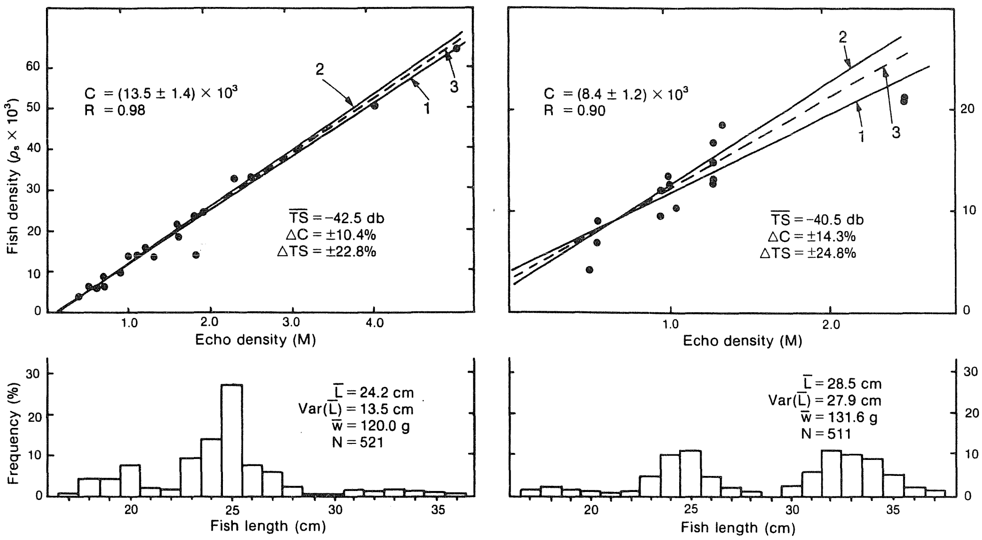

Fig. 6. Statistical relationships between fish density (ρ_s, number of fish per nm^2) and summed echo intensity (M), together with size compositions of fish in catches from the surveyed layer, for two sets of acoustic measurements in May 1984 (col. 5 and 6 in Table 3).

determining the density and spatial orientation of fish in dense aggregations (Ermolchev, 1978; Carscadden and Miller, MS 1980; Olsen, MS 1981; Ermolchev and Zaferman, 1981; Guzmân *et al.*, MS 1982).

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