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THE EQUIVALENT BEAM ANGLE AND ITS EFFECTIVE VALUE WHEN APPLYING AN INTEGRATOR THRESHOLD

by

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ABSTRACT

In a noise-limited echo integration system, a threshold is applied in order to avoid the contribution from noise. As the signal-to-noise ratio decreases with range, the effective observation volume for small targets is reduced. Direct estimates of the effective value of the equivalent beam angle have been made by combining data from echo integration, trace-counting, and <u>in situ</u> target strength measurements. Large deviations from the nominal value of the equivalent beam angle were found using this method on resolved registrations of cod and haddock.

INTRODUCTION

In fisheries acoustics, the beam pattern of the transducer is idealized by a full-response beam, and generally treated as a constant(FORBES & NAKKEN 1972: BURCZYNSKI 1979: JOHANNESSON & MITSON 1983). According to URICK (1975), the equivalent beam angle is defined as:

$$\Psi = \int_0^{2\pi} \int_0^{\pi} b_R(\theta,\phi)\ b_T(\theta,\phi)\ \sin\theta\ d\theta\ d\phi \quad . \qquad (1)$$

Large efforts are being made to obtain a high accuracy in the determining of Ψ, both theoretically, as by FOOTE (1987), or empirically on free or hull mounted transducers (SIMMONDS 1984a,1984b: REYNISSON 1985,1987, ONA & VESTNES 1985). Operating under ideal conditions with no noise, each fish echo will give contributes to the integrator value according to its position in the beam. In a real medium, however, a threshold must be applied to avoid the contributions from noise, and only signals above the threshold are integrated. According to AGLEN (1982)and LASSEN (1986), the worst thresholding occurs under low density, single-fish conditions. As the threshold effect mainly is determined by the signal-to-noise ratio, this will be a function of several parameters, e.g., depth, noise level, fish target strength and density, transmit power and receiving sensitivity of the system, and directivity of the transducer.The effective volume sampled by the system will be reduced when the threshold effect is large, and may lead to substantial underestimation of fish abundance.

In this paper, a method for estimating the effective value of the equivalent beam angle when applying an integrator threshold is described and exemplified through measurements on cod and haddock in the Barents Sea.

MATERIAL AND METHODS

When applying a 20 log R TVG correction on the received signal, the echo integrator deflection can be expressed as:

$$M_0 = I_0 \cdot k \cdot g \cdot \frac{c\tau}{2} \int_0^{\Omega} b^2(\theta,\phi)\, d\Omega \cdot \sigma_F \cdot \rho_A \quad , \qquad (2)$$

with symbols as explained in APPENDIX I. The system-specific constants are generally included in the instrument constant, measured by comparative integration on a fixed sphere on the acoustic axis according to FOOTE et al (1987):

$$C_I = \sigma_{sp} \cdot M_{0(sp)}^{-1} \cdot R_{sp}^{-1} \cdot (1852)^2 \quad . \qquad (3)$$

The area density of fish can then be measured as

$$\rho_A = \sigma_F^{-1} \cdot \sigma_{sp} \cdot M_0^{-1} \cdot R_{sp}^{-2} \cdot \Psi^{-1} \cdot (1852)^2 \cdot M_0 \quad , \qquad (4)$$

when the average backscattering cross section of the fish is known or measured.

Another method, used before echo integration, was echo-counting. In this, the area density could simply be expressed as:

$$\rho_A = N_c \cdot A_c^{-1} \quad . \qquad (5)$$

Under ideal, resolved single-fish registrations, the area density measured by the two methods should be equal, i.e.

$$N_c \cdot A_c^{-1} = <\sigma_F>^{-1} \cdot C_c \cdot \Psi^{-1} \cdot M_0 \quad , \qquad (6)$$

where the part of the instrument constant with Ψ isolated is called C_c . Direct estimates of the effective equivalent beam angle can then be found from the expression:

$$\hat{\Psi}_{eff} = A_c \cdot C_c \cdot M_0 \cdot N_c^{-1} \cdot <\sigma_F>^{-1} \quad . \qquad (7)$$

Working with a well-calibrated echo integration system, with the additional possibility of simultaneous <u>in situ</u> target strength estimation, the only tedious parameter to determine is the effective sampling area, A_c , used for trace-counting.

This was evaluated from 20 log R compensated echograms by measuring the average echo trace lengths in each 50 m integrator channel on a calibrated binocular with a magnifying factor of 12. In one echogram-cell, 50 m deep and 1 nautical mile long, the average distance over which the fish was observed in the beam is calculated as

$$\bar{t}(j,k) = [n_{j,k}^{-1} \sum_{i=1}^{n_{j,k}} t_{i,j,k}] \cdot e_j^{-1} \cdot f \cdot (1852) \quad , \qquad (8)$$

where f - trace magnifying factor (binocular units/mm

e_j - length of the echogram between one nautical mile log markers [mm]

$t_{i,j,k}$ - individual trace length (binocular units)

The average observation distance in the fore-and-aft direction was further based on the mean value over several nautical miles:

$$\text{Ave}(\bar{t}(k)) = n_j^{-1} \sum_{j=1}^{n_j} \bar{t}(j,k) \quad , \qquad (9)$$

from which the corresponding average observation angle is

$$\bar{\Theta}_k = \tan^{-1}[\ \mathrm{Ave}(\bar{t}(k)) \cdot (2 \cdot \bar{z}_k)^{-1}] \qquad , \qquad (10)$$

where $\bar{z}_k$ is the mean depth of the traces within the channel.

The maximum observation angle in which the fish can be detected in a circular beam is then found according to BLINDHEIM & NAKKEN (1971) :

$$\Theta_k(\max) = 4 \cdot \pi^{-1} \cdot \bar{\Theta}_k \qquad . \qquad (11)$$

In the used ES-400 split beam transducers, we can, with a high degree of precision, assume the athwardship detection angle to be identical to the fore-and-aft angle, ONA & VESTNES (1985), FOOTE (1987), giving an observation area with full ping-to-ping overlap of

$$A_c = \bar{z}_k \cdot 1852^{-1} \cdot 2\tan\Theta_k(\max) \qquad . \qquad (12)$$

For convenience this has the units square nautical miles. This method for estimating the observation area for counting, will be more correct than using the largest traces as an estimate for the maximum detection angle, as done by ONA & HANSEN (1986).

The ES-400 split beam echo sounder were also used simultaneously for measuring the average target strength of the fish. All <u>in situ</u> estimates from the cruises on R/V ELDJARN are made from the raw target strength distributions produced by the echo sounder itself. As the maximum resolution in the presented distribution is 1.5 dB, it is difficult to obtain a better accuracy than ± 1 dB in the on-axis sphere calibration of the echo sounder. This will also be the assumed precision of the average target strength of the fish measured from this vessel.

On R/V G.O SARS, from which all the deeper fish are recorded, the serial line of the ES-400 is logged, giving a resolution of 0.375 dB in the measurements. Most of the data are also logged using a software-determined cutoff angle of 2 degrees, avoiding the reported internal non-ideal beam compensation of the ES-400 (MACLENNAN & SVELLINGEN 1986, REYNISSON 1987). Sphere calibration showed a nearly ideal beam compensation within this narrow angle.

Most of the measurements were made at low surveying speeds, and during trawling. The standard sampling trawls for cod and haddock, the CAMPELEN 1800 bottom trawl, and the HARSTAD trawl, a 16 x 16 fathoms- opening pelagic trawl were used for species and size classification. The estimation of the effective equivalent beam angle is independent of the sampling efficiency of the trawls.

RESULTS

Typical examples of the counting conditions for respectively shallow and deep registrations of haddock are shown in Figs.1 and 2, followed by an expanded trace to exemplify the reading of trace length. The results from 16200 countings and 1980 individual readings of trace length are summarized in Table 1 and 2, with indications of vessel and sampling period. Vessel equipment and calibration data are given in APPENDIX II.
The maximum detection angle is gradually reduced with depth from the second integrator channel, 50-100 m, down to the last channel analyzed, 300-350 m. The statistics of the upper, 0-50 m channel is rather poor as less than 100 fishes were registered here. The estimates from this channel are therefore excluded from the regression analysis, Fig.3, and are only indicated in the figure. The averages behind each point in the regression are treated as independent, unweighed samples.
The estimated effective equivalent beam angle is larger than the nominal value above the 200-250 m channel, and lower in the deeper channels. Deviations from the nominal value are up to 3.1 dB.

DISCUSSION

Data on easily countable registrations of evenly sized fish, distributed over a range of depths, are hard to come by. The samples analyzed here are more or less unsystematically gathered during the standard surveys on cod and haddock in the Barents Sea over the last three years. They represent different concentrations of fairly large fish (APPENDIX III) sampled at night during a vertical migration.

The variable quality of the ES-400 data from R/V Eldjarn, where no logging device was available, reduces the precision of the estimates of the equivalent beam angle in the upper layers, as the shallower registrations were made from this vessel. On G.O.SARS, however, the <u>in situ</u> TS data are mainly sampled close to the acoustic axis, where the overall calibration accuracy is well within ± 0.1 dB. Even better estimates of target strength from the 1987 survey will soon be available from logged parallel data.

Keeping in mind the different sources of error when mixing different observations from two vessels, if the general trend in the material is correct, this elucidates the importance of threshold on the observation volume when working in resolved single-fish situations. It must also be stressed that these observations are made on fairly large fish, and that the threshold effect will be significantly larger on smaller fish.

The large deviations from the nominal value in the shallower channels were not expected, as similar measurements made by ONA & HANSEN (1986) showed nearly identical target strengths from counting and split beam measurements. Even correcting this material with a better estimate of the sampling area gives an equivalent beam angle within one dB of the nominal value. More shallow-water measurements, with better logging equipment for split-beam data, must be made to explain the large deviations found here.

The used target strength relation on cod and haddock in Norway was determined by count calibrations in the period 1975 -1978, tuned by the length dependence measured experimentally by NAKKEN & OLSEN (1977). The relatively low target strength found on gadoids by counting,

$$TS = 21.8 \log L - 74.9,$$

compared to the one obtained by split beam measurements,

$$TS = 20 \log L - 67.6 ,$$

FOOTE (1987), may be explained through the earlier estimation procedure, where the total conversion factor between area density and integrated output was expressed through one constant, without isolating the backscattering cross section of the fish from the instrument part of the constant (MIDTTUN & NAKKEN 1971). The actual product of average backscattering cross section and the effective equivalent beam angle was then determined. If the total conversion factor were determined under thresholding conditions as here, the later isolation of the instrument part, C_I , including a nominal Ψ , would give a low target strength. If we now consider using the in situ target strengths obtained by split beam measurements for abundance estimation, the effective value of Ψ , should be used instead of the nominal value. Direct use of the split-beam- derived target strength, without regulating the equivalent beam angle, can cause substantial underestimation of the main concentrations of cod and haddock in the Barents Sea generally found below 200 m.

Besides a more systematic gathering and analysis of data for estimating the effect of thresholding on the equivalent beam angle than is made by this exemplification, improvements in instrumentation should be considered in order to minimize the threshold effect. Historically, going from (1) the stabilized, narrow, 5 x 5.5 degree magnetostrictive transducer, previously installed on G.O.SARS, to (2) an 8 x 8 degree beam-width ceramic transducer, followed by (3) parallel integration on the split-beam transducer with a 6 dB loss of receiving sensitivity, has by no means improved the detection of small targets at deep water.

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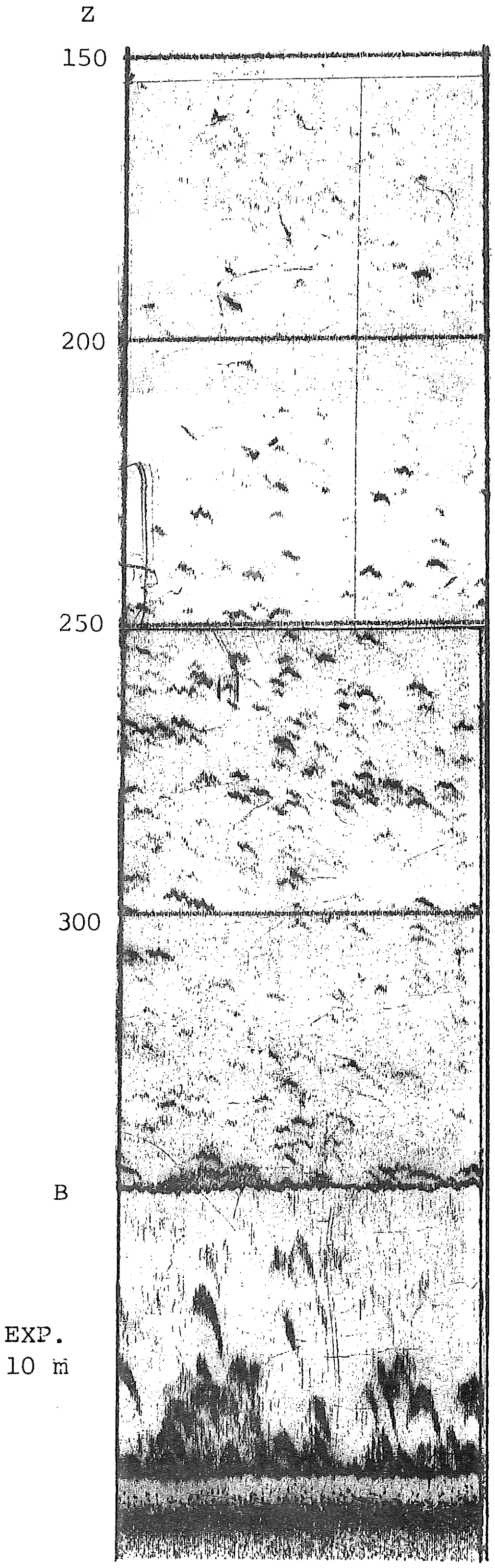


Fig.1 Countable registration from G.O.SARS 1987, after PT 93. Speed 6 knots.

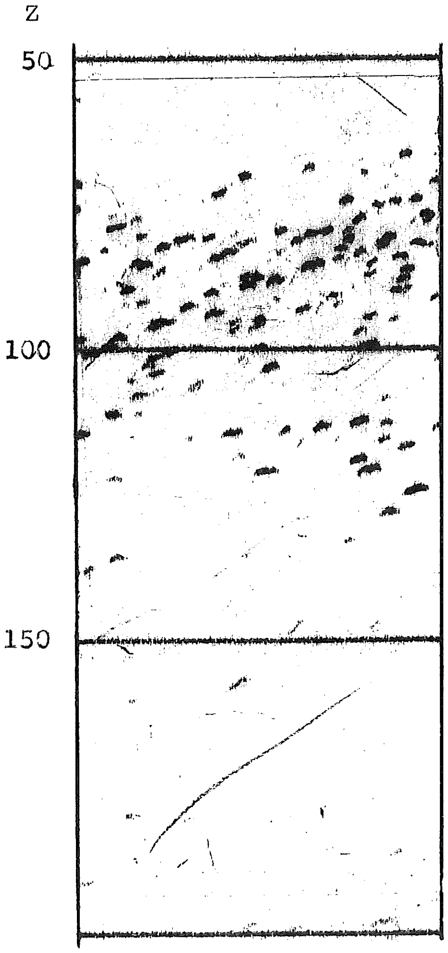


Fig.2. Countable registrations from ELDJARN 1986. During trawling on PT 84. Speed 4.0 knots.

Table. 1. Estimated average detection angle from 1980 individual readings of trace length of 30 - 45 cm cod and haddock observed on the split-beam transducer on board R/V ELDJARN and R/V G.O.SARS. Standard error of the given averages are in the order of 1 - 3%. The regression estimates, based on Fig.3, together with the observation area, are shown separately.

INTEGRATOR	0	50	100	150	200	250	300
CHANNEL	50	100	150	200	250	300	350
G.O.S. 86				4.77	4.58	4.04	4.32
G.O.S. 87					4.26	4.02	4.10
ELDJ. 86A	(5.25)	5.83	4.62	4.28			
ELDJ. 86B	(5.34)	5.48	4.89	4.43	4.46		
Regr. est.	(6.87)	5.47	4.91	4.58	4.35	4.17	4.03
Est. A_c (nm^2)		7.76E-3	1.16E-2	1.51E-2	1.85E-2	2.16E-2	2.47E-2

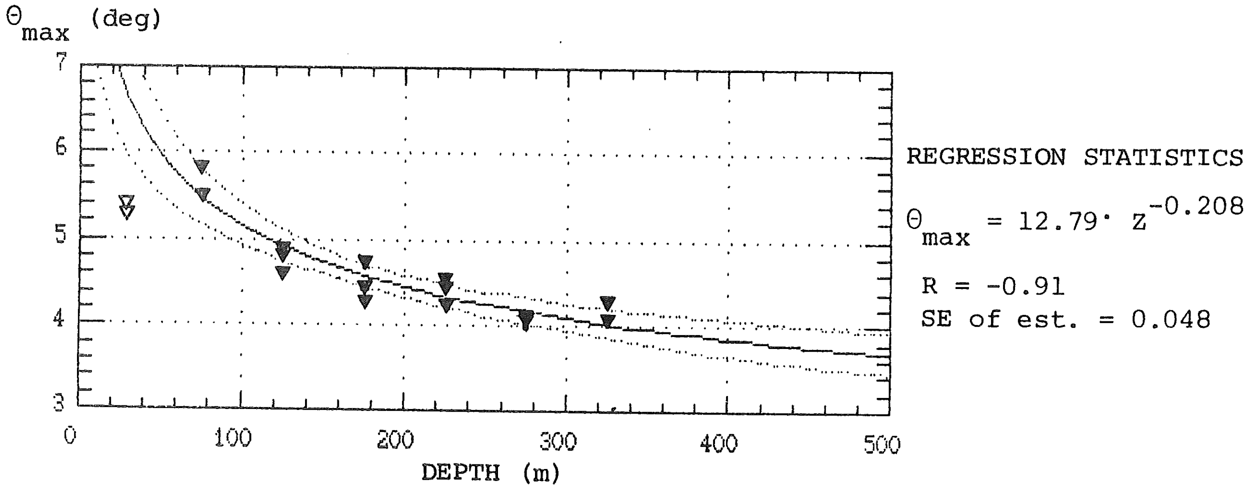


Fig.3. Maximum detection angle as a function of depth. 95% confidence belt for the regression line is shown. The two points in the 0 - 50 m channel are not included in the analysis.

Table 2. Summary of estimated target stength by split beam measurements and counting, with the resulting effective value of the equivalent beam angle.

VESSEL	ELDJARN			G.O.SARS		
INTEGRATOR	50	100	150	200	250	300
CHANNEL	100	150	200	250	300	350
A_c	7.76E-3	1.16E-2	1.51E-2	1.85E-2	2.16E-2	2.47E-2
$<M_{abs}/N_c>$	0.375	0.252	0.142	0.127	0.062	0.055
$<TS_{SB}>$	-39.5^{x}	-39.5^{x}	-39.5^{x}	-37.3^{xx}	-37.3^{xx}	-37.3^{xx}
TS_c	-36.4	-36.3	-37.6	-37.3	-39.7	-39.3
$\hat{\Psi}$	2.24E-2	2.29E-2	1.70E-2	1.09E-2	6.31E-3	6.91E-3
$10\log\hat{\Psi}$	-16.5	-16.4	-17.7	-19.6	-22.0	-21.6

x - Average from 5100 measurements at 50 - 125 m depth.
xx - Average from 14430 measurements at 225 - 311 m depth.

APPENDIX I, List of used symbols

$b_{R,T}$ - Recieving and transmitting directivity pattern function of the transducer

g - Gain at max TVG

I_0 - Intensity of transmitted sound at acoustic axis, 1 m from source

k - Voltage respons

c - Sound velocity

τ - Pulse length

M_0 - Integrator output (mm)

M_{abs} - Absolute integrator output, $C_I \cdot M_0$, i.e., area backscattering coefficient.

ρ_A - Area density of fish

σ_F - Average backscattering cross section of the fish

σ_F - Backscattering cross section of the standard target

Ψ - The equivalent beam angle

$t_{i,j,k}$ - Individual trace length at log no. j, depth layer no k

$\bar{t}(j,k)$ - Average detection distance in one integrator cell, 50 x 1852 m

$\mathrm{Ave}(\bar{t}(k))$ - Average detection distance in one integrator channel

$\bar{Z}_k$ - Average depth of the counted fish

Θ_k - Average detection angle in depth layer k

$\Theta_k(\max)$ - Maximum detection angle in depth layer k.

TS_{SB} - Average target strength , split-beam measurements

TS_C - Average target strength estimated by counting / integration

APPENDIX II, Equipment and instrument performance.

Both R/V ELDJARN and R/V G.O.SARS are equipped with EK-400,38 kHz, working simultaneously with the ES-400 split beam echo sounder, recieving the summed signal from the four quadrants on the split beam transducer. The 20 log R TVG compensated signal is integrated on the ND-10 integrator. All measurements are made with -10 dB attenuator, and pulse length 1 msec. Nominal equivalent beam angle -19.6 dB for both vessels.

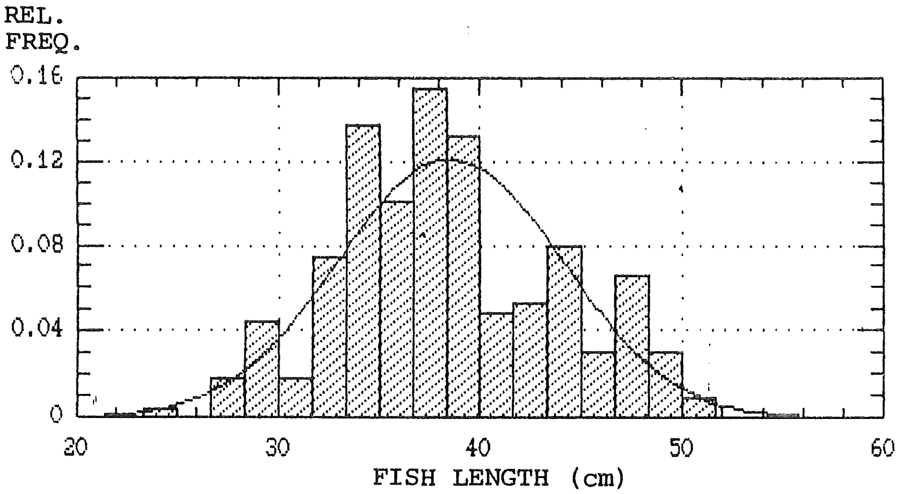
CALIBRATION DATA

VESSEL	ELDJARN		G.O.SARS	
DATE	7.1 1986	15.10.1986	9.2.1986	15.2. 1987
SL + VR (dB)	134.0	134.1	134.9	135.1
C_I ($m^2/nm^2 \cdot mm$)	0.58	0.61	0.44	0.40

THRESHOLD (mV)

0 - 50 m	14	14
50 - 100 m	17	14
100 - 150 m	21	14
150 - 200 m	21	17
200 - 250 m	24	21
250 - 300 m	24	21
300 - 350 m	24	24

APPENDIX III. Catch data from the disperced distributions of fish on which combined counting and target strength data are available.



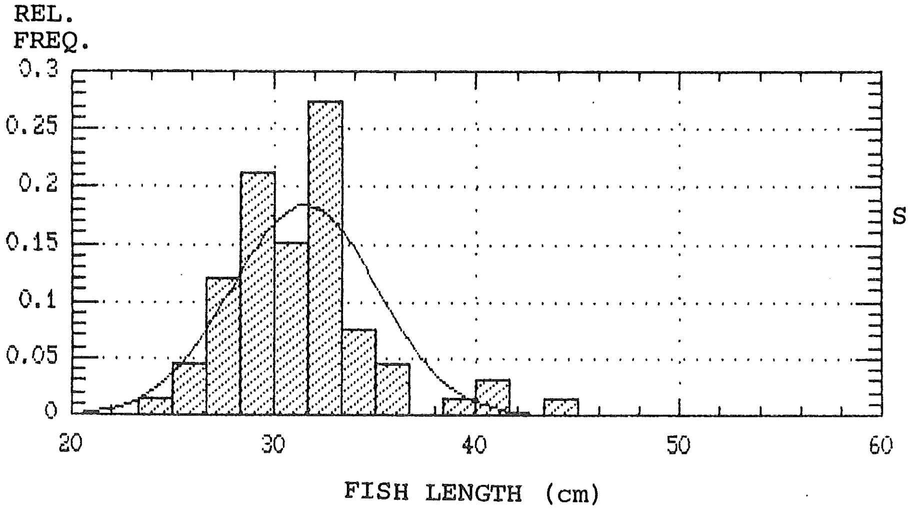
PT 93, 1987

$\bar{L}$ = 38.5 cm
SD = 5.5 cm

Z = 250 - 300 m

$N_{haddock}$ - 228
N_{cod} - 13

Fig.4. Length distribution of haddock on pelagic trawl station PT 93, around which most of the deeper counting and target strength data are sampled. 13 cod of similar length are not included.



PT 84, 1986

$\bar{L}$ = 31.5 cm
SD = 3.6 cm

Z = 100 m

N = 64

Fig.5. Length distribution of haddock on pelagic trawl station PT 84, around which the shallower counting and target strength data are sampled.