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TARGET STRENGTH MEASUREMENTS OF FISH

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INTRODUCTION

Methods of fish sizing using the reflected sound signal from individual fish are developed (CUSHING 1968, CRAIG and FORBES 1969, MIDTTUN 1966). It has also been suggested that discrimination between species might be possible by studying the change in target strength when individual fishes pass through the sound beam (MIDTTUN and NAKKEN 1971). Several workers have studied the frequency responses of fish in order to find methods of identification and sizing (McCARTNEY and STUBBS 1971, HOLLIDAY 1972). So far, the relations between target strength, and fish species and size are not satisfactorly known to enable us doing accurate sizing and reliable identification as routine work at sea.

Due to the complexity of factors governing the reflection of sound from fish it is impossible to calculate the scattered sound field. Thus the relations between target strength and fish parameters (i.e. species and size) have to be established empirically and there are two ways of approach. First, series of target strength measurements can be made with calibrated echosounders at sea provided that the fish under observation within each series belongs to only one species and of equal size, and that representative fish samples can be caught. The target strength observed by this method will be an "average dorsal aspect target strength" depending on the unknown average inclination distribution of the fishes under observation. Second, the target strength can be measured under fully controlled conditions in laboratory experiments and several works of this kind have been reported (LOVE 1969 and 1971, HASLETT 1969, McCARTNEY and STUBBS 1971, MIDTTUN and HOFF 1962, SHIBATA 1970). But as the average inclination of the fish in the field has not been considered, the results from such experiments might bias the estimates of fish lengths made at sea (MIDTTUN and NAKKEN 1971). To support such measurements observations of fish inclinations should therefore be available (OLSEN 1971, BARHAM 1970, BELTESTAD 1973).

In order to obtain more knowledge of the back scattering properties of the fish species which are most commonly recorded in the north-eastern Atlantic, studies of target strength of individual fish were carried out during summer 1971. The experiments were carried out at two frequencies which are commonly used in field work. In this paper results of these studies are reported. Estimates of target strength which are to be expected at sea are obtained by combining the experimental results with field observations of fish inclination.

MATERIAL AND METHODS

Experimental set-up

The experiments were carried out in a sheltered inlet which is 200 m across, 12 - 14 m deep with soft bottom. The experimental set-up is shown in Fig. 1. An anchored raft carried both the laboratory and the accomodations for the staff.

The upward looking transducers were mounted in a heavily loaded steel frame submerged from the raft in adjustable wires. The fish were kept in an upside down position in the central part of the sound beam by a frame of thin nylon gut. A special hoisting device made it possible to hook the fish to the frame at the surface and then lower it to the measuring position at 2.4 m depth.

The aspect of the fish could be continuously changed in two ways, tilting and rolling, without any change of hooking. The fish was tilted by operation of the automatic "tilting bar" between -45° and $+45^{\circ}$ of horizontal position with $\pm 1^{\circ}$ accuracy. The tilting speed was 1° per second. When only tilt variations were wanted a stable upside down position was obtained by small floats attached to the fish belly. When roll variations also were wanted thin nylon guts from the fish sides to a small wheel replaced the floats. The wheel was operated manually and worked normal to the "tilting bar". For complete change of aspect the fish was hauled to the surface and the points of hooking changed.

Instrumentation and data recording

A block diagram of the instrumentation is shown in Fig. 2. Two echosounder working at frequencies 38 kHz and 120 kHz (Simrad Ek 38 A and Ek 120 A) and with transducers 10 x 10 cm and 5 cm in diameter, were used. The transmitted pulselengths, measured at half the amplitude, were 0.6 millisecond for both sounders. The repetion rate of the sounders were increased to 4 pulses per second. For measuring and recording of data a two channel oscilloscope (Hewlett Packard, 141 A), an echo integrator (Simrad echo integrator, QM) with a two channel recorder (Hewlett Packard, 7702 B) and a polarplot level recorder (Brüel and Kjær 2304) were used. One of the channels of both the oscilloscope and the integrator recorder was used for presentation of echo amplitudes, on the other channel the corresponding tilt angles were recorded. A film camera triggered by the echosounders was attached to the oscilloscope.

A hydrophone (LC 32, Atlantic Res.) was used for calibration of the equipment. ~~In addition,~~ a daily calibration was carried out by measuring the target strength of a rigid steel sphere, 5 cm in diameter, which was lowered into the measuring position.

During one measuring program the tilting bar started from horizontal position, moved to +45°, back again through the horizontal to -45° and then back to 0. During the first quarter of this cycle suitable gain settings were selected. The data collected during the complete half cycle between +45° and -45° was used for further treatment. Fig. 3 shows examples of recordings.

The fish was stunned or killed by hitting the frontal part of the brain by a sharp tool. When suspending the fish, care was taken to avoid air in gills and stomach. The measurements were started immediately after the fish had been lowered into the measuring position. In order to obtain necessary information about the relation between target strength characteristics of dead and live fish, a few fish were also measured alive. They were then allowed to move their tail and body without changing their positions within the sound beam.

<u>Data processing</u>

The recorded data consisting of corresponding values of voltage, V, and tilt angle, φ, (Fig. 3) were transferred to punchcards. The amount of data punched from each observation series were large enough to ensure sufficient reproduction of the diagrams. The calculations of target strength, TS, were done by computer from equation

$$TS = 20 \log \frac{V}{V_r} + TS_r \qquad \text{(I)}$$

where V is the observed voltage, V_r is the voltage from the reference sphere and TS_r is the target strength of the reference sphere in decibel (dB). The theoretical value of TS_r is -38.1 dB while the measured values using the data obtained by hydrophone calibration, were -38.0 dB and -38.5 dB for the 38 kHz and the 120 kHz echosounders respectively. When computing TS, the measured values of TS_r were used.

As a first step in the analysis of the material, outprints of the following parameters from each fish, specie and aspect were made:

No : Fish reference number
L : Fish lenght (in cm)
TS_{max} : Maximum observed target strength (dB)
θ : Tilt angle, φ, (in degrees), at TS_{max}
φ is negative for head down, positive for head up.
FV_1 : Interval of φ within which $TS \geq TS_{max}$ -6 dB
FV_2 : Interval of φ within which $TS \geq TS_{max}$ -10 dB
FV_3 : Interval of φ within which $TS \geq TS_{max}$ -20 dB
n_1 : Total number of lobes where $TS \geq TS_{max}$ -6 dB
n_2 : Total number of lobes where $TS \geq TS_{max}$ -10 dB
n_3 : Total number of lobes where $TS \geq TS_{max}$ -20 dB
V_1 : Mean amplitude within FV_1
V_2 : Mean amplitude within FV_2
V_3 : Mean amplitude within FV_3
A : Running mean of amplitudes, calculated from the formula

$$A = \frac{1}{6} \int_{\varphi}^{\varphi+6^{\circ}} V \cdot d\varphi$$

when φ was running from -45° to $+45^{\circ}$. A was printed out for = -21, -15, -9, -3, 3, 9, 15 and 21°.
A_3 : Maximum value of A
FI : Value of φ when $A = A_3$

A linear relation between maximum dorsal aspect target strength (TS_{max}) and fish length (L)

$$TS_{max} = m \log_{10} L + b \tag{II}$$

was assumed to exist for each species and frequency and the coefficients m and b were calculated by a least mean square regression analyses.

TS - length relations, taking into account distribution of the tilt angle, φ, which have been observed at sea, (Fig. 4) were computed for two species, cod and herring, at 38 kHz. The following formulas were used:

$$V_{sea} = \frac{\sum_{\varphi=-21}^{\varphi=+21} \sum_{J=1}^{n} k_{\varphi} \cdot A_{\varphi J} + \sum_{J=1}^{n} \left(\frac{A_{\varphi=21,J} + A_{\varphi=-21,J}}{2} \cdot \left(100 - \sum_{\varphi=-21}^{\varphi=+21} k \right) \right)}{n \cdot 100} \qquad \text{(III)}$$

$$\text{and } TS_{sea} = 20 \log \frac{V_{sea}}{V_r} + TS_r \qquad \text{(IV)}$$

where k_{φ} is the frequencies given in Fig. 4 (in 6 degree classes of φ) and $A_{\varphi J}$ is the amplitude of the J-th fish at tilt angle φ (averaged in 6 degree classes of φ), n is the number of fish in each investigated length group (Table 1).

RESULTS

The observations and the results of the least mean square regression ($TS_{max} = m \log_{10} L + b$) are shown in Table 2 and Fig. 5A-E. It appears the regression lines for cod, saithe and pollack almost coincide, while those for sprat and herring are different. The two latter species having lower maximum dorsal aspect target strengths than the gadoids. The other measured fish were either too few in number or the length range was to narrow for applying a least mean square regression and the results for these fish are shown in Table 3 and Fig. 5F. In Fig. 5F the regression line for cod is shown for comparison. The maximum dorsal aspect target strength of these species is approximately 1-3 dB less than that of cod, except for mackerel, dogfish and prawns which all show considerably lower values. The mean values of mackerel are 10-11 dB lower than those of cod, and 3-4 dB lower than for herring.

The TS-length relations which are to be expected at sea, at 38 kHz, applying the distributions of tilt angle (Fig. 4) to all length groups are shown in Fig. 6 for cod and herring. Fig. 6A shows that the expected mean value of a target strength distribution of cod will be 8-9 dB lower than the corresponding maximum values. The results are compared with the field observations made by MIDTTUN and NAKKEN (1971). Assuming all fish observed to be horizontal, the expected TS-length relation for observations with a 6° transducer beamwidth will be as indicated by line II (Fig. 6A). For herring the expected target strengths at sea will be 6 dB lower than the corresponding maximum values (Fig. 6B). The differences between day and night values are insignificant. The relatively small difference between the expected and the maximum observed values of TS at small fish lengths (Fig. 6A), is caused by the less directivity of small fishes.

The effect of swimming on target strength is shown in Fig. 7 and Fig. 8. The movements of the fish introduced a variation in target strength and this variation increases with increasing swimming activity. No significant change in mean values of target strength can be seen (Table 4). Fig. 8 indicates a periodic relation between target strength and tail beat.

In Table 5 is shown a comparison between the maximum dorsal and maximum side aspect target strength. None of the species observed shows a larger mean difference than 4 dB and significant differences are obtained only for cod, herring and sprat. Fig. 9 which presents target strength as a function of roll angle indicates, however, that the cod may have considerably lower target strengths at roll angles larger than approximately 30°.

The relation between mean values of maximum dorsal aspect target strength in each length group and the angle between 6 dB points in the directivity pattern (Fig. 3) is shown in Fig. 10. The three curves are significantly separated and the obtained values corresponds to the field observations made by MIDTTUN and NAKKEN (1971).

A comparison of all the observed target strengths for the two frequencies applied is madein Fig. 11, where also a frequency difference of 2.4 dB (derived from equ. $TS = 24.5 \log_{10} L - 4.5 \log\lambda - 26.4$, McCARTNEY and STUBBS 1971) is indicated. Fig. 11

indicates that the difference in target strength between 38 kHz and 120 kHz varies with the magnitude of target strength (fish length).

DISCUSSION

The slopes of the regression lines at 38 kHz for cod, saithe and pollack are in accordance with the results reported by McCARTNEY and STUBBS (1971). So is also the slope at 120 kHz for cod, while the lines for saithe and pollack at this frequency show smaller slopes, comparable to the finding of LOVE (1971). The difference in the slopes between 38 kHz and 120 kHz for pollack may, however, not be significant since the length range of the observed fishes are narrow and the variation from specimen to specimen is large. The slopes for herring and sprat are both smaller than those found for the gadoid species. The appearent difference between herring and sprat are not significant and the data could probably have been treated as from one species, resulting in slopes of approximately 16.0 and 20.5 dB/decade at 38 and 120 kHz respectively. For fishes of lengths 6-12 cm the dorsal aspect target strengths of gadoids and clupeoids are approximately equal. For bigger fish the dorsal aspect target strength of the clupeoids will be lower as compared to the gadoids, the difference between a 35 cm cod and a 35 cm herring being 7-8 dB. Table 5 shows that the side aspect target strength of cod is 4 dB lower than the dorsal aspect target strength while herring seem to have a 3.5 dB difference the opposite way (38 kHz). This indicates that herring and cod have approximately equal side aspect target strengths and consequently are equal as targets for horizontal working sonars.

The small difference between the calculated values which are to be expected at sea and the field observation of target strengths (Fig. 6A) are well within the limits of calibration accuracy. However, as both the field observations of target strength and the data on tilt angle distribution are obtained on spawning cod good agreement should be expected. Line III in Fig. 6 is based on the assumption that all length groups have equal tilt angle distributions. To what extent this holds good is not known as data on tilt angle distribution according to length, species and season is lacking.

Fig. 6B shows that the change in the expected target strengths for herring from day to night was insignificant, although both the mean and the spread of the tilt angle distributions changed from day to night. As the mean value of the day observations of tilt angle is much closer to the angle of maximum dorsal aspect target strength than the mean of the night observations (Fig. 4), this will compensate the increment in spread from night to day.

Considering Fig. 6 it is seen that changes of tilt angle distributions both for herring and cod may have considerable effects on mean values of target strength. This is a matter which can lead to serious errors both in sizing and abundance estimation. Reliable estimates of target strengths of individual fish at sea can only be obtained when the fishes are scattered . When such estimates are used to calculate densities of schooling fish the density estimates will be correct if the tilt angle distribution are equal for scattered and schooling fish. If not, large errors might be introduced. More information on tilt angle distributions related to the density of fish consentrations will therefore improve the abundance estimation with acoustic equipment.

It is important to know if the target strength observations made on stunned or dead fish are valid for free swimming individuals. In the experiments done with live fish, the body movements of the fish were observed to be similar to free swimming fish. Most of the recordings were obtained when the fish had a swimming activity comparable to a "fast cruising" situation. For purposes of sizing, identification and abundance estimation, the average value of target strength is the important parameter. Although the fish observed (Table 4) are too few for safe conclusions, there were no indications that the observed periodic target strength variation influenced the mean value significantly. What seems probable, however, is an increased variance on target strength due to swimming. This is particularly clear for the observed saithe. The question of why the target strength variations (Fig. 8) seems related to each tail beat cycle and not to each half cycle, can not be answered from these investigations.

The relation between maximum dorsal aspect target strength and the angle between the 6 dB points in the directivity pattern (Fig. 10) show significant differences between the 3 species (cod, saithe and herring) when the mean values are considered. The values for large cod and coalfish are in close agreement with the field observations made by MIDTTUN and NAKKEN (1971). The variations from specimen to specimen within the same species are, however, large and a similar plot to that of Fig. 10 of individual fish would show a large degree of overlap. MIDTTUN and NAKKEN (1971) suggest that such plots might be used for identification according to species. Fig. 10 indicates that this should be within reach for the 3 species under consideration, when they are unmixed. When mixed recordings occur,it will probably be extremely difficult or impossible to discriminate between species by this method.

Fig. 10 shows also that the dorsal aspect target strength of individual cod at 38 kHz decrease less with tilt angle than for saithe and herring. This means that variation in tilt angle distributions might lead to larger errors in sizing and abundance estimation for the two latter species than for cod. For small fish (low L/λ), changes in tilt angle are of less importance for all 3 species, due to the relatively low directivity of small fish.

The data plot in Fig. 11 will fit a straight line relationship ($k \log\lambda$, where k is a constant) at target strengths below -30 dB if the mackerel is excluded. The curved shape of the plot considering all observations, are probably caused by the fact that merely all our data are within the region of interference effects.

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Table 1. Length distribution of observed fish.

Species	Length groups, cm 5-7	8-10	11-13	14-16	17-19	20-24	25-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-130	Total
Cod	4	6	2			3	8	16	8	7	15	2	1	1		73
Saithe		3	14	8			3	17	2	18	3					68
Pollack					1	19	10	10	2	3	1					46
Mackerel							1	36	2							39
Herring		9	11		1	11	7	2								41
Sprat	3	7	10	7	2											29
Haddock							2	12	1							15
Blue whiting								10								10
Whiting							6	2								8
Spiny dogfish													1		2	3
Wrasse					1	1										2
Ballan Wrasse					1	1										2
Trout								2								2
Horse mackerel								1								1
Lumpsucker							1									1
Poor cod							1									1
Prawn	1	1														2
Total	8	26	37	15	6	35	39	108	15	28	19	2	2	1	2	343

Table 2. Calculated slope (m) and constant (b) of regression lines, TS = m Log_{10} L + b, the correlation coefficient r, the standard error s_{yx} and the number of fish measured N.

Species	Freq. kHz	N	m dB	b dB	r	s_{yx} dB
Cod	38	73	24.5	-66.6	0.972	2.02
	120	72	24.6	-67.6	0.955	2.28
Saithe	38	68	23.3	-64.9	0.975	1.44
	120	68	20.1	-60.1	0.948	1.85
Pollack	38	46	22.7	-65.5	0.879	1.50
	120	46	17.5	-56.4	0.754	1.86
Herring	38	38	13.6	-56.8	0.851	1.51
	120	41	18.8	-62.4	0.890	1.79
Sprat	38	29	17.2	-60.8	0.784	1.66
	120	29	21.4	-66.0	0.819	1.83

Table 3. Mean values ($\overline{TS}$) and standard deviations (St.dev.) of target strength according to lenght (L). N is the number of fish measured.

Species	Freq. kHz	N	L cm	$\overline{TS}$	St.dev. dB
Mackerel	38	16	29 - 34	-40.3	2.7
	"	23	35 - 41	-38.6	3.0
	120	16	29 - 34	-41.9	4.0
	"	22	35 - 41	-40.6	3.6
Horse mackerel	38	1	33	-34.0	-
	120	1	33	-30.9	-
Haddock	38	13	28 - 38	-32.1	1.8
	"	1	48	-28.0	-
	120	14	28 - 38	-30.7	1.5
	"	1	48	-27.6	-
Blue whiting	38	10	31 - 35	-32.0	1.8
	120	9	31 - 35	-33.3	2.7
Whiting	38	4	21 - 22	-35.4	0.4
	"	1	28	-32.2	-
	"	2	38,38	-32.3	1.9
	120	5	21 - 22	-32.0	1.9
	"	1	28	-30.8	-
	"	2	38,38	-29.5	0.7
Spiny dogfish	38	3	81,120,120	-22.8	0.4
	120	3	81,120,120	-22.1	4.2
Prawn	38	1	7	-52.4	-
	120	1	10	-47.4	-
Ballan Wrasse	38	2	19,20	-36.8	0.1
	120	2	19,20	-35.5	0.5
Wrasse	38	2	17,24	-36.0	2.0
	120	2	17,24	-35.0	2.5
Trout	38	2	31,32	-33.2	0.2
	120	2	31,32	-32.6	0.1
Lumpsucker	38	1	29	-32.6	-
	120	1	29	-31.5	-
Poor cod	38	1	23	-34.4	-
	120	1	23	-35.7	-

Table 4. Corresponding dorsal aspect target strength (TS, dB) of swimming and dead fish. The swimming fish are measured at tilt angles of maximum obtainable TS.

Species, length in cm	Mean TS during swim. (95% conf.lim.)	Max Ts of the resp. fish obs. as dead	Corresp. TS of the TS-length rel. (95% conf.lim.)
Cod, 59	-24.3 (+5.0) (-3.2)	-24.6	-32.2 (±4.0)
Cod, 69	-23.5 (+3.5) (-2.5)	-23.9	-21.5 (±4.0)
Saithe, 53	-27.0 (+8.0) (-2.5)	Not obs.	-24.5 (±2.8)

Table 5. Mean values ($\overline{\Delta TS}$) and standard deviations (St.dev.) of the difference between maximum dorsal and maximum side aspect target strength (ΔTS). N is the number of fish measured.

Species	Freq. kHz	N	$\overline{\Delta TS}$ dB	St.dev. dB
Cod	38	7	4.0	3.0
	120	7	2.5	2.6
Saithe	38	29	0.1	1.6
	120	29	1.0	2.4
Pollack	38	11	-0.4	1.2
	120	11	-1.7	2.5
Herring	38	6	-3.5	1.6
	120	6	-1.2	2.2
Sprat	38	4	-3.0	1.0
	120	4	-2.8	2.5
Mackerel	38	6	-1.5	2.9
	120	5	-3.0	1.6

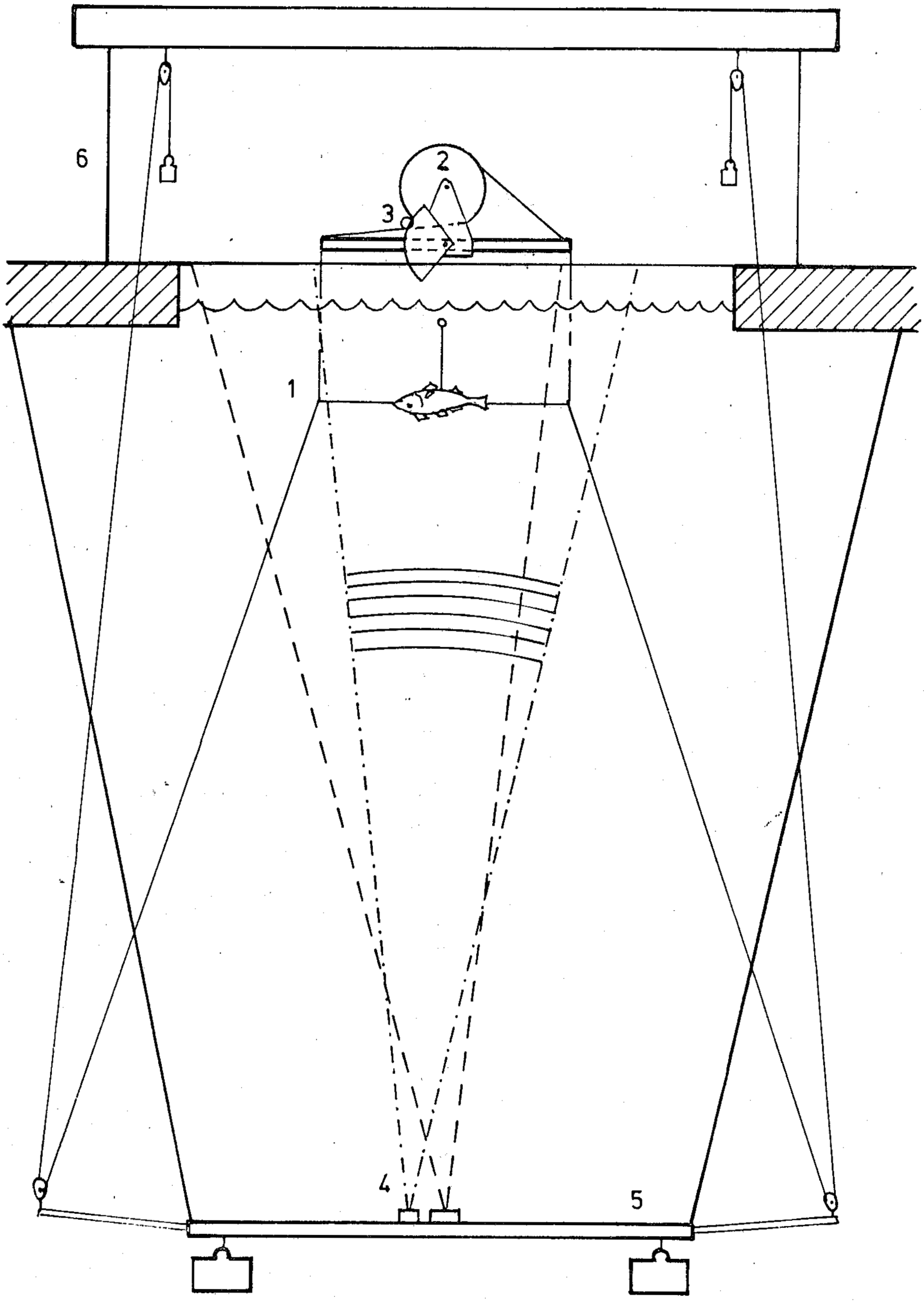


Fig. 1. Experimental set up. 1) Fish suspension, 2) hoisting system, 3) tilting system, 4) transducers, 38 KHz and 120 KHz, 5) transducer base and 6) raft.

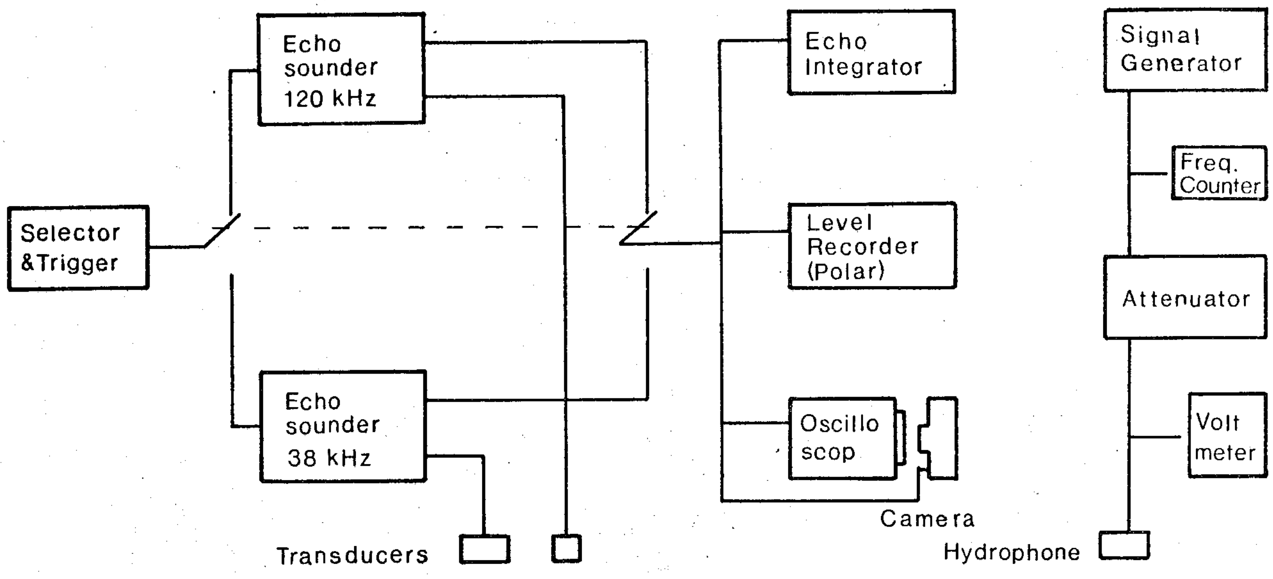


Fig. 2. Block diagram of instrumentation.

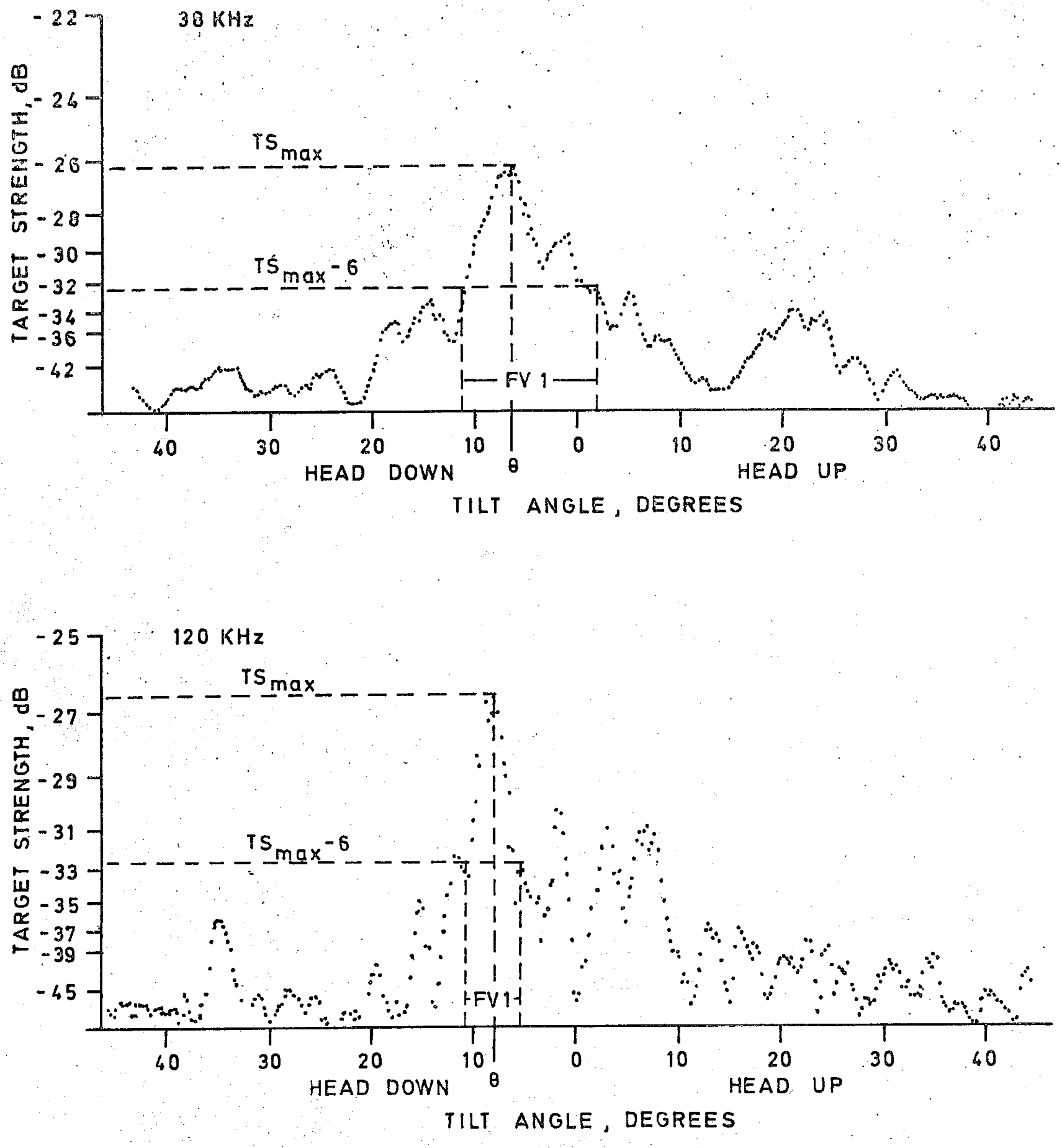


Fig. 3. Recordings of dorsal aspect target strength (TS) as a function of tilt angle (φ) for a cod (45 cm).

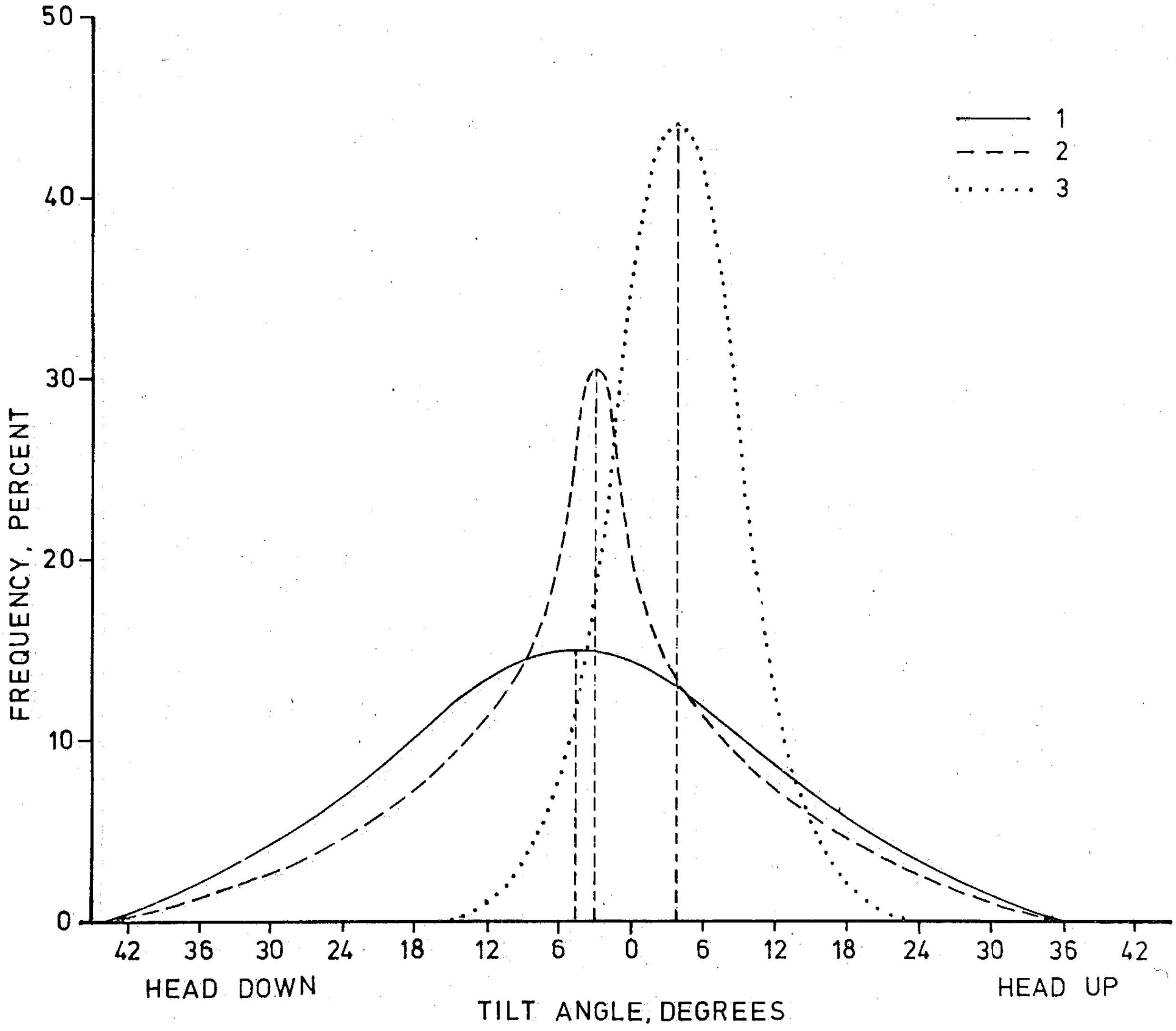


Fig. 4. Distribution of field observations of tilt angle. 1) Cod (mean length 80 cm), day and night (OLSEN 1971), 2) herring (mean length 13 cm), night and 3) herring, day (BELTESTAD 1973).

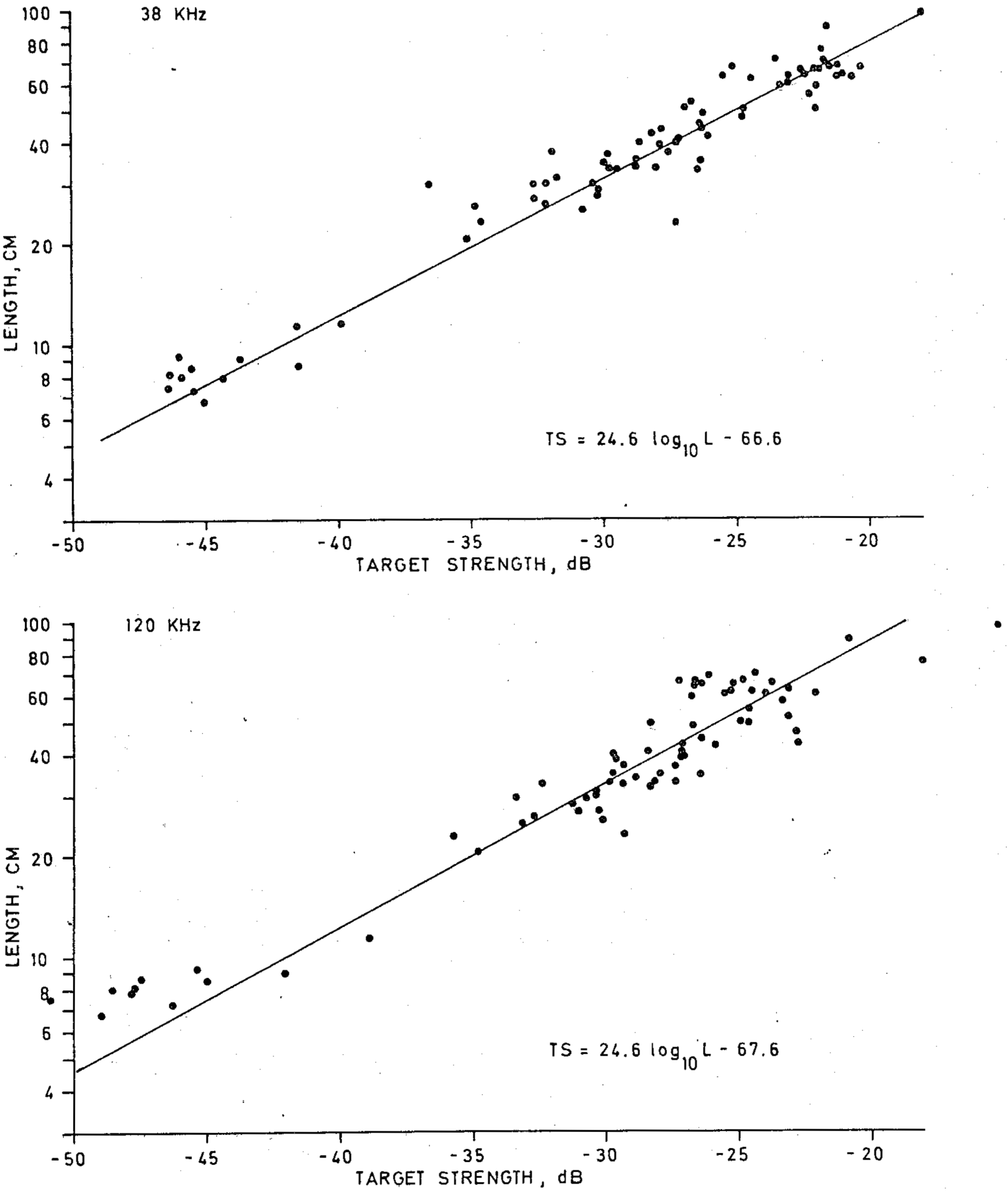


Fig. 5A. Observations of maximum dorsal aspect target strength on cod and the regression line.

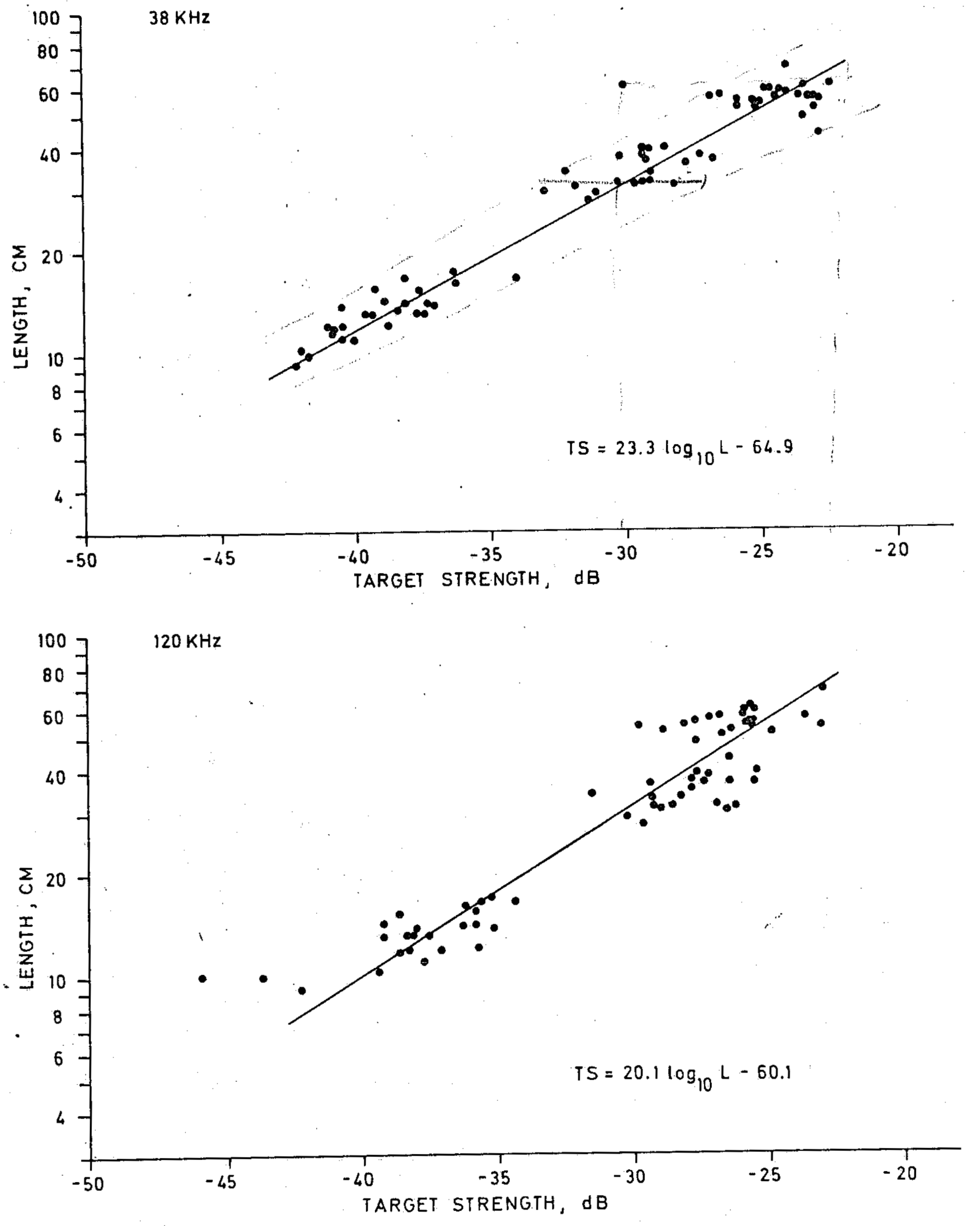


Fig. 5B. Observations of maximum dorsal aspect target strength on saithe and the regression line.

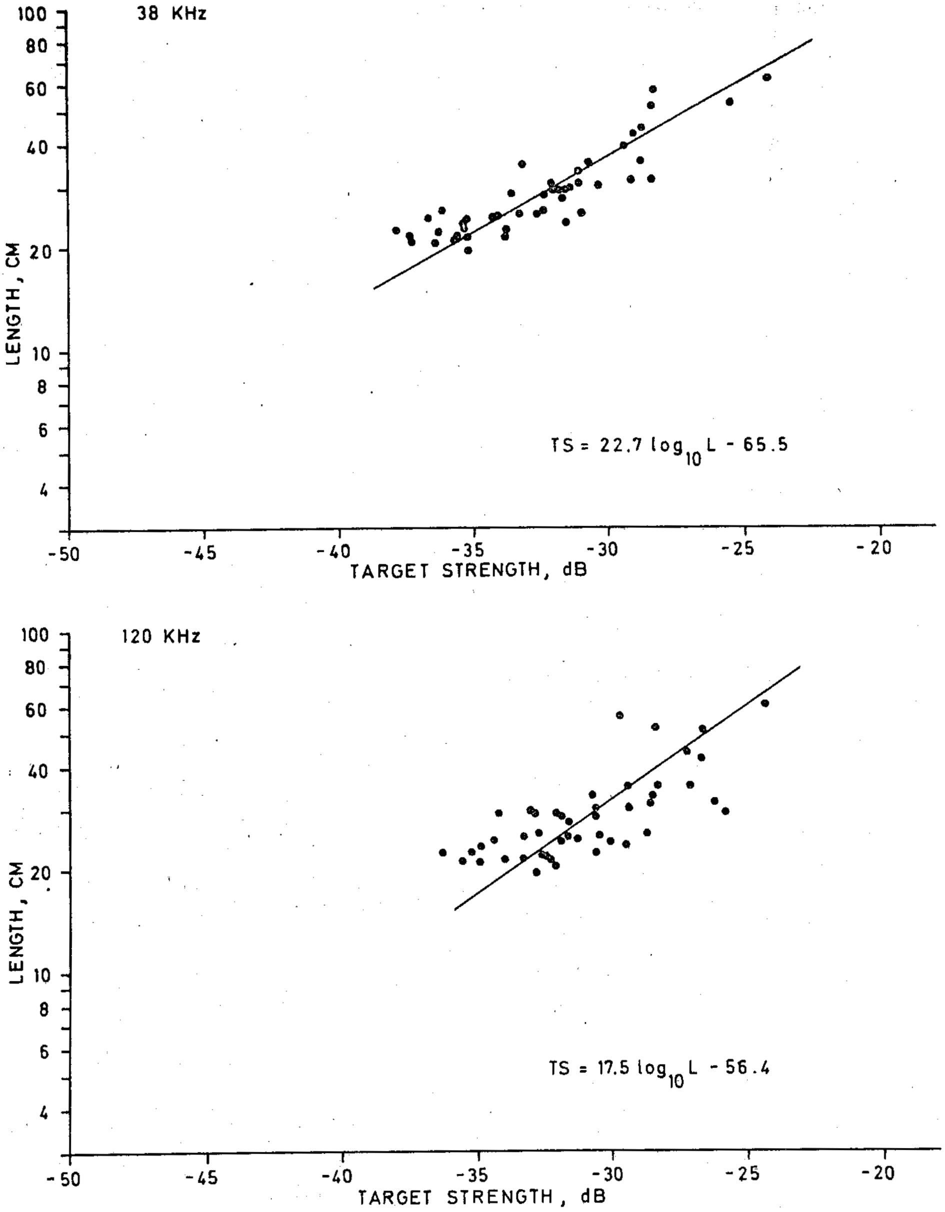


Fig. 5C. Observations of maximum dorsal aspect target strength on pollack and the regression line.

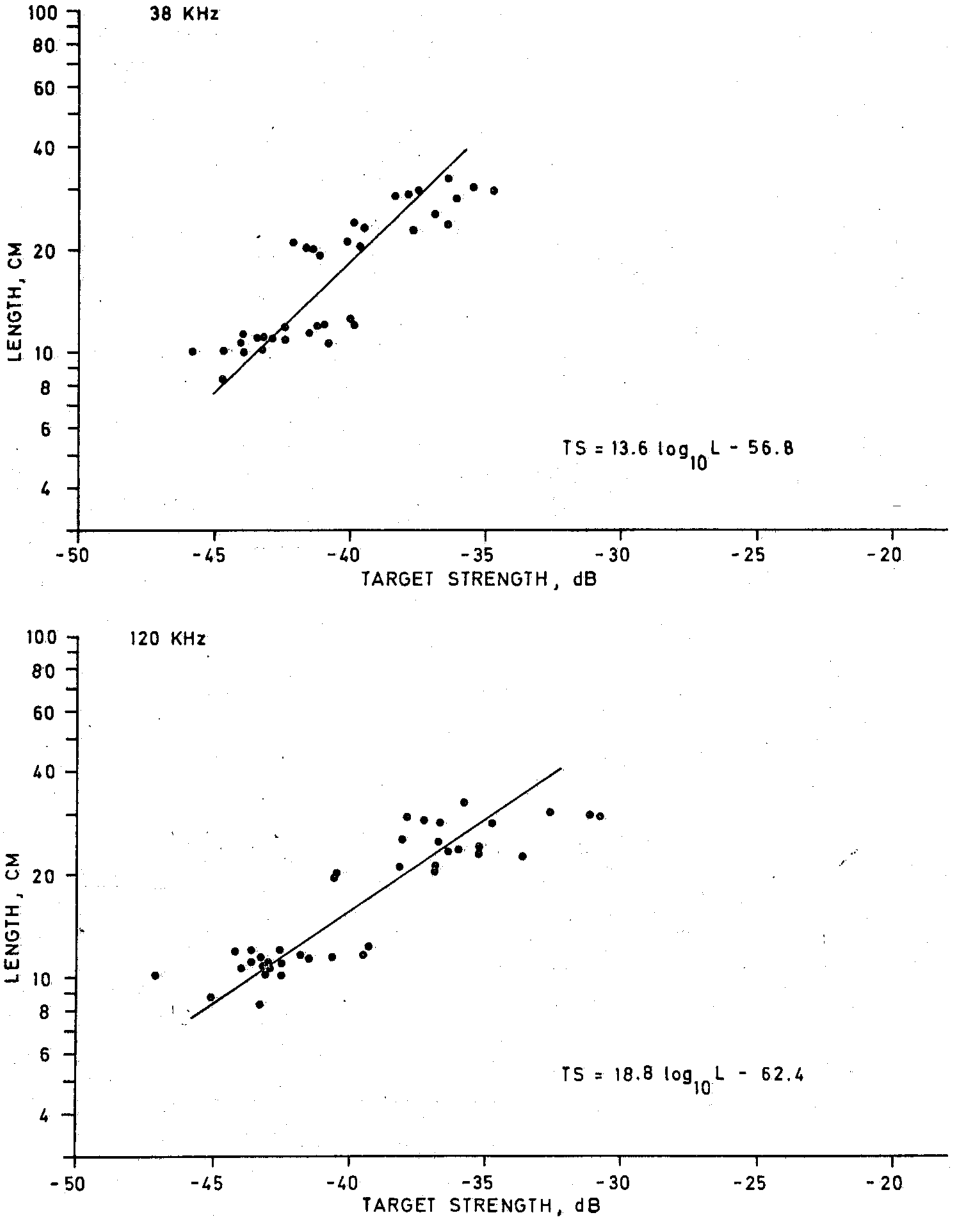


Fig. 5D. Observations of maximum dorsal aspect target strength on herring and the regression line.

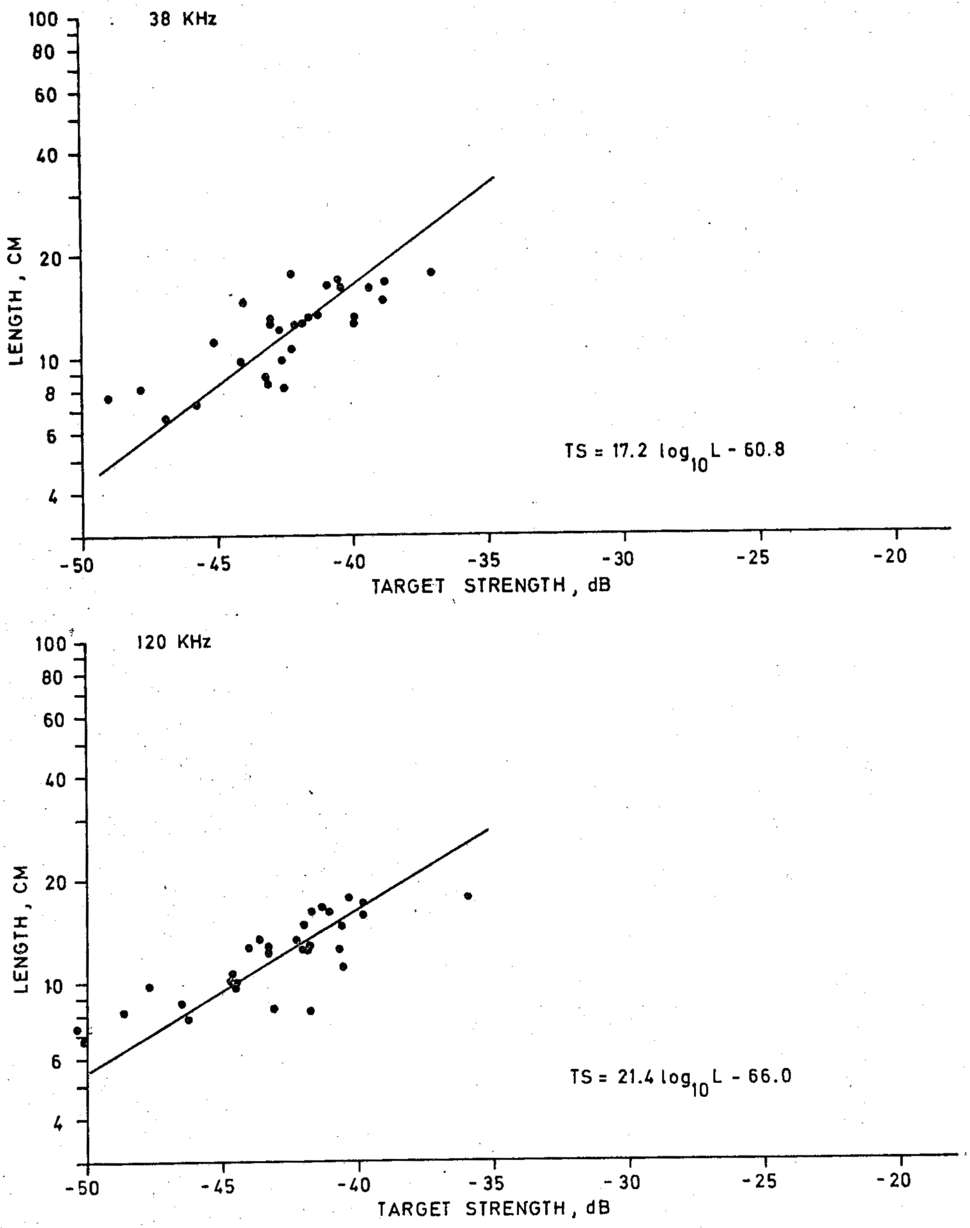
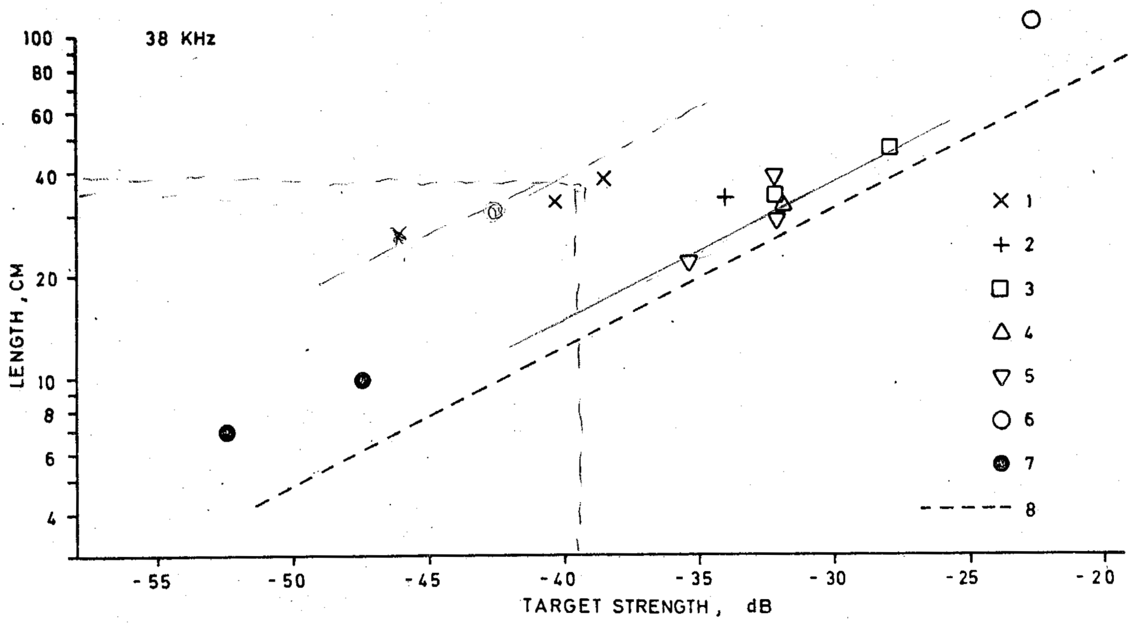


Fig. 5E. Observations of maximum dorsal aspect target strength on sprat and the regression line.



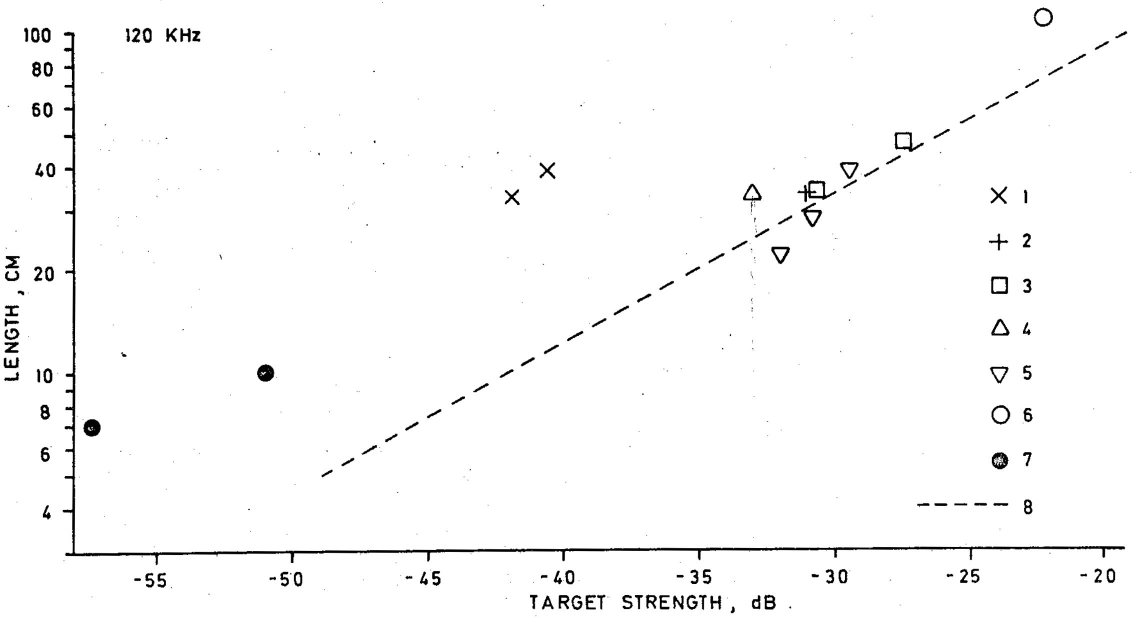


Fig. 5F. Mean values of observations of maximum dorsal aspect target strength of 1) mackerel, 2) horse mackerel, 3) haddock, 4) blue whiting, 5) whiting, 6) spiny dogfish, 7 prawn and 8) the cod regression line.

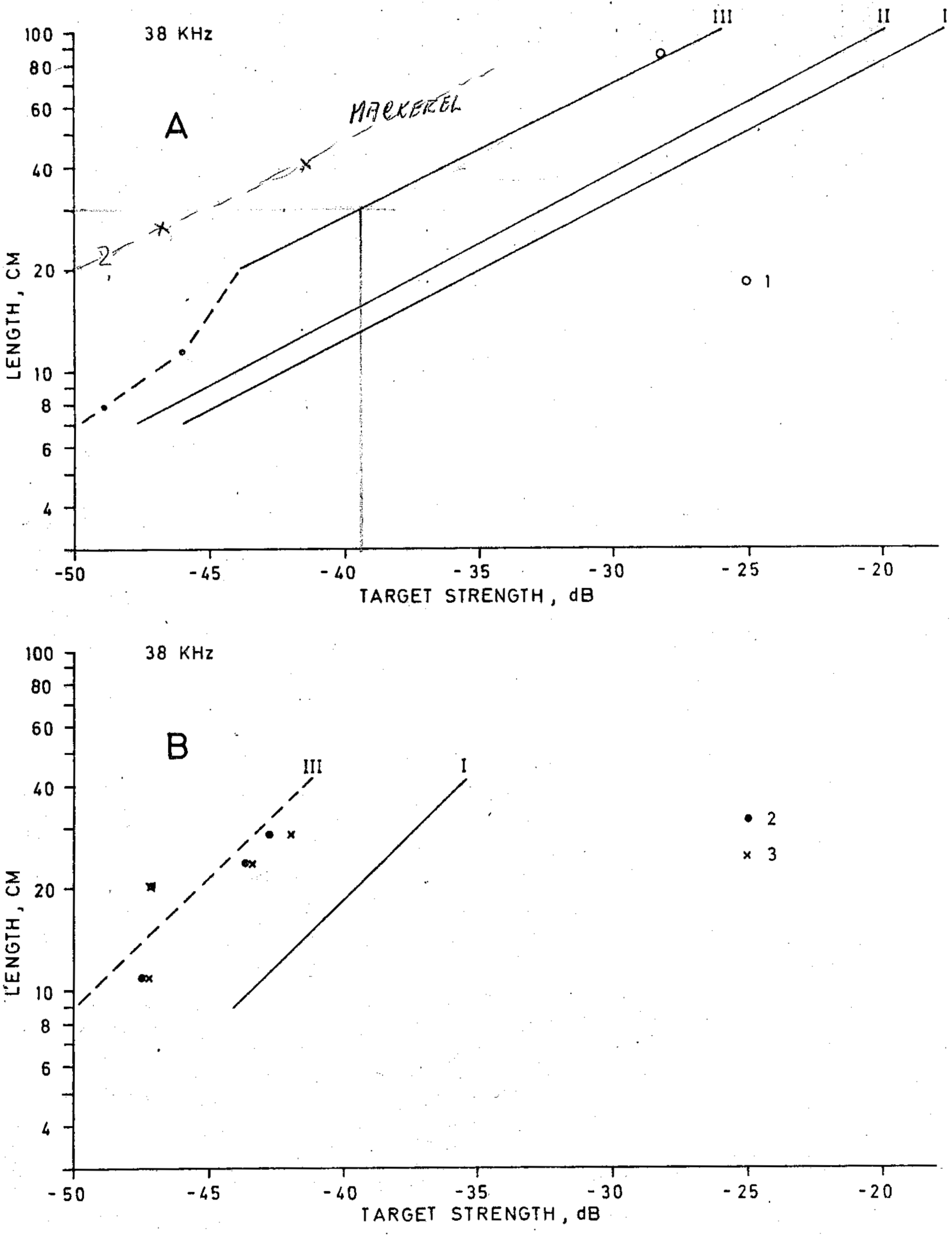


Fig. 6. Dorsal aspect target strength-length relations at 38 KHz for cod and herring. I) Observed maximum values, II) mean values for tilt angles within ± 3^{o} of angle of maximum value (corresponds to 6^{o} transducer beam width), III) expected values in the field (derived from Fig. 4). 1) Field observation of mean value (MIDTTUN and NAKKEN 1971), 2) day and 3) night observations of tilt angle.

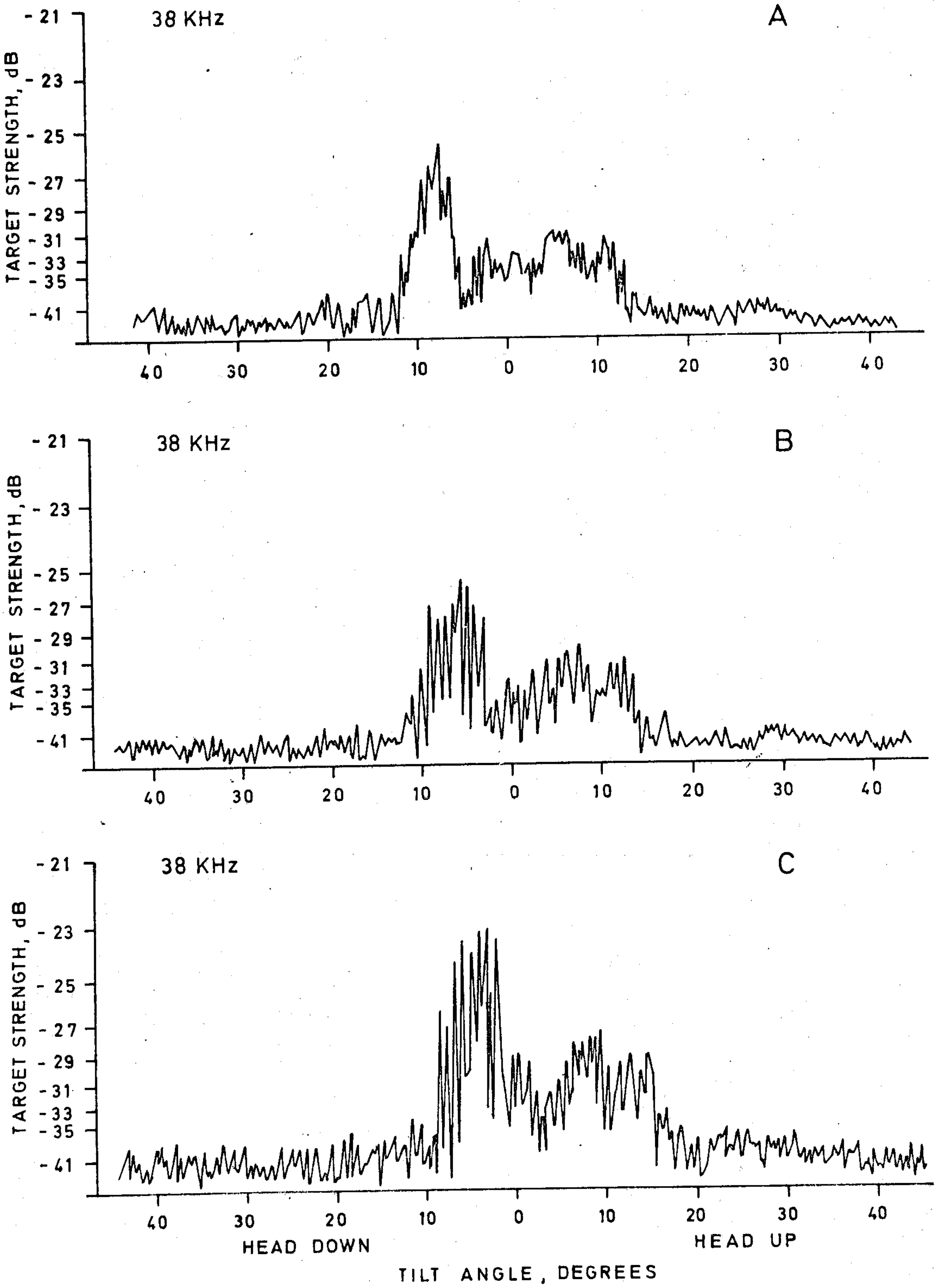


Fig. 7. Observations of dorsal aspect target strength of a swimming saithe. A) Low, B) moderate and C) high swimming activity.

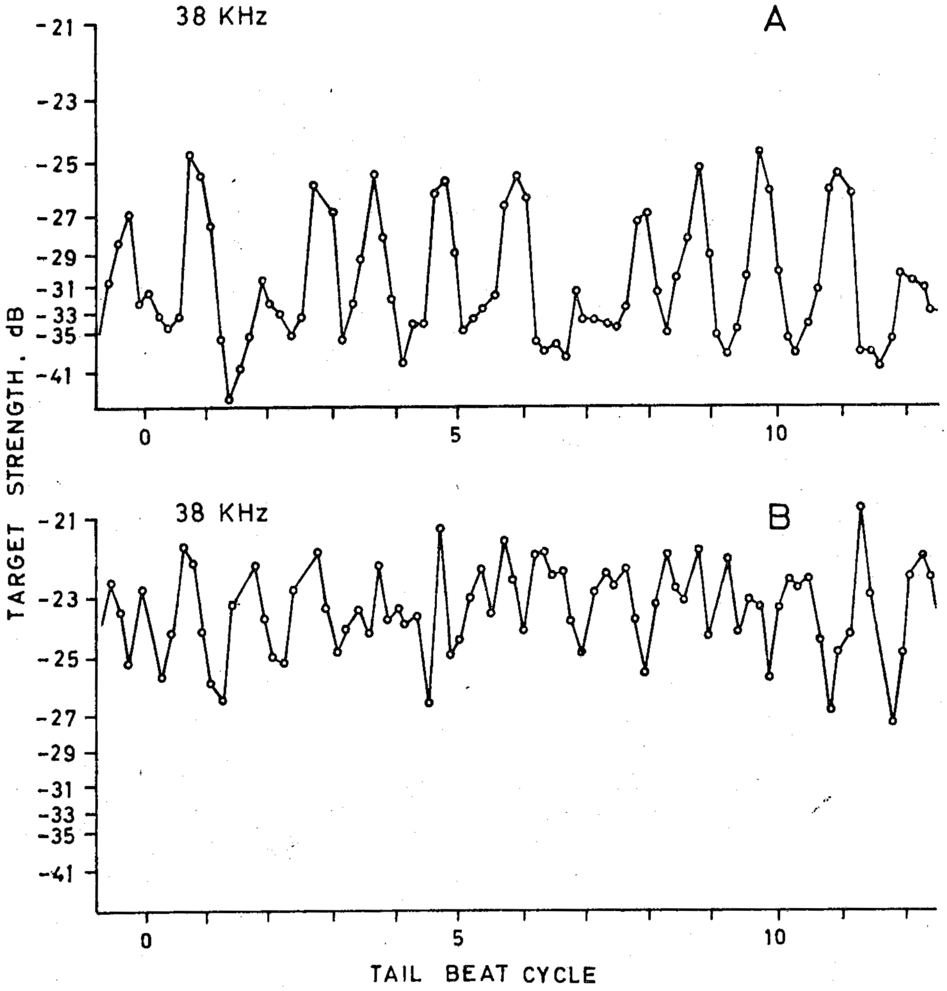


Fig. 8. Observations of dorsal aspect target strength of a swimming cod (69 cm). A) At zero tilt angle and B) at tilt angle of maximum target strength (5°).

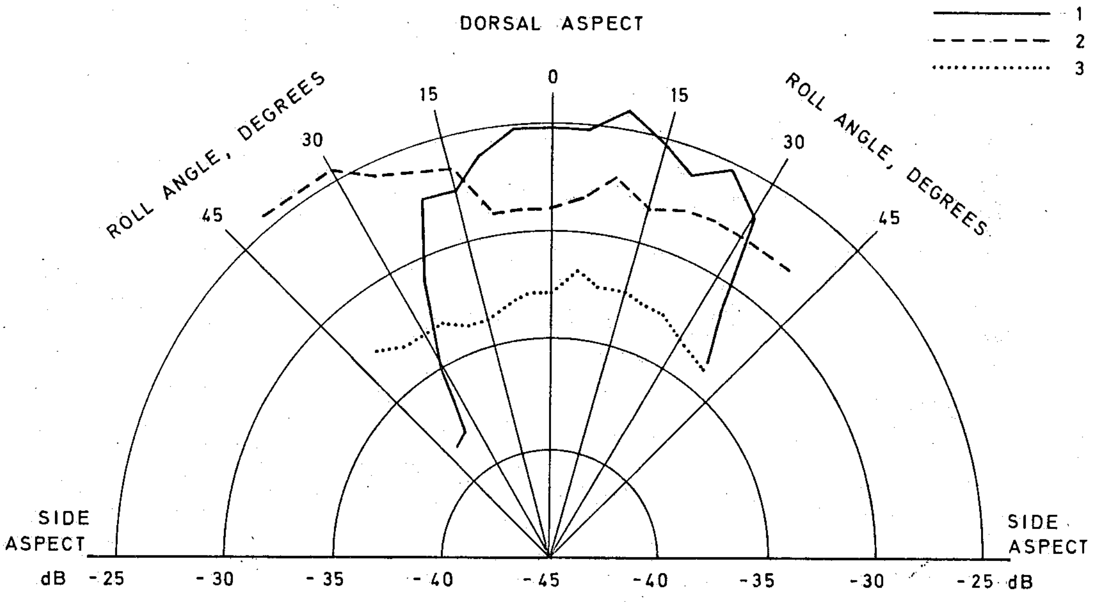


Fig. 9. Target strength as a function of roll angle for 1) cod, 2) saithe and 3) herring.

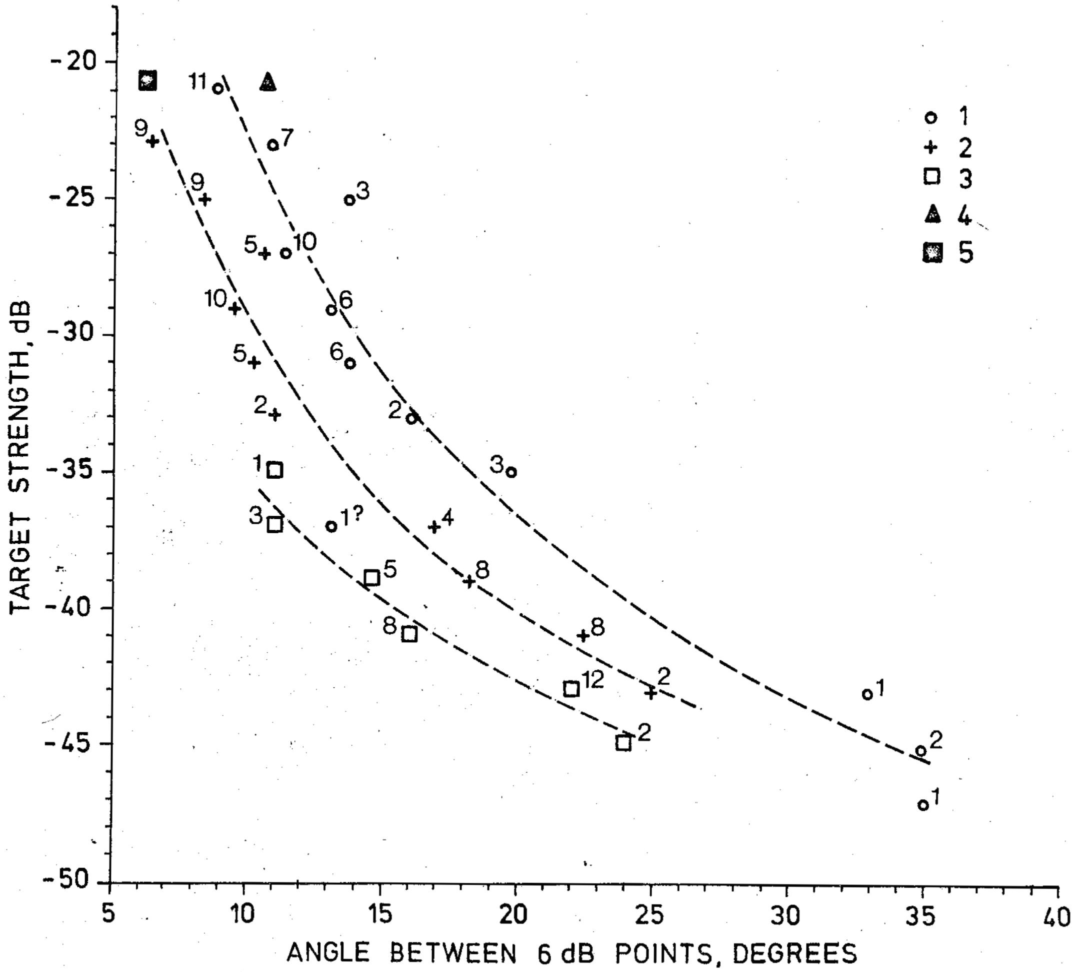


Fig. 10. Corresponding values of maximum dorsal aspect target strength and angle between points of half maximum amplitude (6dB points). 1) Cod, 2) saithe, 3) herring, 4) and 5) field observations of cod and saithe (MIDTTUN and NAKKEN 1971). The values are averaged over the indicated number of fish.

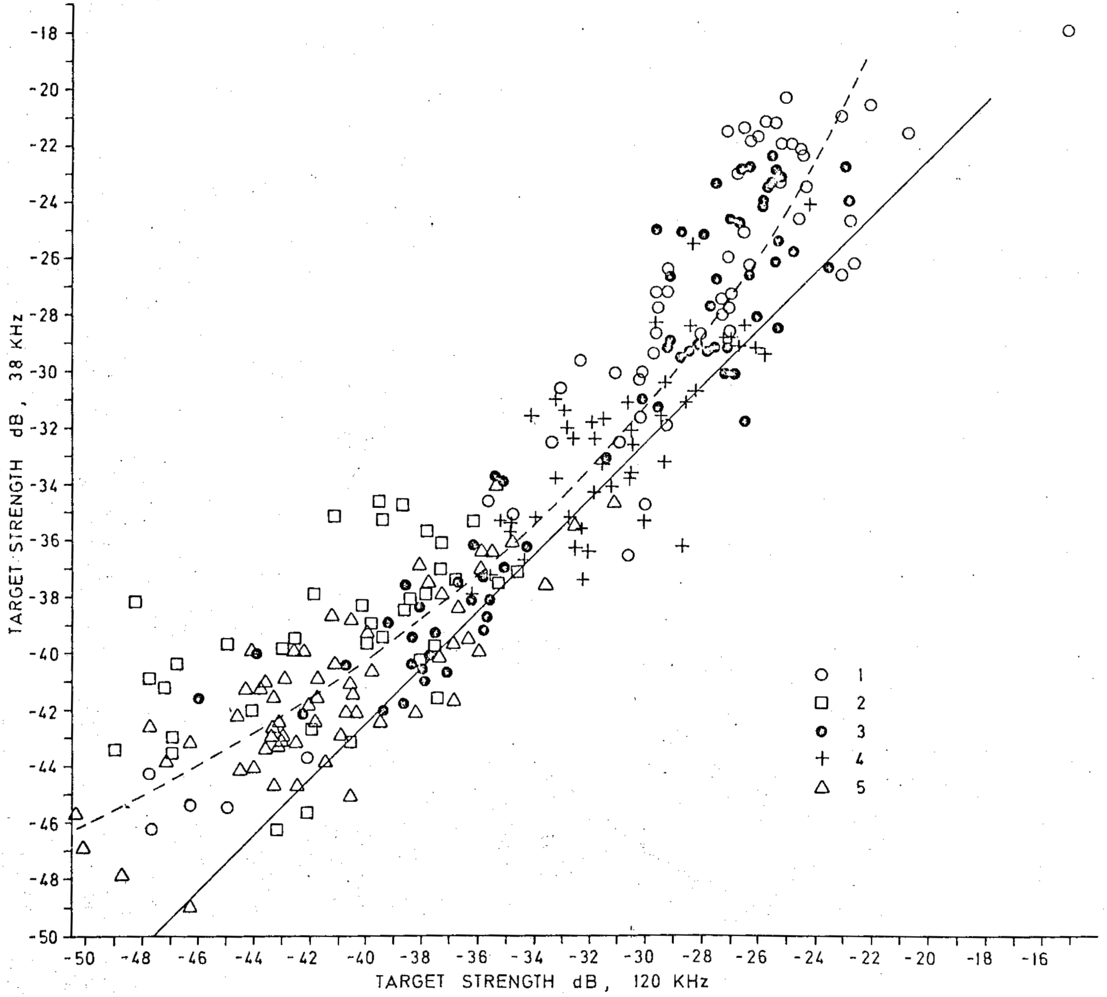


Fig. 11 Maximum dorsal aspect target strength of individual fish at two frequecies, 38 kHz and 120 kHz. 1) Cod, 2) mackerel, 3) saithe, 4) pollack and 5) herring and sprat. Full line: McCARTNEY and STUBBS 1970 (4.5 logλ), broken line: curve fitted to the data.