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ANGULAR MEASURES OF DORSAL ASPECT TARGET STRENGTH FUNCTIONS OF FISH

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ABSTRACT

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Three angular measures of dorsal aspect target strength functions in the pitch plane are computed for previously gathered acoustic data on three gadoid fishes, two clupeoid fishes, and mackerel. These measures are the angle of maximum dorsal aspect backscattering cross section, the central angle of the backscattering cross section, and the dispersion of the cross section about the central angle. Each measure is regressed linearly on fish length. The statistical significances of the estimated regression coefficients are computed. Systematic differences are attributed to fish anatomy: backscattering cross sections of the considered swim bladder-bearing fishes are concentrated about negative tilt angles of several degree magnitude, which is attributed to the inclination of the swim bladder axis. Backscattering cross sections of mackerel, which lacks a swim bladder, are approximately balanced about the horizontal.

INTRODUCTION

The general complexity of the orientation dependence of fish target strength functions or backscattering cross sections at ultrasonic frequencies is well known, cf. references in FOOTE (1979a). For purposes of interpreting the results of echo integration (FORBES and NAKKEN 1972), rather simple relationships of target strength and fish length have been derived. Two methods of determining this relationship have employed regression analysis. In one method the dependent regression variable is a logarithmic measure of a special value of the backscattering cross section, e.g., maximum dorsal aspect value (MIDTTUN and HOFF 1962, YUDANOV *et al.* 1966, NAKKEN and OLSEN 1977), maximum near dorsal aspect value (MCCARTNEY and STUBBS 1971), and maximum side aspect value (LOVE 1969). In the other method the dependent variable is the same logarithmic measure of the average of the backscattering cross section with respect to the geometric, acoustic, and behavioural circumstances of observation (FOOTE 1978, 1979a–c, 1980a). In either case, if only through use of regression analysis to condense large quantities of data to manageable proportions, as in the derivation of simple target strength-to-length relationships, much scattering information is lost.

Some examples of other systematic scattering dependences of interest in acoustic studies of fish stocks, which aim directly or indirectly to improve abundance estimates, are mentioned: The probability density function of observed effective scattering strength of fish may facilitate classification (FOOTE 1979d), as may statistical moments of echo energy from aggregations (FOOTE 1980b). The effective acoustic sampling volume depends on the detailed scattering properties of fish (FOOTE 1979e), which is of significance to the echo-counting method of assessing fish abundance (FORBES and NAKKEN 1972). Correction of echo integrator or echo counter estimates of fish abundance derived from use of sector scanning sonars in the vertical plane, as in avoidance reaction studies, similarly depends on the backscattering cross sections of fish (FOOTE 1979e).

Several additional examples of systematic target strength dependences, which are also of use in avoidance reaction studies (OLSEN 1979), are considered in this paper. These are measures of the angular characteristics of the dorsal aspect target strength function in the pitch plane. Three quantities are considered: the angle of maximum backscattering cross section, the angle of mean concentration of backscattering cross section, and the dispersion of the backscattering cross section about this central angle. The length dependences of the several angular measures are derived in this study for three gadoid species, two clupeoid species, and mackerel, for which measurements of the dorsal aspect target strength functions at 38 and 120 kHz exist (NAKKEN and OLSEN 1977, FOOTE and NAKKEN 1978). The statistical significances of various systematic length dependences and means of the angular measures are discussed.

MATERIALS AND METHODS

The source data for the computations of this study are the tabulated measurements of NAKKEN and OLSEN (1977) of the dorsal aspect target strength functions of six fishes at two ultrasonic frequencies (FOOTE and NAKKEN 1978). The number and represented length ranges of the measured functions for each species and frequency are presented in Table 1.

Table 1. Numbers and applicable length ranges of measured dorsal aspect target strength functions under analysis.

Fish	Data at 38 kHz		Data at 120 kHz	
	Number	Length range (cm)	Number	Length range (cm)
Cod *(Gadus morhua)*	68	6.7–96.0	44	6.7–67.0
Saithe *(Pollachius virens)*	59	9.1–68.0	48	9.1–68.0
Pollack *(Pollachius pollachius)*	44	19.7–61.0	39	19.7–52.0
Herring *(Clupea harengus)*	25	10.0–32.4	30	8.7–32.4
Sprat *(Sprattus sprattus)*	21	6.6–17.6	24	6.6–17.6
Mackerel *(Scomber scombrus)*	35	29.7–41.5	24	29.7–41.5

A characteristic measure of the dorsally sensed backscattering cross section is the pitch or tilt angle of maximum backscattering cross section. This is defined here for a particular backscattering cross section function σ of tilt angle θ by the following prescription:

$$\sigma(\alpha_0) = \text{Max}\ \{\sigma(\theta) \text{ for all } \theta\}, \tag{1}$$

where α_o is the sought angle of maximum backscattering cross section in the pitch plane.

The central tilt angle of backscattering cross section is defined by the expression

$$\alpha_1 = a^{-1} \int_{-\pi/4}^{\pi/4} \theta\ \sigma(\theta)\ d\theta, \tag{2}$$

where a is the normalization factor,

$$a = \int_{-\pi/4}^{\pi/4} \sigma(\theta)\ d\theta. \tag{3}$$

This makes the likely assumption that, for the approximately fusiform fish of consideration, the backscattering cross section function is concentrated in the dorsal region of the pitch plane.

A measure of the dispersion in backscattering cross section about the central angle is the second central moment of backscattering cross section,

$$\alpha_2{}^2 = a^{-1} \int_{-\pi/4}^{\pi/4} (\theta - \alpha_1)^2\ \sigma(\theta)\ d\theta. \tag{4}$$

The same assumption of approximate concentration of backscattering cross section in the dorsal region is also invoked here in the delimitation of the integration range.

Because the measurements of the dorsal aspect target strength functions were made at one-degree intervals over the 90-degree range in tilt angles from –45 to +45 deg, the integrals of Eqs. 2–4 are approximated by finite summations. Extraction of the angle of maximum dorsal aspect backscattering cross section, as in Eq. 1, is similarly approximate. In all computations the length-to-wavelength ratio is confined to the approximate range of 2 to 80, which makes plausible the excellence of the several approximations.

The several computed angular measures are regressed linearly on fish length for similarly analyzed scattering data of homogeneous species and frequency content according to the linear expression

$$\alpha = b_o + b_1\ l,$$

where α is a given characteristic angular measure expressed in degrees and l is the fish length in centimetres. Estimates of the regression coefficients b_o and b_1, which are denoted by the respective circumflexed symbols $\hat{b}_0$ and $\hat{b}_1$, are computed in accordance with the least squares criterion (WILKS 1962). The corresponding standard errors of coefficients are computed.

The significances of the estimated coefficients are obtained from the t-statistic

$$t_b = \hat{b} \;/\; est[SE(\hat{b})],$$

where $est[SE(\hat{b})]$ is the estimated standard error of regression coefficient estimate $\hat{b}$. The number of degrees of freedom of the statistic, whether for $\hat{b}_0$ or $\hat{b}_1$, is $N-2$, where N is the number of independent data in each set. This number is specified in Table 1. Significance levels corresponding to the t-statistics are also tabulated. The meaning of an arbitrary significance level γ, for example, is the following:

$$Prob(b \neq 0) = 1 - \gamma,$$

that is, the probability that the estimated regression coefficient $\hat{b}$ is non-vanishing is $1-\gamma$. Thus the probability of wrongly rejecting the hypothesis that the regression coefficient essentially vanishes is $1-\gamma$. Small values of γ therefore indicate likely non-vanishing values of the estimated regression coefficient.

A similar statistical analysis is carried out for the means of the several angular measures.

RESULTS

Computations of the three angular measures of dorsal aspect target strength functions are presented in Figs. 1–12. Each figure consists in a set of three scatter diagrams of the several angular measures on fish length. The corresponding least squares linear regressions are shown. Statistical analyses of these regressions and of the mean angular measures are presented in Tables 2–4, which are discriminated by type of angular measure.

DISCUSSION

The main characteristics of the angle measure data presented in Figs. 1–12 are the lack of a trend in the maximum and central angles of the backscattering cross section, but general negativity of the same measures in the mean, and a slight upwards trend of the dispersion angle with increasing fish length. These observations are confirmed by inspection of Tables 2–4.

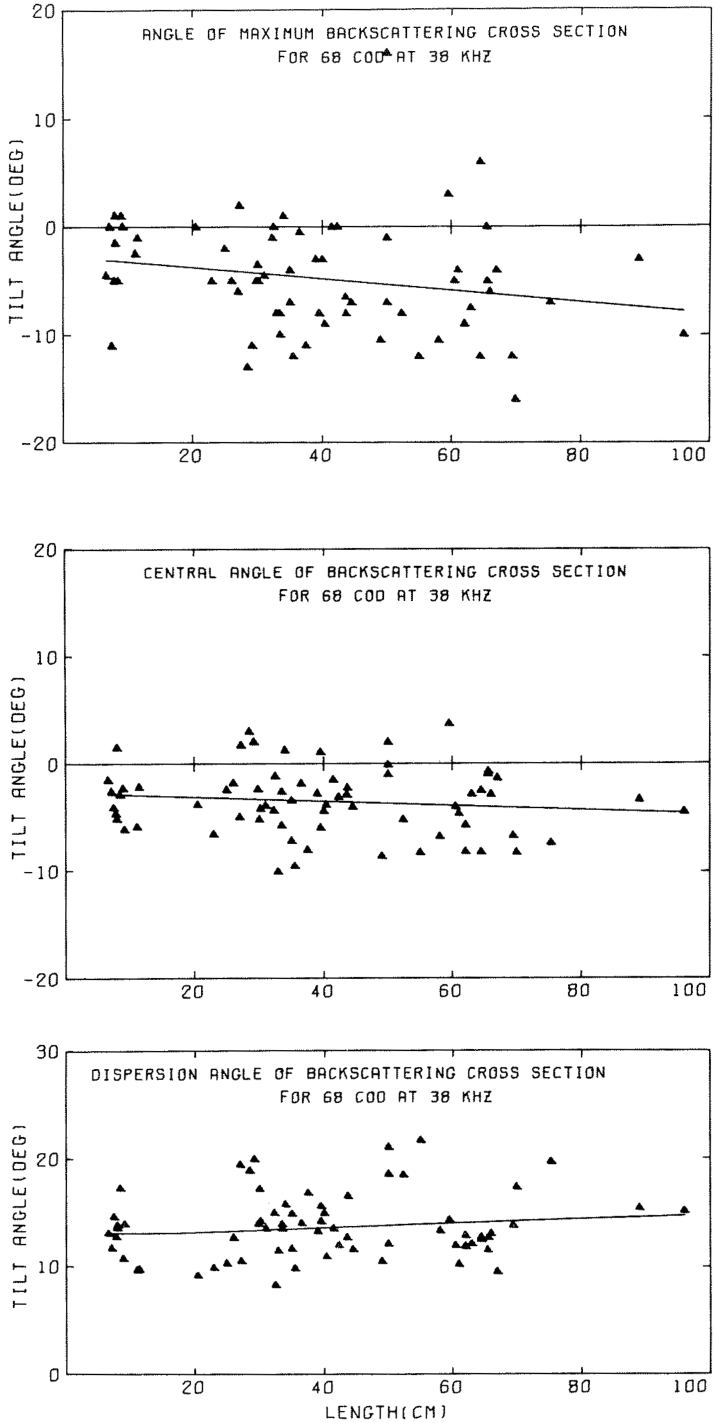


Fig. 1. Characteristic angular measures of measured dorsal aspect target strength functions of 68 cod at 38 kHz.

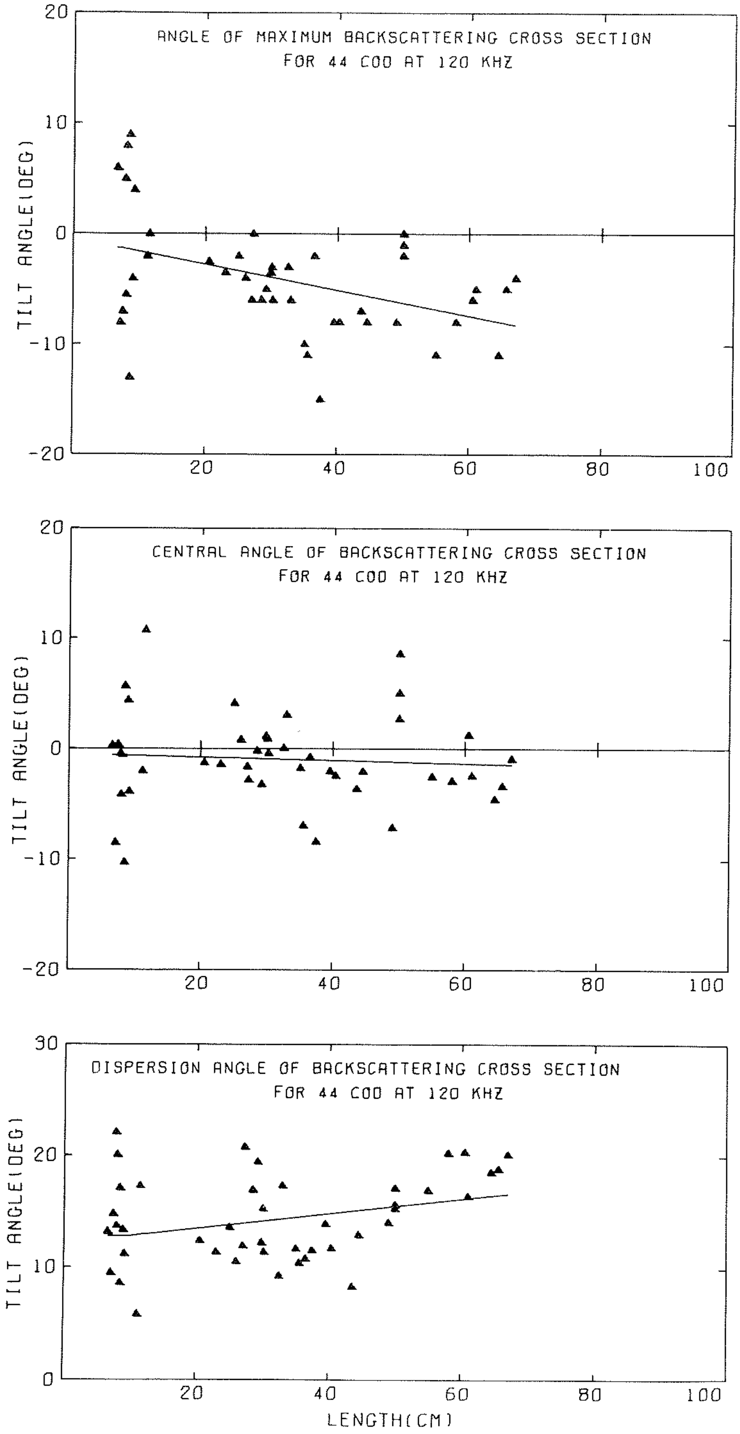


Fig. 2. Characteristic angular measures of measured dorsal aspect target strength functions of 44 cod at 120 kHz.

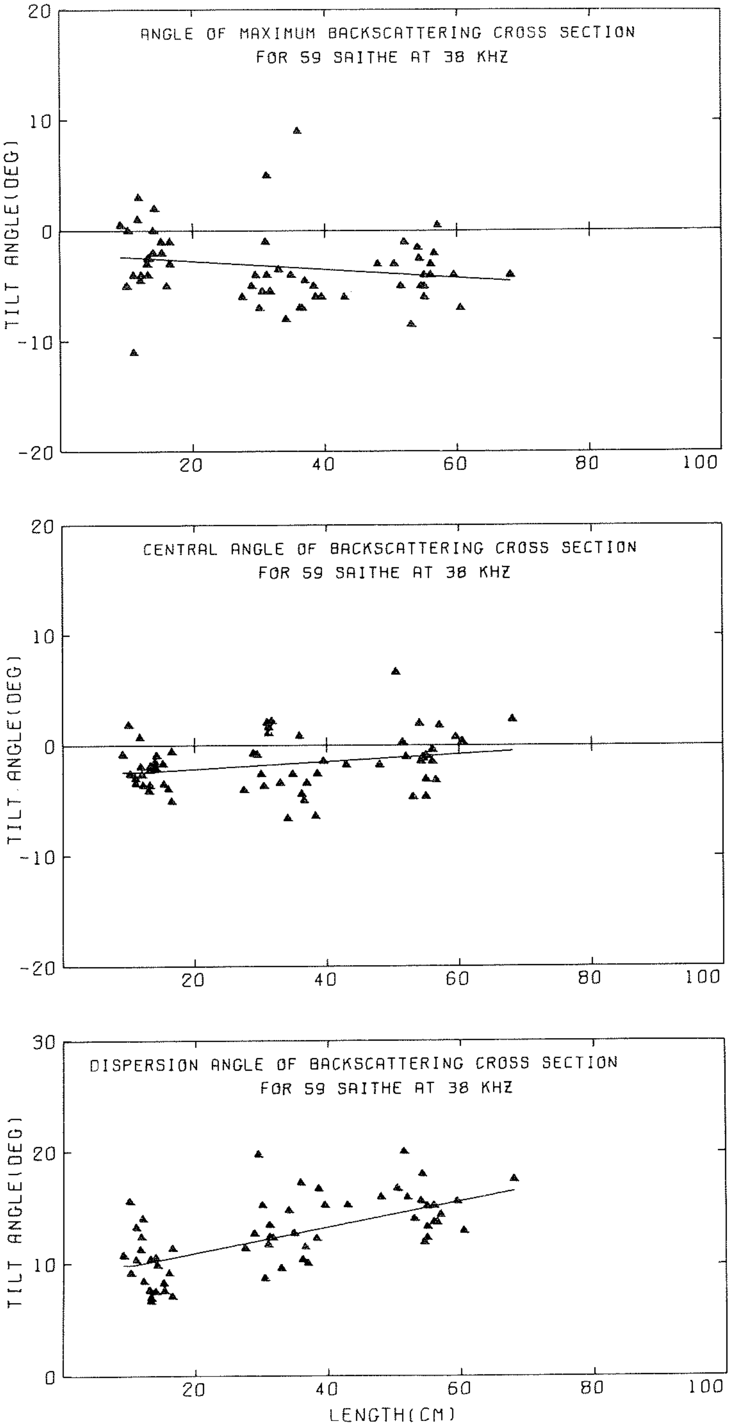


Fig. 3. Characteristic angular measures of measured dorsal aspect target strength functions of 59 saithe at 38 kHz.

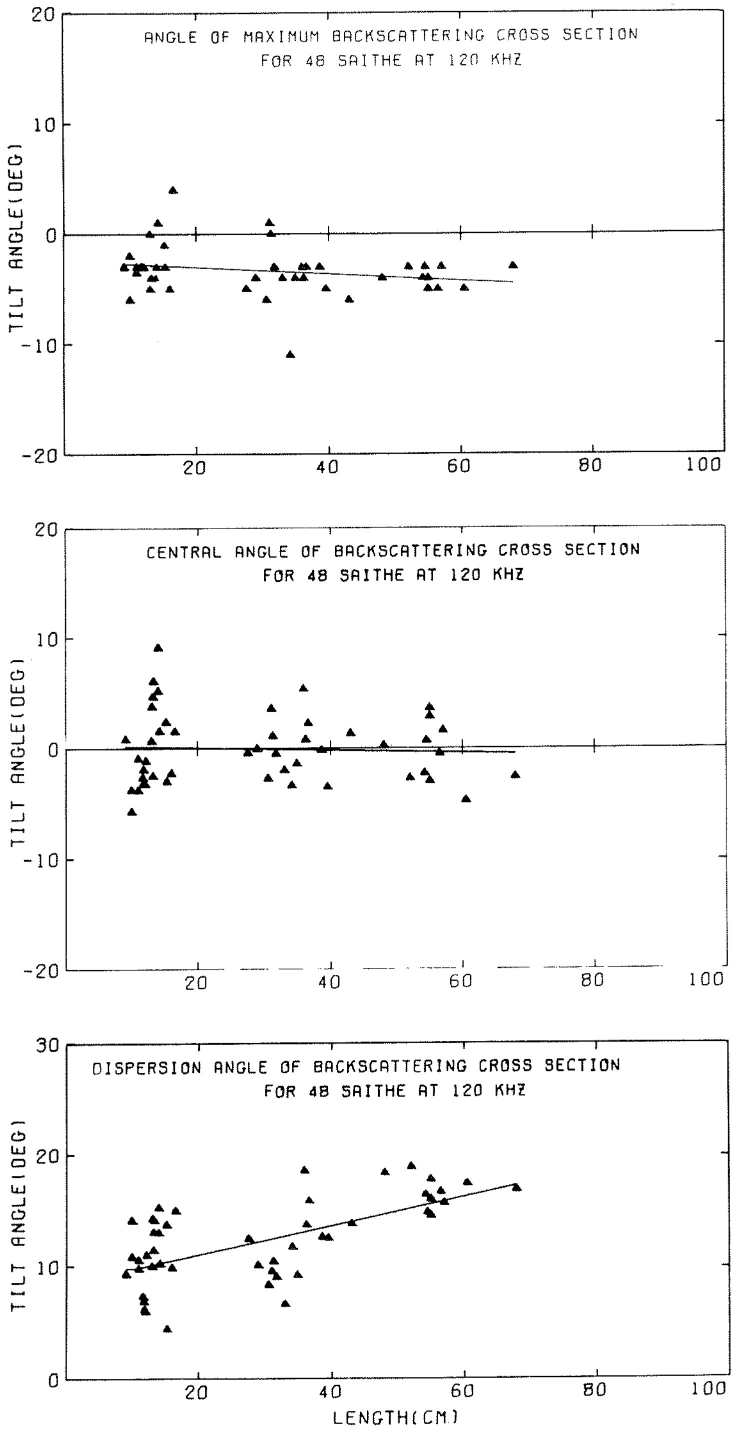


Fig. 4. Characteristic angular measures of measured dorsal aspect target strength functions of 48 saithe at 120 kHz.

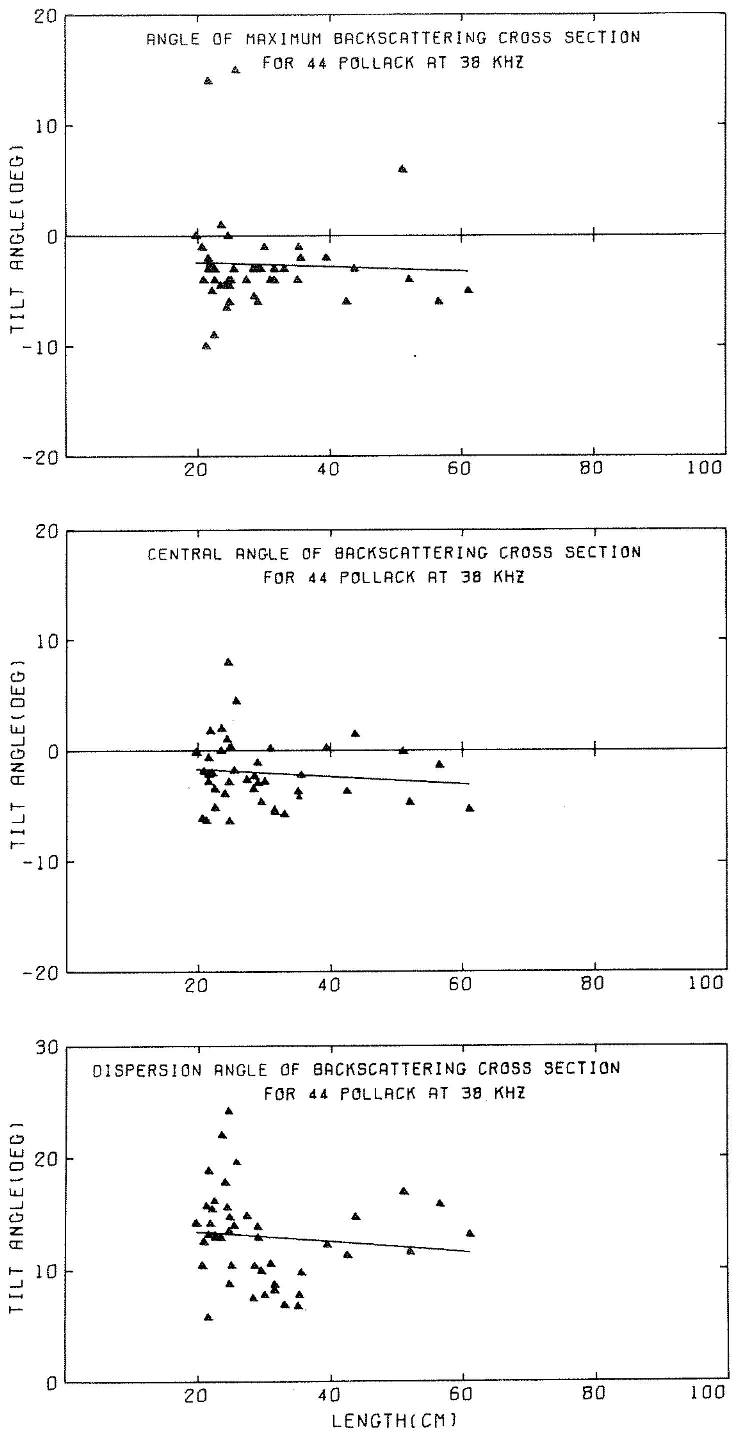


Fig. 5. Characteristic angular measures of measured dorsal aspect target strength functions of 44 pollack at 38 kHz.

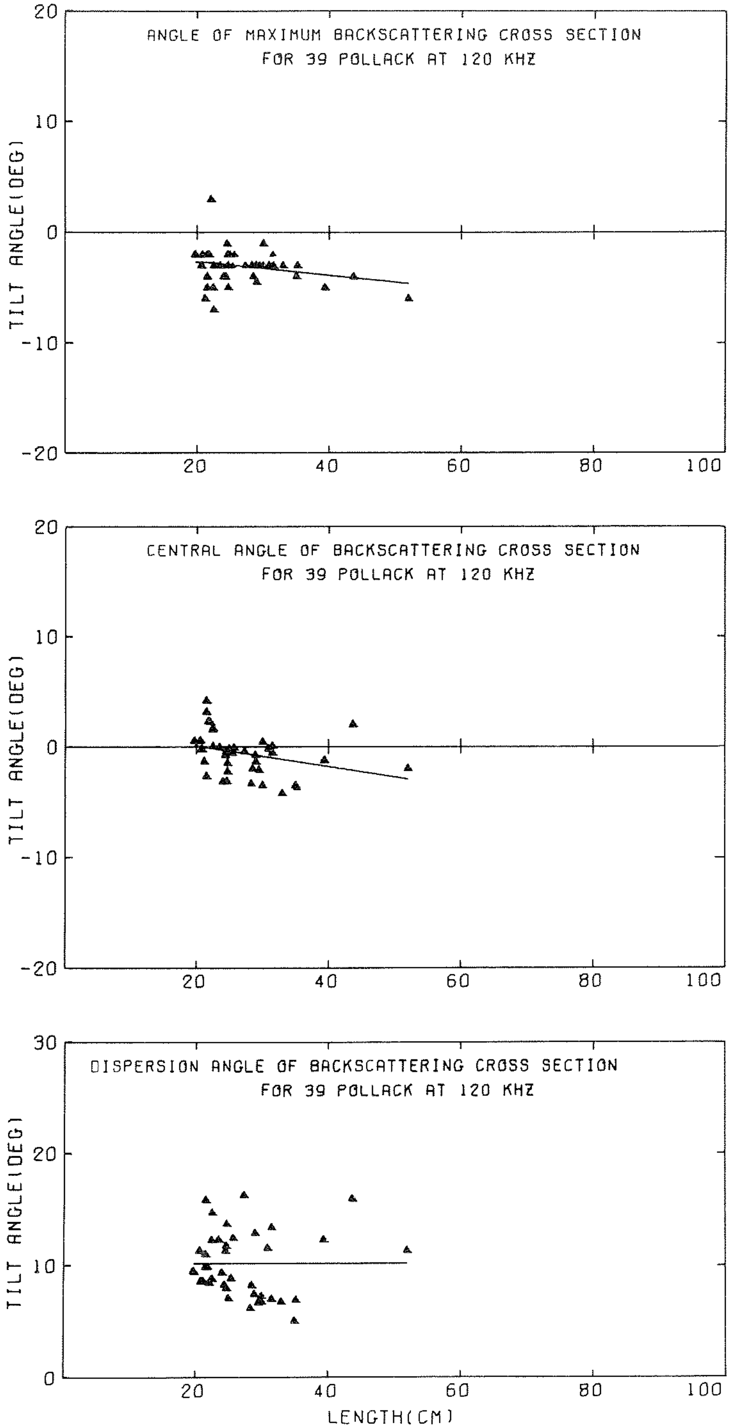
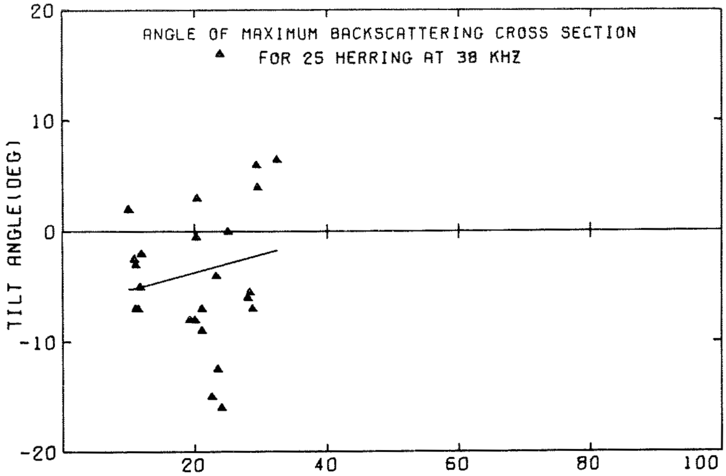
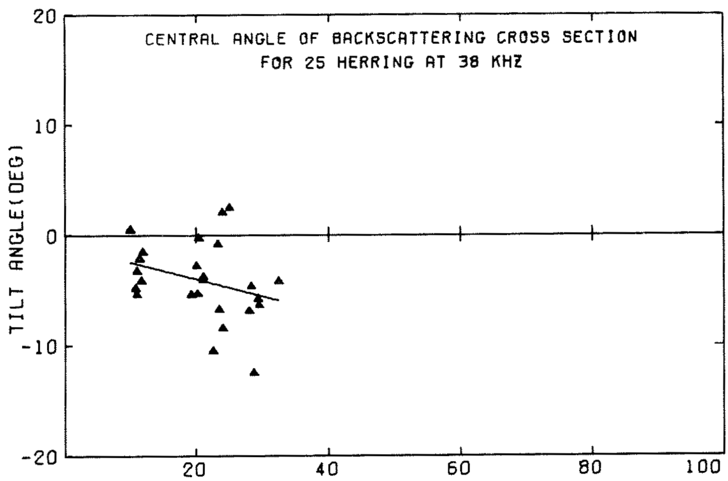


Fig. 6. Characteristic angular measures of measured dorsal aspect target strength functions of 39 pollack at 120 kHz.





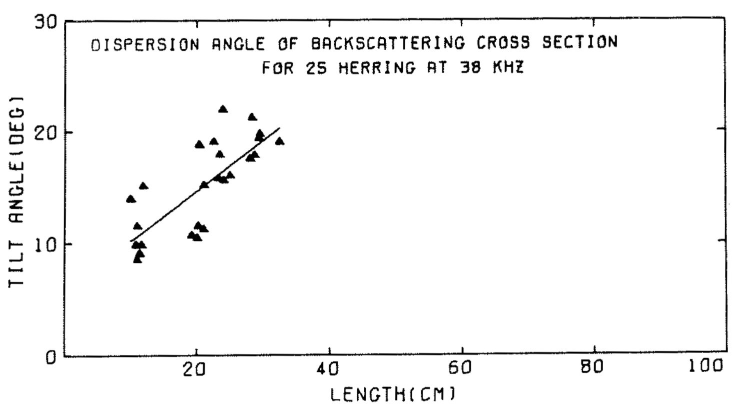


Fig. 7. Characteristic angular measures of measured dorsal aspect target strength functions of 25 herring at 38 kHz.

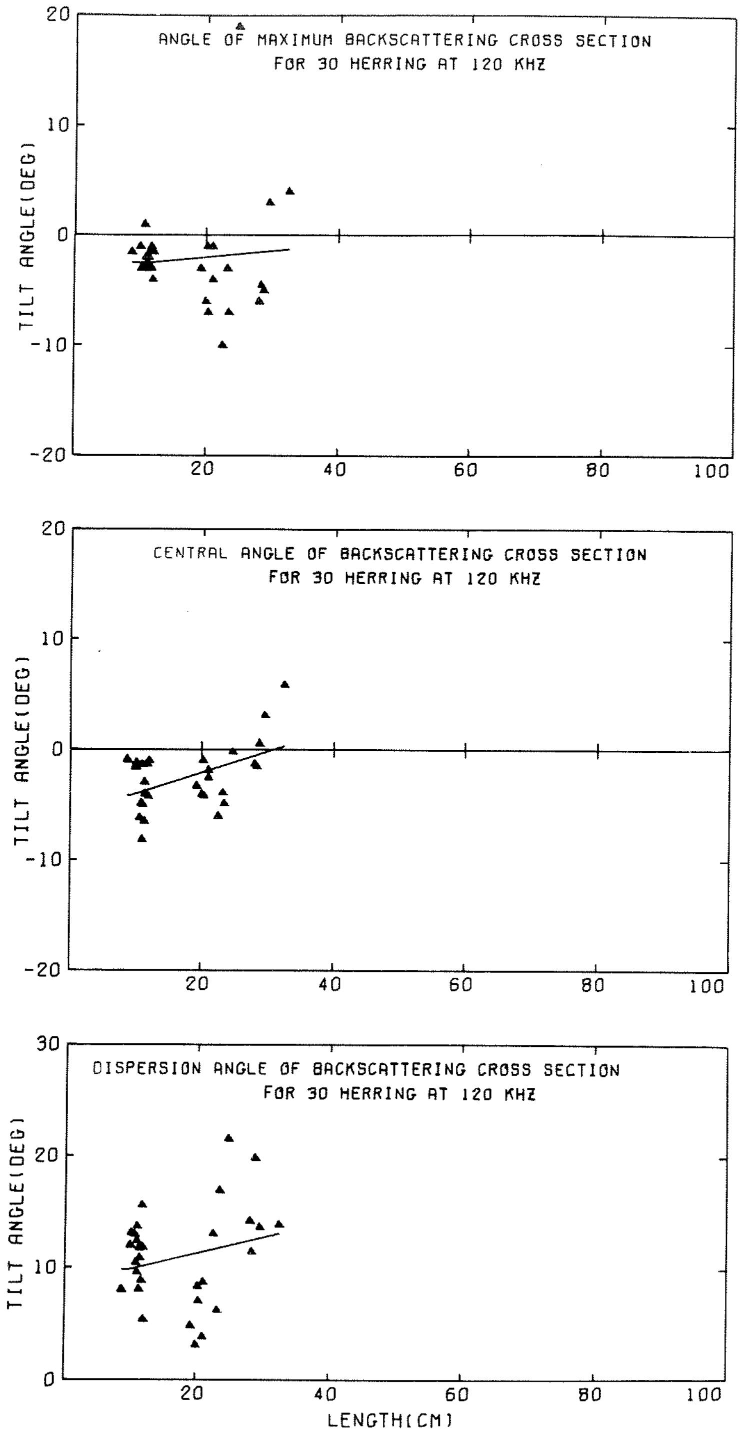


Fig. 8. Characteristic angular measures of measured dorsal aspect target strength functions of 30 herring at 120 kHz.

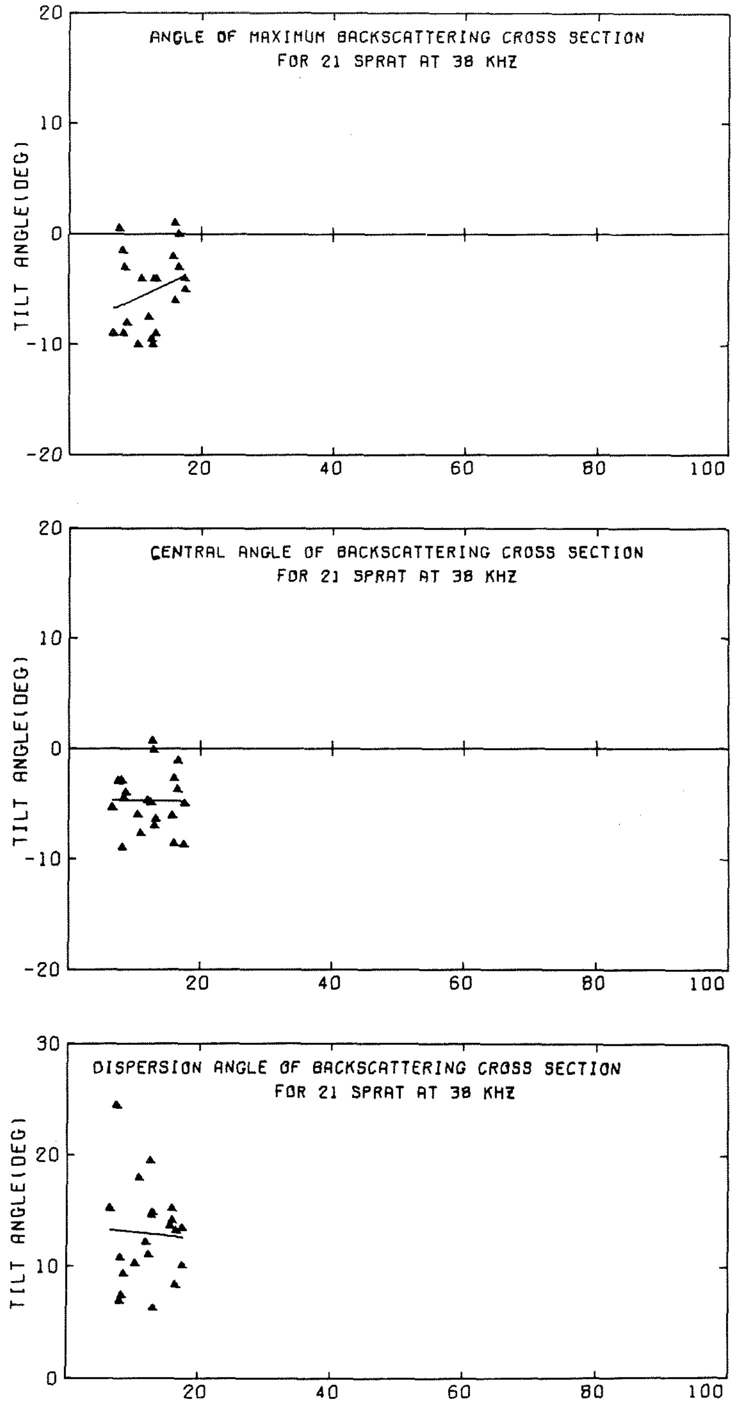


Fig. 9. Characteristic angular measures of measured dorsal aspect target strength functions of 21 sprat at 38 kHz.

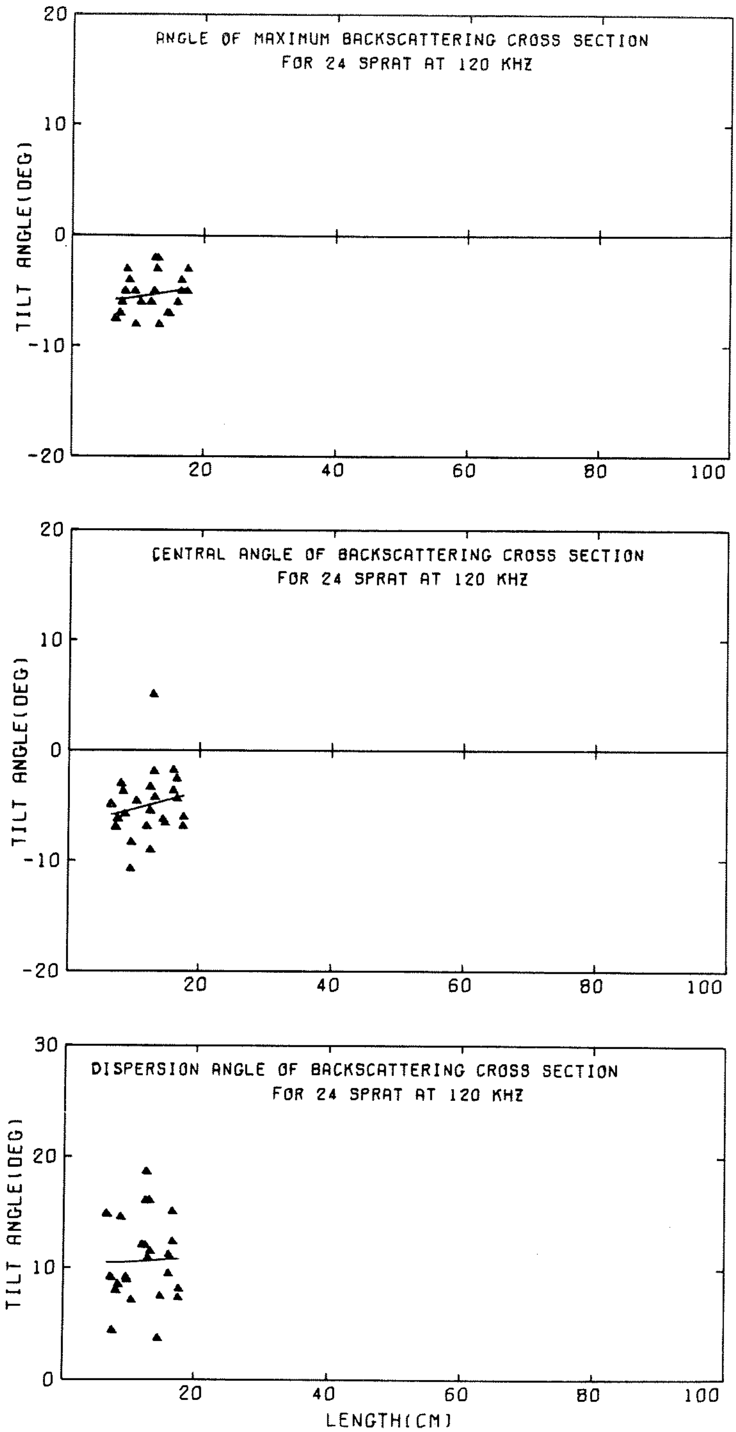


Fig. 10. Characteristic angular measures of measured dorsal aspect target strength functions of 24 sprat at 120 kHz.

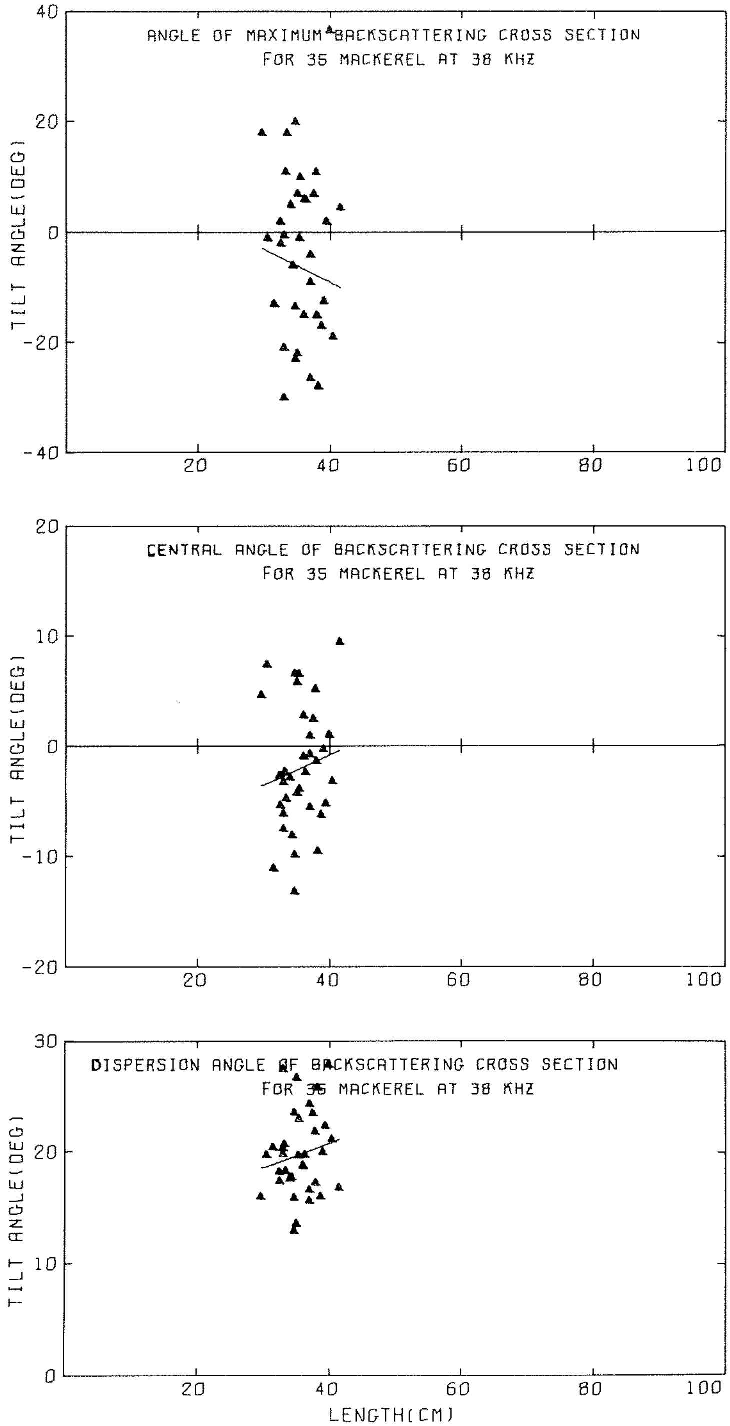


Fig. 11. Characteristic angular measures of measured dorsal aspect target strength functions of 35 mackerel at 38 kHz.

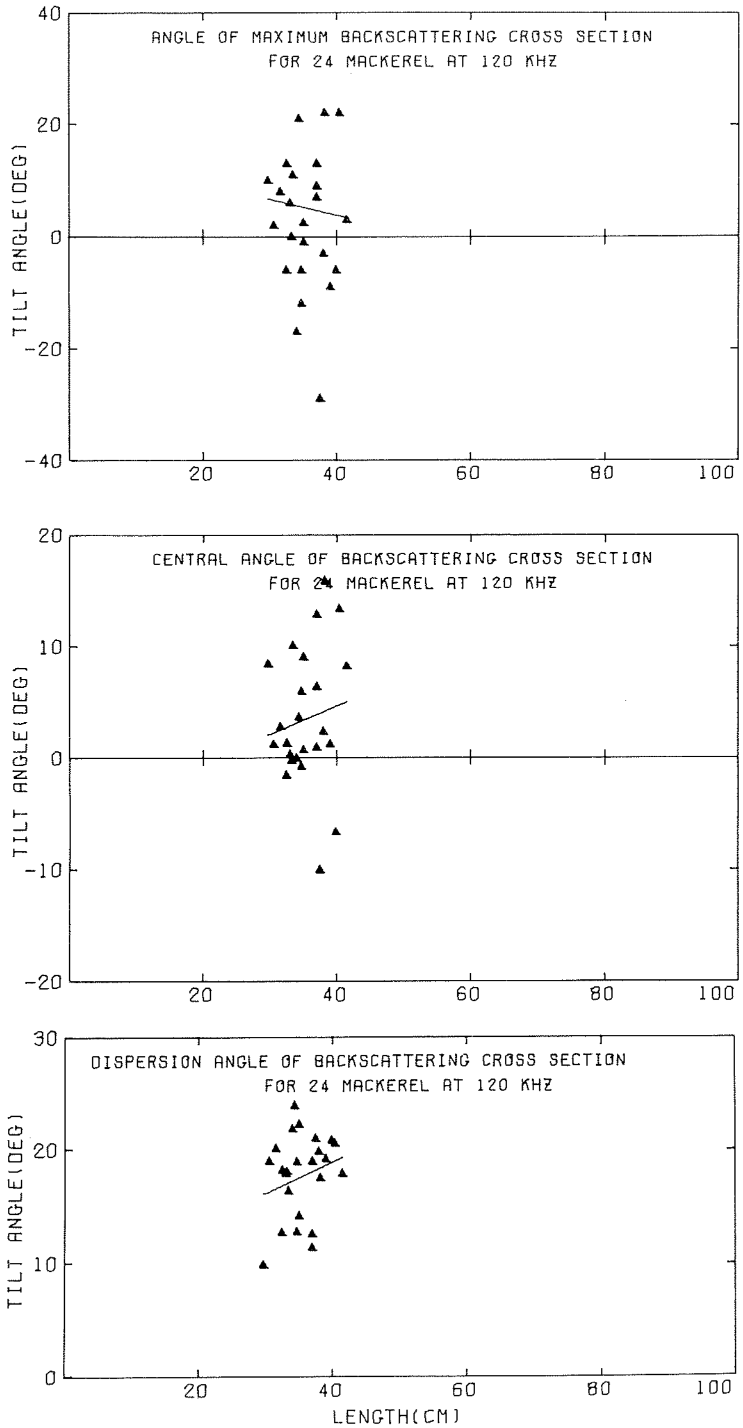


Fig. 12. Characteristic angular measures of measured dorsal aspect target strength functions of 24 mackerel at 120 kHz.

Table 2. Regression coefficients and mean, with statistical analyses, of α_0, the angle of maximum dorsal aspect backscattering cross section in the pitch plane.

Fish	Frequency (kHz)	Regression coefficient b_0				Regression coefficient b_1				Mean α_0			
		est	est(SE)	t	γ	est	est(SE)	t	γ	est	est(SE)	t	γ
Cod	38	−2.75	1.34	−2.04	0.04	−0.05	0.03	−1.80	0.08	−4.90	5.18	−0.94	0.35
Cod	120	−0.54	1.44	−0.38	0.71	−0.12	0.04	−2.99	$<10^{-2}$	−4.27	5.19	−0.82	0.42
Saithe	38	−2.12	0.90	−2.35	0.02	−0.04	0.02	−1.53	0.13	−3.34	3.29	−1.02	0.31
Saithe	120	−2.48	0.61	−4.08	$<10^{-3}$	−0.03	0.02	−1.77	0.08	−3.41	2.21	−1.54	0.13
Pollack	38	−2.01	2.20	−0.91	0.37	−0.02	0.07	−0.31	0.76	−2.66	4.58	−0.58	0.56
Pollack	120	−1.48	1.12	−1.32	0.20	−0.06	0.04	−1.57	0.12	−3.19	1.69	−1.89	0.07
Herring	38	−6.86	4.60	−1.49	0.15	0.16	0.21	0.77	0.45	−3.50	7.15	−0.49	0.63
Herring	120	−3.09	2.38	−1.30	0.20	0.06	0.12	0.47	0.64	−2.05	4.88	−0.42	0.68
Sprat	38	−8.51	2.88	−2.95	0.01	0.27	0.22	1.23	0.23	−5.10	3.60	−1.42	0.17
Sprat	120	−6.45	1.36	−4.73	$<10^{-3}$	0.10	0.11	0.93	0.36	−5.23	1.77	−2.96	0.01
Mackerel	38	7.40	33.7	0.22	0.83	−0.30	0.95	−0.32	0.75	−3.29	15.5	−0.21	0.83
Mackerel	120	7.55	29.7	0.25	0.80	−0.14	0.84	−0.17	0.87	2.52	12.4	0.20	0.84

Table 3. Regression coefficients and mean, with statistical analyses, of α_1, the central angle of the dorsal aspect backscattering cross section in the pitch plane.

Fish	Frequency (kHz)	Regression coefficient b_0				Regression coefficient b_1				Mean α_1			
		est	est(SE)	t	γ	est	est(SE)	t	γ	est	est(SE)	t	γ
Cod	38	–2.80	0.82	–3.43	$<10^{-2}$	–0.02	0.02	–1.09	0.28	–3.59	3.10	–1.16	0.25
Cod	120	–0.54	1.28	–0.42	0.68	–0.01	0.03	–0.42	0.68	–1.01	4.20	–0.24	0.81
Saithe	38	–2.82	0.67	–4.23	$<10^{-3}$	0.03	0.02	1.95	0.06	–1.67	2.46	–0.68	0.50
Saithe	120	0.24	0.90	0.27	0.79	–0.01	0.03	–0.44	0.66	–0.10	3.18	–0.03	0.98
Pollack	38	–1.07	1.42	–0.75	0.46	–0.03	0.05	–0.76	0.45	–2.10	2.97	–0.70	0.48
Pollack	120	1.93	1.29	1.49	0.14	–0.09	0.05	–2.07	0.04	–0.67	1.99	–0.34	0.74
Herring	38	–0.96	2.19	–0.44	0.66	–0.16	0.10	–1.55	0.14	–4.17	3.53	–1.18	0.25
Herring	120	–5.93	1.22	–4.87	$<10^{-3}$	0.19	0.06	3.03	$<10^{-2}$	–2.52	2.87	–0.88	0.39
Sprat	38	–4.56	2.24	–2.03	0.06	–0.02	0.17	–0.10	0.92	–4.78	2.70	–1.77	0.09
Sprat	120	–6.91	2.38	–2.91	0.01	0.16	0.19	0.87	0.39	–4.92	3.07	–1.60	0.12
Mackerel	38	–11.8	12.1	–0.97	0.34	0.28	0.34	0.81	0.42	–1.96	5.62	–0.35	0.73
Mackerel	120	–5.41	14.6	–0.37	0.72	0.25	0.41	0.61	0.55	3.51	6.15	0.57	0.57

Table 4. Regression coefficients and mean, with statistical analyses, of α_2, the angular dispersion of the backscattering cross section about the central angle in the pitch plane.

Fish	Frequency (kHz)	Regression coefficient b_0				Regression coefficient b_1				Mean α_2			
		est	est(SE)	t	γ	est	est(SE)	t	γ	est	est(SE)	t	γ
Cod	38	12.9	0.8	16.3	$<10^{-3}$	0.02	0.02	1.13	0.26	13.7	3.01	4.55	$<10^{-3}$
Cod	120	12.2	1.1	10.8	$<10^{-3}$	0.07	0.03	2.16	0.04	14.3	3.92	3.66	$<10^{-2}$
Saithe	38	8.7	0.7	12.3	$<10^{-3}$	0.12	0.02	6.14	$<10^{-3}$	12.5	3.25	3.86	$<10^{-3}$
Saithe	120	8.5	0.8	10.5	$<10^{-3}$	0.13	0.02	5.45	$<10^{-3}$	12.3	3.66	3.38	$<10^{2}$
Pollack	38	14.2	1.9	7.4	$<10^{-3}$	–0.05	0.06	–0.77	0.45	12.8	4.03	3.17	$<10^{2}$
Pollack	120	10.0	2.0	5.0	$<10^{-3}$	0.00^{-}	0.07	0.00^{-}	1.00^{-}	10.0	2.95	3.40	$<10^{-2}$
Herring	38	5.7	1.7	3.3	$<10^{-2}$	0.45	0.08	5.69	$<10^{-3}$	15.1	4.13	3.64	$<10^{-2}$
Herring	120	8.5	2.1	4.1	$<10^{-3}$	0.14	0.11	1.32	0.20	11.0	4.35	2.53	0.02
Sprat	38	13.6	3.7	3.7	$<10^{-2}$	–0.07	0.28	–0.23	0.82	12.8	4.40	2.90	0.01
Sprat	120	10.1	3.0	3.4	$<10^{-2}$	0.04	0.23	0.18	0.86	10.6	3.79	2.81	0.01
Mackerel	38	11.8	8.1	1.5	0.14	0.22	0.23	1.00	0.32	19.8	3.74	5.29	$<10^{-3}$
Mackerel	120	7.8	8.6	0.9	0.38	0.28	0.24	1.14	0.27	17.6	3.70	4.76	$<10^{-3}$

They are represented further by the condensations of results presented in Tables 5 and 6.

In Table 5 the regression coefficients and means of the several angle measures are classified by their consistency with one of two hypotheses. The null hypothesis H_0 asserts the identity or indistinguishability of the quantities with zero. The alternative hypothesis H_A denies this, asserting the non-vanishing nature of the quantities. The criterion for classification is that the significance level γ shall exceed 0.05 to uphold H_0 and be less than 0.05 to support H_A.

Table 5. Numbers of regression coefficients and means of angle measures consistent with the null or alternative hypotheses at the 0.05 level.

Angle measure	$\hat{b}_0$		$\hat{b}_1$		$\bar{\alpha}$	
	H_O	H_A	H_O	H_A	H_O	H_A
α_0	7	5	11	1	11	1
α_1	8	4	10	2	12	0
α_2	2	10	8	4	0	12

Table 6. Discrimination of regression coefficients and means of angle measures by their signs.

Angle measure	$\mathrm{sgn}(\hat{b}_0)$		$\mathrm{sgn}(\hat{b}_1)$		$\mathrm{sgn}(\bar{\alpha})$	
	+	–	+	–	+	–
α_0	2	10	4	8	1	11
α_1	2	10	5	7	1	11
α_2	12	0	10	2	12	0

The lack of a trend in the maximum and central angles is evident from the results for the regression slope coefficient b_1 in Table 5. The null hypothesis is strongly upheld. Simple application of the binomial test attaches a confidence level of 0.997 to the consistency of b_1 with zero in the case of α_0 and a confidence of 0.98 in the case of α_1.

The same two angle measures are generally negative, however, as indicated by the sign analyses of Table 6. The negative character of maximum and central angle measures is evident from the results for the mean angle measure $\bar{\alpha}$. Similar results for the regression intercept coefficient b_0 support this conclusion. The single exceptional datum for $\bar{\alpha}$ in Table 6 is that for mackerel at 120 kHz. Given the general upwards inclination, in the tail-to-head direction, of the gadoid and clupeoid swim bladder, which is probably the dominant scattering organ of these fishes, and the absence of a swim bladder in mackerel, it seems reasonable to distinguish the data by the presence or absence of a swim bladder. That the angles of maximum and central backscattering cross section are slightly negative, in the mean, for each non-mackerel fish, but apparently vanishing in the case of mackerel, may be regarded as a direct acoustical consequence of the described anatomical difference. An early observation of the acoustic manifestation of swim bladder inclination with respect to the imaginary fish centerline, to which the swim bladder axis is referred, was made by MIDTTUN and HOFF (1962).

The intrinsically positive character of the dispersion angle α_2 is confirmed by the sign analysis of $\bar{\alpha}$ in Table 6. This is supported by the positive regression intercept coefficient $\hat{b}_0$. The upwards trend of α_2 is observed in the positive regression slope coefficient $\hat{b}_1$ in Table 6, although not in the more stringent, but weaker analysis of Table 5. The physical interpretation of the increasing trend of mean dispersion angle with increasing fish length is that the dorsal aspect backscattering cross section or target strength in the pitch plane tends to be less concentrated as fish length increases. This conclusion appears plausible from inspection of the source data (FOOTE and NAKKEN 1978), although the magnitude of the length dependence of α_2 is not easily discerned from the data in this form.

Measures of the angular characteristics of target strength functions as computed in this paper do not seem to have been previously considered. The principal usefulness of the computations is expected to lie in considerations of the sort advanced in OLSEN (1979). Computations of angle measures cannot, however, supplant such measures of fish scattering strength as those considered in FOOTE (1978, 1979a–e, 1980a). These averaged measures of effective backscattering strength are essential to quantitative studies of fish abundance, whether assessed by typical echo sounders or by sector scanning sonars.

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