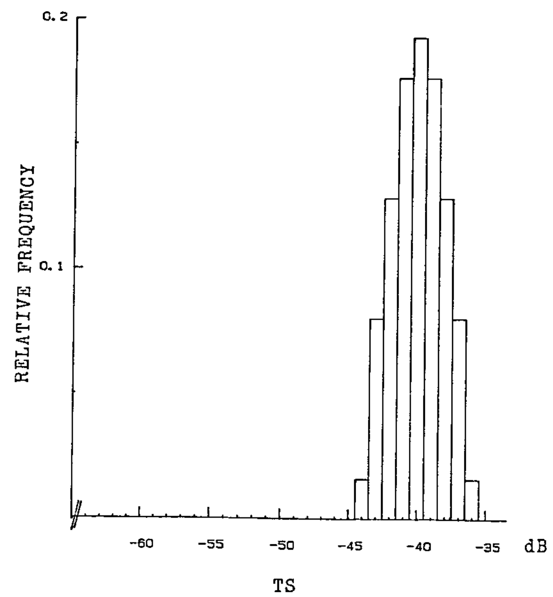

Figure 6. The solution for the first simulation.

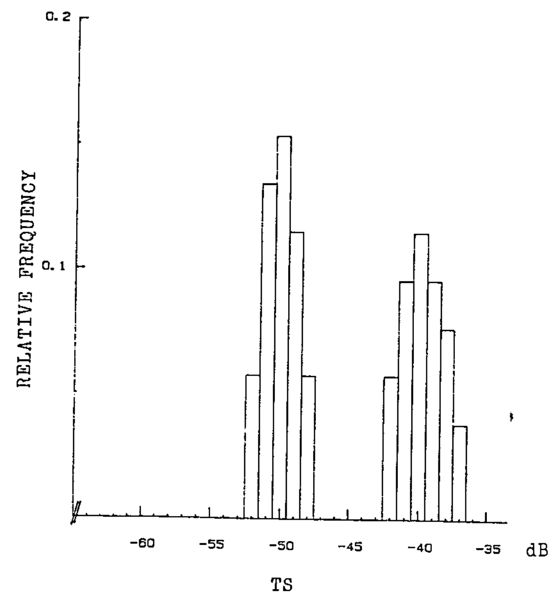

Figure 7. The results from the second simulation. N = 1300.

whitefish. In the second example (Fig. 4) the peaks were considered as having been caused by smelt and whitefish.

The approximation of PDFs with distributions of 1-dB class widths may seem rather rough, but with our 10-bit digitizing system one decibel corresponds to one bit at the lowest intensity values. The method is thus optimal, because all the intensity data can be used.

The method suffers according to the unevenness of fish distribution, but we feel that it can be applied in freshwater conditions.

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Measurements and analyses of dorsal-aspect target strength of six species of fish at four frequencies

Yoichi Miyanohana, Ken Ishii, and
Masahiko Furusawa

Miyanohana, Yoichi, Ishii, Ken, and Furusawa, Masahiko. 1990. Measurements and analyses of dorsal-aspect target strength of six species of fish at four frequencies. – Rapp. P.-v. Réun. Cons. int. Explor. Mer, 189: 317–324.

The dorsal-aspect target strengths of tethered fish with swimbladders were measured: sardine (*Sardinops melanostictus*), Japanese mackerel (*Scomber japonicus*), spotted mackerel (*Scomber australasicus*), walleye pollock (*Theragra chalcogramma*), sea bream (*Pagrus major*), and yellowtail (*Seriola quinqueradiata*), at frequencies of 25, 50, 100, and 200 kHz. The target strengths were measured as a function of fish tilt angle, ranging from −50° (head-down aspect) to 50° (head-up aspect), at 1° intervals. From these functions, the dorsal-aspect maximum and averaged target strengths were derived. The averaging was performed with respect to fish tilt-angle distribution, with mean −5° and standard deviation 15°. The means of the maximum target strength normalized by squared fork length (cm) range mostly from −61 to −59 dB regardless of species or frequency. However, the averaged target strengths decrease with frequency, depending on the difference between backscattering patterns. The merged target-strength data by species and frequencies are compared with theoretical results introduced by using the soft-spheroid model for the swimbladder, and good agreement is found.

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Introduction

Target-strength measurements of fish are essential to fisheries acoustics, especially to quantitative estimations of fish abundance. Although many target-strength measurements of fish have been made (Hashimoto, 1953; Hashimoto and Maniwa, 1957; Maniwa, 1962; Cushing, 1973; Nakken and Olsen, 1977; Midttun, 1984), considerable variability has often been observed in the results. This fact suggests to us that more reliable measuring methods should be developed. Further, the target-strength data so far collected do not address an adequate range of species, sizes, or acoustic frequencies. Moreover, some species of fish which are important in Japanese fisheries are not common in other countries. Thus, the authors developed an accurate and reliable method for target-strength measurements, measured dorsal-aspect target strengths of some fish species, and investigated various important properties of the results, such as length dependence.

In this paper, we describe (1) the principle of our method and our measuring system, (2) dorsal-aspect maximum or averaged target strengths of each species of fish, and (3) the comparison of the measured results with the theoretical ones introduced by Furusawa (1988).

Method and materials

Principle

The authors developed a simultaneous calibration method for target-strength measurement of fish (Miyanohana *et al.*, 1982) after Hashimoto (1953) and McCartney and Stubbs (1971). The principle of this method is shown in Figure 1. A small omni-directional hydrophone is placed between projectors and a target. The receiver output voltages of a direct wave (E_d) and of a reflected wave (E_r) are shown by the following equations, neglecting the absorption term because of the short range:

$$E_d = P_0 \frac{1}{r_h} M_d G_d \quad (1)$$

$$E_r = P_0 \frac{1}{r_r} \gamma \frac{1}{r_r - r_h} Mr\, G_r \quad (2)$$

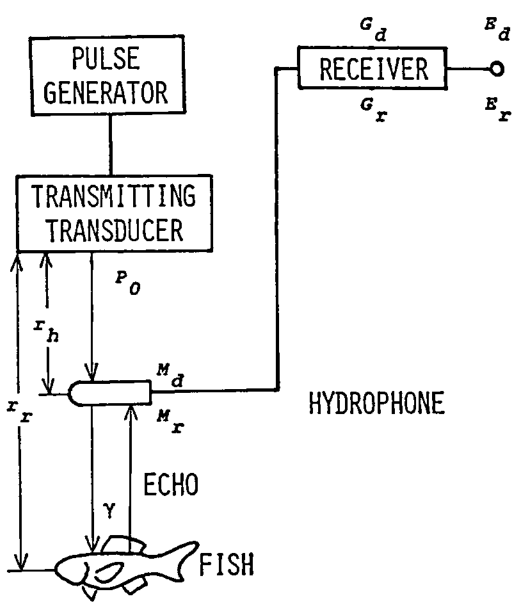


Figure 1. Block diagram of the simultaneous calibration method for target-strength measurement.

where M_d, M_r are pressure receiving sensitivities of the hydrophone, G_d, G_r are gains of the receiver for the direct and reflected waves, respectively, P_0 is the axial source pressure, and γ is the square root of target strength. From these equations, we obtain

$$\gamma = \frac{G_d}{G_r}\,\frac{M_d}{M_r}\,\frac{r_r(r_r-r_h)}{r_h}\,\frac{E_r}{E_d}. \quad (3)$$

The receiving gain ratio, G_d/G_r, is unity, because the linearity of the receiver is sufficient. The ratio of hydrophone sensitivities in opposite directions, M_d/M_r, is approximately unity owing to its omni-directional characteristic. We measured the ratios M_d/M_r, defined the proper setting angle of the hydrophone in the vertical plane, and corrected the residual error.

Since the calibration is carried out simultaneously with the measurements, this method can save time and labour, and calibration errors are very slight.

Experimental arrangement

A block diagram of instrumentation is shown in Figure 2. A programmable multi-frequency transmitter-receiver (PMT) was specially designed for our method (Ishii *et al.*, 1983). It transmits, receives, and processes pulses at four frequencies: 25, 50, 100, and 200 kHz.

This method requires an omni-directional and wideband hydrophone. Since the tail of the direct pulse must not interfere with the reflected pulse, which is received a short time after the direct wave, we must transmit a short pulse with a sufficiently flat top. This requires low-Q or wideband projectors. Therefore, the signal-to-noise ratio in this method tends to be low compared with ordinary methods. Therefore, we applied the following five countermeasures.

(1) In order to exclude unfavourable reverberation, we made the beamwidth of the projectors as sharp as possible (half-beamwidths are 8~15 degrees), so that all parts of the fish body were located in the nearly flat response region of the main lobe.

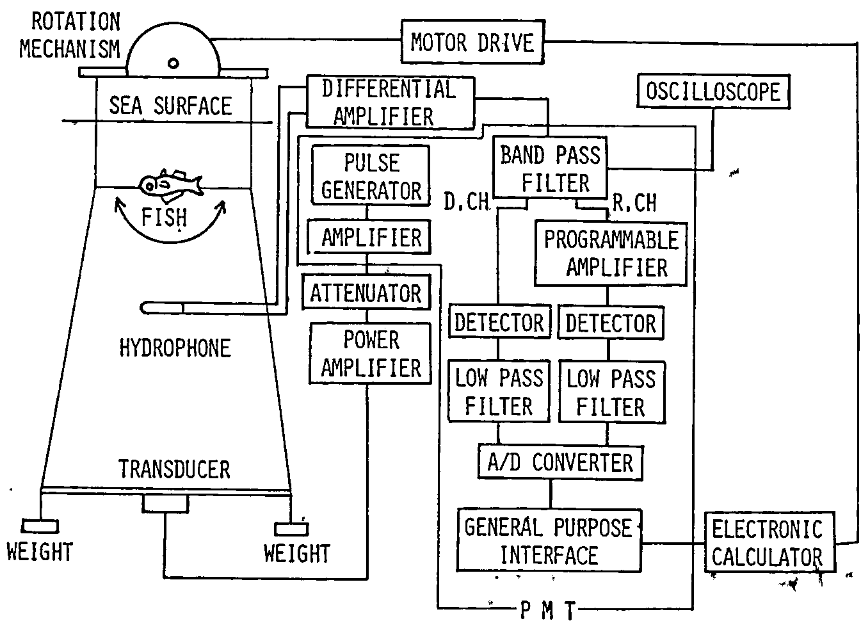


Figure 2. Experimental set-up and block diagram of measuring system. Programmable multi-frequency transmitter-receiver (PMT) is specially designed and transmits, receives, and processes pulses at 25, 50, 100, and 200 kHz.

(2) We made the source level as high as possible, so that saturation of the direct wave in the receiver would not occur.

(3) In receiving, a specially designed balanced-type hydrophone (Towa TM-4409, 10.9 mm ∅) and a differential amplifier (Tektronix 7A22) were used (Fig. 2).

(4) We set the bandwidth of the receiver to match that of the projectors. However, we also set the bandwidth as narrow as possible (10 kHz).

(5) As seen from Equation (3), we made the distance between target and hydrophone (r_r-r_h) as small as possible to obtain a sufficiently high echo level within the above-mentioned interfering limitation.

The last requirement may cause another problem, that of the "near field" effect of the reflected wave. We performed an experiment to examine this effect, using a spheroidal model target made of styrofoam with major and minor radii of 20 and 3 cm, respectively. This model corresponds to the swimbladder of a fish of about 60 cm in length. If r_r-r_h is larger than 1 m, the echo level follows the "far field" law. The r_r-r_h range in our measurements was from 1 to 2 m. Thus, our measurements were performed out of the "near field".

Figure 3 shows a suspension and rotation mechanism for fish (Ishii *et al.*, 1985), based on Nakken and Olsen (1977) but modified for the present work. The most important modification concerns suspension of the hydrophone. It is suspended by a thin nylon string and can be moved by adjusting a reel; depth is displayed on a mechanical counter. Both the hydrophone and fish suspension lines are attached to a rotating bar. Two weights are fastened to the fish suspension strings to lessen initial friction from the pulleys, and residual deviation is corrected by a hydrophone-string guide on the rotating bar.

We developed an automatic rotation mechanism for fish, and a digital processing system (Ishii *et al.*, 1985). The definition of fish tilt angle used is that of Nakken and Olsen (1977). Fish were tilted from −50° (head-down aspect) to 50° (head-up aspect) at 1° intervals. At each pitch angle, a pulse of 0.4~0.6 ms was transmitted each 0.1 s, and the echo was received. The four frequencies were scanned automatically and sequentially. The amplitude ratio was computed from received pulse heights (E_d, E_r), to give a target strength according to Equation (3). The results were printed and stored by the computer.

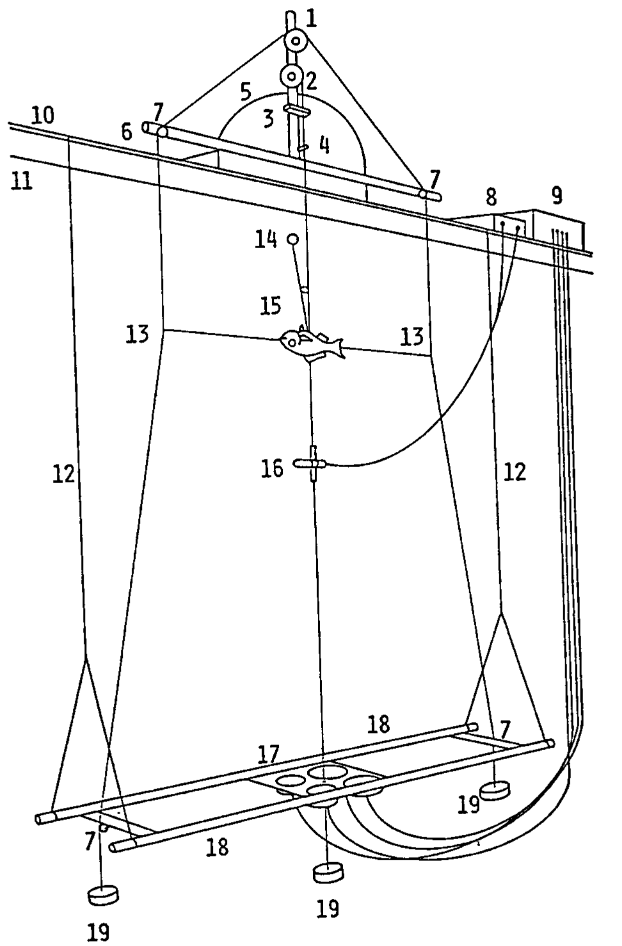


Figure 3. Fish suspension and rotating mechanism for target-strength measurement (not to scale). 1) reel for fish suspension, 2) reel for moving hydrophone, 3) mechanical depth counter, 4) hydrophone-string guide, 5) rotating plate, 6) rotating bar, 7) pulley, 8) differential amplifier, 9) PMT (see Fig. 2), 10) raft, 11) sea surface, 12) rope for suspending transducer base, 13) nylon-string frame for fish suspension, 14) float, 15) target (fish), 16) hydrophone, 17) transducers, 18) transducer base, 19) weight.

Data processing

The two most important indices of target strength are the dorsal-aspect maximum and averaged values. The maximum values (TS_{max}) were obtained easily from the measured target-strength functions.

According to Foote (1980a), measured dorsal-aspect target strengths should be averaged with respect to the beam pattern of the observing echo sounder and to the distribution of spatial and orientation states of observed fish. It has already been shown, however, that averaged target strengths for the echo sounders with half-beamwidths less than 10° are generally indistinguishable (Foote, 1981). We also confirmed this fact by using the observed scattering pattern of a yellowtail at 50 kHz shown in Figure 4. In the case of an echo sounder with half-beamwidth of less than 15°, the difference in averaged values by Foote's strict method and by the simple method ignoring the beam-pattern effect was less than 0.3 dB (Miyanohana *et al.*, 1986).

Therefore, without regard to the directional beam

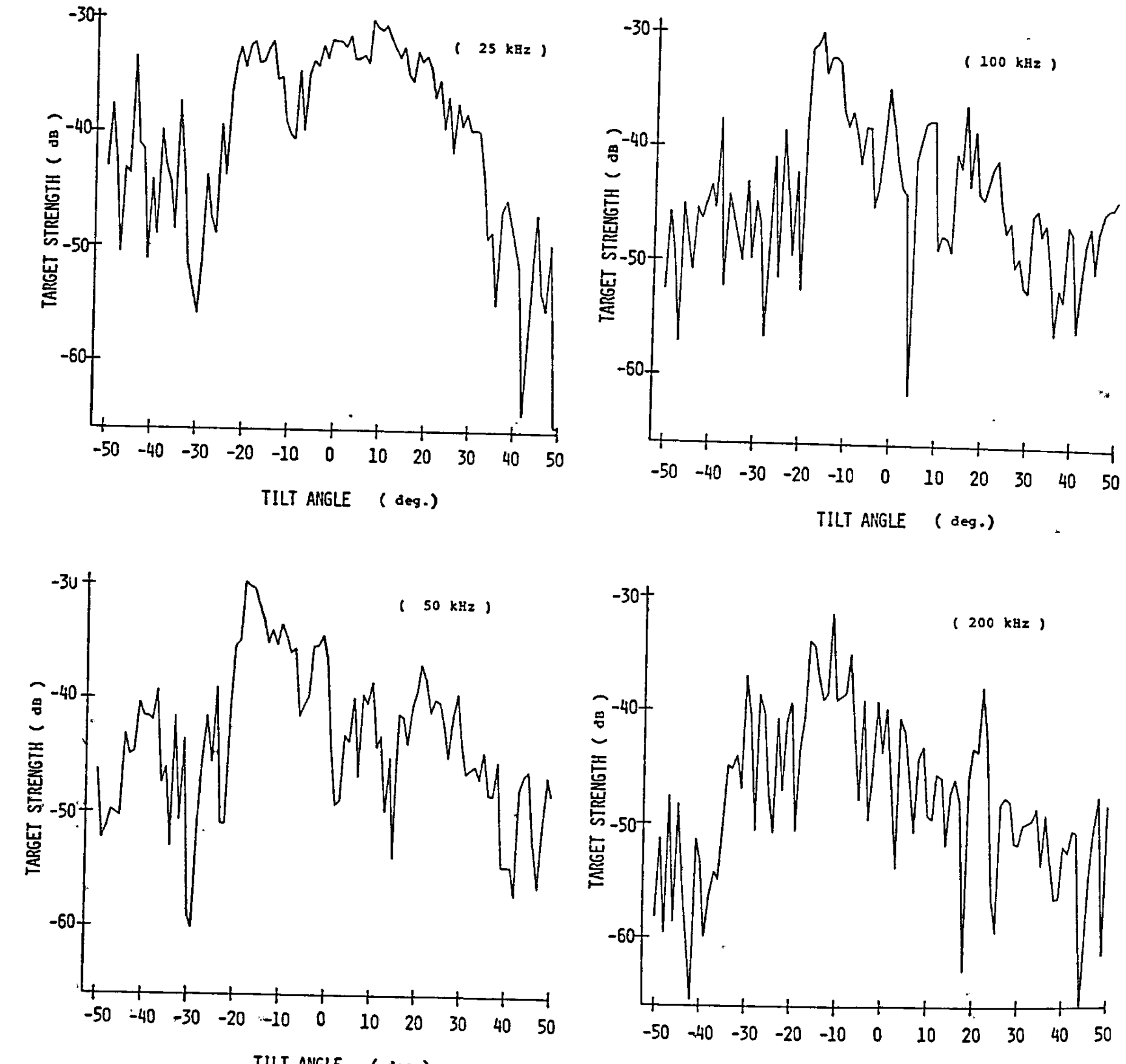


Figure 4. Directional diagrams of target strength measured in pitch plane at four frequencies for a yellowtail of 29.1-cm forklength.

pattern of the observing transducer, averaging may be performed only with respect to tilt-angle distribution of fish. Thus, the averaged backscattering cross-section $<\sigma>$ can be simply shown as

$$<\sigma> = \int_{-\pi/2}^{\pi/2} \sigma(\theta)\, f(\theta)\, d\theta \qquad (4)$$

where $f(\theta)$ is the probability density function of the fish tilt-angle variable θ. We adopt the truncated normal distribution after Foote (1980). A distribution is denoted by its mean $(\bar{\theta})$ and standard deviation (σ_θ), i.e. $(\bar{\theta}, \sigma_\theta)$, and $\sigma(\theta)$ is related to the dorsal-aspect target-strength function $TS(\theta)$ by the definition (Urick, 1975):

$$TS(\theta) \equiv 10 \log[\sigma(\theta)/4\pi]. \qquad (5)$$

Averaged target strength $<TS>$ is similarly defined:

$$<TS> \equiv 10 \log(<\sigma>/4\pi). \qquad (6)$$

Equation (4) corresponds to the formula used by Nakken and Olsen (1977). Thus, the averaging method introduced by Foote (1980a) may be considered a generalization of that of Nakken and Olsen (1977).

Linear relationships between the dorsal-aspect maximum (TS_{max}) or averaged target strengths (TS_{ave}) and the logarithm of fish length (L) are assumed for each species and frequency as follows:

$$TS_{max} = m \log L + A_{max}$$
$$TS_{max} = m' \log L + A_{ave}$$

where the coefficients m, m', A_{max}, and A_{ave} are determined by least-square regression analyses.

It is reasonable to assume that the backscattering cross-section of fish is approximately proportional to the squared fish length (Furusawa, 1988). We therefore set the coefficient m or m' at 20. Thus TS_{max} and TS_{ave} were normalized by the squared forklength (cm) of fish, and the results were averaged for each species and frequency.

Target strength to length regressions should be established by using large numbers of measurements. However, our measurements were insufficient in number and length range (Table 1). Although merging of target strength among species and frequencies is not generally justified (Foote, 1979), we pooled our data and compared our results with the corresponding theoretical results obtained by the prolate spheroidal model (Furusawa, 1988).

In this theory, the soft spheroid was considered to be a model of a swimbladder, and other components were neglected. The morphological parameters of the model were determined through measurements and references.

Specimens

The fish considered were sardine (*Sardinops melanostictus*), Japanese mackerel (*Scomber japonicus*), spotted mackerel (*Scomber australasicus*), walleye pollock (*Theragra chalcogramma*), sea bream (*Pagrus major*), and yellowtail (*Seriola quinqueradiata*). All are fish with swimbladders. Fresh or stunned fish were used. The number of specimens, and the range of their forklengths and body weights, are listed in Table 1.

Preliminary measurements were made at Kanzaki-Ura in Mie prefecture in 1981, and performed annually at Heda Bay in Shizuoka prefecture from 1982 to 1985. Both are shelteted inlets with water depths greater than 15 m.

Results

Figure 4 shows the directional patterns of target strength measured on a yellowtail. The weight was 405 g and the forklength was 29.1 cm. Similar patterns were collected for all the specimens.

The normalized maximum and averaged target-strength values (A_{max}, A_{ave}) are plotted as functions of forklength to wavelength ratio (L/λ) in Figures 5 and 6. The solid and dashed lines in Figures 5 and 6 are the normalized maximum and averaged target strengths calculated theoretically for modelled swimbladders (Furusawa, 1988). The solid lines are obtained by the exact solution, and the dashed line by the geometrical approximation. A_{max} and A_{ave} are averaged for each species and frequency, and shown in Figure 7.

Discussion

Directional patterns of target strength

Figure 4 shows that the maximum peaks are generally observed within a tilt angle range of −20 to −10° (slightly head-down aspect) regardless of frequency, and that the main lobes become more directional as the frequency increases. This indicates that fish behaviour affects echo level more significantly at higher frequencies. The directional pattern trends observed in yellowtail also occurred in sardine, Japanese mackerel, and spotted mackerel. However, in general, the main lobes of the smaller fish were less directional.

In contrast, the backscattering patterns of sea bream, in length approximately the same as yellowtail, were less directional, and target-strength values for the head-down aspect were much higher than those for the head-up aspect (Miyanohana *et al.*, 1983). In the backscattering patterns of walleye pollock, maximum peaks

Table 1. Numbers of specimens and length ranges of fish for which target-strength functions were obtained.

Species of fish	Number	Forklength (mm)	Body weight (gm)
Sardine (*Sardinops melanostictus*)	15	112–244	13– 150
Mackerel (*Scomber japonicus*)	10	196–391	97– 820
Spotted mackerel (*Scomber australasicus*)	15	216–360	121– 683
Walleye pollock (*Theragra chalcogramma*)	7	342–454	305– 650
Sea bream (*Pagrus major*)	9	122–390	50–1 120
Yellowtail (*Seriola quinqueradiata*)	10	291–658	405–4 100

Figure 5. Comparison of normalized maximum target strengths obtained by model and measurements.

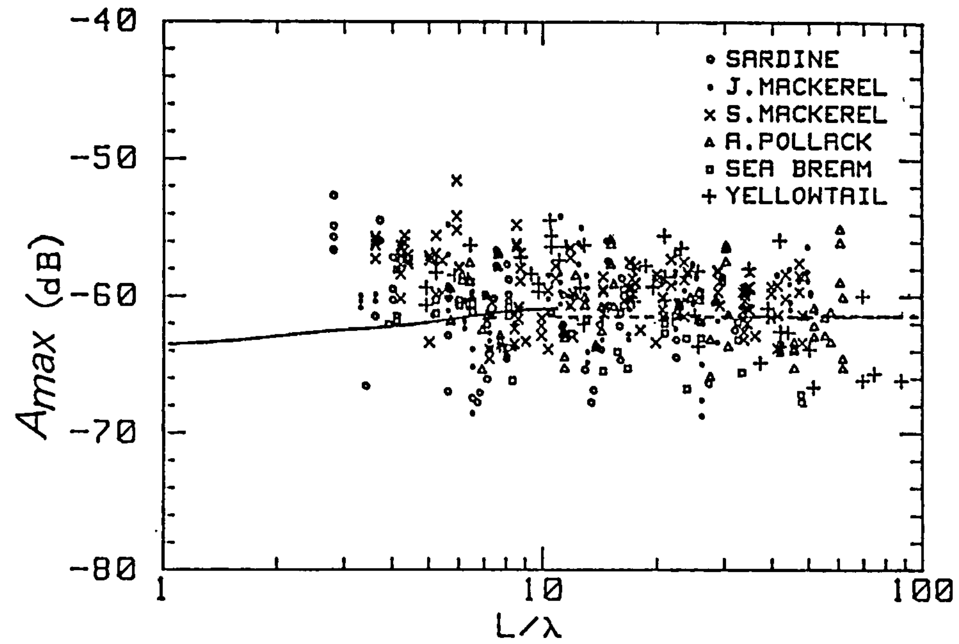
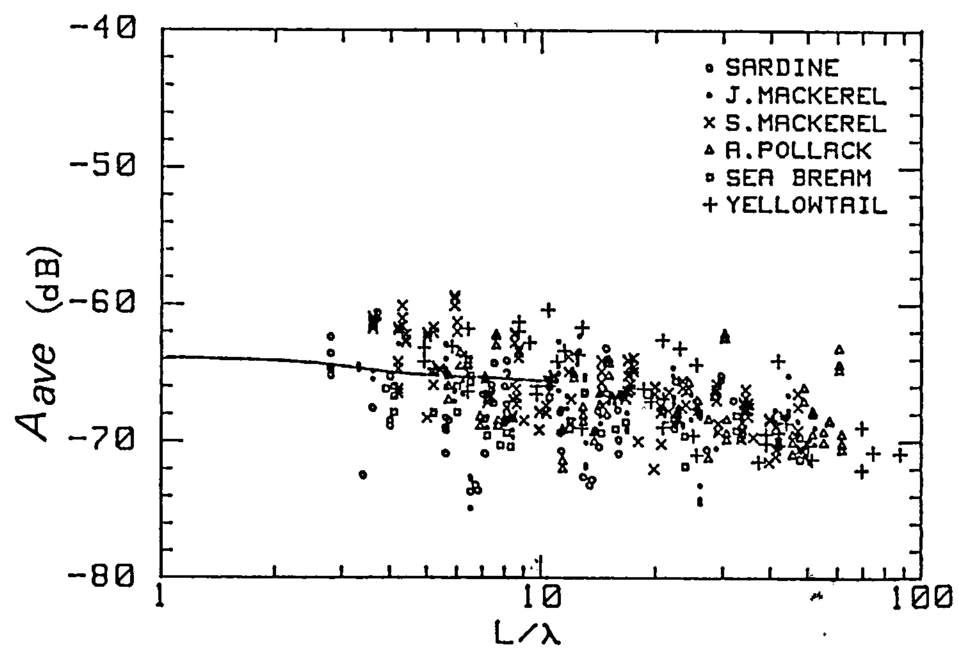


Figure 6. Comparison of normalized target strengths averaged for fish-orientation distribution obtained by model and measurements. The mean and standard deviation of tilt-angle distribution are assumed to be −5° and 15°.



were observed at negative tilt angles of a few degrees. These differences in the backscattering patterns may be attributed to fish anatomy or morphology (e.g., swimbladder).

Dorsal-aspect maximum target strength

The maximum target-strength values normalized by squared body length, A_{max}, were distributed in a rather wide range for each species and frequency, as can be seen in Figure 5. This fact suggests that slight differences in structure or shape of fish may affect echo formation. The interferences of waves scattered from various parts of a fish body are very significant, even in the "far field". Accordingly, some averaging of sufficient target-strength data is needed in order to determine a general value; we averaged the data (A_{max}) for each species and frequency (Fig. 7).

Precise measurement of maximum peak values of 100 kHz or higher is considered to be difficult because scattering patterns are highly directional (Figure 4). This is probably why mean values of A_{max} decreased slightly with frequency (Fig. 4). With a few exceptions, however, these mean values of A_{max} are generally distributed between −61 and −59 dB.

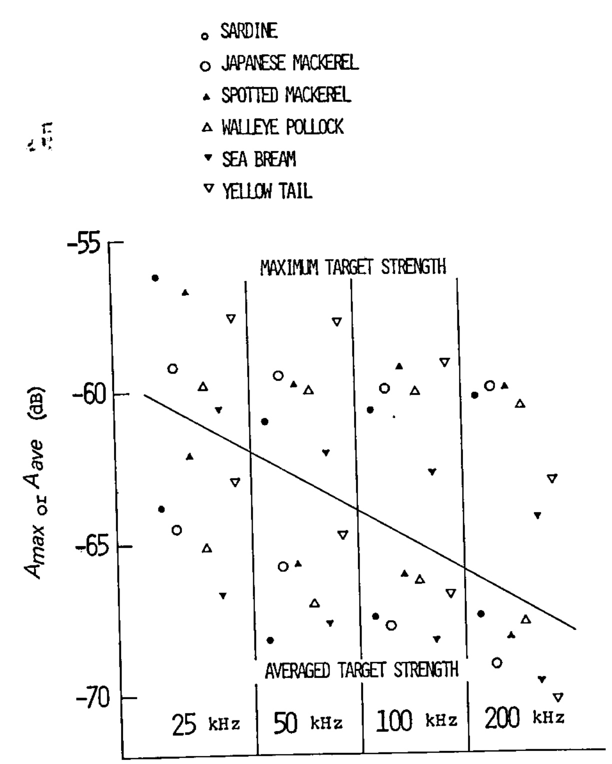


Figure 7. Mean values of normalized maximum and normalized averaged target strength for each species and frequency.

Dorsal-aspect averaged target strength

First, we discuss the effect of fish behaviour on target strength. In the case of yellowtail, whose scattering patterns are shown in Figure 4, the averaged target-strength values for head-down aspect are higher than those for head-up aspect, because the backscattering energy of the fish is concentrated at negative tilt angles. For example, the averaged value for head-down aspect (−5, 15) is 1.4 dB greater than that for head-up aspect (5, 15) at 50 kHz. Thus, the difference in averaged values between these two aspects is not especially large. In addition, the difference becomes smaller for fish which show less directional backscattering patterns (Miyanohana *et al.*, 1986). Although ignorance of fish behaviour leads to considerable errors in abundance estimation (Foote, 1980c), the means of A_{ave} shown in Figure 7 can be used in cases where the mean tilt angle is generally between −5° and 5° and the standard deviation is greater than 15°.

Secondly, we discuss the frequency dependence of target strength for each species. At higher frequencies, the averaged target-strength value is generally lower than that at lower frequencies because backscattering patterns are more directional (Fig. 4). For example, the mean of A_{ave} of Japanese mackerel decreases with increasing frequency, while the mean of A_{max} does not appear to change with frequency (Fig. 7). Similar frequency dependence is observed for spotted mackerel although the trends are not as strong. For yellowtail, the difference of the means of A_{ave} between 25 kHz and 200 kHz is as great as 6.7 dB. In this case, however, the negative frequency dependence may be exaggerated because of inaccuracies in peak-value measurement caused by the highly directional backscattering patterns of these large fish. In contrast, for sea bream or walleye pollock, the difference among the means of A_{ave} between 25 and 200 kHz is less than 3.0 dB because their backscattering patterns are less directional. The means of A_{ave} of sardine, which are generally small in length (Table 1), cannot be distinguished by frequency except at 25 kHz.

Thirdly, we discuss suitable frequencies for quantitative surveys. Backscattering patterns of fish are considerably directional at 200 kHz. Therefore target strength is very sensitive to fish behaviour and A_{ave} is generally low. Thus, echo sounders operating at such a high frequency should only be used for quantitative surveys of small-sized fish. However, scattering patterns at 25 kHz are less directional. Thus, fish behaviour affects target strength to a lesser degree and the averaged value is generally high. Therefore, echo sounders operating at lower frequencies are more suitable for estimating fish biomass densities. At 50 kHz or 100 kHz, the means of A_{ave} are generally distributed from −68 to −66 dB regardless of species. At 25 or 200 kHz, however, variation with species is observed. The difference at these frequencies might be caused by the scattering characteristics peculiar to the species, but we could not conclude that with certainty because of our small sample size and limited length range.

Comparisons with Furusawa's model

Though the model predicts maximum values 2 to 3 dB lower than those observed at low L/λ, theoretical and experimental results agree well at $6 < L/\lambda < 100$ (Fig. 5). Very good agreement in both trend and value is observed in averaged values (Fig. 6). Since our observations are in general agreement with the theoretical predictions, we conclude:

(1) Our measuring method and system are reliable, and the measured dorsal-aspect target-strength functions are adequate for estimation of maximum or averaged values.

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(2) The soft spheroid is a very effective model for fish with swimbladders and can be used to predict general scattering properties.
(3) At lower L/λ values, measured data can be extrapolated by use of the model and theoretical results can be extrapolated to higher L/λ values.
(4) The swimbladder scatters most of the echo energy. This modelling approach will become more effective as further information on the acoustic properties of swimbladders and additional behavioural observations become available. The model should be extended to consider higher values of L/λ.

Conclusions

(1) The simultaneous calibration method is reliable for target-strength measurements.
(2) In general, the main lobes of the backscattering patterns of fish become more directional with increasing frequency between 25 and 200 kHz. Therefore, fish behaviour causes more variability in target strength at higher frequencies.
(3) The means of the maximum target strength normalized by squared forklength (cm) generally range from −61 to −59 dB regardless of species or frequency.
(4) The averaged target strengths with respect to fish tilt angle, whose mean and standard deviation are assumed to be (−5, 15), decrease with frequency, owing to the directionality of the backscattering patterns.
(5) At 50 or 100 kHz, the means of the averaged target strength normalized by squared forklength are distributed between approximately −68 and −66 dB regardless of species. At 25 or 200 kHz, however, they vary with species. The observed difference at these frequencies may be caused by the small sample size of data and limited length range.
(6) Merged target-strength data (by species and frequency) were compared with theoretical values, determined by using the soft spheroidal model, and good agreement was found.

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Fish and standard-sphere target-strength measurements obtained with a dual-beam and split-beam echo-sounding system

Jimmie J. Traynor and John E. Ehrenberg

Traynor, Jimmie J., and Ehrenberg, John E. 1990. Fish and standard-sphere target-strength measurements obtained with a dual-beam and split-beam echo-sounding system. – Rapp. P.-v. Réun. Cons. int. Explor. Mer, 189: 325–335.

A new echo-sounding system, which has both dual-beam and split-beam target-strength measurement capability, is described. A method of calibrating this system using a tungsten carbide standard sphere is presented. Comparisons of target-strength measurements using the dual-beam and split-beam techniques are presented for the calibration sphere as well as fish targets. The target-strength measurements for 40-cm walleye pollock (*Theragra chalcogramma*) ranging from −29.8 to −31.5 dB/kg compare favorably with previous *in situ* estimates as well as estimates based on swimbladder measurements.

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Introduction

The importance of knowledge about the target-strength characteristics of the surveyed fish population to the accuracy of acoustic assessments using echo integration is well known. Recently, there has been a concerted effort by many researchers to obtain *in situ* target-strength measurements of fish in their natural environments. Because of their often superior performance (Ehrenberg, 1979), direct assessment techniques have frequently been chosen. The dual-beam technique has been applied by many researchers (e.g., Traynor and Ehrenberg, 1979; Traynor and Williamson, 1983; Dickie *et al.*, 1984). Foote *et al.* (1985, 1986) describe the first applications of a split-beam direct target-strength measurement system to fish target-strength measurement. The purpose of the present paper is: (1) to describe a new echo-sounding system which has both split-beam and dual-beam target-strength measurement capability, (2) to describe the analysis procedure and the calibration technique used with that system, and (3) to present comparisons of dual-beam and split-beam target-strength measurements made from walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea.

Background

The difficulty with *in situ* target-strength measurement is that the voltage level out of an echo sounder is a function of both the acoustic size of the fish as measured by target strength and the position of the fish in the transducer beam. A single-beam echo-sounder output level in dB for an acoustic echo reflected from an individual fish is expressed by:

$$V_0 = SL + G_R + TS + 2B(\theta,\varphi) - 40\log(R) - 2\alpha R + G_{TVG}$$

where SL is the transmitted source level, G_R is the fixed receiving gain from transducer input to sounder output, $40\log(R) + 2\alpha R$ is the spreading and absorption loss, G_{TVG} is the time-varied-gain of the sounder, TS is the target strength of the individual fish located at angular coordinates (θ,φ), and $B(\theta,\varphi) = 10\log[b(\theta,\varphi)]$ is the transducer beam-pattern factor. The source level and gain can be measured during calibration or measured using standard targets. The range-dependent loss can be removed with the time-varied-gain. However, the relative contribution of TS and $B(\theta,\varphi)$ to the output level cannot be determined for a given echo level using a single-beam echo-sounding system.

Various techniques for separating the beam-pattern effect from the target strength using a collection of echo levels have been developed. A review of these indirect target-strength estimation methods is contained in the paper by Ehrenberg (1983a). All of the indirect techniques are susceptible to numerical and statistical errors and do not work well in many cases of interest. An alternative to the indirect method is to remove the