Depth-dependent target strength of anchovy (*Engraulis japonicus*) measured *in situ*

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Three sets of target strength (TS) data were collected in the southern part of the Yellow Sea using a calibrated, 38 kHz, Simrad EK500 split-beam echosounder. Midwater trawl sampling showed that >97% of the catch by number was anchovy (*Engraulis japonicus*), with total lengths ranging from 6 to 15 cm, and that the arithmetic-mean length and root-mean-square length were 10.6 and 10.8 cm, respectively. The mean TS of anchovy in the 10–45-m layer was estimated to be −50.9 dB, with a 95% confidence interval of (−51.0, −50.8) dB. The TS data showed, however, a clear depth-dependence that was very close to and not significantly different from what might be expected according to Boyle's law. The TS model was estimated to be $TS = 20 \log L - 71.6$ for the conventional relationship between TS and length, but $TS = 20 \log L - (20/3) \log (1+z/10) - 67.6$ when the depth (z, m) effect was included according to Boyle's law. These results may have a significant influence on abundance estimates of anchovy derived from acoustic surveys, both in the Yellow Sea and in other parts of the world.

Keywords: anchovy, Boyle's law, depth-dependence, target strength, Yellow Sea.

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Introduction

Anchovy (*Engraulis japonicus*) is a key fish species in the Yellow Sea ecosystem, supporting one of the largest fisheries in China (Tang, 1993; Zhao *et al*., 2003). The wintering anchovy stock in the Yellow Sea has been monitored acoustically since 1984 (Zhu and Iversen, 1990; Iversen *et al*., 1993; Zhao, 2001), and during recent years the acoustic survey of anchovy has been extended to all four seasons in the China–GLOBEC Program (Tang, 2000). However, only a few estimates of the target strength (TS) of *E. japonicus* have been reported (e.g. Chen and Zhao, 1990; Yoon *et al*., 1996). In fact, the relationship between TS and fish length currently used to support the acoustic estimate of anchovy in the Yellow Sea was still one "borrowed" from that of herring (*Clupea harengus*) in the 1980s (Zhu and Iversen, 1990).

Knowledge of the TS of fish is crucial to acoustic surveys of fish abundance. However, it varies considerably in relation to the behavioural and physiological conditions of the fish (Foote, 1980a; Ona, 1990; Zhao, 1996; Ona *et al*., 2001a). Detailed and systematic study of fish TS is therefore necessary to improve acoustic estimates of stock size; prerequisites for survey-based fishery management and the study of ecosystem dynamics.

For physostomatous fish without a gas-secreting mechanism (Blaxter and Batty, 1984), the size of the swimbladder will vary in response to changes in depth as a consequence of the compliant nature of the gas-filled swimbladder. Being the primary organ responsible for the reflected acoustic energy by fish (Foote, 1980b), any change in the size of the swimbladder will cause the TS of a fish to vary. Indeed, the depth-dependence of the TS of fish with swimbladders has been observed by several authors, both in controlled experiment (Edwards and Armstrong, 1983; Olsen and Ahlquist, 1989; Mukai and Iida, 1996; Ona *et al*., 2001b; Ona, 2003) and through modelling (Gorska and Ona, 2003). However, direct measurement of fish in their natural environment has been rare (Ona, 2003).

Here, we describe an *in situ* measurement of anchovy TS in the Yellow Sea, with emphasis on its depth-dependence. This is part of an effort to study the temporal (diurnal, seasonal) and spatial (depth) variations of anchovy TS in the Yellow Sea and its implications for stock assessment.

Material and methods

Measurement site

Anchovy TS measurements were made on board the RV "Bei Dou", a 56.2-m stern trawler designed for acoustic and trawl surveys. Data were collected on a dispersed anchovy aggregation from 22:15 on 31 March to 00:45 on 1 April 2001 in the southern part of the Yellow Sea (Figure 1), a traditional wintering ground of anchovy (Zhu and Iversen, 1990; Iversen *et al*., 1993) with a bottom depth of ~70 m.

Biological sampling

Biological samples were collected with a four-panel, midwater trawl with stretched-mesh size of 400 mm in the forward section and 24 mm in the codend. The trawl was monitored by a SCANMAR Trawlsounder (model: TS150): its vertical opening and wing spread were ~20 and 25 m, respectively. The trawl was

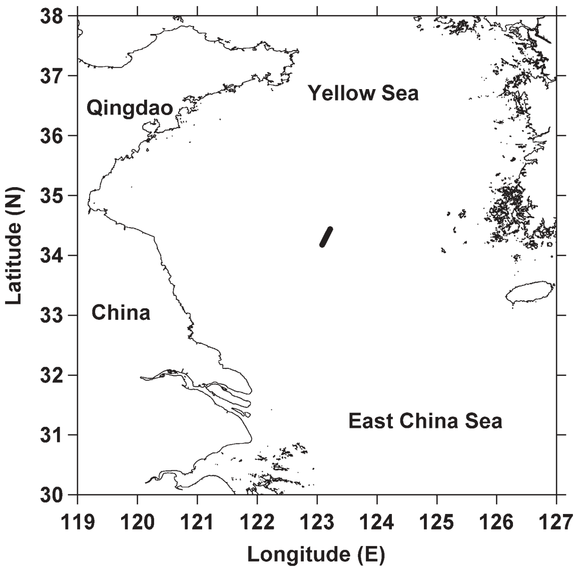

Figure 1. Area of data collection. The TS measurement site is shown by a thick line.

towed at a speed of ~3 knots for 30 min in the 10–45-m layer, with the warp length adjusted from 70 to 100 m.

The whole catch was sorted according to a standard procedure. For anchovy, all 232 individuals caught were sorted into 1-cm total length groups, and the number of fish in each 1-cm group was counted to calculate the root-mean-square (RMS) length of the fish (Zhao, 2001). The fish were then frozen for individual-based laboratory measurement of, *inter alia*, total length, fork length, gutted weight, maturity stage, and stomach fullness. Fulton's condition factor (Ricker, 1975) was calculated from

$$K = \frac{w}{l^3} \times 100, \tag{1}$$

where K is Fulton's condition factor, w the gutted weight of the fish (g), and l the fork length (cm).

Collection of echo data

Three sets of echo data were collected with a 38-kHz Simrad EK500 split-beam echosounder. The echosounder was calibrated with a 60-mm copper sphere according to standard procedures (Foote *et al.*, 1987; Ona, 1999), and the sound speed was controlled according to a CTD (Seabird-19) cast at the calibration site. Relevant instrument settings are listed in Table 1. The raw echo data, as accepted by the filtering algorithm of the echosounder, were logged via the serial port of the echosounder and stored on a PC via PROCOMM (V2.4, Datastorm Technologies Inc., 1986). Some typical echograms associated with TS data collection are shown in Figure 2.

Table 1. Simrad EK500 echosounder (V5.31) parameter settings for anchovy TS measurements.

Parameter	Settings	Unit
Ping interval	1	s
Pulse duration	1.0	ms
Bandwidth	3.8	kHz
Maximum transmitting power	2000	W
Range	100	m
S_v colour minimum	−70	dB
TS transducer gain	26.83	dB
Alongship 3 dB beam width	7.0	degree
Athwardship 3 dB beam width	6.8	degree
Alongship offset angle	0.01	degree
Athwardship offset angle	0.05	degree
Minimum TS value	−70	dB
Minimum echo length	0.8	–
Maximum echo length	1.3	–
Maximum gain compensation	6.0	dB
Maximum phase deviation	3.0	–

Data analysis

TS data were extracted from the raw echo data using a dedicated Pascal program (Zhao, 1996). For each of the three datasets, the echogram was carefully checked and only the data corresponding to constant vessel speed (~10 knots) and clear single-fish echo-traces were selected for further analysis. The data suitable for estimating TS were obtained by specifying the selected time intervals and range limits through a subroutine of the program; only the data collected in the 10–45-m layer in which the sample was caught were chosen for this purpose. The TS data (including the corresponding range data) were then reformatted into the standard case-by-variable format and imported into SYSTAT (V10.2, SYSTAT Software Inc., 2002) for final analysis.

The conventional relationship between TS and fish length was estimated using the model

$$\mathrm{TS} = 20 \log L + b_{20}, \tag{2}$$

where L denotes the RMS total length of the anchovy in centimetres and b_{20} the intercept term b with the slope term preset to "20".

To investigate the depth-dependence of anchovy TS, the selected data in each of the three datasets were divided into five successive depth bins of varying thickness; the actual thickness of each of the five depth bins was chosen so that a similar quantity of TS data was found in each, to give a similar precision to each individual TS estimate. The depth of the fish was approximated by the range of the echo with the draft of the vessel (5 m) added, and the mean depths and fish TSs within each of the five depth bins in each of the three datasets were calculated. In all, 15 TS estimates and corresponding fish depths were so obtained, and these were then used as input to a regression analysis using the following model of depth-dependent TS on fish length:

$$\mathrm{TS} = 20 \log L - 10\gamma \log\left(1 + \frac{z}{10}\right) + b_{20,z}, \tag{3}$$

where γ denotes the contraction rate of the backscattering cross section of the fish with depth (Ona, 2003), z the depth of the fish, and $b_{20,z}$ the b_{20} when a depth effect is included in the model.

To calculate mean TS, averaging was generally carried out on the backscattering cross section (σ_{bs}), and the output was converted into TS strength according to the formula (MacLennan *et al.*, 2002):

$$\mathrm{TS} = 10 \log \sigma_{\mathrm{bs}}. \tag{4}$$

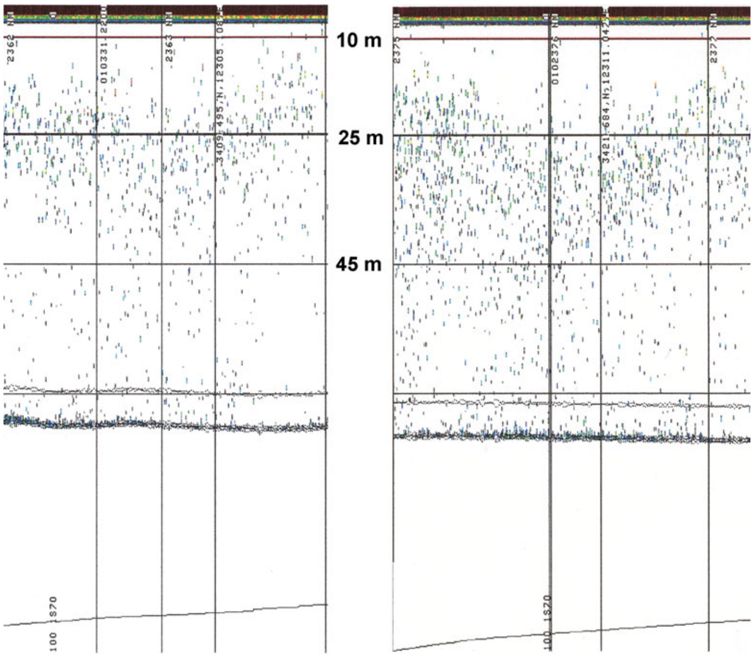

Figure 2. Two segments of echograms showing single-fish echotraces. The values between the echograms are the depths of the integration layers with the vessel's draft included.

Results

Biological aspects

Table 2 shows the species composition of the catch from which samples were derived. Anchovy constituted 97.1% of the catch in number and 85.6% by weight. Other species were negligible in quantity, so were not expected to influence the estimate of anchovy TS significantly. Figure 3 shows the length distribution of anchovy. It ranged from 6 to 15 cm, its arithmetic mean length was 10.6 cm, with a standard deviation of 1.8 cm, and its RMS length was 10.8 cm.

The state of maturity of the anchovy was variable, with many maturity stages present, from immature to spent, among the 100 fish analysed. However, the gonads of most fish were either undeveloped (65%) or spent (3%), and only a few (5%) were mature; the balance of the gonads were in a developing stage.

Fulton's condition factor for anchovy was in the range 0.50–1.04, with a mean of 0.70. Gut examination showed that all fish had at least some food in their stomach, but that just 3% had full stomachs.

Table 2. Species composition of the sample haul.

Species		Number of fish		Weight of fish	
Common name	Scientific name	Individuals	%	g	%
Anchovy	*Engraulis japonicus*	232	97.07	1 839.5	85.62
Chub mackerel	*Scomber japonicus*	1	0.42	100.0	4.65
Gizzard shad	*Konosirus punctatus*	3	1.26	206.0	9.59
Skinnycheek lanternfish	*Benthosema pterotum*	3	1.26	3.0	0.14

Mean TS

Figure 4 shows the TS distributions obtained from the three sets of selected data, as well as that from the combined data. Generally, the TS distributions were single mode, except that for dataset 1 (Figure 4a), for which a lower mode at −60 to −58 dB was weakly visible.

Table 3 lists some of the basic statistics and the mean TS associated with the three sets of selected data, and that of the combined data. The mean TS estimates were −51.0, –50.6, and –51.3 dB for datasets 1–3, respectively. The mean TS of anchovy estimated from the combined data was −50.9 dB, with a 95% confidence interval of (−51.0, −50.8) dB. The relationship between TS and length in the conventional form (Equation 2) was then estimated to be

$$\mathrm{TS} = 20 \log L - 71.6. \qquad (5)$$

Depth-dependence

Table 4 and Figure 5 show the mean TS values for anchovy in different depth bins. A decreasing trend of TS with increasing

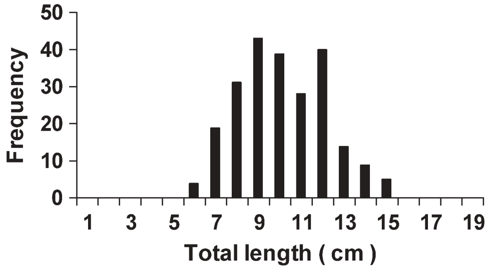

Figure 3. Length composition of anchovy caught in the sample haul.

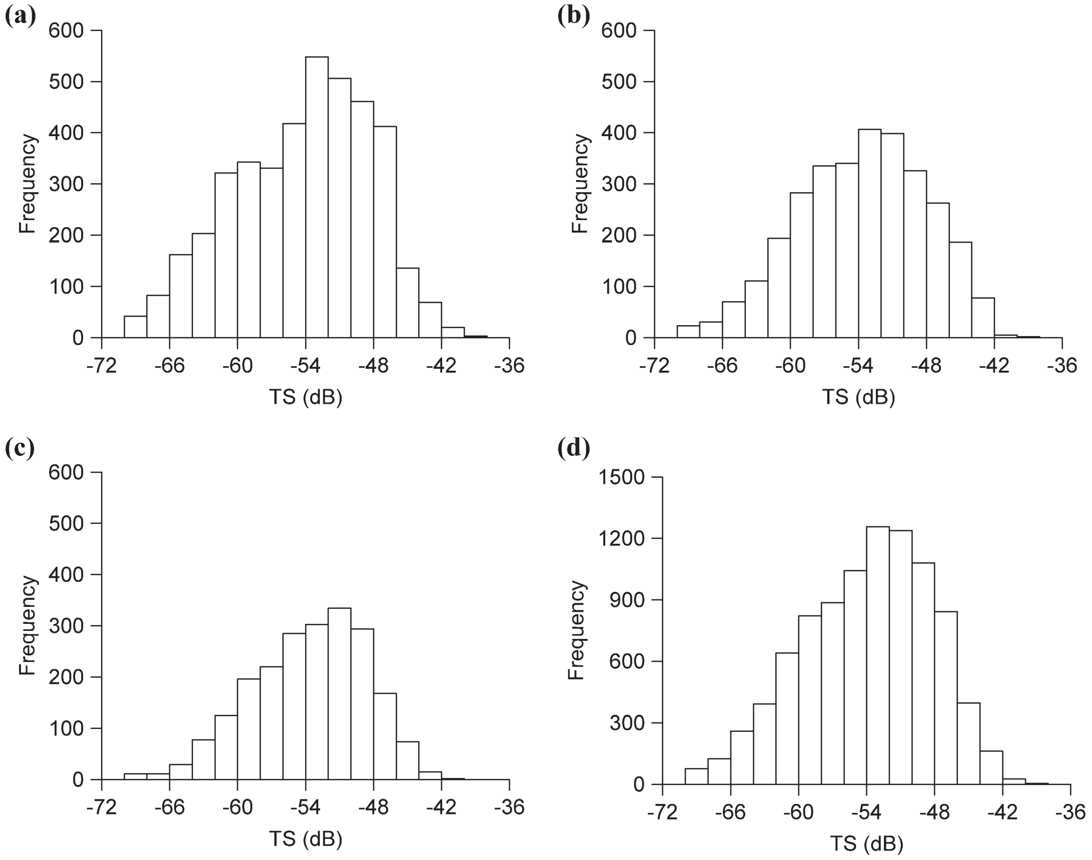

Figure 4. TS distributions of anchovy for (a) dataset 1, (b) dataset 2, (c) dataset 3, and (d) combined data for all three datasets.

Table 3. Some basic statistics and mean TS (dB) estimates of anchovy associated with the three sets of selected data and that of the combined data.

Variable	**Dataset**			
	1	**2**	**3**	**Combined**
Number of datum	4 059	3 053	2 145	9 257
Mean fish depth (m)	30.4	28.0	32.9	30.2
Minimum TS	−70.0	−70.0	−69.7	−70.0
Maximum TS	−39.4	−36.9	−41.4	−36.9
Mean TS	−51.0	−50.6	−51.3	−50.9
95% CI of mean TS	−51.1, −50.8	−50.8, −50.4	−51.5, −51.1	−51.0, −50.8

depth is clearly demonstrated in all three datasets. This trend is further illustrated by Figure 6, where a gradual shift of the TS mode towards lower TS with increasing depth is evident.

Table 5 lists the results of a regression according to the model given by Equation (3). The corresponding TS model is then

$$\mathrm{TS} = 20\log L - 6.1\log\left(1+\frac{z}{10}\right) - 68.1. \qquad (6)$$

The coefficient of determination (r^2) of the regression, adjusted for the number of independent variables and the sample size, was 0.65, i.e. 65% of the variation of the TS of anchovy can be explained by the depth effect.

The parameter γ was estimated at 0.61, with a standard error (s.e.) of 0.12 (Table 5), which is not significantly different from 2/3, the contraction rate of the backscattering cross section predicted from the free-balloon model according to Boyle's law. Assuming that the 10γ value in Equation (6) equals $10\times 2/3$, and adjusting the $b_{20,z}$ in Equation (6) using the mean depth of the fish (30.2 m, Table 3) as reference depth, then Equation (6) becomes

$$\mathrm{TS} = 20\log L - \frac{20}{3}\log\left(1+\frac{z}{10}\right) - 67.6. \qquad (7)$$

This is the TS model for anchovy estimated with a depth effect (z, m) included according to Boyle's law.

Table 4. Mean TS of anchovy and the corresponding mean fish depth in different depth bins.

Dataset	Depth bin	Bin limits (m)	Mean fish depth (m)	Number of echoes	Mean TS (dB)
1	1	10.0–20.0	16.3	603	−50.48
	2	20.1–27.0	23.7	880	−50.35
	3	27.1–33.0	30.0	861	−50.69
	4	33.1–39.0	36.0	836	−51.16
	5	39.1–45.0	42.0	879	−52.21
2	1	10.0–19.0	15.7	581	−50.23
	2	19.1–25.0	22.1	664	−50.05
	3	25.1–31.0	28.0	653	−50.78
	4	31.1–38.0	34.3	606	−50.86
	5	38.1–45.0	41.5	548	−51.15
3	1	10.0–25.0	21.4	345	−50.28
	2	25.1–30.0	27.8	433	−50.64
	3	30.1–35.0	32.4	446	−51.14
	4	35.1–40.0	37.5	476	−52.02
	5	40.1–45.0	42.6	445	−52.53

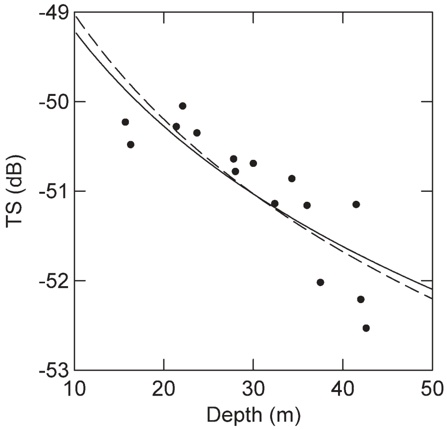

Figure 5. Scatterplot of mean TS in each depth bin and the corresponding mean depth of the anchovy. Solid line, data-fitted curve according to Equation (3); dashed line, TS estimated from the model given in Equation (7).

Discussion

Sources of error

Although the coexisting species (Table 2) were of negligible quantity compared with that of anchovy, they are still a possible source of error. Its effect on the TS estimate for anchovy is difficult to quantify, but the potential error is believed to be small; 100% pure anchovy, single-fish-echo registration is very difficult to find. The percentage of anchovy reported here was among the highest obtained in the Yellow Sea in the past 20 years.

The well known multiple-target problem (Soule *et al.*, 1995; Ona, 1999) might be another source of error. To estimate the probability (p) of having more than one fish-per-pulse volume, the mean number (N) of fish per detection volume was calculated for the data corresponding to the echogram shown in the right panel of Figure 2. According to Ona (1999):

$$N = \frac{s_{\mathrm{A}}(c\tau/2)r^2\Omega_D}{4\pi 10^{\mathrm{TS}/10}\Delta z(1852)^2}, \qquad (8)$$

where s_{A}, the nautical-area-scattering coefficient (MacLennan *et al.*, 2002), was 58.1 m^2 per nautical mile^2 for the 10–45-m layer; the corresponding thickness of the integration layer, Δz, was 35 m; $c\tau/2$ was assumed to be 0.75 m for the sake of simplicity; the detection range, r, was assumed to be 30.2 m, i.e. the mean depth of the fish (Table 3); the solid angle of the sampled volume, Ω_D, was 0.02391 steradians (Ona, 1999); and TS was assumed to be −50.9 dB, i.e. the estimated mean TS of the fish (Table 3). N was then estimated to be 0.08 fish per detection volume. The corresponding value of p was $<5\%$, which in turn was less than the 10% recommended by Ona (1999). Therefore, given the low probability of having more than one fish per sampled volume estimated, and further mitigated by the careful data-selection procedures applied, the effect of multiple-targets should have been kept to a minimum.

Table 5. Summary statistics of the regression of TS against depth according to the model given in Equation (3).

Variable	Coefficient	s.e.	p
$b_{20,z}$	−68.1	0.7	<0.00001
γ	−0.61	0.12	0.00016

The adjusted r^2 of the regression is 0.65, and the standard error (s.e.) of the estimate is 0.44.

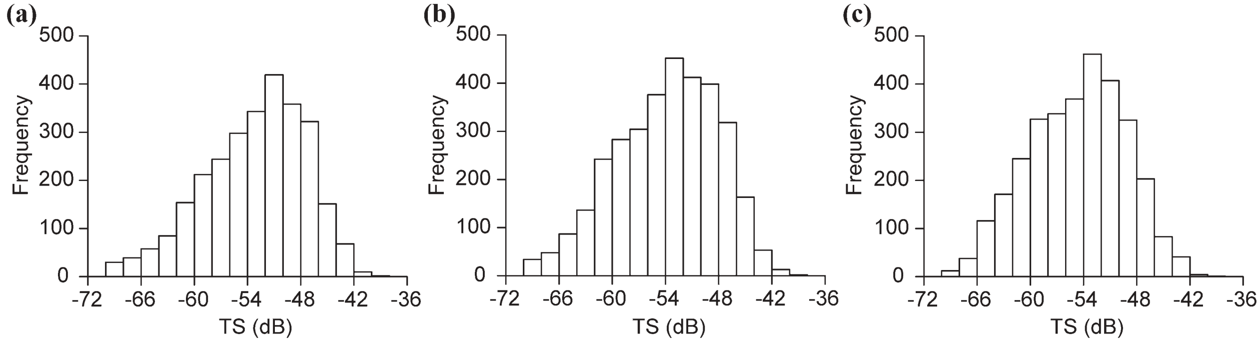

Figure 6. TS distributions of anchovy in different depth bins: (a) 10–25 m; (b) 25–35 m; (c) 35–45 m. A gradual shift of the mode towards a lower TS with increasing depth is clear.

TS of anchovy

To facilitate comparison of the present estimate with existing estimates of the TS of *E. japonicus*, the b_{20} values of some of the published TS-to-length relationships of this fish are listed in Table 6. The present result is clearly the highest among the estimates, 0.9 dB higher than that currently applied for acoustically assessing the anchovy stock in the Yellow Sea.

There are many factors that may affect the TS of fish, including, *inter alia*, the behaviour or the tilt-angle distribution of the fish (Foote, 1980a), and the physiological conditions of the fish (Ona, 1990), such as fat content (Reynisson, 1993) and stage of gonad development (Zhao, 1996; Ona *et al*., 2001a). The tilt-angle distribution of the anchovy subjected to TS measurement here is unknown. The TS distributions in this study were unimodal in general (Figures 4 and 6), which is neither an exception nor the norm according to our own *in situ* observations; Yoon *et al*. (1996) reported bimodal distributions with the two modes separated by almost 20 dB. Concurrent tilt-angle observation may help to elucidate the impact of fish behaviour on the mean as well as the distribution of anchovy TS.

According to modelling output, the predicted TS distribution of a 12.6-cm anchovy is multimodal in nature because of the highly directive sound-scattering property of the swimbladder, coupled with the behaviour pattern of the fish (Yu and Zhao, 2007). The length distribution of the fish in this study was bimodal (Figure 3), and the range of fish length, 6–15 cm, is also quite large for a fish with an observed maximum total length in the Yellow Sea of just 17 cm (Zhao, 2006). These factors may be partially responsible for the unimodality observed in the TS distribution.

The fat content of anchovy was not measured. According to a recent systematic seasonality study, the fat content of anchovy in the Yellow Sea is $6.44 \pm 3.73\%$ in March, ~2% less than in November, when the measurements by Chen and Zhao (1990) were made. This difference in fat content may be partially responsible for the difference in TS estimates observed (Reynisson, 1993).

The stage of gonad development and the degree of stomach fullness of the anchovy were both low. Neither was therefore expected to influence the swimbladder and hence the TS in any appreciable way.

Depth-dependence of the TS of anchovy

The depth-dependence of the TS of a fish with a swimbladder has been long recognized (Edwards and Armstrong, 1983; Ona, 1984, 1990; Olsen and Ahlquist, 1989; Mukai and Iida, 1996), but it has been difficult to measure on natural or near-natural swimming fish (Reynisson, 1993; Zhao, 1996). However, Ona *et al*. (2001b) and Ona (2003) recently quantified the depth-dependence of the TS of natural or near-natural swimming herring (*C. harengus*) in a rigorous manner. The contraction rate of the backscattering cross section of herring they estimated was much lower than would have been estimated directly from the volume of the swimbladder of herring (Ona, 1984), which is in accord with the free-balloon model according to Boyle's law. This apparent discrepancy can be explained by an alternative swimbladder-compression scheme with fixed-end positions and pressure-sensitive diameter of the swimbladder (Gorska and Ona, 2003). On the other hand, in an experiment on tethered, anaesthetized kokanee salmon (*Oncorhynchus nerka*), Mukai and Iida (1996) showed that the depth-dependence of the TS can indeed follow Boyle's law.

Table 6. Summary of some of the *in situ* TS estimates of anchovy (*Engraulis japonicus*) at 38 kHz.

b_{20}	Area	Method	Source
−71.6	Yellow Sea	Split-beam	Present study
−72.5	Yellow Sea	Currently used	Zhu and Iversen (1990)
−73.2	Yellow Sea	Single-beam	Chen and Zhao (1990)
−72.9	Southern Korean waters	Split-beam	Yoon *et al*. (1996)

The b_{20} is used to facilitate the comparison.

Based on observations on the same fish aggregation simultaneously at different depths, the depth-dependence of anchovy TS was clearly demonstrated (Table 4, Figure 5). However, because the tilt-angle distribution of the fish was not measured, whether the observed depth-dependence of the TS of this fish species was due to swimbladder compression alone is not clear. Figure 5 shows that the data points in the middle of the depth range conform to Boyle's Law very well, but the data at either end of the depth range fall below the fitted line. The exact reason for this is not known. Two phenomena in connection with unfavourable tilt-angle distribution, however, can cause lowered TS in shallow and deeper water. One is the phenomenon of vessel avoidance at shallow depth (Olsen *et al*., 1983; Ona and Toresen, 1988; Ona *et al*., 2007), and the other is the "rise and glide" compensatory strategy of negatively buoyant fish in deeper water (Huse and Ona, 1996).

Nevertheless, the results (Table 5) here show that the mean TS of anchovy decreased monotonically with increasing depth in the natural environment, and that the depth-dependence of anchovy TS can indeed follow Boyle's law. The lower TSs at either end of the depth range led only to a lowered value of the intercept (b_{20}), whereas the slope (or γ) remained more or less intact. This means that the γ value of anchovy can be much higher than the 0.23 obtained for herring (Ona, 2003). Detailed comparative studies on the morphologies and compression schemes of the swimbladder of anchovy and herring are clearly needed to understand the differences in the depth-dependence of the TS of these two fish species.

Anchovy is a pelagic fish that performs distinct diurnal vertical-migrations. As acoustic surveys are often operated on a 24-h basis, the observed depth-dependence of the TS may have a significant effect on the abundance estimates of anchovy, both for this particular species in the Yellow Sea and for related species in other parts of the world. According to Equation (7), the TS of the same anchovy would be elevated by 2 dB when the fish migrate from 50 m deep during daylight to 20 m deep at night; the corresponding night-time estimate of abundance would be 58% higher than that of the daylight estimate if the same TS-to-length relationship was used. As the behaviour and hence the tilt-angle distributions of the fish can be very different between daylight and night (Beltestad, 1973), systematic day compared with night investigation, with concurrent tilt-angle observation, of the depth-dependence of anchovy TS is desirable to improve the acoustic estimates of this commercially and ecologically important species.

As physiological factors may also play important roles (Ona, 1990), simultaneous observation of the same fish aggregation, as done here, may be of great help in providing a simpler situation for studying a complex problem such as the depth-dependence of fish TS.

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