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III. Fish and plankton target strength

Empirical determination of *in situ* target strengths of three loosely aggregated pelagic fish species

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In situ measurements of target strength (TS) at 38 kHz have been taken from night-time scattering layers of anchovy, pilchard, and Cape horse mackerel in the course of routine surveys. These species have different numerical packing densities, which necessitates treating the TS data differently in each case, as the performance of single-target detectors is strongly dependent on target densities. Evidence for the presence of multiple targets in their TS distributions is presented, and empirical methods of extracting mean target strengths from them described. After careful assessment of the quality of each data point, and the removal of unwanted influences where possible, the data were used to fit TS/length expressions for the three species.

Key words: anchovy, horse mackerel, methodology, pilchard, split-beam, target strength.

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Introduction

Target strength (TS) is the scaling factor required to convert echo intensity to fish density. Since the development of split- and dual-beam technology (Ehrenberg, 1979), and especially since the commercialization of echo-sounder systems incorporating TS analyzers, *in situ* TS measurements have become part of routine acoustic surveys. Although these analyzers are designed to minimize the proportion of multiple echoes mistakenly accepted as originating from single scatterers, they are not entirely successful (Soule *et al.*, 1995, 1996). Furthermore, while data should only be collected in conditions of ''low'' fish density, TS analyzers continue to deliver results regardless of their quality. In recent years several authors have expressed concern that their *in situ* TS estimates were higher than expected (e.g. Kautsky *et al.*, 1990; Nainggolan *et al.*, 1993; Reynisson, 1993). Poor performance of the single-fish detectors has been suggested as one of some plausible possibilities (Soule *et al.*, 1995), as the bias due to failure to reject multiple echoes can be very significant (Foote, 1994). Thresholding has also been recognized as a possible source of TS overestimation (Wiemer and Ehrenberg, 1975).

As a consequence of this problem *in situ* TS data are often not used to their full potential. While the performance of the technology is now well understood, it would seem that objective criteria are required to allow users to critically interpret their *in situ* TS data. This is especially noticeable in the case of small pelagic fish species, whose packing densities are likely to prevent the successful rejection of multiple echoes. In this paper we attempt to determine *in situ* TS expressions for three species of pelagic fish which have different characteristic numerical packing densities: the South African anchovy (*Engraulis capensis* Gilchrist), pilchard (*Sardinops ocellatus* [Pappe]) and Cape horse mackerel (*Trachurus trachurus capensis* Castelnau).

Material and methods

TS data were collected from February 1992 to December 1994, during eleven South African pelagic assessment cruises on board RS ''Africana'' and RS ''Algoa''. SIMRAD ES400 echo-sounders were employed, using a SIMRAD ES38 split-beam transducer on RS ''Africana'' and a SIMRAD ES38B on RS ''Algoa''. Both transducers were hull-mounted, protected by plexiglass windows, and driven by a SIMRAD EK400 transmitter using a 1.0 ms pulse. Routine calibrations were carried out using copper spheres.

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Table 1. Measured characteristics of the 38 kHz transducers used in this study, and equivalent beam-angle measurements applied in the compensation algorithms.

	RS "Africana"	RS "Algoa"
Athwart. half-power angle	4.6°	4.2°
Athwartships offset	− 0.1°	0.1°
Alongships half-power angle	3.9°	4.2°
Alongships offset	0.2°	0.3°
Shape factor	1.2	1.1
Equivalent beam angle	− 19.1 dB	− 19.2 dB

Target amplitude, range and bearing were sampled from the parallel port of the ES400 at 0.133 ms intervals. Echoes were stored if (a) the peak exceeded a set threshold and (b) the sample-to-sample variation in bearing in both axes did not exceed two phase steps (0.26°) for at least four successive samples. Only targets detected within 3° of the beam axis were processed. Potential single targets were screened further according to shape, and their angular bearings used to compensate the peak amplitude as described in Barange *et al.* (1994). It should be noted that the −3 dB points of both transducers, which were applied in the compensation expressions, were significantly different from the nominal values (Table 1), probably because of their mounting arrangements (Reynisson, 1987).

TS data were generally collected before, during, and, at times, after trawling. Only those associated with catches resulting in more than ca. 80% by weight of the target species were analyzed. On occasion, data were continuously collected from scattering layers in order to study the influence of fish aggregation patterns on the estimates of average TS. A custom-built, multi-channel digital echo-integrator was available for this purpose. The integrator was coupled to the EK400 receiver and was calibrated with copper spheres at the same time as the ES400.

All trawls were carried out with Engels 308 commercial midwater trawl nets, fitted with 8-mm anchovy-mesh codend liners. Trawl location and depth was determined on the basis of echo-sounder observations, generally in the upper 50 m of the water column. All data were collected at night, when the fish were dispersed in scattering layers.

Results

Relationship between TS and fish density

This problem was examined for the South African pilchard, a clupeoid typically between 10 and 24 cm (TL)? long at the time of the surveys. They form dense schools during the day which generally break into scattering layers at night. An echo chart of one such layer is presented in Figure 1A. Backscattering strengths were measured and TS estimated along this approximately 5 nmi long layer. Data were grouped into six continuous subsets (Fig. 1A), each one terminated by the identification of 450 potential single targets. The plot of average MVBS (Mean Volume Backscattering Strength) against estimated mean TS for each subset (Fig. 1B) suggests a strong relationship between the variables. This can also be seen from a comparison between Figures 1D and 1E. Similar patterns were observed in the vertical dimension (Fig. 1F, G), except above 20 m. In this layer, although density decreased noticeably, TS estimates remained high. This appears to be due to extensive ringing (noisy environment) caused by the plexiglass window through which the transducer was fired. Figure 1C shows the relationship between TS and the ratio of the number of pings fired to the number of single targets identified (detection rate). It can be observed that the estimated TS decreased with the detection rate. These results strongly suggest that overlapping echoes, whose frequency is likely to increase with fish density, were erroneously accepted as single echoes, indicating that the single-target detectors did not perform adequately.

To provide further insight into this problem, we examined the probability of overlapping echoes in the densest part of the aggregation. Maximum volumetric densities were computed for each subset, using the MVBS of the peak 1 m vertical channel, and the pilchard TS expression presented in Table 2. The reverberation volume (RV) was estimated using the expression:

$$\mathrm{RV}=\frac{c\tau}{2}\mathrm{R}^2\Psi, \tag{1}$$

where c is the speed of sound (nominally 1500 m s^{-1}), τ the pulse length (1 ms), R the depth of the channel (m), and Ψ the solid angle of the transducer's equivalent beam, obtained from:

$$10\log\Psi=10\log(\theta_a\,\theta_b)-31.6,\ \text{(Urick, 1975)} \tag{2}$$

where θ_a and θ_b are the athwartships and alongships half-power angles (Table 1) respectively.

The frequency of multiple targets will be negligible in comparison with that of genuine single-target echoes if densities are well below one target RV^{-1}. In such situations, average TS estimates should be reliable. If densities approach or exceed this limit multiple echoes are likely to severely corrupt the TS estimates (Soule *et al.*, 1995). The calculated densities RV^{-1} are presented next to the corresponding data points in Figure 1B. It will be seen that maximum densities were below 0.5 targets RV^{-1}, although when averaged over smaller distances (i.e. 25 pings), maximum densities exceeded 2 targets RV^{-1}. The conclusion is that, although the maximum number of targets RV^{-1} is a useful parameter when assessing the potential quality of TS

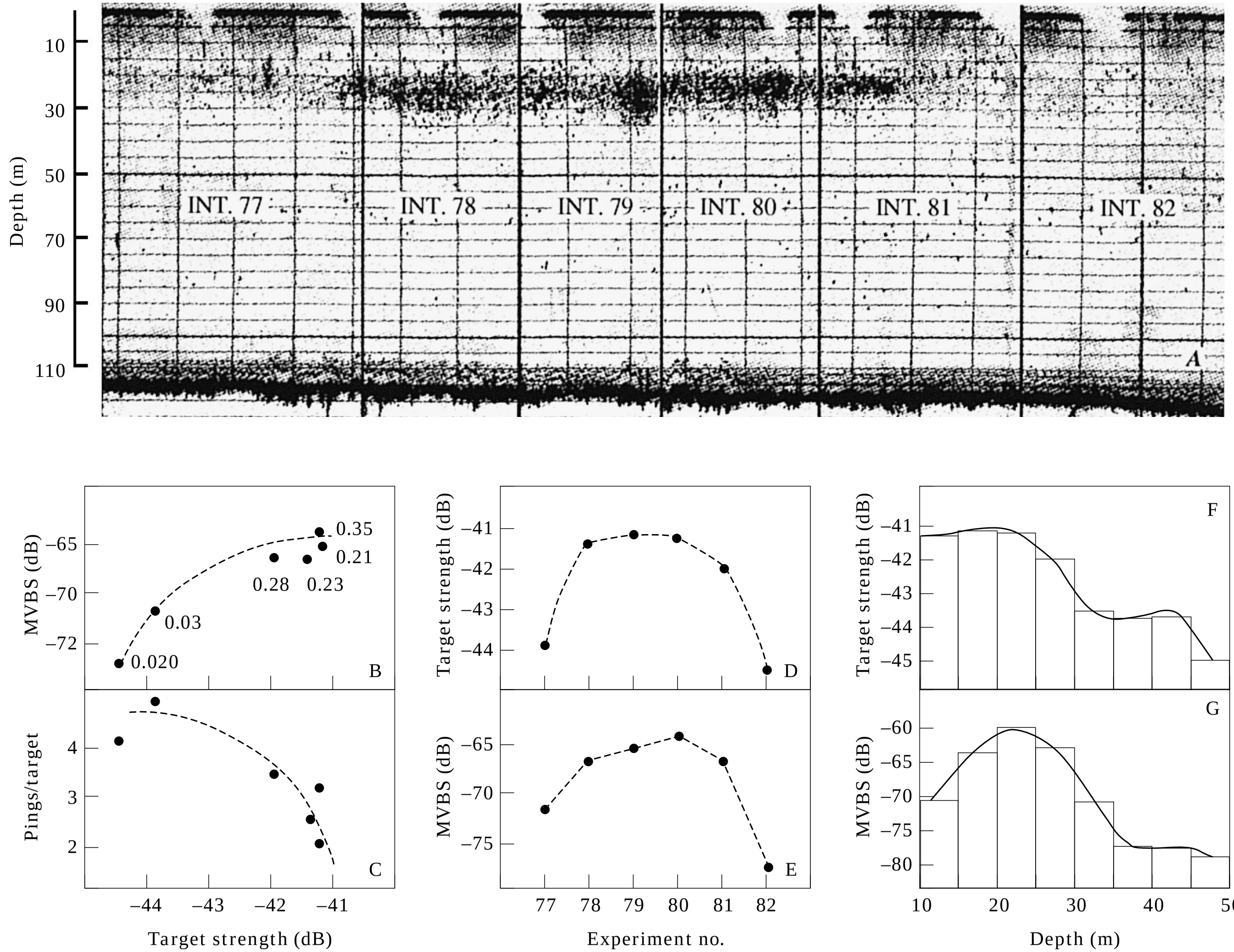

Figure 1. Echochart of a night-time pilchard aggregation (A), relationship between mean TS and both MVBS (B) and the number of pings fired per target detected (C). Also shown are patterns of mean TS (D, F) and MVBS (E, G) versus distance and depth, respectively. Numbers in (B) are mean estimates of fish RV^{-1} in the densest 1 m vertical channel for each experiment.

Table 2. Parameters of the regression equations fitted to the target-strength data for anchovy, pilchard, and horse mackerel. (s.e.m. denotes standard error of the mean; s.e. of Y indicates the standard error of the dependent variable).

	(dB individual^{-1})		(dB kg^{-1})
	$Y = 20 \log TL - b_{20}$	$Y = a \log TL - b$	$Y = a \log TL - b$
Anchovy	n = 18 b_{20} = 76.10 s.e.m. = 0.15	a = 19.50 b = 75.57 r^2 = 0.81 s.e. of Y = 0.66	a = − 12.15 b = 21.12 r^2 = 0.59 s.e. of Y = 0.70
Pilchard	n = 13 b_{20} = 70.51 s.e.m. = 0.10	a = 17.07 b = 66.73 r^2 = 0.87 s.e. of Y = 0.35	a = − 14.90 b = 13.21 r^2 = 0.87 s.e. of Y = 0.30
Horse mackerel	n = 21 b_{20} = 66.80 s.e.m. = 0.16	a = 14.66 b = 58.72 r^2 = 0.78 s.e. of Y = 0.63	a = − 15.44 b = 7.75 r^2 = 0.80 s.e. of Y = 0.63

estimates (Sawada *et al.*, 1993), it is important to average over distances compatible with the scales of local patchiness. Averaging over too large a distance is likely to smooth density patterns, underestimating the probability of multiple echoes.

Similar studies to the one presented in Figure 1 have been conducted on the other two species discussed in this paper, particularly on anchovy. This is a small engraulid of between 6 and 15 cm total length (TL) at the time of the surveys, capable of reaching much higher packing densities than pilchard. To compare packing densities between the two species, and therefore the potential corruption from multiple targets, night-time data from 15 cruises conducted around the South African coastline from 1990 to 1994 were examined, taking only data where one of the two species was the dominant scatterer (>80% in mass). The density of the peak 1 m channel of each ESDU was calculated as described earlier, and the values grouped into 5 m depth classes. The results are presented in Figure 2, which also shows the density corresponding to one target RV^{-1} for each depth class. The figure indicates that below 10 m anchovy scattering layers have packing densities that, on average, exceed the resolution capabilities of the system. Any TS measurements taken in such layers are likely to be corrupted by multiple echoes. Pilchard densities in layers shallower than 30 m seem less problematical, in that their averages do not reach one target RV^{-1} (Fig. 2). However, the figure underestimates maximum fish densities, as they were calculated over ESDUs of typically 5–10 nmi. Nevertheless, the comparison between the anchovy and pilchard cases clearly indicates the different extent of the multiple target problem for the two species, suggesting that the required degree of post-processing of the data will be different. Although our horse mackerel database is not large enough to apply a similar analysis, it seems that the extent of the problem is similar to that of pilchard.

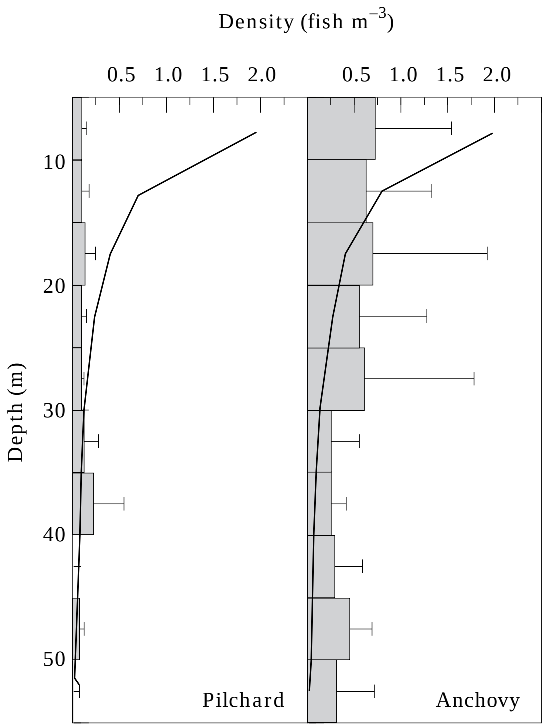

Figure 2. Maximum packing densities of pilchard and anchovy, averaged for all night-time integration intervals in cruises between 1990 and 1994, grouped according to the depth of maximum scattering. Horizontal bars indicate s.d. Solid lines represent densities of one fish RV^{-1}.

Post-processing of potential single targets

Given that multiple echoes will often not be excluded by single target detectors, we developed here empirical

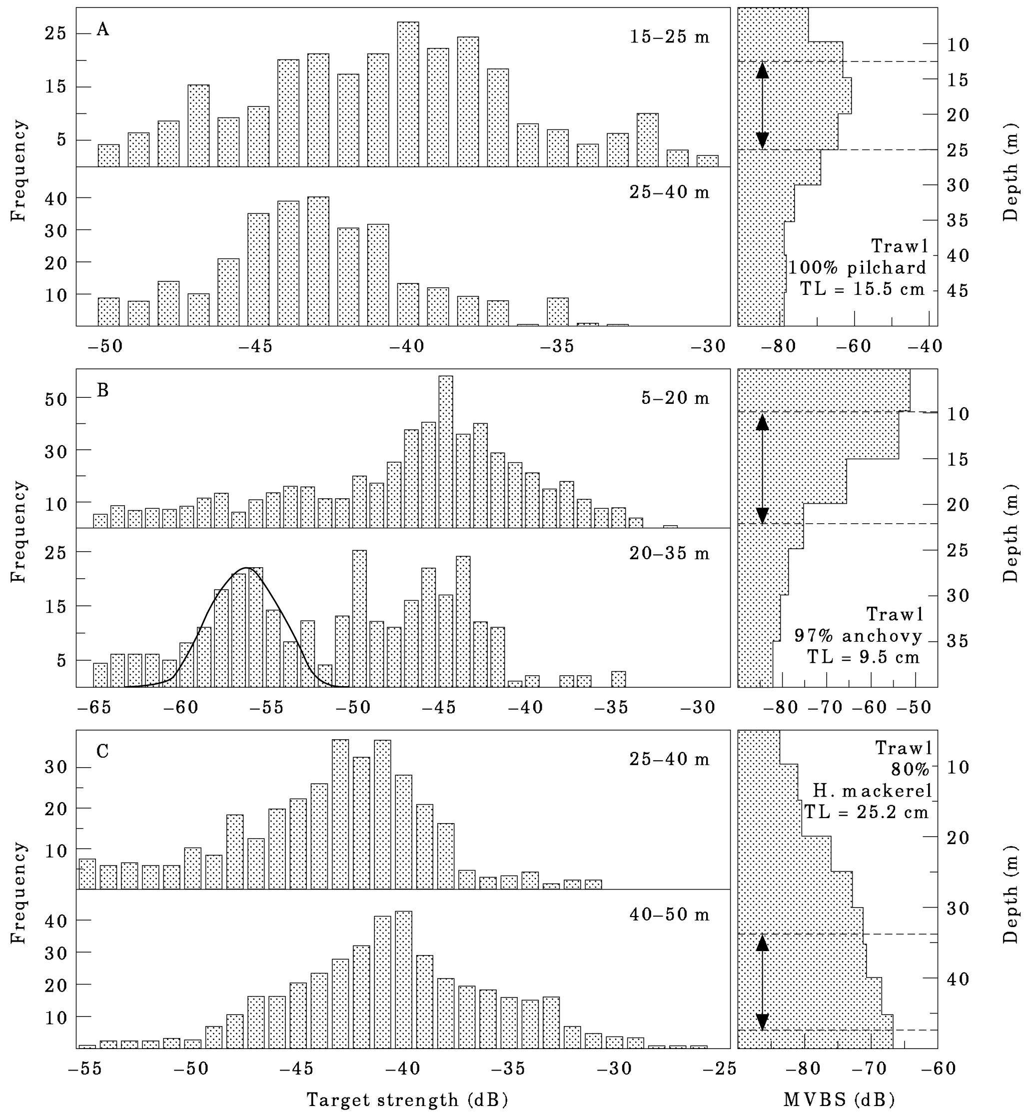

Figure 3. Examples of pilchard (A), anchovy (B), and horse mackerel (C) TS frequency distributions by depth channels. Corresponding vertical profiles of MVBS across the fish layers are shown in the right panels. Arrows indicate the region where the nets were trawled. Catch (% composition and mean length) details are also included.

post-processing methods of screening out these echoes. TS frequency distributions were first obtained for areas of high and low density within the scattering layers to examine possible patterns that could indicate a high proportion of multiple echoes in certain regions. Other relevant information on data quality were the maximum densities RV^{-1} and the single-target detection rate, as previously defined. Good TS data could generally be obtained for pilchard by simply discarding data coming from those depth channels with high fish density. An example of the sort of distortion in TS distributions frequently observed in the core of pilchard scattering layers can be seen in Figure 3A. Estimates of average TS were 3.2 dB higher there than on its edges. There was no evidence from the trawl to suspect that other species may have contributed to the scattering. In these cases, TS data collected near the edges of the layer were assumed to be unbiased, and were processed further.

In the case of anchovy (Fig. 3B), where packing densities were typically an order of magnitude higher, TS frequency distributions were often heavily distorted. In this example, which portrays an extreme situation, a bi-modal TS distribution was observed, although the relative importance of each mode was depth-dependent. Trawl information again indicated that there was only one species contributing to the echo. Let us assume for

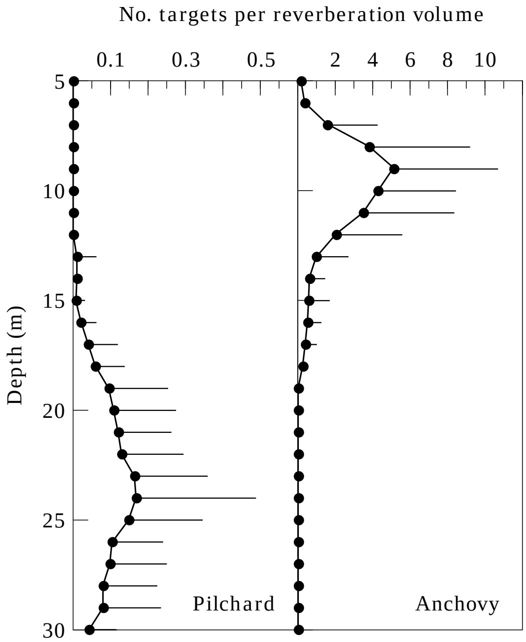

Figure 4. Vertical profiles of the mean and SD (horizontal bars) of the number of targets RV^{-1} for the pilchard and anchovy examples in Figure 3.

now that the weaker peak (depicted by a solid line in Fig. 3B) was generated by genuine single targets from the edge of the scattering layer, and that the stronger peak was due to multiple echoes from its centre. The upper peak appears to be about 10 dB higher than the lower one, or equivalent to a signal of 3.2 times the amplitude generated by a single target. To compare this value with estimated densities, backscattering strengths were integrated in 1 m channels in blocks of 25 pings (70 m), and transformed to densities using the TS expression in Table 2. The result indicates that, on average, anchovy densities were around 5 targets RV^{-1} in the core of the scattering layer (Fig. 4B). If their echoes were all in phase, the resulting echo would be on average 14 dB higher than that from the average single target, or 7 dB if the phases were random. Since Soule *et al.* (1995, 1996) have shown that in-phase overlapping echoes are preferentially accepted, the difference would be expected to be somewhere between these two figures. The difference of around 10 dB in the peaks therefore seems consistent with the postulate that the upper peak was produced by multiple echoes and the lower one by genuine single targets, although this is not the only plausible hypothesis. Some rare, single peaks in the TS distributions could be obtained when anchovy densities were extremely low. An identical analysis was carried out with the pilchard example described in Figure 3, indicating mean peak densities of less than 0.5 targets RV^{-1}, although values of up to 2 targets per RV were encountered on occasion. These densities are not inconsistent with the 3 dB shift observed in Figure 3A.

It is clear that, in order to estimate mean anchovy TS from our data, the peak generated by genuine single targets had to be extracted. The process assumed that the backscattering cross-section follows a lognormal distribution. This assumption was based on visual interpretation of the data and was considered a reasonable approximation (Weimer and Ehrenberg, 1975). The left side of the distribution was then fitted to a one-tail normal function to estimate its standard deviation, while the mean was estimated from the targets that formed the identified peak (solid line in Fig. 3B). Finally, 1000 values were randomly extracted from a normal function having this mean and standard deviation, and averaged in the cross-sectional domain. This process, although not totally satisfactory, provides reasonable TS estimates in conditions where current technology is incapable of resolving single targets adequately.

The third species studied was the Cape horse mackerel, a carangid typically 20 to 45 cm TL long, which at night generally forms dispersed aggregations. For these fish, night-time densities were often low enough for TS to be estimated without the kind of post-processing needed to interpret the anchovy data. However, as shown in Figure 3C, it was necessary to screen out echoes collected from the densest part of the scattering layer to avoid multiple targets. A greater problem with this species was the tendency of the fish to change their tilt angles in response to the trawl used for target identification, causing reductions in TS (Barange and Hampton, 1994).

Target-strength expressions

Figure 5 shows scatterplots of TS versus fish length for the three species considered, extracted as previously described. Also shown are the b_{20} constants and fitted line, according to the equation $TS = 20 \log TL - b_{20}$. Properly fitted expressions, for individual as well as weight-normalized TS, are presented in Table 2.

Discussion

The results presented indicate that defensible *in situ* target strength estimates can be obtained even when target densities are above the resolution capabilities of current TS analyzers. While the limitations of these systems are generally known, reported inconsistencies between stock estimates based on *in situ* TS and other methods suggest that the problem may not have been fully acknowledged in the past. The main reasons are that current TS analyzers continue to deliver results regardless of their quality, and that they are strongly biased in favour of constructively interfering overlapping echoes, leading to severe overestimation of TS

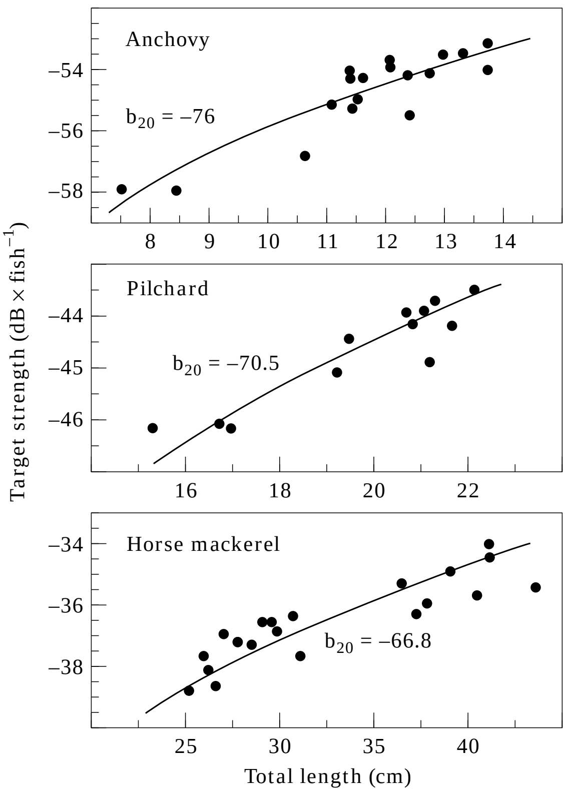

Figure 5. Relationships between individual TS and fish length for anchovy, pilchard, and horse mackerel, with the corresponding b_{20} expressions (solid line) and their related fitted constants.

(Soule *et al.*, 1995, 1996). It is therefore recommended that a critical approach be applied to TS data collected *in situ*, until such time as advances improve the performance of the single-target detectors (see Soule *et al.*, 1996, for suggestions regarding possible improvements).

The TS expressions obtained here can be compared with other published values. In the case of horse mackerel, our predicted values lie within 0.3 dB of those obtained by Torres *et al.* (1984), and our b_{20} constant is only 0.6 dB higher than Foote's (1987) general expression for gadoids. To our knowledge there are no published *in situ* estimates of pilchard TS. The closest comparison would be with the North Sea herring, for which b_{20} values between −67.1 and −72.6 dB have been reported (Reynisson, 1993). Our b_{20} value for pilchard is consistent with this range, although 1.4 dB higher than Foote's (1987) recommended expression for physoclists.

There is no literature on *in situ* measurements of anchovy TS, with the exception of the extremely high values obtained by Nainggolan *et al.* (1993) (−37.4 dB for a mean length of 11.6 cm). There is, however, collateral support for our expression from a comparison between stock estimates obtained using this expression and estimates from joint egg-production surveys (Hampton, 1996). However, our b_{20} expression predicts TS more than 4 dB lower than the general physostome (open swimbladder) expression (Foote, 1987). This clearly indicates that further work is required to understand the basic scattering properties of this species, as well as to confirm the proposed hypothesis of single/multiple scattering. In particular, the influence of fish behaviour in determining mean TS should be explored further.

TS is a variable dependent on a number of factors which are smoothed out when fitting general TS/length relationships. Our results clearly indicate that the use of individual measures of mean TS over each ESDU to transform MVBS values to fish densities is not yet possible. Technological improvements to current single-target detectors are required before TS estimation becomes a routine part of echo integration surveys.

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