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EXECUTIVE SUMMARY

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In situ data collected on southern blue whiting (*Micromesistius australis*) since 1998 have been re-scrutinised and re-analysed with the objective of obtaining accurate and unbiased estimates. A rigorous and systematic approach has been used for data inspection and selection. A series of analytical techniques have been used to filter the data and minimise potential biases due to multiple targets, including range discrimination, selection of data based on density calculations, and target tracking. Most of the *in situ* experiments analysed have been rejected based on unacceptable catch composition (less than 80% southern blue whiting by weight) or mismatch, either in space or time, between acoustic measurements and trawl data collection. Furthermore, most of the samples that satisfied those criteria revealed inconsistent target strength information, mainly due to suspected contamination by smaller targets (not properly sampled by the trawl) and high density of southern blue whiting affecting single target selection. These data suggest strong bias due to multiple echoes. Of the 22 experiments initially reviewed, only 3 proved to be adequate and likely to represent southern blue whiting target strength. These data suggest that the currently used target strength to length relationship is inadequate and support a relationship with a steeper slope, as suggested by recent models based on swimbladder morphology.

1. INTRODUCTION

Southern blue whiting (*Micromesistius australis*) is an important commercial species that occurs in Sub-Antarctic waters and has know spawning grounds, the largest of which is on the Campbell Island Rise. Acoustics have been used to estimate southern blue whiting (SBW) spawning stock biomass since 1993, with surveys typically in late August and September. During spawning, SBW form large aggregations with little if any contamination from other fish species of similar size, which makes them an ideal candidate for acoustic assessment. However, there has been considerable debate on the acoustic target strength of SBW, and up to now the biomass estimates have relied on a target strength to fish length relationship devised for blue whiting (*Micromesistius poutassou*), a different species altogether occurring in the northern hemisphere, for which the validity of target strength (TS) estimates has also been questioned (Godo et al. 2002). Furthermore, *in situ* TS of adult SBW estimated up to now have been significantly higher than swimbladder modelling results for similar-sized fish (Dunford & Macaulay 2006). Discrepancies between *in situ* data and models have been an ongoing issue for southern blue whiting (McClatchie et al. 1998).

Many factors confound and limit our ability to correctly estimate target strength in the wild, including accurate spatiotemporal match between fish catch (e.g., trawl station) and target strength marks, the mixture of other species, and the effect of measurement range and fish densities on single target resolution (Gauthier & Rose 2001). Although contamination by other species is likely to be minimal for SBW, their gregarious behaviour during spawning and potential polarised avoidance to deep-towed acoustic systems may lead to biases due to multiple targets. In this report, data collected for SBW target strength have been re-scrutinised and re-analysed using a series of vigorous techniques to minimise these potential biases. The aim is to provide accurate *in situ* measurements of TS and reconcile them, if possible, with published model results based on SBW swimbladder morphology.

2. MATERIALS AND METHODS

2.1 Datasets

In situ target strength data have been collected during SBW spawning biomass surveys of the Campbell Island Rise in 1994, 1998, 2000, 2002, and 2004. In addition, target strength data from the Bounty Platform have been collected in 1999 and 2001. All surveys were performed by NIWA's research vessel *Tangaroa*. Acoustic data, echograms, and associated trawl station data from these voyages have been scrutinised to identify valid and adequate samples for target strength estimation. To be valid, a sample needed to include the following.

- Collection of target strength data from a calibrated split-beam echosounder within close-range of fish marks (less than 200 m).
- Clean acoustic data, with no signs of noise or interference, and with no apparent mixing of species (i.e. not having different schools or shoals merging together). Data also had to be collected under clement weather with a stable towbody.
- A suitable sampling technique (e.g., bottom or midwater trawl) carried out in proximity of the TS marks and within a short time of the acoustic data collection (ideally immediately before or after the TS experiment).
- A catch consisting primarily of SBW (defined as more than 80% of the catch by weight).
- Length measurements of at least 100 SBW.

When a dataset satisfied all of the above criteria, it was selected for further analyses; otherwise it was rejected and deemed unsatisfactory.

2.2 Match and mismatch

One of the biggest problems associated with *in situ* TS is species (and size distribution) uncertainty. It is very difficult (if not impossible) to ascertain that the organisms insonified are the same as the ones caught in the trawl, or that they are a fair representation thereof. For this reason, the time delay and spatial disparity between TS experiment and trawl sampling was noted. The further they are apart, the less confident should we be about the validity of the sample. For this reason, samples were selected based on matching criteria. The spatial disparity was estimated using the starting and end location of both acoustic measurements and trawl samples. If position at the closest extremities differed by more than 1 nautical mile the experiment was rejected. Similarly, asynchrony was estimated using the start and end time of trawl and TS experiment. If the shortest time between the two was more than 3 h, the experiment was rejected.

2.3 Trawl data collection

Trawling was carried out using bottom and midwater trawls. Midwater samples were collected using the NIWA 119 hoki midwater trawl (headline height, 40 m; codend mesh, 40 mm). The bottom samples used the orange roughy wing trawl (also called the 'ratcatcher'; headline height, 3.5 m; codend mesh, 32 or 40 mm). For each trawl the catch was sorted into species and weighed on motion-compensating scales accurate to about 0.3 kg. A random sample of up to 500 SBW and 50–200 of other abundant species from every tow was used for length measurements. Acoustic data were collected during trawling operations using the 12 kHz and 38 kHz hull-mounted *CREST* acoustic system.

2.4 Acoustic data collection

All target strength data were processed and stored using the NIWA *CREST* data acquisition system (Coombs et al. 2003) with a towed split-beam 38 kHz transducer. System configuration (Table 1) consisted of a four channel towed system with underwater electronics connected to a deep-rated Simrad ES38DD split beam transducer. The receiver and transmitter were mounted in a flat-nosed, torpedo-shaped, 3 m long 'heavy weight' towed body. *CREST* is computer based, using the concept of a 'software echo sounder'. It supports multiple channels and the receiver has a broadband wide dynamic range pre-amplifier and serial analog-to-digital converters (ADCs) which feed a digital signal processor. The ADCs have a conversion rate of 60 or 100 kHz and the data from these are complex (quadrature) demodulated, filtered, and decimated. The filter was a 100-tap linear-phase finite impulse response digital filter. For target strength work the bandwidth was 4.86 kHz and the decimated frequency 10 kHz. Following decimation a 40 log R time-varied gain was applied. The results were shifted to give 16-bit resolution in both the real and imaginary terms and the complex data were stored for later processing. The transmitter is a switching type with a nominal power output of 2 kW rms. For target strength work the transmitted pulse length was typically 0.32 ms (12 cycles at 38 kHz) with transmits every 1.2 seconds.

The digital data from the receiver are sent to a control computer where they are combined with position and transect information before being stored. The data are transmitted via the tow cable to the control computer on the towing vessel. All four transducer quadrants (beams) are energised simultaneously from a single transmitter, but on receive the system operates as four semi-independent units, in which data are processed independently on the four synchronised channels. During target strength data collection, the beams are treated separately to reject multiple or bad echoes and measure the position of the echoes within the beam. Details of the system are provided in Table 1. On each voyage the echosounder was calibrated using a 38.1 mm diameter tungsten-carbide sphere following recommended procedures (MacLennan & Simmonds 1992).

During target strength experiments, the vessel speed was decreased (2–4 knots) and the heavy towed-body lowered close to the fish aggregation, often within 300 m of the bottom. When possible, multiple passes were made over the same aggregation. Depth, pitch, and roll sensors were fitted to the towed-body and monitored to ensure data quality.

2.5 Analyses

2.5.1 Single target detection

Once a dataset satisfied the criteria required for target strength estimation (sections 2.1 and 2.2), the data were further scrutinised and filtered to retrieve valid target strength information for single fish. The echoes were first filtered based on characteristics of the echo envelop (Soule *et al.* 1995, 1997). Echoes were filtered according to their pulse width at half amplitude (overall and within the separate split-beam quadrants), the phase standard deviation between quadrants, the proximity of other echo peaks, and the off-axis angle position within the beam. The settings for the various parameters were the same as those described by Dunford (2004), namely:

- The width of the echo was between 63% and 187% of the transmit pulse width at half the maximum echo amplitude (the 6dB amplitude points).
- The width of the four individual echoes at the 6dB amplitude points varied by less than 32% of the transmit pulse width.
- The standard deviation of the electrical echo phase between the 6dB amplitude points was less than 0.1 radians on the combined echoes.
- The standard deviation of the angle of arrival phase difference was less than 1 degree.
- The echo peak was more than 0.6 m in range from other echoes.
- The mean and standard deviation of the difference between the echo amplitude on beam 1 and the same echo on beams 2, 3, and 4 were less than 3.0 and 1.5 dB respectively for all three comparisons.
- The estimated angle of arrival of the echo was within 3.55 degrees of normal incidence to the transducer face.

Echoes that pass through all of these filters were then processed as single fish targets. Position within the beam was measured based on differences in arrival time between the four quadrants and amplitudes were corrected accordingly. Target strength was estimated by taking the maximum of a quadratic fitted to the three samples that made up the peak of the echo.

2.5.2 Depth and range of targets

Targets were filtered according to their position in the water column and range from the transducer. This was done in the first instance to insure that the observed targets were located within or near the trawl path for a particular sample. Furthermore, presence of particularly high or low target strength values, or the presence of a broad distribution of TS (including multi-modal distributions), may indicate the presence of other species and/or widely different size groups. These were removed to retain only portions of the water column that were consistent with the trawl path and that didn't appear to include other species, unless clusters of targets overlapped. When there was minimal overlap in the TS modes but overlap in target range, thresholds were applied to the data to remove targets that belonged to the modes outside the TS values of interest. Targets immediately under the transducer face (less than 20 m range) were also removed, as these were more likely to include fish diving as a reaction to the towed body.

2.5.3 Density of fish

When fish are found in a dense shoal (as with SBW), echoes produced by more than one organism can still be accepted as single targets if they occur at roughly the same range. This is an inherent bias of *in situ* data. To minimise this bias, it is recommended that target strength data are collected only from regions of low densities (Gauthier & Rose 2002) where the probabilities of having targets close to one another are lower. One way to quantify this is by estimating the number of fish per acoustic reverberation volume (Sawada et al. 1993, Gauthier & Rose 2001).

$$N_v = \frac{c\tau\psi R^2 n_{EI}}{2}$$

where c is the soundspeed in $m{\cdot}s^{-1}$, τ the the pulse length in s, ψ is the equivalent beam angle in steradians, R is the range from the source in m, and n_{EI} is the volumetric fish density in $fish{\cdot}m^{-3}$. Volumetric densities estimated from echo-integration (EI) were estimated as:

$$n_{EI} = \frac{s_v}{\sigma_{bs}}$$

where s_v is the integrated volume scattering coefficient (linear value) and σ_{bs} is the representative backscattering cross-section of the insonified fish. Echo integrals were calculated over small bins (1 m depth x 1 transmit wide) to estimate N_v at a fine resolution scale. Integration was performed on the same file that included the TS data, processed with a 20 log TVG (instead of 40) and appropriate calibration coefficients.

The N_v approach is somewhat circular, since it filters targets based on fish density that are in turn estimated using an "expected" backscattering cross-section value for all fish. For SBW, the current TS to length relationship was used to estimate the backscattering cross-section, based on the mean length of fish caught in each trawl. Furthermore, the upper threshold for N_v is greatly affected by the bin or cell size used to estimate density (Gauthier & Rose 2001). In one reverberation sample (volume defined by the angle and pulse length of the beam), the theoretical limit is one fish, but as the size of the cell volume increases the value of this limit will decrease (for example in a bin of 100 m depth by 100 transmits, the N_v threshold will need to be well below 1). As a conservative value, an upper N_v limit of 0.1 fish per reverberation volume was used. It was hence assumed that cells (or bins) having numbers of fish per volume superior to 0.1 were likely to include multiple targets and were rejected. As a caveat it should be noted that since N_v calculations are based on expected target strength values, they are likely to remove valid echoes or accept multiple ones if the actual target strength of the fish is significantly lower or higher than expected. For this reason, results with an upper N_v threshold value of 1 were also collected. This allowed more flexibility around target strength value for SBW, while at the same time removing areas that had unacceptably high fish density values, even if target strengths were well beyond expected values.

Another metric that can be used as a diagnostic tool in combination with N_v is the number of detected targets per reverberation volume:

$$T_v = \frac{c\tau\psi R^2 n_{EC}}{2}$$

where n_{EC} is the volumetric density of targets, or the number of targets per reverberation volume, as measured by echo counting:

$$n_{EC} = \frac{targets_{\Omega}}{V_{\Omega}}$$

where $targets_{\Omega}$ and V_{Ω} are, respectively, the number of targets and volume at the cutoff angle (Ω) used to detect single targets. In theory the number of targets per reverberation volume should be the same as the number of fish per reverberation volume, up to the point where multiple targets bias occurs and the target count consequently decreases. This should occur when there is more than one fish per reverberation volume, and at lower values in bins that contain more than one reverberation sample (e.g. bins of 1 m thickness). This metric hence has the potential of detecting the density level at which multiple targets are likely to occur, and to test whether the N_v value used as an upper limit for unbiased target strength estimates is valid. For further details about the use of these metrics, consult Gauthier & Rose (2001). The bin size used to estimate T_v was the same as that used to estimate N_v, i.e., 1 m depth by 1 transmit wide.

2.5.4 Target tracking

Another potential way of eliminating multiple targets is by target tracking (McQuinn & Winger 2003). Target tracking consists of selecting successive detected targets that potentially belong to the same organism, based on echo properties and position, and grouping them into single tracks. At the slow vessel speed used to collect target strength data (2–4 knots), single fish are likely to produce several echoes as they pass through the acoustic beam. This usually results in a track, unless other fish are in close range and some of the echoes fail the criteria for single target detection, resulting in echo rejection and breaks in the track. The presence of successive pings with targets (all passing through single echo criteria) that are within a defined range of amplitude, distance, and position thus reinforce the likelihood of these targets belonging to a single fish. Echoes were considered to be part of the same tracks if they were no more than 10 samples apart (0.75 m) in range and were recorded in at least three consecutive pings. All other echoes not assigned to tracks were rejected.

2.5.5 Target strength to length relationship

Each analytical step described above potentially reduces the biases associated with SBW target strength. The best estimate of *in situ* target strength is obtained from filtered single targets, selected within a suitable depth and range. The filters were applied in the same order they have been described: 1) single target detection algorithms, 2) filter on depth and range, 3) filter on density using N_v and T_v. If, at the end of this process, 100 or more echoes remained they were selected to estimate the mean TS for SBW in that sample, in association with the mean length calculated from the catch data. When more than one trawl was associated with a particular TS experiment, the length distributions were merged. Target tracking was used as a separate estimate of TS, applied after the single target detection algorithms and a fish density filter based on an N_v threshold of 1, to remove potential biases due to excessively high fish densities.

Because target strength is a logarithmic variable, the mean target strength (dB) was calculated by taking the linear mean value of all the backscatter in a sample. If α_{bs} is the acoustic backscattering cross-section of a target (units of m^2 m^{-2}) then 'target strength' (TS) is:

$TS = 10Log_{10}(\alpha_{bs})$ or equivalently $\alpha_{bs} = 10^{TS/10}$

and the linear mean of a set of target strength values is obtained by converting from TS to α_{bs}, taking the mean of these values and converting the result back into TS. Target strength to fork length relationship can then be calculated based on the mean using

TS = a Log10 (length [cm]) + b

where a is the slope and b the intercept of the regression.

3. RESULTS

3.1 Validity of datasets

A total of 22 *in situ* target strength experiments have been performed as part of SBW surveys since 1998, all of which comprised data collected using the *CREST* system with a towed body. Data on target strength were also recorded in 1994, but measurements were made using a single beam transducer. Single beam transducers do not provide information on target position within the beam, and consequently target strength need to be estimated based on the deconvolution technique (Clay 1983). Some split beam data were also collected using a hull mounted Simrad EK500 system. This means that the measurements were made at a greater range from the fish, which increases potential biases due to multiple targets. Furthermore hull-mounted transducer measurements are more sensitive to foul weather conditions. These data were not included in the present analyses.

Of the 22 experiments, 13 had valid samples comprising southern blue whiting (Table 2). The other samples were rejected based on unacceptable catch composition. Species that were often abundant and contaminated the catches included oblique banded rattail (*Caelorinchus aspercephalus*), javelinfish (*Lepidorhynchus denticulatus*), pale ghostshark (*Hydrolagus bemisi*), silverside (*Argentina elongata*), and ling (*Genypterus blacodes*).

3.2 Match and mismatch

Spatial and temporal match between target strength experiments and trawl samples was often poor (Table 3). More than half of the experiments were rejected based on a maximum of 1 n.mile and/or 3 h disparity at the shortest points between the TS measurements and trawl operations. These cut-off values were fairly conservative, given the nature of the operations and the fact that southern blue whiting have been known to form rather large shoals. The six remaining TS experiments were considered for further analyses.

3.3 Effect of range

Target strength changed according to range in most cases (Figures 1–3). For example, in experiment 11 (tan0009), target strength was low up to a range of approximately 60 m. Thereafter another cluster of target was found that had much higher values (Figure 1). In experiment 19 (tan0212), similar clusters were significantly overlapped, making it much more difficult to isolate targets belonging to SBW (Figure 2). In the last experiment (tan0410) there were three distinct groups: a cluster of smaller targets at short range, higher target strength values at intermediate range (thought to belong to SBW), and a cluster with widespread values at long range, the latter probably including a mixture of species (Figure 3). Clusters of targets with significantly low target strength values (-50 db to -70 dB) or those that encompassed the whole spectrum of values were removed when their range did not overlap with the targets of interest. For the particular example in Figure 3, only targets in the range 50 m to 136 m were retained for further analyses.

3.4 Effect of fish density

The estimated number of fish per acoustic reverberation volume was often well beyond one in many cases (Figures 4 to 6). High values were an indication that targets identified in these regions likely belonged to multiple echoes from more than one fish. Values of N_v typically increased asymptotically with target strength (Figures 4 and 5). A threshold of 0.1 (or even 1 in these examples) removed practically all targets with values of -35 or -30 dB and higher. In other cases (Figure 6), N_v increased with TS, but a fair proportion of large targets remained at low densities, suggesting the presence of large single fish in low density areas.

The T_v index, or the number of targets per acoustic reverberation volume, did not provide consistent results. This index is difficult to interpret as it is influenced by the various algorithms used for single target detections. As expected, the number of detected single targets per volume decreased as the fish density per volume increased: Values of T_v were well below 1 (Figure 7), suggesting that a threshold value of 0.1 for N_v was appropriate.

3.5 Target strength

In this section, each of the six valid target strength experiments will be addressed individually. Results on target strength distribution were obtained following filters on range and fish density as discussed in Sections 3.3 and 3.4.

Experiment 2 from the 1998 *Tangaroa* voyage was one of the cleanest target strength experiments (Figure 8). The target strength and associated length distribution from this sample were fairly monotonic. Target strength data did not have contamination from small targets. Experiment 11 from tan0009 was the only valid sample for SBW with a mean fork length below 30 cm (Figure 9). Data appeared to reveal a fairly wide but monotonic distribution of target strength. However, the N_v threshold of 0.1 removed practically all traces of targets above -45 dB, suggesting that fish densities were too high, or that the target strength of these fish was much lower than expected. This is supported by results obtained with an N_v threshold of 1, which indicate a mean target strength of -45.2 dB.

Single target algorithms selected only 211 targets from experiment 14 (tan0114), all of which were low and suggested contamination from other species. After adjusting the range, fewer than 50 targets were accepted and the experiment was rejected. Experiments 18 and 19 from the 2002 voyage displayed broad target strength distributions with several modes (Figures 10 and 11). In experiment 18, higher target strength values disappeared with the application of an N_v threshold. With a threshold of 1, the higher values merged into a broad and relatively low TS density function that most likely included smaller fish species. The trawl in experiment 19 caught large SBW, yet very few high target strength values were recorded. As in experiment 18, most of these larger targets were removed after applying filters based on fish density (Figure 11). In contrast, many large targets were observed within low density areas in the tan0410 experiment (Figure 12). The length obtained from the catch in this last experiment indicated a broad and bimodal size distribution. It was not possible to know whether the target strength mode identified in the acoustic data was representative of the overall length distribution or if it corresponded to the highest mode. For this reason the overall mean of all length was used. With the application of the N_v threshold, the number of high target strength values was significantly decreased and the resulting distribution of TS was more or less concurrent with the length distribution. Table 4 summarises the results of target strength experiments for all valid samples.

3.6 Target tracking

Target tracking gave results consistent with the previous analyses (Figure 13). The criteria for selection of tracks being somewhat rigorous resulted in relatively few targets. Numbers of echoes were particularly low for experiment 18 and 19 (Table 5). No targets at all were selected from experiment 14. Exploratory analyses using more flexible single target algorithms and filters gave inconsistent results, mainly due to the high numbers of small targets present in the datasets.

3.7 Target strength to length relationship

Based on range and fish density filters, only two samples were likely to be representative of southern blue whiting. If we accept that the TS of small fish might have been much lower than expected from the current model, than the data from experiment 11 using an N_v filter of 1 may also be valid. Data from target tracking also included three valid samples. Data from experiment 18 were rejected due to small sample size (n = 9 targets), while data from experiment 19 were rejected based on small sample size (n = 30 targets) and suspicion that they were belonging to smaller targets, as supported by the broad TS distribution observed in the overall data (Figure 11). These points have been plotted along the target strength to length relationships currently used (developed for blue whiting) and recent swimbladder model results in Figure 14. It was considered ludicrous to attempt to rationalise a new target strength to length relationship based on three data points. The relationships used for comparisons with the data were:

Monstad et al. (1992): $TS = 21.8 \cdot \mathrm{Log}_{10}(\text{length [cm]}) - 71.8$

Dunford & Macaulay (2006): $TS = 38 \cdot \mathrm{Log}_{10}(\text{length [cm]}) - 97$

4. DISCUSSION

Most datasets on the target strength of southern blue whiting have been rejected due to invalid catches or mismatch between acoustic data collection and trawl samples. Even when those were accurately matched, there was no way to ascertain that the samples collected were a fair representation of the actual organisms insonified during acoustic measurements. Exploratory analyses of those samples revealed inconsistent patterns and similar biases in the data as the ones observed in the valid datasets. Many species found in SBW catches can be quite small and abundant (e.g. javelinfish, rattail), most of which are probably not sampled appropriately by the trawl. Furthermore, many smaller fish found at depth, like myctophids, are not sampled by the trawl at all, but can form small swarms with measurable target strengths. In fact, abundance of small gregarious fish may produce multiple targets having values well above the expected target strength for a single individual. This appears to be fairly common with SBW data, as demonstrated by clusters of targets of similar intensities at different ranges. It is also quite possible that SBW behaviour drives some of the patterns observed in the data. For example, avoidance reaction may cause fish to dive under the transducer when in close range, resulting in lower target strength due to swimbladder orientation. Furthermore, avoidance reaction may coerce fish in tighter shoals, resulting in higher densities at longer range and increased bias due to multiple targets.

Application of filters based on estimates of fish density removed almost all high values of target strength in the data. This suggests that SBW shoal in high density, and are consequently poor candidate for *in situ* target strength measurements, despite the fact that they aggregate in large monotypic shoals with few species of similar sizes. Behaviour of the fish while spawning may exacerbate this issue, and make it quite difficult to obtain reliable TS data *in situ* during that period, especially if active foraging, whence such fish often scatter, is absent or limited.

The mean target strength of all unfiltered targets was often close to the one expected based on the current TS to length relationship. These data were, however, obviously biased and should not be taken at face value. The quality of the data collected up to now on southern blue whiting is at best questionable, mostly due to the aforementioned biases. The few valid samples analysed had highly variable values and were inconsistent with current models. These data, however, suggested that the relationship based on recent swimbladder modelling was more accurate for southern blue whiting than the currently used relationship developed for northern hemisphere blue whiting (*Micromesistius poutassou*). The swimbladder models and data both suggest a much steeper slope for the TS to length relationship. Difference in slope may have a significant effect on overall estimates of biomass and population trends (Dunford 2004). A number of factors can cause significant variability in target strength and have not been considered up to now for SBW, including swimming behaviour and orientation, ontogenic shift in swimbladder morphology, gonadal stage and maturation, and condition factors (Ona 1990, Horne 2003).

4.1 Recommendations

These results suggest that there is a real need for more comprehensive data on the target strength of southern blue whiting. Although this species is an excellent candidate for acoustic survey, the same cannot be said for *in situ* target strength measurements. Combination of simultaneous video and acoustic data could provide invaluable insights into this issue. The refinement of swimbladder and fish body scattering models would also be beneficial and a good basis for future developments. *In situ* data should be viewed critically and collected in light of the potential biases discussed in this review.

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Table 1: Echosounder configuration settings for the 38 kHz CREST system used to collect target strength data during SBW surveys.

Transducer model	Simrad ES38DD
Transducer serial nos.	28326, 28327, 28331
Nominal 3 dB beamwidth (°)	7.0
Effective beam angle (sr)	0.0079 to 0.0083
Operating frequency (kHz)	38.156
Transmit interval (s)	1.2
Nominal pulse length (ms)	0.32
Filter bandwidth (kHz)	4.53 to 4.86
Initial sample rate (kHz)	60.0 or 100.0
Decimated sample rate (kHz)	10.0
TVG	40 log R

Table 2: List of target strength experiments and associated trawl samples. Validity of the sample was based on a catch of southern blue whiting of 80% by weight. The first two numerical digits of the voyage code indicate the year (for example tan9811 is voyage 11 of *Tangaroa* in 1998). Experiments have been arbitrarily numbered by the author for indexing and reference purposes.

Voyage	experiment	Trawl	SBW catch (kg)	% SBW	Mean FL (cm)	Validity
tan9811	1	2	1059.0	97.3	24.0	Valid
	2	6	5235.3	100.0	40.0	Valid
	2	7	2238.1	100.0	40.4	Valid
tan9910	3	6	0.0	0.0	n/a	Invalid
	4	7	29.9	13.6	39.3	Invalid
	4	8	129	27.6	31.7	Invalid
	4	9	3.1	9.7	31.2	Invalid
	5	13	2225.1	95.2	39.4	Valid
	6	14	0.0	0.0	n/a	Invalid
	6	15	91.0	21.4	22.3	Invalid
	7	18	2238.8	84.9	37.1	Valid
tan0009	8	4	982.5	95.0	29.4	Valid
	9	11	12.3	15.9	40.3	Invalid
	10	15	226.8	93.3	39.9	Valid
	10	16	188.6	71.8	35.6	Invalid
	11	17	430.4	94.2	27.2	Valid
	12	27	455.4	81.7	33.9	Valid
tan0114	13	6	979.1	69.9	39.5	Invalid
	14	34	41.6	100.0	39.1	Valid
	14	35	964.7	87.8	36.8	Valid
	15	36	0.5	0.3	40.0	Invalid
	16	39	0.0	0.0	n/a	Invalid
	17	40	1412.5	83.5	28.0	Valid
	17	41	0.9	81.8	26.5	Valid
tan0212	18	9	3258.0	100.0	44.6	Valid
	19	10	243.6	92.6	42.4	Valid
	20	17	35.4	21.8	18.9	Invalid
	21	20	2.1	1.1	16.3	Invalid
tan0410	22	12	959.3	99.6	36.5	Valid
	22	13	773.1	93.2	36.8	Valid

Table 3: Spatial and temporal match between target strength experiment and trawl samples. Spatial disparity was the shortest distance between the acoustic measurements and trawl sampling. Similarly, temporal disparity was the least amount of time between the two.

Voyage	Experiment	Spatial disparity (n.mile)	Temporal disparity (h:min)	Acceptable
tan9811	1	2	3:03	NO
	2	< 1	0:45	YES
tan9910	5	5	6:12	NO
	7	< 1	8:06	NO
	8	3	3:24	NO
tan0009	10	1	3:44	NO
	11	< 1	0:45	YES
	12	> 10	2:04	NO
tan0114	14	< 1	1:29	YES
	17	< 1	4:10	NO
tan0212	18	< 1	1:55	YES
	19	< 1	0:59	YES
tan0410	22	< 1	0:49	YES

Table 4: Summary of target strength results for valid experiments. All TS values are in decibels.

Experiment – Value (number of echoes)	2	11	14	18	19	22
Mean FL (cm)	40.0	27.2	39.1	44.6	42.4	36.6
Expected TS (Monstad et al. 1992)	-37.9	-41.5	-38.1	-38.6	-37.3	-38.7
Mean TS unfiltered	-30.2 (5632)	-43.9 (6359)	-39.88 (211)	-37.7 (39482)	-39.7 (8032)	-34.1 (7412)
Mean TS filtered on range	-30.2 (5632)	-40.5 (1915)	-33.8 (50)	-36.7 (28699)	-38.3 (5297)	-31.0 (2689)
Mean TS filtered on range and N_v (1)	-33.8 (4649)	-45.2 (1285)	-	-47.7 (24276)	-46.3 (4719)	-31.7 (2003)
Mean TS filtered on range and N_v (0.1)	-34.0 (4639)	-49.2 (203)	-	-51.9 (21409)	-51.5 (3410)	-34.2 (829)
Likely to represent SBW TS	YES	uncertain		NO	NO	YES

Table 5: Summary of target strength results based on target tracking for all valid experiments.

Experiment	Mean TS (dB)	Number of tracks	Total number of echoes
2	-34.5	37	117
11	-46.6	16	54
14	n/a	0	0
18	-39.8	3	9
19	-41.4	10	30
22	-30.3	15	47

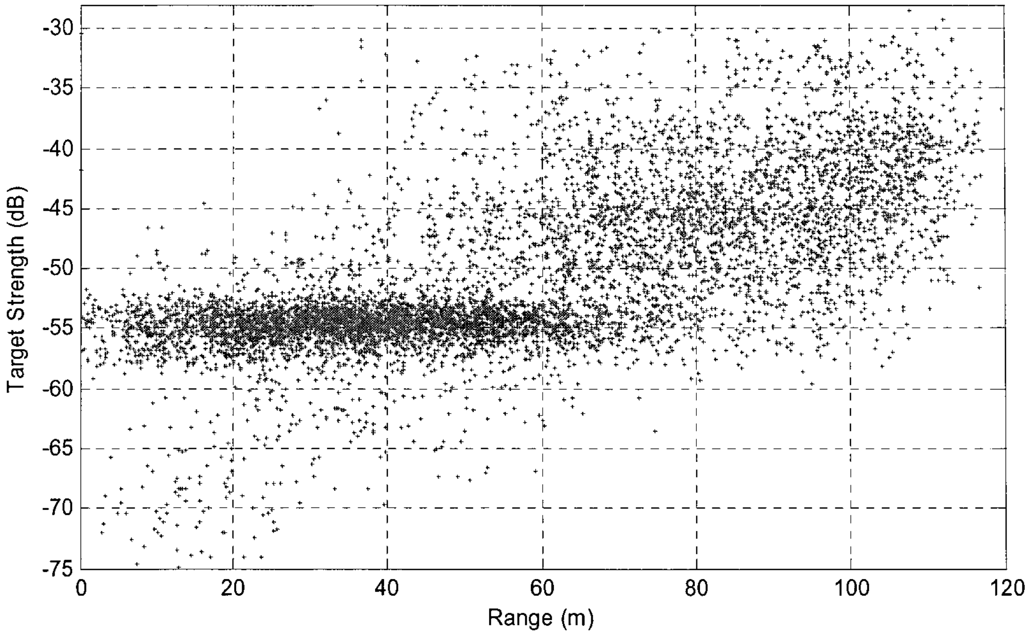


Figure 1: Target strength as a function of range for experiment 11 in voyage tan0009.

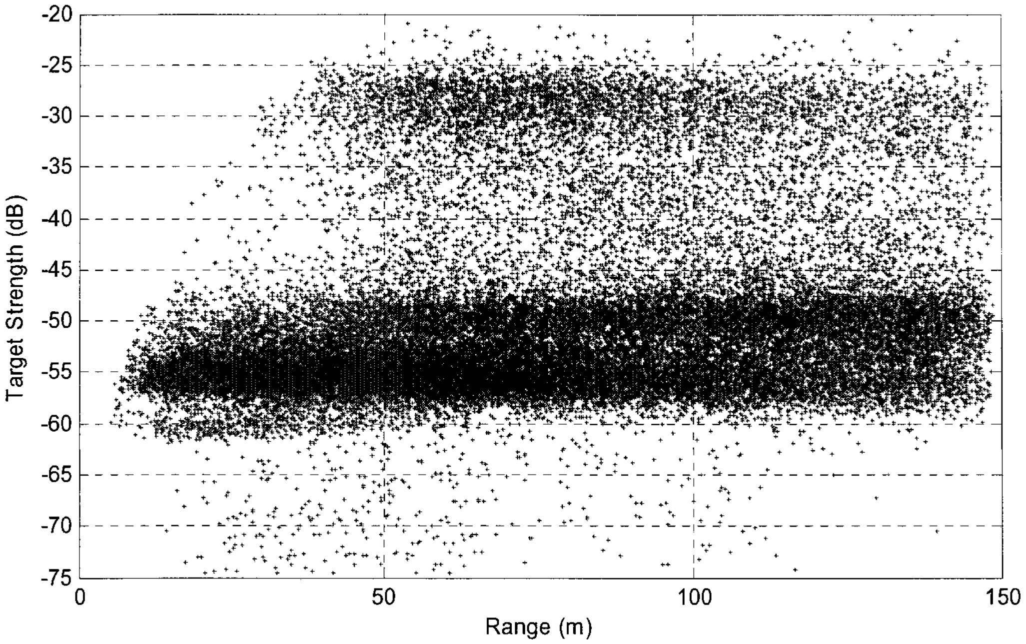


Figure 2: Target strength as a function of range for experiment 19 in voyage tan0212.

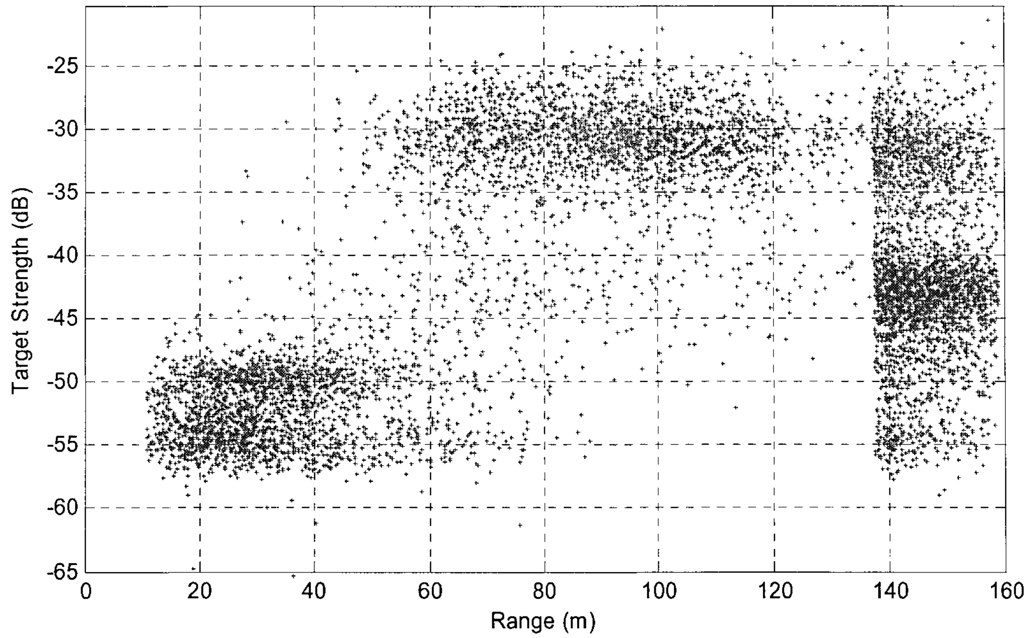


Figure 3: Target strength as a function of range for experiment 22 in voyage tan0410.

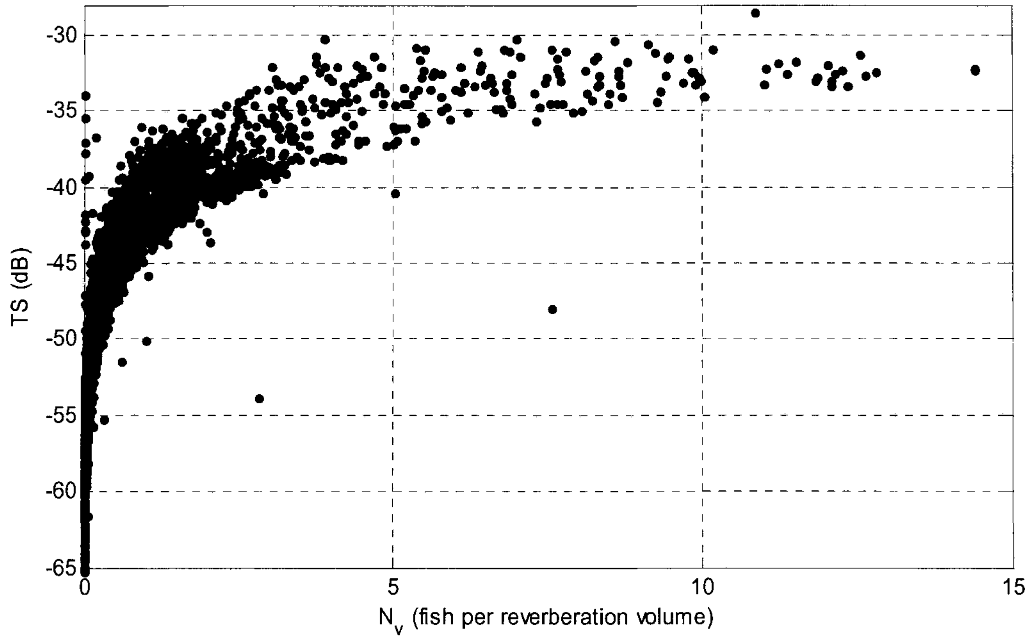


Figure 4: Effect of N_v on target strength for experiment 11 in voyage tan0009.

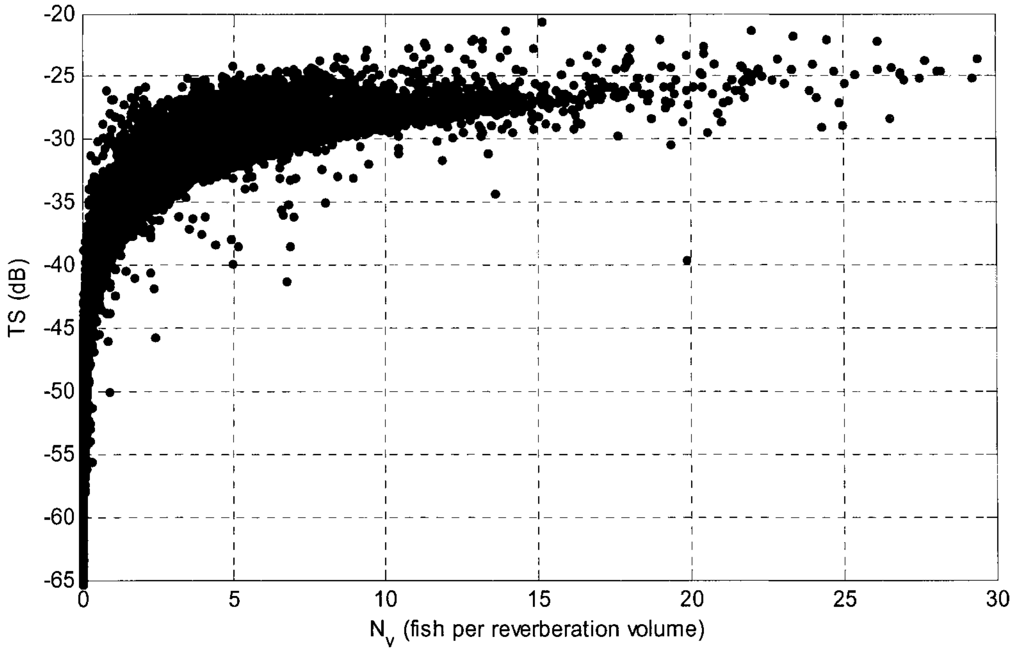


Figure 5: Effect of N_v on target strength for experiment 18 in voyage tan0212.

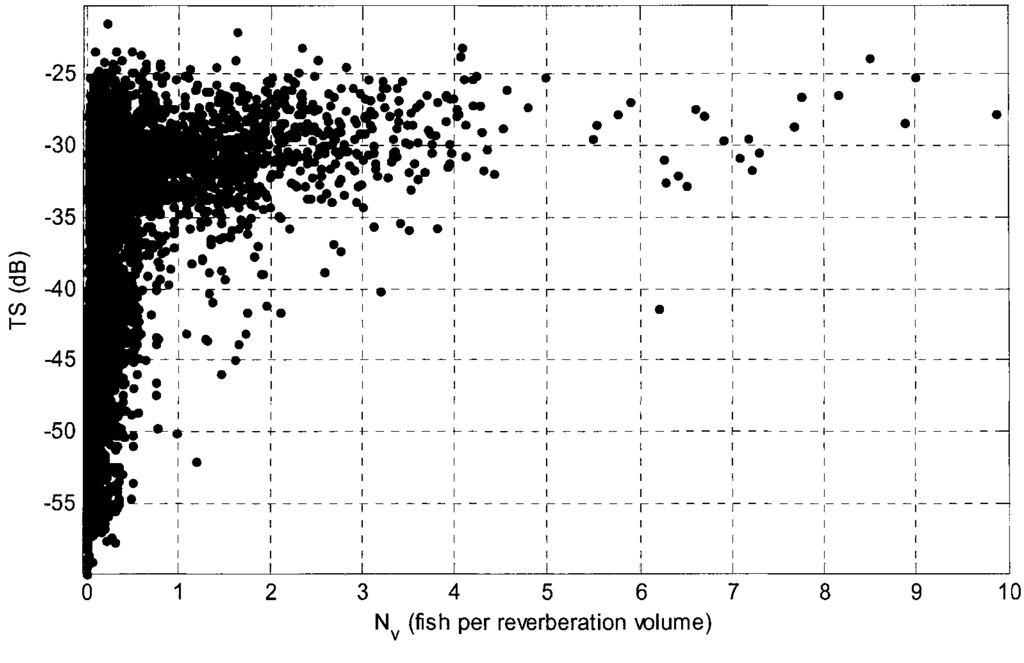


Figure 6: Effect of N_v on target strength for experiment 22 in voyage tan0410.

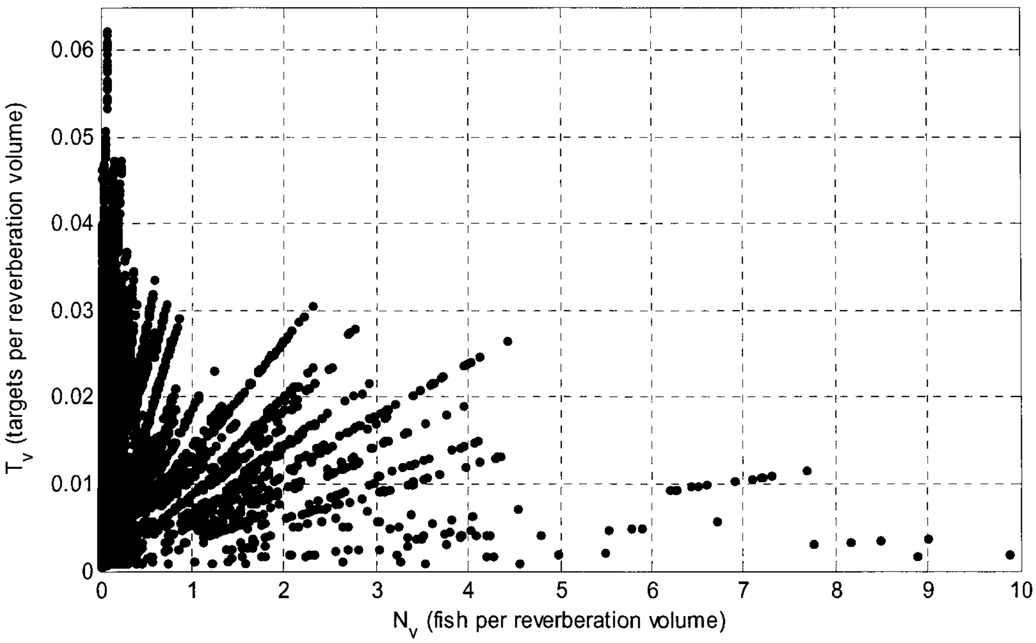


Figure 7: Relationship between the number of fish and number of targets detected per reverberation volume for experiment 22 in voyage tan0410.

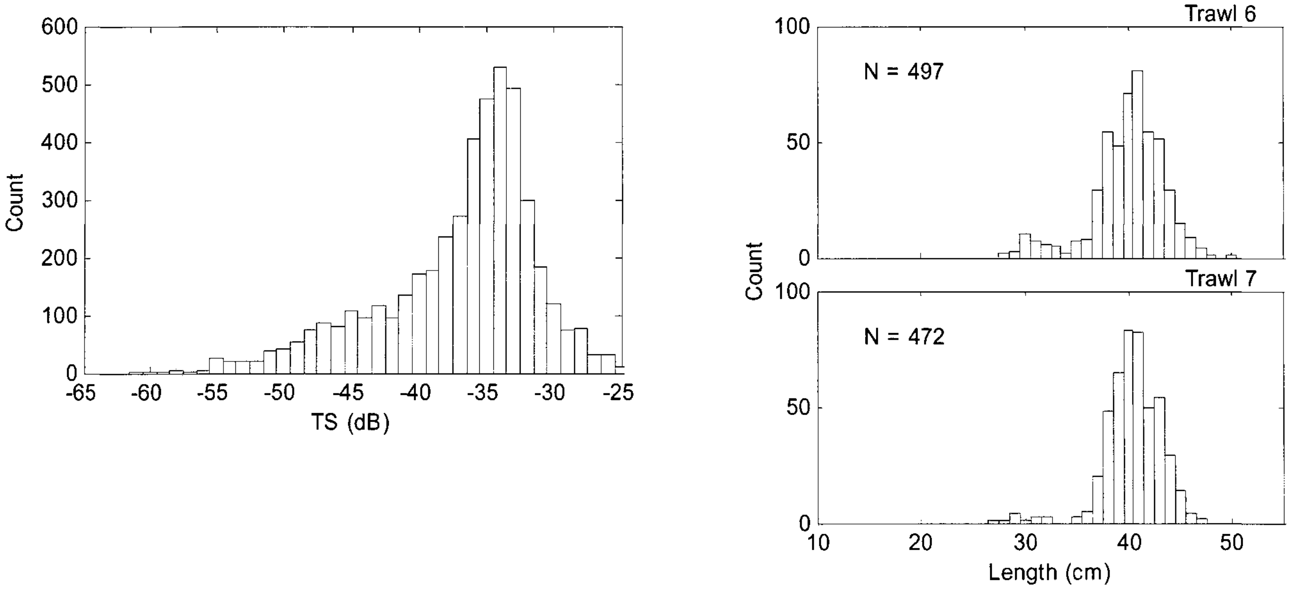
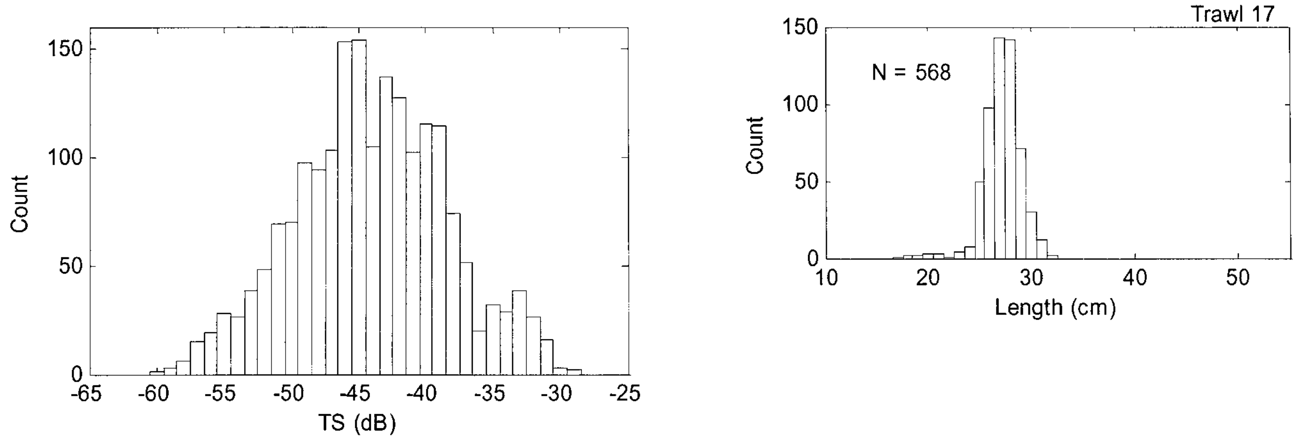
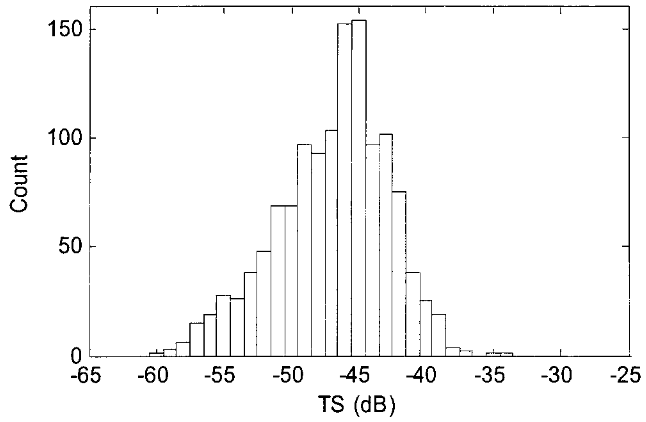


Figure 8: Target strength and associated length distribution for experiment 2 (voyage tan9811). Target strength results are shown only for a threshold of 0.1 fish per reverberation volume.

No N_v threshold



N_v threshold 1



N_v threshold 0.1

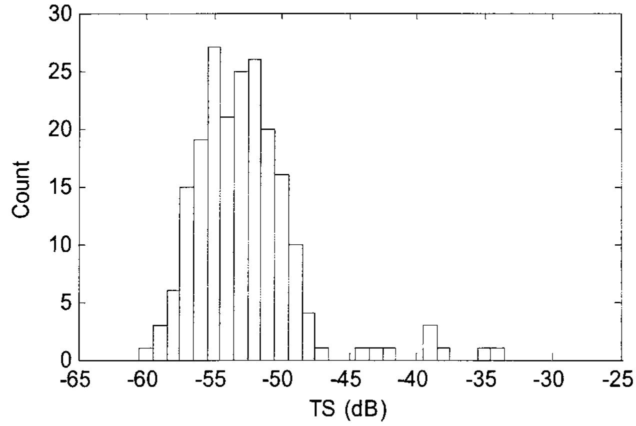
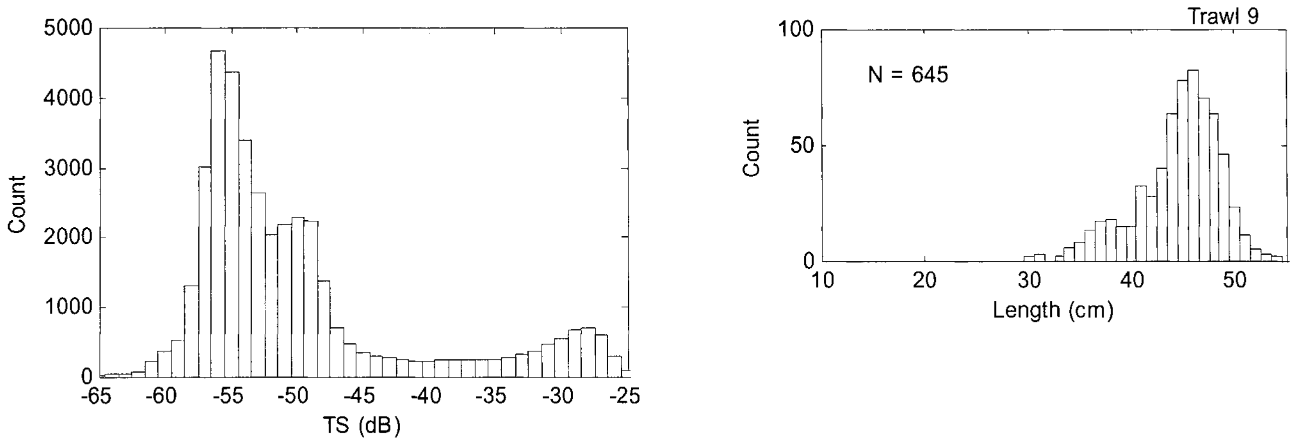
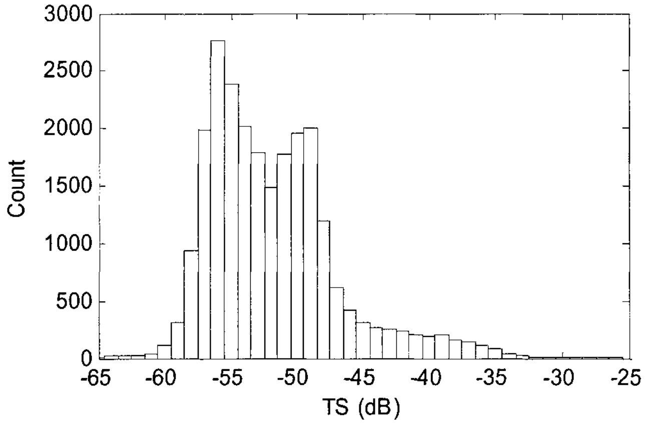


Figure 9: Target strength and associated length distribution for experiment 11 (voyage tan0009). Target strength results are shown with no threshold on N_v, for a threshold of 1, and 0.1 fish per reverberation volume.

No N_v threshold



N_v threshold of 1



N_v threshold of 0.1

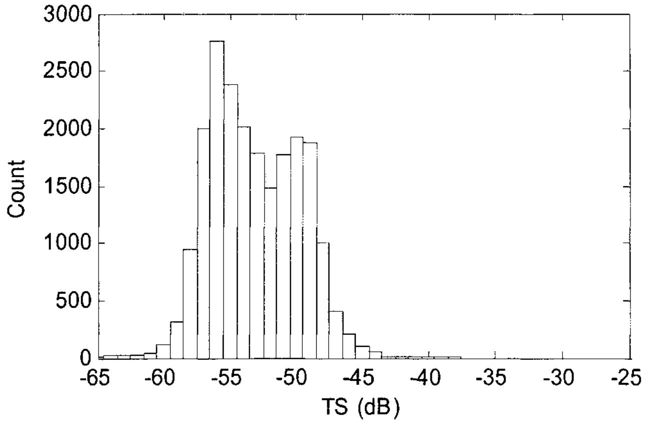
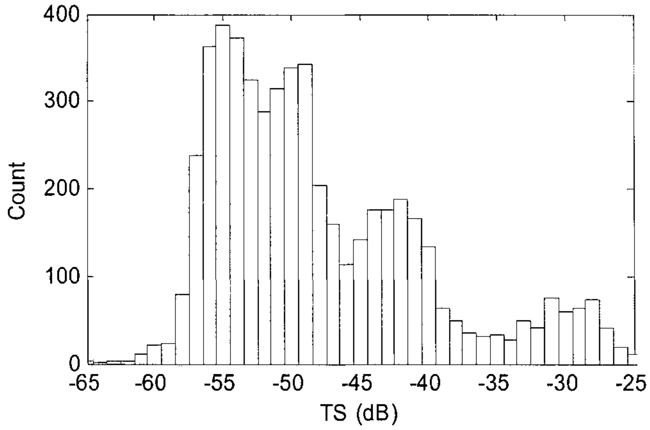
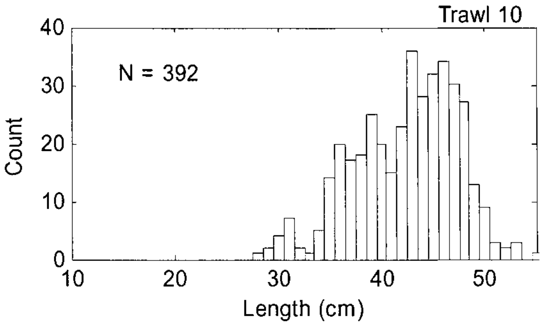


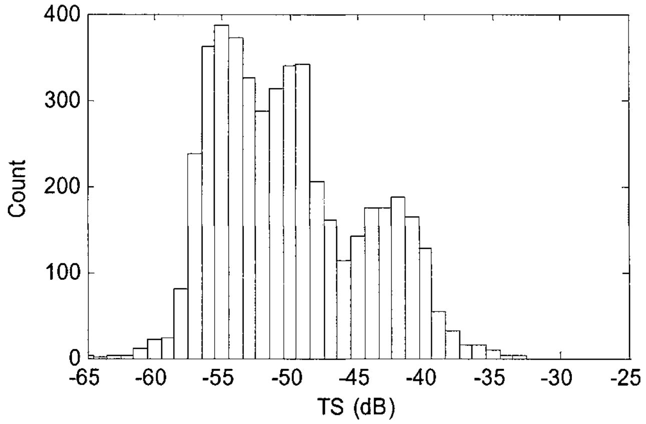
Figure 10: Target strength and associated length distribution for experiment 18 (voyage tan0212). Target strength results are shown with no N_v threshold, a threshold of 1, and 0.1 fish per reverberation volume.

No N_v threshold





N_v threshold of 0.1



N_v threshold of 0.1

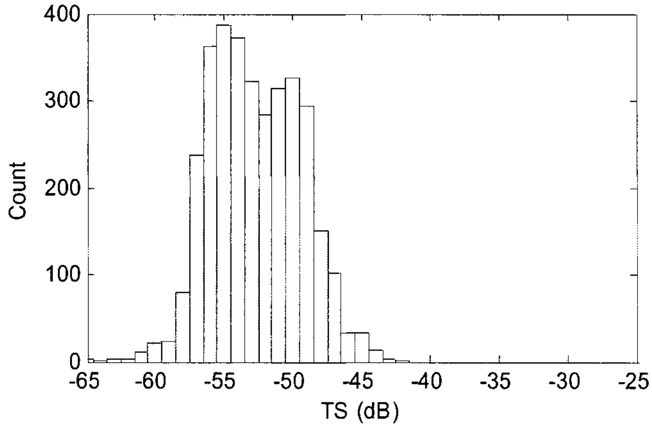
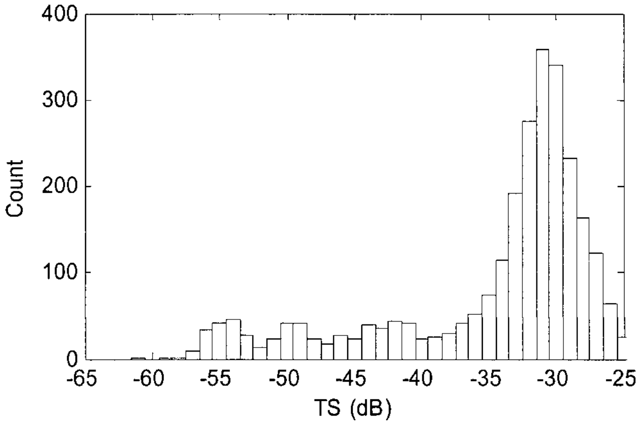
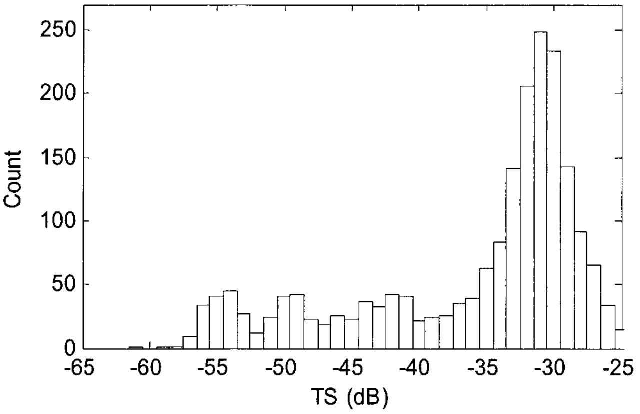


Figure 11: Target strength and associated length distribution for experiment 19 (voyage tan0212). Target strength results are shown with no N_v threshold, a threshold of 1, and 0.1 fish per reverberation volume.

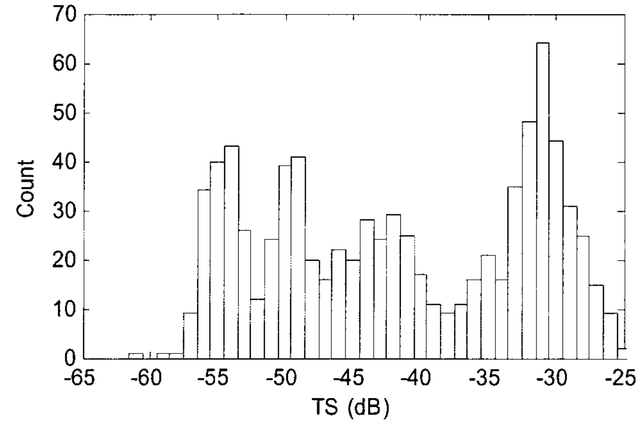
No N_v threshold



N_v threshold of 1



N_v threshold of 0.1



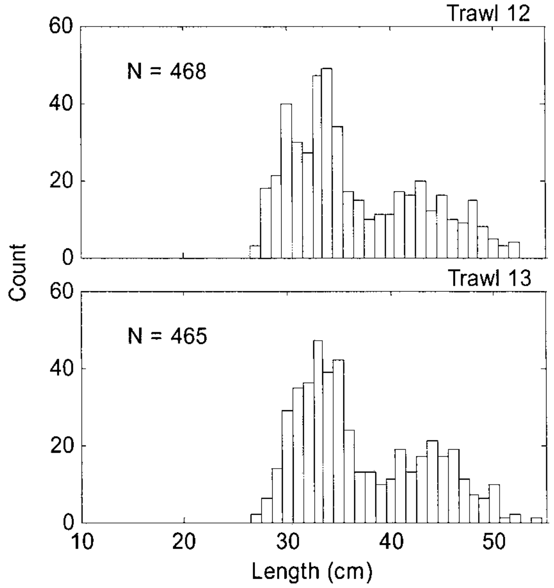
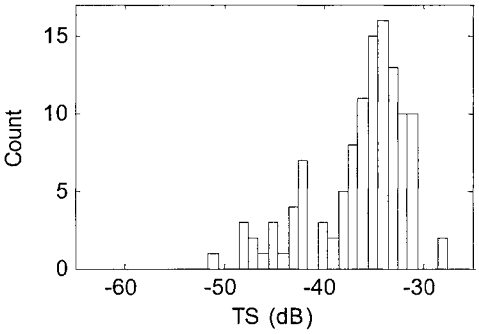
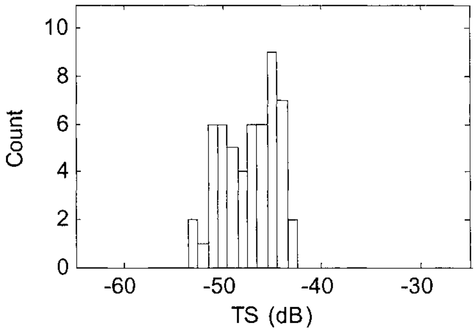


Figure 12: Target strength and associated length distribution for experiment 22 (voyage tan0410). Target strength results are shown with no N_v threshold, a threshold of 1, and 0.1 fish per reverberation volume.

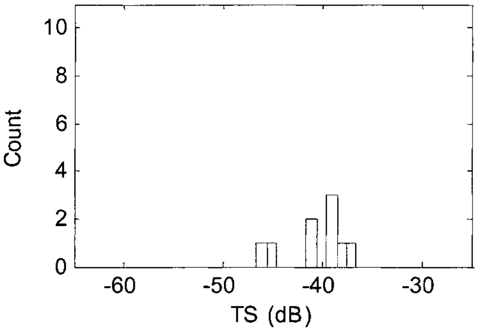
Experiment 2 (tan9811)



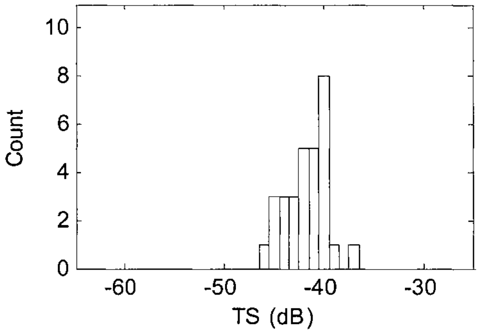
Experiment 11 (tan0009)



Experiment 18 (tan0212)



Experiment 19 (tan0212)



Experiment 22 (tan0410)

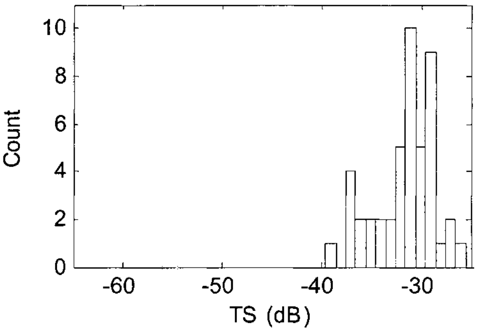


Figure 13: Target strength distribution for echoes selected using target tracking from all valid experiments.

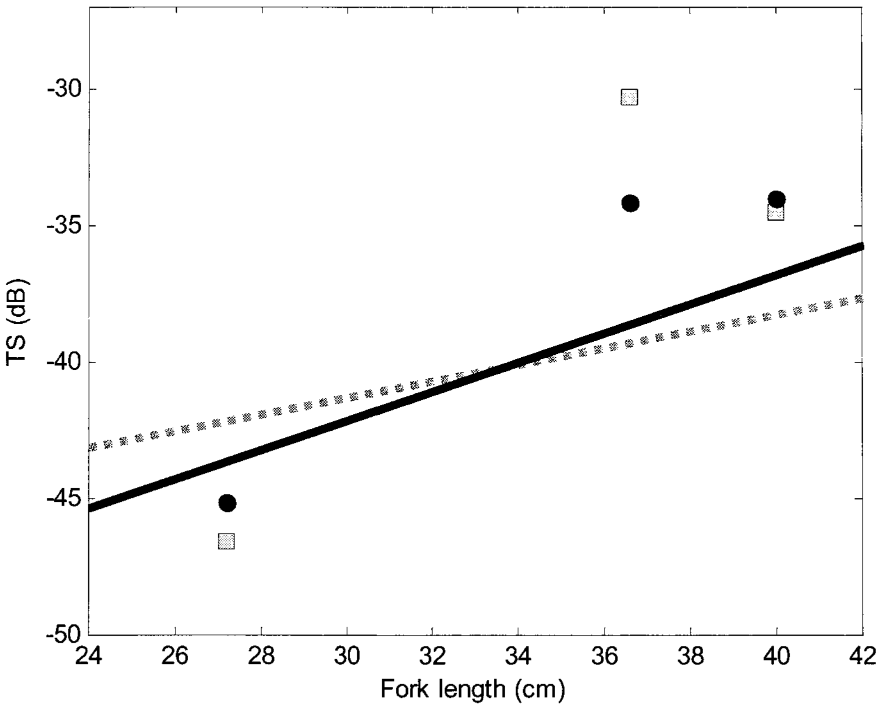


Figure 14: Target strength (dB) to fork length (cm) relationship for southern blue whiting. The circles are the mean target strength for data filtered on range and density on the valid datasets, while the squares are the mean target strength obtained by target tracking on the same samples. The solid line is the equation based on recent swimbladder models (Dunford & Macaulay 2006) and the dotted line is the currently used relationship (based on blue whiting).