

An expanded target-strength relationship for herring

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Target-strength (TS) experiments on captive, adult herring have been conducted at intervals over several years to investigate the acoustic effect of pressure and seasonal changes on fish physiology. Experiments in a large, net pen (4500 m³) were done at 18, 38, and 120 kHz frequencies with calibrated, split-beam echosounders. The main *ex situ* results at 38 kHz, including a vertical-excursion experiment, were combined with *in situ* TS data collected at 38 kHz with a probing, split-beam transducer lowered into the dense herring layers, recorded during two surveys in the wintering area of the Norwegian spring-spawning stock. Multiple-linear regression analysis was used to investigate the functional relationship between TS and the measured parameters. The mean TS of herring was found to be significantly dependent on the depth (pressure) and the gonadosomatic index. These are the additional parameters included in the new TS relationship.

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Introduction

In acoustic-biomass estimation, the target strength (TS) of the surveyed fish is the core parameter needed to determine the true level of stock abundance. Unlike many other fishes, the ability of the herring (*Clupea harengus* L.) to use the swimbladder as an efficient buoyancy regulator has been questioned (Brawn, 1962; Blaxter and Batty, 1984; Ona, 1990). As this organ is considered to be the main reflector of acoustic energy in herring (Foote, 1980), the TS may be more variable than assumed previously because of the vertical migrations exhibited by this fish.

TS data have been collected during various experiments on the Norwegian spring-spawning herring, which is an important stock in the Northeast Atlantic ecosystem (Dragesund *et al.*, 1980). The spawning stock is currently about 6.1 million tons, with an international total allowable catch (TAC) of 850,000 tons (ICES, 2001).

Cage experiments and *in situ* measurements on free-swimming herring using split-beam echosounders have been performed by Foote *et al.* (1986), Kautsky *et al.* (1990), Reynisson (1993), Zhao (1996), Huse and Ona (1996) and Ona *et al.* (2001, 2003). The TS–length relationship at 38 kHz, as currently applied in the acoustic assessment of the Norwegian spring-spawning herring, is that recommended by Foote (1987) for clupeoids: $TS = 20 \log(L) - 71.9$ giving TS in dB for fish length L in centimeter. This formula has been adopted by the ICES

Atlanto-Scandian Herring and Capelin Working Group (ICES, 1988).

This article reports some experimental results on adult herring close to the sea surface together with *in situ* TS measurements at depths from 40 to 470 m.

Material and methods

Pen experiments

The pen experiments were conducted at the Aquaculture Station of the Institute of Marine Research, where about 3 tons of herring were kept in captivity for more than 2 years, from April 1995 to June 1997. The experiments were designed to provide a series of TS records covering two complete reproduction cycles of the captive fish, consisting of several discrete measurement periods each lasting approximately 1 week.

The methodology used in this study is described by Ona *et al.* (2001) and in detail by Zhao (1996). At the beginning of each measurement period, about 40–60 herring were transferred from the storage pen (12.5 × 12.5 × 7 m³) to the measurement pen (12.5 × 12.5 × 21 m³, 14-mm mesh size) using a scoop net. A period of at least 4 h was allowed for the fish to acclimatize to the new pen before data collection began. During the TS measurements, the herring could move around the 4500 m³ enclosure freely. The bottom depth beneath the measurement pen was about 37 m.

A SIMRAD EK500 scientific echosounder (Bodholt *et al.*, 1989) was used with three frequencies (18, 38, and 120 kHz) operating in parallel. The split-beam transducers were mounted in the center of the pen at 0.65 m depth. They had nominal beam widths of 11, 12 (7), and 9°, respectively. Echosounder settings were as reported by Ona *et al.* (2001). Filtered and accepted single-fish echoes were logged via the serial port of the echosounder and stored in a computer. The sound speed was computed from temperature and salinity recorded by a portable CTD. The echosounders were calibrated prior to each measurement period, using the established standard-sphere technique (Foote and MacLennan, 1984) and the dedicated software LOBE V5 (Anon., 1996). Three standard spheres were used: 64 mm copper (18 kHz), 60 mm copper (38 kHz), and 38.1 mm tungsten carbide (120 kHz). The target strengths of the spheres are known functions of the sound speed (Foote, 1990).

After each experiment, the bottom frame of the measurement pen was hoisted slowly to about 1-m depth, and the herring scooped into a circular, anaesthetizing bin in batches of 3–5 fish. This allowed for individual measurements of the swimbladder volume, total length, ungutted weight, gonad weight, and (later) fat content. The results from these experiments are referenced in the figures as “PENEXP”.

Vertical migration experiment

The vertical migration experiments were conducted in April 1997 from the 45-ft long RV “Fjordfangst” at a deep-moored aquaculture plant at Tysnes, south of Austevoll. The bottom depth below the plant was about 150 m. The experimental $12.5 \times 12.5 \times 21 \text{ m}^3$ pen was used initially in its normal configuration as an open-topped enclosure. Before the depth excursion, however, it was fitted with a top frame and netting, converting the pen into a large cage. The echosounder was a SIMRAD EK500 with an oil-filled, pressure-stabilized, split-beam transducer (ES38D). The transducer was mounted at an opening in the upper-net panel, thus the fish could be observed from above at cage-relative distances irrespective of the water depth. An underwater video camera with a 360°-pan unit was lowered into the pen by a cable guided through a nylon ring in the upper-net panel. All instruments were operated from the vessel berthed at the pier of the plant. The cage and the attached transducer were moved slowly over each depth interval, and the behavior of the herring was monitored during the excursion. Biological measurements were conducted as for the pen experiments. Calibration of the transducer was conducted at depth intervals between the surface and 100 m. Results from this experiment are referred in the figures as “VERTEXP”.

In situ TS measurements

TS measurements were performed from RV “Johan Hjort” during surveys of the wintering herring population in

the Vestfjord–Ofotfjord area. With the vessel stationary, a pressure-stabilized, split-beam transducer (SIMRAD ES38D, or ES38DD in later experiments) was lowered into, or held closely above, the fish layer (Figure 1). The transducer was connected to a SIMRAD EK500 split-beam echosounder, operating at the maximum pulse-repetition frequency of $3\text{--}4 \text{ s}^{-1}$ at 25 or 50 m range. TS data were collected as for the pen experiments. In the later work, raw data from the SIMRAD EK60 echosounder was also stored. Data collection continued for 1–3 h at each station, depending on the density and movement of the fish layer, with the completely darkened vessel drifting freely. Seventy data sets, covering most of the horizontal distribution area of the herring, were collected at 15 specific stations or localities in 1997 (Ona *et al.*, 2003). These included most of the vertical migration range of the herring layers, 40–350 m. Additional data sets were similarly collected in December 2000.

Immediately after the TS-data collection, the observed herring layer was sampled with a standard “Harstad” pelagic trawl, fitted with the multi-net system (Engås *et al.*, 1997). Biological data from the trawl catches were recorded with measurements being made of length, weight, gonad weight, and age. The length distribution from the 28 trawl samples taken in 1997 was remarkably narrow ($31.8 \pm 1.4 \text{ cm}$) and ideal for TS measurements, since any bias from trawl sampling should be negligible. The 19 trawl samples taken during the December 2000 experiment showed slightly larger herring and a wider standard deviation ($33.2 \pm 2.4 \text{ cm}$), while the very deep herring sampled were more homogeneous in length ($33.4 \pm 1.5 \text{ cm}$).

The calibration of the split-beam transducer system was done in two stages. First, a standard-target calibration of the beam pattern was conducted for the pen experiments, with the transducer at 10-m depth. Secondly, the pressure performance of the transducer was mapped from 10 to 400 m (later 500 m) (Ona and Svellingen, 2001). All TS measurements were first matched to the near-surface (10 m) calibration, and later corrected for changes in transducer sensitivity with depth. The maximum correction applied was 0.4 dB.

Data analysis

Split-beam echosounders are designed to measure the TS of single fish within the pulse volume. However, false data may be generated when the system fails to reject multiple targets within this volume (Sawada *et al.*, 1993; Soule *et al.*, 1995). Therefore, the measured TS were first scrutinized in conjunction with the printed echograms in order to remove doubtful data using time and depth as selection limits. Software developed in-house was used to select reliable parts of each data set. When the fish density was above an acceptable limit (cf. Ona, 1999), the data set was completely removed.

Tracking software (Ona and Hansen, 1991) was used to perform target-tracking analysis, to isolate the best parts of the files further. Typically 2000–10,000 TS measurements

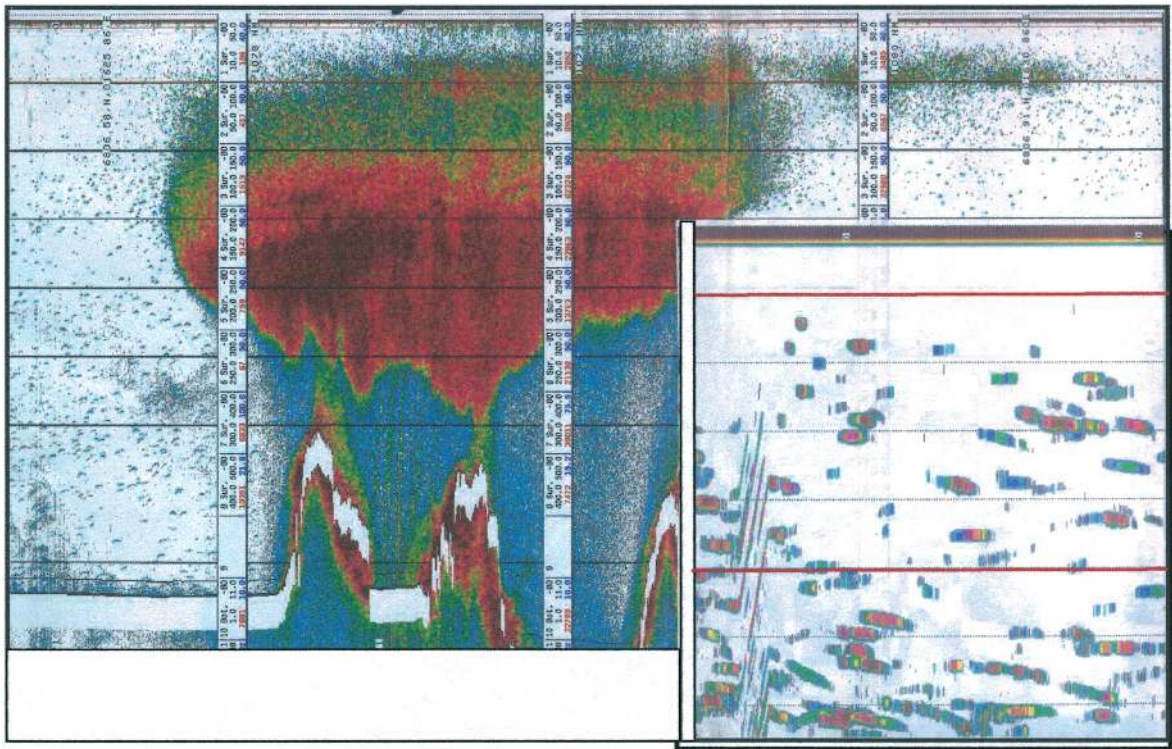


Figure 1. A sample echogram from the Vestfjorden 1997 survey showing a large (approximately 250 000 tons) herring school. The main echogram is about 3.5-nmi long and 0–500 m vertically (50 m between the marker lines). Inserted to the right is an echogram from the probing transducer at 100-m depth in the middle of the school, resolving individual herring tracks. Typically, TS data would be collected 5–25 m from the transducer (range indicated by red lines).

were collected in each series. The so-called mean TS was calculated from the mean-backscattering cross-section (i.e. in the linear domain). The narrow fish-length distribution observed in the selected experiments permitted the measured target-strengths, TS_m , to be normalized to a common fish size of 32 cm by the formula

$$TS_A = TS_m - 20 \log(L/32) \quad (1)$$

where L (cm) is mean fish length and TS_A is the normalized TS.

Seasonal TS variability in herring close to the sea surface was reported by Ona *et al.* (2001) and by Zhao (1996). The effects of swimbladder size (or fat content), GSI, pressure, and tilt-angle distribution were analyzed. The TS showed a substantial variation with gonad size and tilt, while the effect of pressure and swimbladder size (fat) was not significant. However, the pressure gradient was very small within the 5–20 m depth range of the measurement pen, and the variability in fat content between samples was similar to the variability within each sample, which means that the experimental procedures were unsuitable for investigating these two parameters. The presumed effect of pressure was therefore investigated further, through the vertical-exursion experiment and the *in situ* TS experiments in the herring-wintering area (Ona *et al.*, 1993).

The TS (dB) is obtained from the acoustic-backscattering cross-section, σ_{bs} (m^2), by the formula (MacLennan *et al.*, 2002)

$$TS = 10 \log(\sigma_{bs}). \quad (2)$$

Since the backscattering cross-section is assumed to be largely proportional to the dorsal surface area of the swimbladder, the following model has been used to fit the recorded data

$$\sigma_z = \sigma_0(1 + z/10)^\gamma \quad (3)$$

where σ_z is the mean-backscattering cross-section at depth z , equal to σ_0 at the sea surface ($z = 0$), and γ is the estimated contraction-rate parameter (−0.67 for a free spherical balloon). Data from the TS analysis for two series separately and for all series pooled have been fitted to Equation (3) by non-linear regression, giving estimates of γ and σ_0 with corresponding regression statistics (Table 1).

Results

Examples of TS distributions recorded at various depths are shown in Figure 2, with more than 2000 accepted measurements in each distribution. The TS is highly

Table 1. The estimated regression parameters, with associated statistics, from the compression model for 1997 *in situ* data, vertical-excursion experiment, deep herring and all data combined (including pen experiments). Results based on the model $\sigma_z = \sigma_0(1 + z/10)^\gamma$.

Experiments	Estimated regression parameters			
	σ_0 (cm ²)	s.e. (σ_0)	γ	s.e. (γ)
<i>In situ</i> (1997)	3.82	0.59	−0.29	0.061
Vertical-excursion experiment (1997)	3.22	0.55	−0.45	0.097
Deep herring (2000)	3.18 (forced)	n.e.	−0.35	n.e.
All data	2.98	0.19	−0.23	0.035

n.e., Not estimated.

variable and generally bimodal. The total spread of the distribution is nearly 30 dB at all depths. The relative weight of the upper and lower modes changes, however, leading to a gradual reduction of mean TS with increasing depth. The tendency for the lower mode to disappear and the upper mode to shift downwards gradually can be seen from the overall TS distribution ($n = 9668$) recorded in very deep herring (Figure 3).

The precision of the estimated σ_z depends on the number of accepted targets. Analysis of many TS distributions obtained on herring in Vestfjorden at different depths (Zhao, 1996) indicates that when 500–1000 TS values are accepted, the standard error of σ_z is typically less than 5% of the mean. In the present analysis of *in situ* TS, therefore, the mean values are computed from selected data sets containing more than 2000 measurements (Ona *et al.*, 2003). For the pen data, however, the hourly mean TS was used, with typically 500–4500 measurements in each series (Ona *et al.*, 2001).

The measured σ_z for herring from all four experiments are summarized in Figure 4. Results from 120 measurement series are shown, but with each series separately tagged (markers), and normalized to a fish length of 32 cm. The data have been fitted to Equation (3) by non-linear regression to estimate σ_0 , the backscattering cross-section at the surface, and the rate of reduction with depth (γ). Also shown in Figure 4 is σ_{bsf} , the depth-independent value indicated by Foote (1987) TS–length relationship (0.661 cm^2 for a 32 cm fish). All the empirical results are more than σ_{bsf} , many by a large margin. Although the pressure dependence is low ($\gamma = -0.23$), it is significantly different from 0 ($p < 0.001$), with a 95% confidence interval of -0.16 to -0.30 . Considering only the large data sets recorded in 1997, the estimated γ was -0.29 ; for the vertical migration experiment and the deep herring it was -0.45 and -0.35 , respectively (Table 1). σ_0 is estimated to be 2.98 cm^2 with a 95% confidence interval of 2.60 – 3.36 cm^2 . This estimate is more precise than those obtained from earlier data, and it fits well with at least three of the near-surface data series from the pen experiments.

Discussion

A major concern with the TS data presented here is the large spread in the results for herring of nearly the same size at similar depths. Earlier work on tilt-angle distributions *in situ* has shown that herring behave differently during day and night, being more loosely aggregated at night and in deep water (Huse and Ona, 1996). Swimming angles can be determined by target-tracking if the vertical resolution of the sampled data is good enough (Ona, 2001). However, for most of the recordings at 38 kHz, this was difficult with the standard sample resolution of 10 cm (Ona *et al.*, 2003). Measurements of swimming angle are also complicated by vessel motion that can affect the transducer and recordings, even in calm weather conditions. Tracking analysis will then extract the transducer movement rather than the fish behavior. However, in the deep herring layers from 350 to 500 m, a particular “sinking” behavior (not seen in shallower fish) was observed. Using accurate angle sensors to compensate for transducer rotation (Ona and Svellingen, 2001) proved this not to be an artefact either of the vessel motion or of the swimming direction of the fish. A clear, but slow, sinking was observed, averaging 0.086 m s^{-1} and stopping at about 450–500 m. The TS was easily extracted in these layers, but the tilt angle of the fish while sinking is unknown. Similar behavior has recently been observed from bottom-mounted transducers below the deep-herring layers (unpublished data from winter observations 2002–2003).

The unweighted mean-backscattering cross-section of 1.92 cm^2 for the entire water column (5–500 m) corresponds to $\text{TS} = -37.2 \text{ dB}$. A new depth-independent TS relationship for herring, in the standard form, has been obtained from these results

$$\text{TS} = 20 \log L - 67.3. \quad (4)$$

This is 4.6 dB higher than the Foote (1987) equation. However, it is evident from the data presented here (Figure 4) that the depth has an important, first-order effect on the acoustic-backscattering from herring. Inclusion of this term yields the equation

$$\text{TS} = 20 \log L - 2.3 \log(1 + z/10) - 65.4. \quad (5)$$

This is an improved version of the equation proposed by Ona *et al.* (2003), which was based only on the 1997 *in situ* data. Strictly, Equation (5) is estimated for, and based on adult herring in the length range 29–34 cm. The usual TS–length dependency ($20 \log L$) has been assumed. The accuracy of that term has not been investigated here.

The pressure term is now closer to that determined from maximum TS values over fish tracks ($\gamma = -0.18$; Vabø, 1999; Ona *et al.*, 2003), but is much lower than expected from a simple model of the swimbladder acting as a free, spherical balloon ($\gamma = -0.67$). Values of γ between 0 and

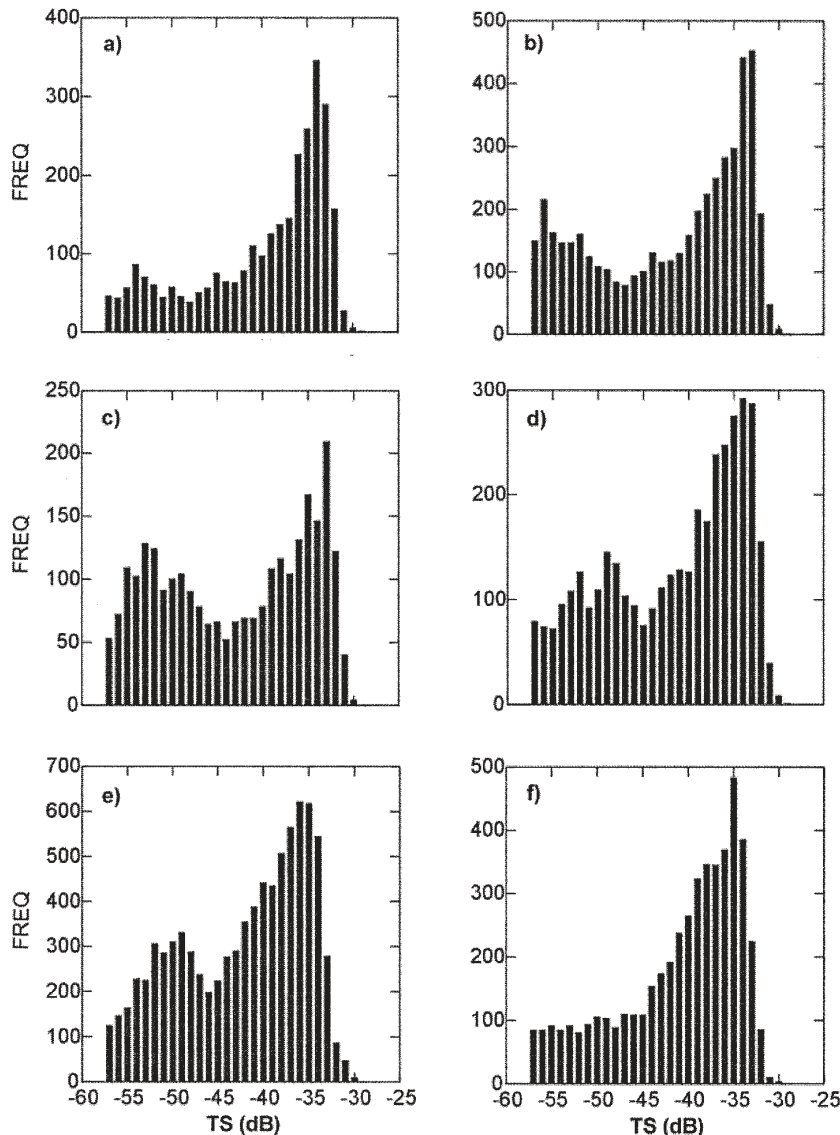


Figure 2. An example of TS distributions within six 20-m depth intervals obtained from different stations in 1997. Cut-off limits are -58 and -29 dB. The mean TS corresponding to the mean cross-section by depth are: (a) 40–60 m, $TS = -37.0$ dB; (b) 50–70 m, $TS = -37.8$ dB; (c) 90–110 m, $TS = -38.4$ dB; (d) 150–170 m, $TS = -37.9$ dB; (e) 200–220 m, $TS = -38.9$ dB; (f) 280–300 m, $TS = -38.2$ dB.

-0.67 support the alternative concept of a swimbladder with fixed-end positions and pressure-sensitive diameter (Gorska and Ona, 2003).

The gonad size, fat content, and tilt-angle distribution may also influence the TS of herring. These parameters were investigated in the net-pen experiments (Ona *et al.*, 2001; Zhao, 1996) and will only briefly be considered here. The TS values recorded in one of the pen experiments were around 3 dB higher than the others made at comparable depths. These were the measurements in herring with large gonads, mean $GSI = 14.5\%$ (range 7.8–32.3%). Multiple-linear regression showed that the GSI explained nearly 83%

of the observed variability. The results at 38 and 120 kHz were consistent, suggesting the following equation to include the GSI expressed in percent of total body weight.

$$TS = 20 \log L - 2.3 \log(1 + z/10) - 65.4 + 0.24(GSI). \quad (6)$$

However, most of the *in situ* data obtained in November 1997 and December 2000 were from fish with ripening gonads ($GSI \approx 10\%$). The GSI effect is therefore already partly included in Equation (5). Furthermore, we expect the gonads to influence the TS indirectly by deforming

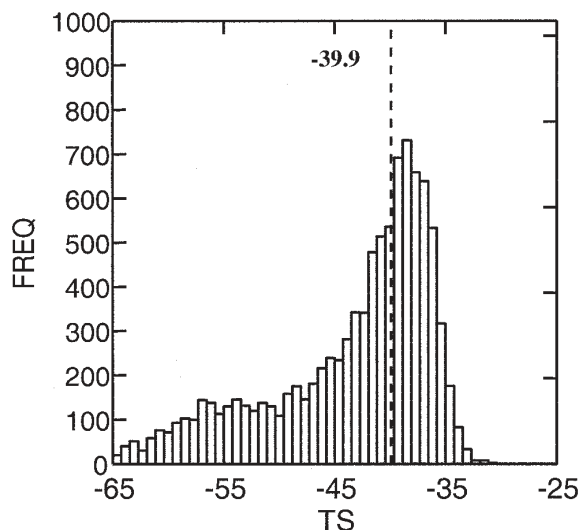


Figure 3. A histogram of all TS measurements ($n = 9668$) in the deep herring layer between 400 and 500 m, recorded in December 2000. The mean TS (-39.9 dB) is indicated.

the swimbladder. The independent effects of pressure and gonads are therefore not easily separated. It is likely that some of the observed variability may arise from their interaction. At present, therefore, Equation (5) rather than Equation (6) is preferred as a general TS function for herring. Excluding the effect of gonad development and fat content, however, leaves a larger uncertainty in the TS relationship of about $\pm 13\%$ estimated from the 95% confidence intervals of the regression.

An important consequence of these findings in regard to acoustic surveys of herring is that the fish abundance should be computed from vertically resolved echo integrals. In general, the new TS formula will drastically reduce the abundance estimate, more so at night than during the daytime (Vabø *et al.*, 2002). For example, the estimated abundance from the November 2001 herring survey would be reduced by about 50% if the new TS relationship (Equation (5)) were applied. Survey results from areas where herring mainly are found close to the sea surface are likely to require even more adjustment. However, shallow-water density estimates may be substantially reduced by vessel avoidance (Olsen *et al.*, 1983a, b; Vabø *et al.*, 2002) and by acoustic extinction (Foote *et al.*, 1992; Zhao and Ona, 2003). Including corrections for these effects would compensate the pressure adjustment to some extent, as both the pressure effect and herring avoidance are greatest near the surface. The survey records on the Norwegian spring-spawning herring comprise backscattering measurements in 10-m depth bins averaged over distances of 0.1 nmi. This is also the resolution used for the correction of acoustic extinction in the high-density parts of the echograms (Foote *et al.*, 1992).

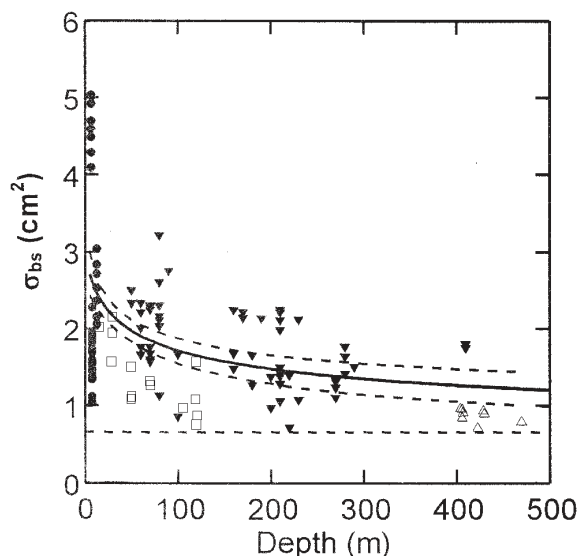


Figure 4. The mean-backscattering cross-section of 32-cm herring from four experiments plotted against depth. The fitted pressure model (Equation (5)) is the dark black curve and the currently applied value (Foote, 1987) is the black, dashed line. Data from series in each of the different experiments are indicated by the different symbols: (●) Pen experiments; (▼) *in situ* 1997 experiment; (□) vertical-cage experiment; and (Δ) deep-herring experiment. The 95% confidence belt for the estimated-pressure model, as estimated from bootstrapping, is indicated as dashed curves.

The area-backscattering coefficient divided by the mean-backscattering cross-section correctly estimates the area and volume density of the observed herring. To obtain absolute-abundance estimates, however, it is imperative to quantify and correct the important vessel-avoidance reactions in herring, and for acoustic extinction. Further research is in progress to determine the total uncertainty in the survey estimates, as earlier suggested and simulated by Aglen (1994), but now using estimated uncertainties for each parameter in the computations. In this work, establishing accurate TS for the surveyed fish is only the first step.

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