The influence of uncertainty in target strength on abundance indices based on acoustic surveys: examples of the Baltic Sea herring and sprat

Svetlana M. Kasatkina


In situ, target-strength (TS) measurements at 38 kHz and an analysis of biometric fish characteristics are presented for the Baltic Sea herring (Clupea harengus membras) and sprat (Sprattus sprattus). It is demonstrated that the application of two TS–length functions for the Baltic Sea clupeids, the first for young herring and sprat and the second for adult herring, is reasonable, and the two functions can therefore replace the well-known equation used since 1983. Parameters of the proposed relationships, accompanied by their statistical characteristics, are included in a model to obtain uncertainty in acoustically derived abundance indices. Major components of survey uncertainty, such as spatial variability, species composition, and size structure, are also included in the simulation. The proposed TS functions should permit estimates of more realistic abundance dynamics of Baltic Sea clupeids, by years and age groups, thereby providing important information for stock assessment models.

Keywords: abundance, acoustic survey, Baltic Sea, herring, sprat, target strength, uncertainty.

Received 8 August 2008; accepted 2 December 2008; advance access publication 8 April 2009.

S. M. Kasatkina: Atlantic Research Institute of Marine Fisheries and Oceanography (AtlantNIRO), S. Dm. Donskoy Sr., Kaliningrad 236022, Russia; tel: +7 4012 925 469; fax: +7 4012 219997; e-mail: ks@atlant.baltnet.ru.

Introduction

In the Baltic International Acoustic Surveys (BIAS), target-strength (TS) estimates for herring (Clupea harengus membras) and sprat (Sprattus sprattus) are based on the traditional function: TS = 20 log L – 71.2 dB (where L is the fish length in centimetres), established ∼25 years ago, but with no indication of its accuracy (ICES, 1983). Further, in situ TS measurements made during the past seven years established higher values for the parameter B20 in the general function TS = 20 log L + B20. These B20 values are within the range –68.9 to –63.6 dB (Ona et al., 2001; Ona, 2003; Didrikas and Hansson, 2004; Peltonen and Balk, 2005). Modelling has also demonstrated high TS values for herring comparable with these in situ results (Fässler et al., 2007; Gorska, 2007).

The assumption of particular acoustic properties for the Baltic Sea clupeids underlies the current practice of TS estimation for herring and sprat, based on the function cited earlier (ICES, 2006, 2008). However, up to now that assumption lacks support either by experimental or modelling studies or by comparative analyses of the biological characteristics of the two fish species as acoustic targets.

Conversely, the urgency for further studies of the Baltic clupeid TS is also dictated by the need to assess the TS functions together with relevant statistics. The latter are essential to present-day measurements of TS, because they are an important component of the overall uncertainty of the acoustic-survey results (Demer, 2006; Kasatkina and Gasyukov, 2006; Woillez et al., 2006).

In view of this problem, proposals to improve the clupeid TS estimates used in the BIAS are discussed in this paper. The results of in situ TS measurements for herring and sprat are presented, with analyses comparing these results with the biometric characteristics of the two species. A simulation method is used to incorporate the uncertainty in TS estimates into the acoustically derived abundance indices to compare the statistical features of the abundance indices based on the traditional and new TS functions.

Material and methods

In situ TS measurements

In situ TS measurements were made on board the RV “Atlantida” during acoustic surveys conducted in the Baltic Sea during 2003–2005. The echosounder (Simrad EK 500, 38 kHz, split-beam transducer type ES38) was run continuously during the surveys, so acoustic data were available for each trawl station.

Single-target echoes from free-swimming fish, identified by trawling as herring or sprat, were collected and processed using SonarData Echoview software. The echosounder was calibrated using a standard target at the start of each cruise. The target-position information provided by Echoview was used to locate the target in range and off-axis angles. Single-target echo detections from fish were filtered to retain only those from targets <1° off the central axis of the transducer. Then, the TS was compensated to provide values that the target would have exhibited on the axis.

The insonified, dispersed aggregations recorded at depths from 15 to 70 m were fished using a midwater trawl PT/TM 70/300
(vertical mouth opening 34 m) at 3.9–4.0 knots towing speed. Tow duration was 30 minutes. The vertical opening and mouth shape were observed by the trawl sonar Simrad FS 900/025 MK II. The codend had a liner of 6-5 mm mesh, thus retaining all herring and sprat irrespective of the length range (Ivanova et al., 2002). For those trawl stations where herring contributed >95% by weight in the catch, and those where sprat contributed >98.5%, single-target echo detections were extracted corresponding to the sections of the water column sampled by the gear.

Samples of TS values and fish-length compositions observed simultaneously were used to construct TS functions; for herring ranging from 11 to 30 cm in length, the data came from 299 single-target echoes and 12 970 fish in eight trawls (the 2005 survey); for sprat ranging from 6 to 15 cm in length, 420 single-target echoes and 88 800 fish from 12 trawls (the 2005 survey), and 300 single-target echoes and 52 600 fish from seven trawls (the 2003 survey), see Kasatkina (2007).

A TS function can be estimated by matching two sets of observations, namely distributions of TS and fish lengths. D. A. Demer (pers. comm.) has suggested a method for mapping one of these distributions onto the other. This approach is briefly described by Kasatkina and Gasyukov (2004), and it consists of the following steps.

(i) The first point of the fish-length distribution is mapped at the first point of the TS distribution.

(ii) Any other point of the fish-length distribution (with ordinal number \( N_T S \) and length \( L_i \)) is mapped at the point \( N_{T S} \) of the TS distribution according to the following rule:

\[
N_{T S} = N_{T S} + r \times (N_{T S} - N_{T S})
\]

where \( N_{T S} \) and \( N_{T S} \) are the ordinal numbers of the fish in the sample distribution (i.e. the last and the first), \( N_{T S} \) and \( N_{T S} \) the ordinal numbers of TS values in the sample distribution (i.e. the last and the first), TS (with the ordinal number \( N_{T S} \) in the TS sample) the TS value corresponding to the \( N_{T S} \)th fish with length \( L_i \). The index \( i \) is used to show that there can be several fish with the same length in the sample.

This mapping provides a set of measurements \( (L_i, TS) \) suitable for estimating the parameters of the TS function using the bootstrap technique (Efron and Tibshirani, 1993). Bootstrap sampling allows calculation of the distribution, mean value, variance, and confidence intervals of \( B_{T S} \) estimates. In this study, the parameter \( B_{T S} \) was used as a common basis for comparisons with other TS functions reported in the literature.

**Biometric indices of Baltic Sea clupeids**

Biometric data of herring and sprat were collected on board the RV “Atlantida” during acoustic surveys in the Baltic Sea in 2003–2005. The features used for biometric comparison of the two species were as follows:

(i) the fish weight–length relationship based on data from 2000 individuals, and

(ii) the maximum body girth, maximum body height, and weight based on data from 1200 herring and 600 sprat.

---

**Simulation model to estimate uncertainty in acoustically derived, abundance indices**

Simulating the effect of uncertainty in acoustically derived, abundance indices was based on the method of Kasatkina and Gasyukov (2006) for quantifying and summarizing components of the overall uncertainty in sampling surveys. The spatial variability of the nautical-area-scattering coefficient \( (s_i) \) of the fish-species composition and their size structure within the surveyed area and the uncertainty of the TS were chosen as the main sources of uncertainty. Vessel avoidance as an issue in Baltic surveys was not considered. The effects were simulated independently using a bootstrap resampling technique to reveal the spatial variability and a Monte Carlo simulation for the TS-defining parameters.

The suggested simulation method was also based on the current algorithms of BIAS data processing (ICES, 2002). In this case, the stratum density was estimated from the mean \( s_{iN} \) and the mean backscattering cross sections \( (\sigma) \) within the stratum, where \( \sigma \) is calculated by inverting the TS functions, and weighting by the length and species compositions obtained from all trawl stations in the stratum:

\[
\sigma = \sum_i f_i \sigma_i = \sum_i f_i \sum_j f_{ij} \sigma_{ij},
\]

where \( \sigma_{ij} \) is the backscattering cross section of the \( j \)th length class of species \( i \), and \( f_{ij} \) is the respective frequency, whereas \( f_i \) is the frequency of species \( i \) in the stratum.

Sprat and herring abundances were estimated by splitting the total abundance according to the species frequency in the stratum, because \( N_i = N f_i \).

The input data for the simulation were the following.

(i) Variable data:

(a) the TS functions with mean and standard deviation \( (s.d.) \), estimates of \( B_{T S} \); a normal distribution of \( B_{T S} \) is assumed,

(b) \( s_i \) values along each acoustic transect, and

(c) length frequencies for all fish species, weighted by the total catch at each trawl station.

(ii) Fixed data:

(a) length–weight functions for each species or the weights obtained for each length class,

(b) geographic area covered by the acoustic survey, and

(c) number of realizations in the simulation process (500 realizations).

**Algorithm for the simulation**

**Step A.** For each stratum:

(a) the value of \( B_{T S} \) was simulated according to the normal (Gaussian) distribution,

(b) the set of \( s_i \) values was simulated according to the empirical distribution in the stratum,

(c) for each length class, the number of fish “caught” at a trawl station was simulated according to the empirical distribution in the stratum,
(d) the length frequency sets formed at each station and frequencies for each length group were determined, and
(e) weighted-mean TS values were estimated, and mean density, abundance, and biomass estimates were calculated.

**Step B.** The abundance and biomass in the studied area were estimated based on the stratified-sampling technique.

**Step C.** Steps A and B were repeated to produce the given number of realizations.

**Step D.** The statistical characteristics of abundance and biomass (mean values, variances, standard errors, coefficients of variation, and 95% confidence intervals) were estimated from the set of realizations obtained.

As an example, the simulation method was applied to estimate the statistics of fish-abundance indices in ICES Subdivision 25 (Baltic Sea), using data from the BIAS in 2004–2006.

**Results**

**TS–length relationships**

Bootstrap distributions for $B_{20}$, based on linking observed in situ TS distributions with fish length frequency distributions obtained from catches, are given in Figure 1.

The estimates obtained for herring ($B_{20} = -67.55 \, \text{dB}$, s.d. = 0.26 dB), sprat in 2003 ($B_{20} = -73.33 \, \text{dB}$, s.d. = 0.20 dB), and sprat in 2005 ($B_{20} = -71.9 \, \text{dB}$, s.d. = 0.39 dB) differ from the $B_{20} = -71.2 \, \text{dB}$ currently used in the BIAS. Specifically, important differences were found between the TS functions applying to herring and sprat.

The in situ data also revealed that $B_{20}$ is between $-73$ and $-72 \, \text{dB}$ for young herring smaller than 16 cm. These values are comparable with those obtained for sprat of all lengths from 6 to 15 cm. In view of this finding, the wisdom of using the same TS function for sprat and young herring should be considered.

Differences between some biometric characteristics of the two species, revealed by the survey data in 2003–2005, are indirect evidence in support of this hypothesis. Statistics of the parameters in the relationship $W = aL^b$ between fish weight ($W$, g) and fish length ($L$, cm) are indicated in Tables 1 and 2. The relationships for the two herring groups (young and adult fish) differ, whereas those of sprat and young herring are comparable (Tables 1 and 2). Thus, sprat and young herring are characterized by similar values of body perimeter and weight at the same length.

**Uncertainty in acoustically derived abundance indices**

The model results for ICES Subdivision 25 were obtained using the traditional $B_{20} = -71.2 \, \text{dB}$ and our alternatives for Baltic Sea clupeids, as suggested above ($B_{20} = -73.33 \, \text{dB}$, s.d. = 0.20 dB for fish $<16 \, \text{cm}$ in length; $B_{20} = -67.55 \, \text{dB}$, s.d. = 0.26 dB for fish $>16 \, \text{cm}$). Confidence limits on the traditional $B_{20} = -71.2 \, \text{dB}$ are unknown (ICES, 1983), so a standard deviation of 0.5 dB was assumed for modelling purposes.

The uncertainty in acoustically derived abundance indices varies considerably by year (Table 3). The uncertainty in TS is an important component of the overall variance of the abundance indices (Figure 2).

**Figure 1.** Bootstrap distributions of the parameter $B_{20}$ in TS functions estimated for sprat (top panel) and herring (bottom panel) from in situ measurements.

**Table 1.** Mean and standard errors of parameters in the relationship $W = aL^b$ between fish weight ($W$, g) and fish length ($L$, cm) estimated for sprat and herring.

<table>
<thead>
<tr>
<th>Fish species</th>
<th>Parameter $a$ [mean $\times 10^3$] (s.e. $\times 10^3$)</th>
<th>Parameter $b$ [mean (s.e.)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprat</td>
<td>9.25 (0.91)</td>
<td>2.81 (0.40)</td>
</tr>
<tr>
<td>Young herring</td>
<td>7.20 (1.06)</td>
<td>2.94 (0.07)</td>
</tr>
<tr>
<td>Herring $&gt;16 , \text{cm}$</td>
<td>3.17 (0.69)</td>
<td>3.22 (0.07)</td>
</tr>
</tbody>
</table>

**Table 2.** Mean and standard errors of parameters in the relationship $P = cL^d$ between maximum perimeter of the fish body in girth ($P$, cm) and fish length ($L$, cm) estimated for sprat and herring.

<table>
<thead>
<tr>
<th>Fish species</th>
<th>Parameter $c$ [mean $\times 10^3$] (s.e. $\times 10^3$)</th>
<th>Parameter $d$ [mean (s.e.)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprat</td>
<td>6.05 (0.40)</td>
<td>2.97 (0.03)</td>
</tr>
<tr>
<td>Young herring</td>
<td>7.06 (1.45)</td>
<td>2.95 (0.07)</td>
</tr>
<tr>
<td>Herring $&gt;16 , \text{cm}$</td>
<td>4.09 (0.64)</td>
<td>3.13 (0.46)</td>
</tr>
</tbody>
</table>

Applying the new TS functions to the survey data resulted in different interannual dynamics of the values and uncertainties of the estimated fish-abundance indices (Table 3). Further, changing the TS function caused a shift in the time-series of the abundance.
indices by fish group, including those of recruits, i.e. 0-group for sprat and age-1 group for herring (Figure 3).

**Discussion**

The $T_S$ function obtained for herring is characterized by $B_{20} = -71.2$ dB (s.d. = 0.5 dB), which is 4 dB higher than the traditional $B_{20} = -73.3$ dB that has been applied for the past 20 years in the BIAS. The obtained $B_{20}$ is consistent with the above-mentioned results of *in situ TS* measurements and modelling reported by various authors in the past 7 years. Therefore, our results are further confirmation that current practice in the BIAS considerably underestimates the $T_S$ of herring.

Conversely, the results suggest appreciable differences between the $B_{20}$ values for sprat (mean $B_{20} = -71.9$ to $-73.3$ dB, s.d. = 0.20–0.39 dB) and herring (mean $B_{20} = -67.5$ dB, s.d. = 0.26 dB), which are explained by the different biometric characteristics of the two species.

The results from the $T_S$ measurements reveal that the traditional $B_{20} = -71.2$ dB measure used for estimating $T_S$ both for herring and sprat is wrong. Alternative $T_S$ functions for the Baltic Sea clupeids need to be considered.

The biometric indices of the two species are similar within the length range 6–16 cm, which includes all sizes of sprat, whereas those of adult herring differ. This suggests the possibility of adopting two $T_S$ functions for Baltic Sea clupeids. These would be applied to the length range from 6 to 16 cm, including young herring and all sizes of sprat, and lengths >16 cm for adult herring only.

We believe that adopting a separate $T_S$ function for sprat and young herring will give more reliable abundance indices for fish <16 cm, which comprise the bulk of Baltic Sea clupeid stocks. For example, these small fish contributed more than 86% of the total herring and sprat abundance during autumn 2007 (ICES, 2007).

Furthermore, application of the new $T_S$ functions will change the absolute values and uncertainties of the abundance indices, and their annual rate of change. This is highly relevant to the use of abundance indices for VPA tuning, for instance by the XSA method of Shepherd (1999), which depends on the index trends in the most recent years. An important consequence is the change in the estimated quantities of younger fish used as recruitment indices: 0-group for sprat and age-1 group for

**Table 3.** Statistics of acoustically derived abundance indices for Baltic Sea clupeids obtained with the traditional $B_{20} = -71.2$ dB (s.d. = 0.5 dB), indicated as I variant, and with our alternatives indicated as II variant ($B_{20} = -73.3$ dB; s.d. = 0.20 dB for fish <16 cm and $B_{20} = -67.5$ dB; s.d. = 0.26 dB for fish >16 cm).

<table>
<thead>
<tr>
<th>Statistical characteristics</th>
<th>Survey 2004</th>
<th>Survey 2005</th>
<th>Survey 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I variant</td>
<td>II variant</td>
<td>I variant</td>
</tr>
<tr>
<td>Total fish abundance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>31 147.7</td>
<td>26 532.9</td>
<td>12 914.8</td>
</tr>
<tr>
<td>s.d.</td>
<td>3 118.1</td>
<td>2 259.5</td>
<td>1 303.7</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>0.10</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>Lower limit (95% CI)</td>
<td>25 081.2</td>
<td>22 523.8</td>
<td>10 256.5</td>
</tr>
<tr>
<td>Upper limit (95% CI)</td>
<td>37 598.1</td>
<td>31 358.4</td>
<td>15 419.1</td>
</tr>
<tr>
<td>Sprat abundance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>25 055.2</td>
<td>21 306.4</td>
<td>7 998.5</td>
</tr>
<tr>
<td>s.d.</td>
<td>2 743.4</td>
<td>2 201.5</td>
<td>1 298.6</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>0.11</td>
<td>0.10</td>
<td>0.17</td>
</tr>
<tr>
<td>Lower limit (95% CI)</td>
<td>20 010.9</td>
<td>17 270.3</td>
<td>5 268.7</td>
</tr>
<tr>
<td>Upper limit (95% CI)</td>
<td>30 641.9</td>
<td>26 018.3</td>
<td>10 361.9</td>
</tr>
<tr>
<td>Herring abundance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>6 092.5</td>
<td>5 226.6</td>
<td>5 116.2</td>
</tr>
<tr>
<td>s.d.</td>
<td>880.9</td>
<td>567.3</td>
<td>727.7</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>0.14</td>
<td>0.11</td>
<td>0.14</td>
</tr>
<tr>
<td>Lower limit (95% CI)</td>
<td>4 538.8</td>
<td>4 128.4</td>
<td>3 894.9</td>
</tr>
<tr>
<td>Upper limit (95% CI)</td>
<td>8 000.3</td>
<td>6 407.3</td>
<td>6 677.1</td>
</tr>
</tbody>
</table>

The fish quantities are in millions of fish. CI, confidence interval.

**Figure 2.** Contributions of the main sources of uncertainty to the variance of total fish abundance based on (top panel) the traditional $T_S$ function and (bottom panel) the new $T_S$ functions for Baltic Sea clupeids. Modelling results are illustrated using the 2004–2006 acoustic surveys as examples.

indices by fish group, including those of recruits, i.e. 0-group for sprat and age-1 group for herring (Figure 3).
herring. As for total abundances, the temporal dynamics of recruitment-abundance indices may also change compared with traditional calculations. The application of new TS-length functions based on our results should allow a more realistic assessment of herring and sprat abundances for each age group, by year.

Conclusions
The current TS value used for the BIAS acoustic estimate of herring and sprat abundance is a significant source of uncertainty in the surveys. Using different TS functions for large and small fish, with young herring and sprat included in the latter group, seems to be more appropriate. Introducing such TS functions in the BIAS analysis should improve the reliability of abundance indices for young, recruiting fish, and should allow more realistic estimates of each age group by year, so providing vital information for tuning stock-assessment models.

Acknowledgements
The scientists participating in the Baltic International Acoustic Surveys are thanked for submitting survey data for the investigations. I also thank David Demer, who suggested applying the bootstrap method for TS data processing, David MacLennan for his help and useful comments, and Richard O’Driscoll and an anonymous reviewer for their valid comments.

References


doi:10.1093/icesjms/fsp086