Methods and results of in situ target-strength measurements of Atlantic cod (Gadus morhua) during combined trawl-acoustic surveys

Viacheslav A. Ermolchev


This paper presents methods for collecting acoustic and biological data, including in situ target-strength (TS) estimates of fish, with results presented for Atlantic cod (Gadus morhua) obtained from combined trawl-acoustic surveys. These include fish in the small, average, and maximum length classes, within the range 5–136 cm (total fish length, LT). The investigations were done using Simrad EK500/EK60 echosounders with split-beam transducers and special post-processing software. Based on an analysis of data collected in the Barents Sea during 1998–2007, a relationship TS = 25.2 log10(LT) − 74.8 was obtained for Atlantic cod at 38 kHz, with TS in dB and LT in centimetres. Seasonally, and for depths between 50 and 500 m, the variability in cod TS was 3.1 dB, decreasing with depth. The largest day–night difference in mean TS was in August–September, with changes as large as 1.0–1.7 dB. In the other seasons, the day–night difference was <1.0 dB.

Keywords: length classes, target strength, trawl-acoustic surveys.

Introduction

Trawl-acoustic surveys (TAS) for estimating fish-stock abundance have been intensively developed, but they still need improvement regarding their accuracy. The accuracy of stock estimates obtained with TAS depends on several important factors, notably the target strength (TS). One of the main challenges in this work is to determine how TS depends on fish length over different seasons, diel periods, and the depth distributions of the target fish species.

The results of TS measurements on wild gadoids by Norwegian and Canadian scientists have been reported in many papers, e.g. Dalen and Smedstad (1979, 1983), Foote et al. (1986), Foote (1987), McQuinn and Winger (2003), Ona (1994), Ona and Hansen (1986), Rose and Porter (1996), and Simmonds and MacLennan (2005).

From 1976 to 1981, Norwegian scientists of the Institute of Marine Research (IMR, Bergen) investigated juvenile Atlantic cod (Gadus morhua) and haddock (Melanogrammus aeglefinus) in the Barents Sea to determine a cod TS in situ, using a Simrad EK-38 kHz scientific echosounder, with a single-beam transducer and an analogue echo integrator. They derived the following relationship for young cod and haddock, giving the mean TS in dB for fish total length, LT (in cm; Dalen and Smedstad, 1979, 1983):

\[ \text{TS} = 21.8 \log_{10}(LT) - 72.7. \]  \hfill (1)

Later, from the areas of the Lofoten Islands, the Norwegian coast and Bear Island, the Norwegians estimated the in situ TS for wild gadoids using more advanced, split-beam echosounders, notably the Simrad ES380 and later the EK500 (Foote et al., 1986; Ona and Hansen, 1986; Foote, 1987; Simmonds and MacLennan, 2005). Based on these data, new relationships were proposed for cod, following Love (1977) and Foote (1987), expressed with the length dependence in a standard form, i.e. \( \text{TS} = 20 \log_{10}(LT) + b \); first, for wild gadoids with LT ranging from 12.4 to 81.6 cm (Foote et al., 1986):

\[ \text{TS} = 20 \log_{10}(LT) - 68, \quad n = 6. \]  \hfill (2)

and, second, for wild gadoids with LT ranging from 9 to 105 cm (Foote, 1987):

\[ \text{TS} = 20 \log_{10}(LT) - 67.4. \]  \hfill (3)

From data collected in Newfoundland between 1990 and 1992, Rose and Porter (1996) derived another, very different relationship, for 18–60-cm cod, also at 38 kHz:

\[ \text{TS} = 26.1 \log_{10}(LT) - 75.7; \quad n = 39, \]  \hfill (4)

or, when converted to the standard form: \( \text{TS} = 20 \log_{10}(LT) - 66 \).

Using single-target data collected in 1998 along the west coast of Newfoundland with an EK500 echosounder and a split-beam transducer, McQuinn and Winger (2003) logged variations in mean TS from −32.9 to −30.3 dB for cod with mean lengths from 40.3 to 46.4 cm. Biological samples were collected from bottom trawls; and a high correlation between the mean TS and
the tilt-angle distribution of the fish, as measured from the tracks of individual fish, was reported. These measurements were made at night in May, at depths between 180 and 210 m. A series of experiments was conducted on cod, in which a stationary 38 kHz, split-beam transducer was positioned over large cod aggregations, to measure TS over diel and seasonal periods. The TS varied by nearly 10 dB under various conditions (Rose, 2008).

At present, the TS–length relationship in Equation (1) is also applied for estimating stocks of polar cod (Boreogadus saida) and blue whiting (Micromesistius poutassou) in the Barents and Norwegian Seas (Aglen et al., 2004), whereas Equation (2) is used for estimating stocks of cod and haddock (Anon., 2005). The difference between the TS–length relationships in Equations (2) and (4) is, however, significant.

Research on estimating fish TS in situ has been carried out by the Polar Research Institute of Marine Fisheries and Oceanography (PINRO) since 1998 (Ermolchev et al., 1999; Ermolchev, 2000, 2006). These investigations were done using research vessels equipped with Simrad EK300/EK60, 38 kHz scientific echosounders. The LTSD100 software developed at PINRO (Ermolchev et al., 2004), or the FAMAS software developed at the Pacific Research Institute of Marine Fisheries and Oceanography (TINRO; Nikolayev and Ubarchuk, 2004), or the Simrad B60 post-processing software was used for post-processing the raw echosounder data during TS analysis. This paper presents the results of in situ TS measurements on cod done in the Barents Sea from 1998 to 2007 and describes the daily and seasonal variations of cod TS observed at different depths.

### Table 1. Examples of cod in situ mean TS (TS) estimates in the Barents Sea from a comparison of trawl catches with acoustic registrations in the active fishing zone.

<table>
<thead>
<tr>
<th>Date</th>
<th>Number of echoes</th>
<th>Mean TS (TSmean, dB)</th>
<th>Minimum TS (TSmin, dB)</th>
<th>Maximum TS (TSmax, dB)</th>
<th>Standard deviation (STD, dB)</th>
<th>Time of day</th>
<th>Depth of the fishing zone (m)</th>
<th>Mean total length of cod (L_T, cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 February 2003 Night</td>
<td>59</td>
<td>−62.0</td>
<td>−67.0</td>
<td>−55.0</td>
<td>2.9</td>
<td>Night</td>
<td>75</td>
<td>10</td>
</tr>
<tr>
<td>04 November 2004 Day</td>
<td>60</td>
<td>−57.0</td>
<td>−62.0</td>
<td>−55.0</td>
<td>2.9</td>
<td>Day</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>12 October 2007 Day</td>
<td>60</td>
<td>−57.0</td>
<td>−62.0</td>
<td>−55.0</td>
<td>2.9</td>
<td>Day</td>
<td>70</td>
<td>10</td>
</tr>
<tr>
<td>05 December 2007 Night</td>
<td>59</td>
<td>−62.0</td>
<td>−67.0</td>
<td>−55.0</td>
<td>2.9</td>
<td>Night</td>
<td>75</td>
<td>10</td>
</tr>
</tbody>
</table>

**Material and methods**

When conducting in situ TS measurements during conventional acoustic surveys, three important stages are used in applying the method for estimating a representative fish length (Ermolchev, 2006, 2008).

**Stage 1:** During the surveys, data on fish TS are collected over the entire depth range, using scientific echosounders with split-beam transducers and appropriate data-collection and processing software. Trawls are made while simultaneously measuring the TS distribution within the actual fishing zone. The length composition of the insonified fish is determined from the trawl catches, using codends fitted with small-mesh liners to reduce their selectivity.

**Stage 2:** Acoustic and biological data collected are processed. Two methods have been used for this purpose; both have advantages and disadvantages, but they can complement each other to give better TS estimates for each length class. These methods are described below.

First, the TS distribution and the mean TS are estimated within the fishing zone, using the post-processing software. Echo tracks observed within the fishing zone and visually confirmed from their backscattering amplitudes to be single-fish targets are selected for analysis. The TS distribution of cod is distinguished within the overall multimode TS distribution by eliminating data from non-cod targets (the latter are assumed to be smaller objects that have a lower TS than that expected for cod). This is done by visual inspection of the TS distribution and choosing a threshold, $TS_{thr}$ at 1–2 dB less than the minimum TS expected for cod in the smallest size class represented in the catch (Table 1). The mean length $L_T$ of the fish in the catch is also estimated and the TS in the fishing zone is associated with the $L_T$ of the catch. This method allows estimation of TS for fish in the small and medium length classes, i.e. cod from 5 to 70 cm total length.
The second method assumes that the maximum observed TS is associated with the largest fish caught in proximity to the relevant echo tracks. Using the post-processing software, a number of single-fish tracks with near-maximum TS are selected from the echogram of the active fishing zone (Figure 1). The mean greatest TS, $T_{Sm}$, from within an echo track, the standard deviation, $SD_{T_{Sm}}$, and the largest cod in the trawl catch had $L_{Tm} = 123$ cm and weight ($w$) = 20 981 g. The mean greatest TS, $T_{Sm}$, from within an echo track, the standard deviation, $SD_{T_{Sm}}$, and the largest cod in the trawl catch had $L_{Tm} = 136$ cm and weight ($w$) = 26 049 g.

**Figure 1.** Examples of 38 kHz Simrad EK60 echograms of the fishing zone with the tracks of single targets having the greatest TS, selected using BI60 post-processing software. Top panel: $T_{Sm} = -19.8$ dB, $SD_{T_{Sm}} = 1.0$ dB; the largest cod in the trawl catch had $L_{Tm} = 123$ cm and weight ($w$) = 20 981 g. Bottom panel: $T_{Sm} = -17.2$ dB, $SD_{T_{Sm}} = 1.2$ dB, $L_{Tm} = 136$ cm, and $w = 26 049$ g.
Table 2. Examples of cod in situ greatest TS ($T_{Sm}$) estimates in the Barents Sea from a comparison of trawl catches with acoustic registrations in the active fishing zone.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time of day</th>
<th>Depth of the fish track (m)</th>
<th>Maximum total length of cod ($L_{Tm}$ cm)</th>
<th>Mean greatest TS ($T_{Sm}$ dB)</th>
<th>Standard deviation ($SD_{T_{Sm}}$ dB)</th>
<th>Minimum TS in the track (dB)</th>
<th>Maximum TS in the track (dB)</th>
<th>Number of echoes from one track</th>
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<td>Results with only one echo track in the fishing zone</td>
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<tr>
<td>11 December 2004</td>
<td>Day</td>
<td>132</td>
<td>111</td>
<td>-20.2</td>
<td>1.2</td>
<td>-22</td>
<td>-18</td>
<td>10</td>
</tr>
<tr>
<td>03 September 2007</td>
<td>Day</td>
<td>230</td>
<td>100</td>
<td>-22.1</td>
<td>1.3</td>
<td>-27</td>
<td>-20</td>
<td>23</td>
</tr>
<tr>
<td>22 November 2003</td>
<td>Night</td>
<td>200</td>
<td>128</td>
<td>-20.1</td>
<td>2.1</td>
<td>-22</td>
<td>-18</td>
<td>10</td>
</tr>
<tr>
<td>23 October 2004</td>
<td>Night</td>
<td>214</td>
<td>123</td>
<td>-19.8</td>
<td>1.0</td>
<td>-22</td>
<td>-18</td>
<td>19</td>
</tr>
<tr>
<td>25 November 2007</td>
<td>Night</td>
<td>354</td>
<td>136</td>
<td>-17.2</td>
<td>1.2</td>
<td>-24</td>
<td>-15</td>
<td>26</td>
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<td>Results with several echo tracks in the fishing zone</td>
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<tr>
<td>31 October 2004</td>
<td>Night</td>
<td>285</td>
<td>101, 89, 88</td>
<td>-19.8</td>
<td>0.7</td>
<td>-22</td>
<td>-16</td>
<td>9</td>
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<td></td>
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<td></td>
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<td>-21.5</td>
<td>0.9</td>
<td>-23</td>
<td>-20</td>
<td>5</td>
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<td>-21.7</td>
<td>2.5</td>
<td>-28</td>
<td>-18</td>
<td>10</td>
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<td>-21.7</td>
<td>2.1</td>
<td>-26</td>
<td>-17</td>
<td>26</td>
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<td>$&lt;L_{Tm}&gt; = 107.7$</td>
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<td>$&lt;T_{Sm}&gt; = -21.0$ dB, $SD_{T_{Sm}} = 2.1$ dB</td>
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<td>$&lt;T_{Sm}&gt; = -24.9$ dB, $SD_{T_{Sm}} = 0.9$ dB</td>
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<td>$&lt;T_{Sm}&gt; = -23.8$ dB, $SD_{T_{Sm}} = 1.5$ dB</td>
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<td>$&lt;T_{Sm}&gt; = -28$ dB, $SD_{T_{Sm}} = 2.8$ dB</td>
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<td>$&lt;T_{Sm}&gt; = -28$ dB, $SD_{T_{Sm}} = 2.8$ dB</td>
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<td></td>
<td>$&lt;T_{Sm}&gt; = -22$ dB, $SD_{T_{Sm}} = 1.3$ dB</td>
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</tbody>
</table>
for each track and the mean standard deviation, SD\(_{TSm}\), over all the selected tracks are estimated. From the chosen tracks, values of \(TS_m\) within SD\(_{TSm}\) of the greatest \(TS_m\) are selected. \(<TS_m>\) is the mean of these values. The corresponding fish in the catch are those from the maximum length, \(L_{TM}\), down to a lower limit, as determined by SD\(_{TSm}\). The mean length of these fish is denoted \(<L_{TM}>\) (Table 2). An analysis of echo tracks from cod, with TS ranging from 50 to 136 cm, at 50–500-m depths revealed that the TS variations within an echo track might range from 2 to 20 dB, whereas SD\(_{TSm}\) varied from 0.7 to 3 dB, with a mean SD\(_{TSm}\) of \(\sim 2\) dB. By inverting Equation (2) and considering length classes per 5 cm intervals, we found that the value SD\(_{TSm}\) = 2 dB corresponded to the following groups: 4–5 length classes (from 40 to 65 cm) for fish with \(L_T = 50\) cm; 6–8 length classes (from 60 to 100 cm) for fish with \(L_T = 80\) cm; and 8–9 length classes (from 80 to 125 cm) for fish with \(L_T = 100\) cm.

If there is only one track in the fishing zone within SD\(_{TSm}\) of \(TS_m\), \(TS_m\) is compared with \(L_{TM}\). If there are several tracks meeting this criterion, \(<TS_m>\) is compared with \(<L_{TM}>\) (Table 2). This method allows us to estimate TS of the largest fish, i.e., cod from 70 cm to the maximum length.

In the single-target measurements by the second method, there is significant uncertainty when comparing \(TS_m\) and \(L_{TM}\) because of the difficulty in correctly pairing the data. However, when the number of paired data is large enough, their averaged statistics allow an acceptable determination of particular TS–length relationships.

It must be emphasized that the second method has the advantage that it is more applicable when fishing commercially, that is, without a small-mesh liner in the codend. It can also be used in mixed-species conditions, when the catch is dominated by one size group, but there are a few larger targets. For instance, when haddock is more abundant than cod, individual cod are larger and therefore their tracks can be easily identified and analysed using the \(TS_m\) data.

**Stage 3:** The TS–length relationships are estimated for all length classes using the acoustic and biological data obtained by

![Figure 2](https://academic.oup.com/icesjms/article-abstract/66/6/1225/690675/1229)

**Figure 2.** Dependencies between the mean in situ TS at 38 kHz of cod with total lengths \((L_T)\) from 50 to 100 cm at depths of 50–100 m (top) and 200–300 m (bottom) in August–September; the day–night difference is \(\Delta TS = 1.5\) dB at depths of 50–100 m and \(\Delta TS = 1.7–1.0\) dB at 200–300 m; open circle, daytime data; filled circle, night-time data.
both above-mentioned methods, namely TS and $L_T$, $L_{Tm}$, in accordance with the methods described by Ricker (1973) and Glantz (1994). The geometrical-mean TS–length linear regressions (GM regression) and the corresponding 95% confidence limits (95% c.l.) are estimated. Doubtful data outside the 95% c.l. are then removed. The variance $\hat{S}_Y^2$ and 95% c.l. for each predictive value, $\hat{Y}$, in the formula $\hat{Y} = A + BX$ (where $Y = TS$ and $X = \log L_T$), are calculated as follows (Ricker, 1973):

\[
\hat{S}_Y^2 = \frac{\sum (Y - \hat{Y})^2 (1 - r^2)}{n - 1} + B^2 (1 - r^2) (X - \bar{X})^2
\]

and

\[
95\% \text{ c.l.} = \hat{Y} \pm t_{5\%} S_Y,
\]

where $r$ is the correlation coefficient, $t_{5\%}$ the Student’s $t$-test coefficient defining the confidence for $p = 0.95$, and $n$ is the number of TS and $L_T$ paired samples.

**Results and conclusions**

Approximately 1000 bottom trawls were made with simultaneous estimation of fish TS distributions in the fishing zone. The TS–length relationships for cod at depths of 50–100, 100–200, 200–300, 300–400, and 400–500 m during the day and at night were determined for surveys in February, May–June, August–September, and October–December.

Seasonal and diurnal variations of cod TS at different depths were estimated by comparing the TS–length relationships for cod of 30–136 cm total length (Figures 2 and 3). For the length range 5–30 cm, the data were insufficient to establish differences in the mean TS at different depths and diel periods.
Table 3. Seasonal and daily variations of cod TS at different depths in the Barents Sea, where \( n \) is the number of paired TS and \( L_T \) samples.

<table>
<thead>
<tr>
<th>Depth of the fish (m)</th>
<th>Day</th>
<th>Night</th>
<th>( \Delta TS )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TS</td>
<td>( n )</td>
<td>TS</td>
</tr>
<tr>
<td>February</td>
<td></td>
<td></td>
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<td>50 – 100</td>
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<td>100 – 200</td>
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<td>200 – 300</td>
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<td>300 – 400</td>
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<td>400 – 500</td>
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<td>May – June</td>
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<td>50 – 100</td>
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<td>100 – 200</td>
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<td>200 – 300</td>
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<td>300 – 400</td>
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<td>400 – 500</td>
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<td>August – September</td>
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<td>400 – 500</td>
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<td>October – December</td>
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<td>50 – 100</td>
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<td>400 – 500</td>
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Mean in situ TS estimations for a mean fish length \( L_T = 80 \text{ cm} \), and the difference \( \Delta TS \) between TS by day and at night (dB).

Figure 4. The key in situ TS–length relationship at 38 kHz for cod with total length from 5 to 136 cm. Top panel: \( \overline{\text{TS}} \) and \( \overline{L_T} \) values of paired samples, \( \overline{\text{TS}_m} \) and \( \overline{L_{Tm}} \) > \( \text{TS} \) > \( \overline{\text{TS}_m} \) values paired samples. Bottom panel: summary of in situ cod TS–length relationships at 38 kHz estimated by Norwegian [Equations (1)–(3)] and Canadian investigators [Equation (4)], and that reported here [Equation (7)].
Over a year, at depths with 50 to 500 m, the cod TS varied by 3.1 dB and it generally decreased with depth (Table 3). The largest day–night difference (ΔTS), 1.0–1.7 dB, was observed at depths of 50–100 and 200–400 m, in August–September (Figure 2, Table 3). The smallest day–night differences were recorded in February, May–June, and October–December when these were <1.0 dB (Figure 3, Table 3). This possibly relates to the great seasonal differences in the transition from day to night in polar latitudes, and consequent effects on the vertical migration of fish.

We conclude that to improve the accuracy of acoustic estimates of cod stocks in different seasons, TS–length relationships should be derived for each season’s diel time and depth, in this manner partitioning the acoustic data. For example, cod TS varied by <0.5 dB at night for depths from 300 to 400 m in February and August–September, at depths from 100 to 500 m in October–December, and during the day at depths from 300 to 500 m in October–December. Consequently, the following TS–length relationship for cod from 5 to 136 cm in length was derived:

\[ TS = 25.2 \log_{10}(L/4) - 74.8; \quad r^2 = 0.94; \quad \text{s.e.} = 1.2; \quad n = 484. \] (7)

or in the standard form: \[ TS = 20 \log_{10}(L/4) - 64.9 \] for \[ L = 77.8 \text{ cm}. \]

The TS–length relationship (7) is suggested as the most significant one, and it should be applied for the stated months, depths, and diel time. Appropriate adjustments can be made to cover other situations. Relationships (4) and (7) are similar, but they clearly differ from the dependencies in Equations (1)–(3), especially for adult fish (Figure 4, bottom). Using relationships (1), (2), or (3), instead of (7), the last of these being considered the most accurate, will probably result in underestimation of cod TS and hence cause an overestimation of the fish biomass, especially in years when adult fish dominate the stock.

References


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