Towards a standard operating procedure for fishery acoustic surveys in the Laurentian Great Lakes, North America

Lars G. Rudstam, Sandra L. Parker-Stetter, Patrick J. Sullivan, and David M. Warner

Rudstam, L. G., Parker-Stetter, S. L., Sullivan, P. J., and Warner, D. M. 2009. Towards a standard operating procedure for fishery acoustic surveys in the Laurentian Great Lakes, North America. – ICES Journal of Marine Science, 66: 1391–1397.

Acoustic surveys are conducted annually in all five of the Laurentian Great Lakes and Lake Champlain to assess forage-fish abundance. The main target species are rainbow smelt (*Osmerus mordax*), alewife (*Alosa pseudoharengus*), and several coregonine species (*Coregonus* spp.). The Great Lakes Fishery Commission sponsored an Acoustic Study Group from 2002 to 2006 to discuss common problems and suggest standardized methods across these lakes. The study group produced a set of recommendations, available as a Great Lakes Fishery Commission Special Publication and on the web, that use *in situ* target strength (TS) to scale volume backscattering. Here, we review these recommendations with special attention to four often-overlooked topics of interest to all acoustic users, namely issues associated with first, the choice of thresholds for both TS and volume-backscattering strength, second, different settings for single-echo detection algorithms for measures of *in situ* TS, third, those taking account of measuring *in situ* TS in dense fish concentrations, and finally, detection limits.

Keywords: alewife, analysis thresholds, detection limits, hydroacoustics, Laurentian Great Lakes, rainbow smelt, standard operating procedures.

Received 22 July 2008; accepted 13 November 2008; advance access publication 10 February 2009.

L. G. Rudstam and P. J. Sullivan: Department of Natural Resources and Cornell Biological Field Station, Cornell University, Fernow Hall, Ithaca, NY 14850, USA. S. L. Parker-Stetter: School of Aquatic and Fishery Sciences, University of Washington, PO Box 355020, Seattle, WA 98195-5020, USA. D. M. Warner: US Geological Survey Great Lakes Science Center, 1451 Green Road, Ann Arbor, MI 48105, USA. Correspondence to L. G. Rudstam: tel: +1 315 633 9243; fax: +1 315 633 2358; e-mail: rudstam@cornell.edu.

Introduction

Acoustic methods have been used for more than three decades to estimate fish abundance in both marine and fresh-water systems (Simmonds and MacLennan, 2005), including early surveys in the Laurentian Great Lakes (Peterson *et al.*, 1976; Heist and Swenson, 1983; Mason *et al.*, 2001). Acoustic surveys are now conducted annually in all five of the Laurentian Great Lakes and Lake Champlain. The target-fish species are the main prey of several salmonid species (*Salmo*, *Salmoides*, *Oncorhynchus*, most lakes) and walleye (*Sander vitreus*, Lake Erie): rainbow smelt (*Osmerus mordax*, all lakes), alewife (*Alosa pseudoharengus*, all lakes except Lake Superior), and coregonines (*Coregonus* spp., Lakes Superior, Michigan, and Huron). Despite having similar target species, assessment methods differ across lakes (Table 1).

Recognizing the need to standardize assessment approaches, the Great Lakes Fishery Commission funded a study group on hydroacoustics from 2002 to 2006. This group comprised acoustic users from academia and from federal, state, and provincial agencies in both Canada and the USA. The group met twice a year, sometimes with invited experts in specific topics. The resulting document (Parker-Stetter *et al.*, 2009), hereafter referred to as the GL-SOP, is available through the Great Lakes Fishery Commission and the USGS Great Lakes Science Center. Most of the material is also available through the website "Acoustics Unpacked—a general guide for deriving abundance estimates from hydroacoustic data" by Sullivan and Rudstam (www.acousticsunpacked.org).

The GL-SOP presents a list of recommendations for the analysis of acoustic-survey data in the Great Lakes (Table 2). These recommendations are based on the approach of scaling area- or volume-backscattering coefficients (s_a or s_v) with the *in situ* mean backscattering cross section. This parameter is σ_{bs}, which is often given as the target strength (TS) through $\mathrm{TS} = 10 \log_{10} \sigma_{\mathrm{bs}}$ (dB re 1 m^2); in this paper, all references to mean TS are based on calculations of mean σ_{bs} transformed to TS for ease of comparison with the literature. There are alternatives to scaling with *in situ* σ_{bs}, including echo counting and scaling with known TS. The latter typically involves calculation of TS from fish sampling and empirical TS functions of fish length. However, echo counting is not possible in most of the Great Lakes because of high fish densities, and scaling with "known TS" adds uncertainty associated with the TS–length regressions, variable tilt angles in the field, and fish sampling with trawls and nets.

Scaling with *in situ* σ_{bs}, also known as *in situ* TS-scaling, requires careful consideration of both the lower threshold on the TS to be included in the calculations and the associated threshold on the volume-backscattering strength ($S_v = 10 \log s_v$). It also requires consideration of potential biases in the *in situ* TS associated with single-echo detection (SED) algorithms and with high fish densities and considerations of the range (depth) limitations of the method. Independent of methods used to derive densities, we also need to consider which approach is most practical for the survey design and the associated analysis of mean and variance. In this paper, we present our recommendations and rationale for analysis thresholds, *in situ* TS detection

Table 1. Frequencies, thresholds, and collection/analysis settings for acoustic surveys in the Great Lakes in recent years.

Lake	Frequency (kHz)	Year started	Beam width (°)	TS/S_v threshold (dB)	Ping rate (pings s^{-1})	Depth layers	ESDU (m)	*In situ* TS settings
Erie	70, 120 (S)	1993	11, 7	−70/−80	0.5	Three layers	800	6 dB, 1.0
Michigan	120, 129 (B)	1991	7	−60/−80	0.5–1	10 m	1 000	6 dB, 0.6
Superior	120 (B)	1996	7	−55/−60	0.5–1	10 m	1 000	12 dB, 2.0
Ontario	120 (S, B)	1992	7	−70/−80	1	2 m	2 000	6 dB, 0.6
Huron	70, 120 (B)	2004	5, 7	−60/−80	0.5–1	10 m	1 000	6 dB, 0.6
Champlain	70 (S), 120 (B)	2001	11, 7	−76/−80	1	Varied	Varied	6 dB, 0.6

B (Biosonics) or S (Simrad) identifies the echosounder manufacturer. All surveys use *in situ* TS to scale area- and volume-backscattering coefficients. Depth layers are the depth intervals used in the analysis; in Lake Erie, these are based on temperature. *In situ* TS settings illustrated are beam compensation (dB, two-way) and s.d. of angle data (mechanical degrees). ESDU is the elementary sampling distance unit used in the analyses. Transmit power is <300 W for Simrad instruments. Biosonics data are collected without power reduction, as recommended by the manufacturer. ESDU, elementary sampling distance unit.

Table 2. Recommended steps for data collection and analysis of acoustic data for fishery assessment in the North American Great Lakes (Parker-Stetter *et al.*, 2009).

1. Choose a survey design based on known fish distributions and survey objectives.
2. Calibrate the echosounder (both S_v and TS) with a standard target and settings used during the survey (pulse duration, power settings, single fish detection, etc.).
3. Test the acoustic equipment with standard vessel speed and use of ancillary equipment (e.g. trawl winches). Record passive acoustic data at standard survey speed.
4. Collect raw data to below the bottom or maximum range of usable data. Recommended collection settings: pulse duration 0.4 ms (0.2–0.6 ms), power setting 300 W or less (Korneliussen *et al.*, 2008), ping rate 0.5–4 pings s^{-1} (the slower rate in deep water), TS_u data collection threshold −100 dB or less for Biosonics ("squared" threshold in the Biosonics software), no lower threshold for Simrad.
5. Base data analysis on raw data. Enter sound speed, absorption coefficient, calibration settings, and transducer depth. Calculate average sound speed and acoustic-absorption coefficient using average temperature in the water column down to the fish layer of interest.
6. Calculate minimum depth to be included in the analysis; this should be at least the transducer depth plus twice the nearfield.
7. Run bottom-detection algorithm and set the backstep 0.5 m above the detected bottom (0.2–1 m acceptable). Visually scrutinize the whole echogram for bad data sections and poor bottom detection. Remove questionable data and redefine bottom as needed.
8. Remove ambient noise by calculating S_v noise at 1 m; subtract noise from data. Note that noise levels at 1 m expressed in TS_u or S_v are related but not identical. Alternatively, use power samples directly before applying a TVG function. A noise-removal algorithm using subtraction and power samples is included in some software.
9. Run single-echo or target-detection algorithms using initial settings of −75 dB for the lower threshold, −6 dB from the peak value for defining echo duration, 0.6 and 1.5 for the minimum and maximum ratio of echo- and transmitted-pulse lengths, 6 dB for maximum two-way beam compensation (3 dB for one-way beam compensation), and an angle variance of 0.6° (mechanical degrees).
10. Determine depth layers for analysis by inspecting a graph of TS vs. depth. Changes in the TS distribution with depth may indicate different fish species or age groups. Compare TS distribution in different zones of the lake (nearshore, offshore). Choose depth layers that have homogeneous TS distributions. Different depth layers may have to be used in different parts of the lake.
11. Set the minimum TS of interest based on the observed and/or known TS distribution of the fish species of interest. Common values for minimum TS of interest range from −66 to −54 dB.
12. Calculate detection limits for different size groups depending on minimum TS and noise levels (example in text).
13. Set the S_v threshold so that all backscattering from the minimum TS of interest when detected within the beam width is included in the analysis. This is the S_v threshold equivalent to a TS_u threshold 6 dB below the minimum TS. This S_v threshold will be depth-dependent (further details in the text).
14. Choose the elementary sampling distance unit (ESDU), typically 200–1000 m giving 20–50 single-fish echoes in most analysis cells. If the depth layers are shallow, the ESDU might have to be increased to detect enough targets in the analysis cells.
15. Export area-backscattering coefficient (s_a) and mean backscattering cross section (σ_{bs}) for each analysis cell given the selected thresholds.
16. Check for biased *in situ* TS using the N_v index. Use the mean σ_{bs} by depth region to calculate the N_v index. If N_v is >0.1, replace the mean σ_{bs} in that cell with the mean σ_{bs} in surrounding cells or a mean from the appropriate depth layer (see example in the text).
17. Calculate fish density by dividing s_a by the mean σ_{bs} for each analysis cell. This yields a density in number of fish m^{-2} for each analysis cell. The density per unit surface area is obtained by summing over all depth layers in each ESDU (interval, segment).
18. Apportion the acoustic fish density to different fish species. This should be based on temperature profiles, known fish temperature preferences, and catch data.
19. Calculate fish density and species composition in surface and bottom acoustic dead-zones. The report should state whether fish densities in these zones are included in the total estimate and what assumptions were made for density calculations.
20. Calculate average fish density by species for the whole sampling area with appropriate statistics for the survey design used.
21. Determine the uncertainty of the results including all factors known at the time. List the sources of uncertainty included in these calculations, such as errors in calibrations, mean σ_{bs}, and species allocations; describe the method used to calculate sampling variance (e.g. cluster analysis, geostatistics).

parameters, and biases associated with dense fish layers and detection limits. These four issues are seldom discussed in published papers and were identified as needing additional examination by the Great Lakes Study Group. Examples are taken from surveys of alewife and rainbow smelt in the USA and Canada.

Considerations for analysis

Analysis thresholds

A review of the literature indicated that the choice of thresholds varied among users and among surveys for similar target species. In addition, there was no consensus on how an *in situ* TS threshold relates to a S_v threshold. In several published surveys, the same thresholds were applied for both TS and S_v data. Others used a rule of having the S_v threshold 10–20 dB lower than the TS threshold.

We propose that thresholds be based on the minimum expected TS of the fish of interest ($\mathrm{TS}_{\min}$). This is not the same as that obtained from published TS–length functions evaluated for the smallest fish length of interest, because TS is highly directional and therefore highly dependent on tilt angle. As a result, the TS distribution from a single fish can range between 20 and 30 dB (Frouzova *et al.*, 2005; Horne and Jech, 2005). We therefore suggest graphing the whole *in situ* TS distribution down to −70 dB or lower and selecting the lowest expected TS based on this distribution and prior knowledge. As an example, Parker-Stetter *et al.* (2006) demonstrated that most targets in the meta- and hypolimnion were adult rainbow smelt in Lake Champlain and these targets were stronger than −60 dB at 70 kHz. Based on this, they proposed a lower TS limit of −60 dB for this fish group (Figure 1). Similarly, Brooking and Rudstam (in press) established that 98% of targets from 130 mm alewife insonified in a net cage were stronger than −60 dB at both 70 and 120 kHz (Figure 1). Support for this $\mathrm{TS}_{\min}$ for alewife was obtained from the TS distribution from Onondaga Lake in 2005 where alewife (108–164 mm total length) constituted >99% of the catch in vertical gillnets (Figure 1).

After deciding on a $\mathrm{TS}_{\min}$ (e.g. −60 dB), we can derive the appropriate threshold for S_v data, but we first need to clarify the relationship between the S_v and TS values used to construct echograms. Acoustic data are often displayed either as a S_v echogram, also called a 20-log*R* echogram, or as a TS echogram, which is also called an uncompensated TS (TS_u) or 40-log*R* echogram. Note that although the term TS echogram is used, these data are not actual TS values, a property of the fish and incident direction; rather they are the echo amplitudes from which TS can be derived by compensating for target location in the sound beam, and hence the alternative term uncompensated TS or TS_u. Here, we will use TS_u for these data.

The goal of applying thresholds is to include all backscatter from the fish of interest and exclude all backscatter from smaller targets such as bubbles, invertebrates, and smaller fish. Bubbles are a special problem because of resonance. For example, 0.06-mm diameter bubbles resonate at 120 kHz (Lurton, 2002). This can result in volume backscattering above the chosen threshold. However, removing resonant backscatter requires multiple frequencies, which are typically not available in fresh-water applications. We propose choosing a S_v threshold that includes backscatter from all $\mathrm{TS}_{\min}$ targets located within the one-way, half-power beam width, hereafter called "beam width". The corresponding TS_u threshold will be lower than $\mathrm{TS}_{\min}$ when the target is not located at the centre of the beam. The TS_u threshold will be exactly 6 dB lower (3 dB one-way, 6 dB two-way) than $\mathrm{TS}_{\min}$ when the target is at the beam-width angle. With this threshold, all backscatter from a fish at the $\mathrm{TS}_{\min}$ and located within the beam width will be included. Some backscatter from insonified fish outside the beam width will be excluded, and this will cause S_v values to be biased low. However, including smaller targets will bias high the S_v from the fish of interest. All thresholds are a compromise between including wanted and excluding unwanted backscatter.

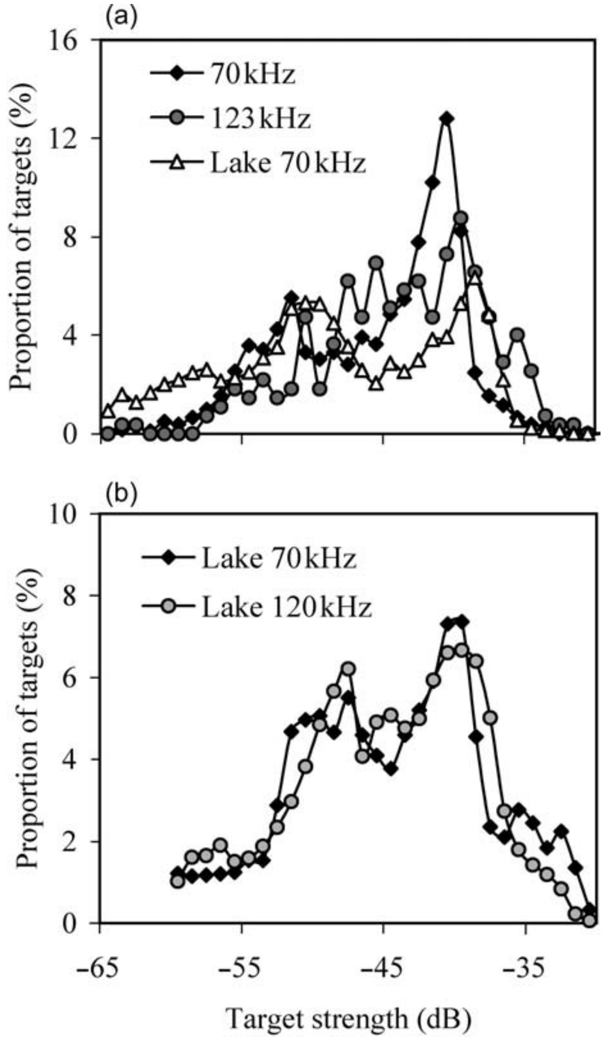

Figure 1. TS distributions for (a) alewife and (b) rainbow smelt. The alewife data are from adults observed in a net cage in July 2005 with both 70 kHz (Simrad) and 123 kHz (Biosonics) units (0.2 ms pulse duration). Field data are from Onondaga Lake, May 2005 (Simrad EY500, 70 kHz, 11.4° beam width, 0.2 ms pulse duration). Rainbow-smelt data are from Lake Champlain in June 2007 (Biosonics DtX, 120 kHz, 7.2° beam width, 0.4 ms pulse duration; Simrad EY60, 70 kHz, 11.4° beam width, 300 W power, 0.256 ms pulse duration).

Once TS_u is determined, the corresponding S_v threshold can be calculated from the relationship between TS_u and S_v. These values are related through the sampling volume that depends on range (R, m), pulse duration (τ, s), sound speed (c, m s^{-1}), and equivalent beam angle (Ψ, sr). Using dB units:

$$\mathrm{TS}_{\mathrm{u},R} = S_{v,R} + 20\,\log R + 10\,\log\left(\frac{c\tau\psi}{2}\right), \tag{1}$$

where $\mathrm{TS}_{\mathrm{u},R}$ is the uncompensated TS, and $S_{v,R}$ is the volume-backscattering strength, both at range R. The S_v threshold

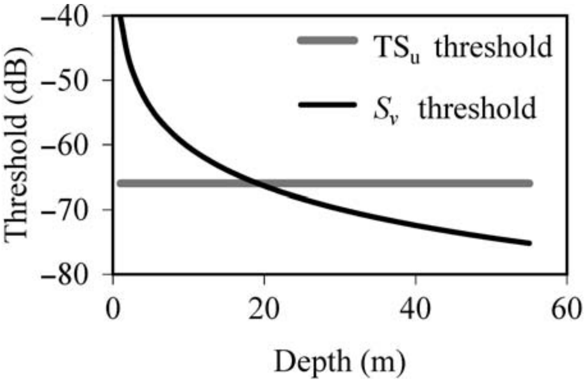

Figure 2. Threshold in the S_v domain corresponding to a constant TS$_u$ threshold of −66 dB (see text).

equivalent to a constant TS$_u$ threshold decreases with range because the sampling volume increases with range (Figure 2). Both Sonar5 (Balk and Lindem, 2007) and Echoview (v4.4, Myriax, 2007) have options to apply a TS$_u$ threshold directly to the S_v data before echo integration; this procedure will result in the correct range-dependent S_v threshold.

The difference between a range-dependent S_v threshold and the commonly applied constant S_v threshold is most obvious in shallow water, because of the non-linear decrease of the sampling volume with depth and the consequent non-linear increase in the S_v threshold. In shallow water, when a fish is present the S_v is high because the sampling volume is small. What we propose is to use this relationship to remove more of the unwanted backscatter from smaller targets in shallow water than is possible with a constant S_v threshold. In an example from Lake Erie, the density of age-0 rainbow smelt in the 2–6-m depth layer was calculated as 0.66 fish m^{-2} with a constant S_v threshold of −110 dB, and as 0.47 fish m^{-2} when applying a range-dependent S_v threshold based on a TS$_{min}$ for age-0 smelt of −66 dB (−72 dB in TS$_u$), a decline of 28%. In deeper water, the difference is much less; the density at 16–20-m depth was only 2% lower with the range-dependent threshold than with the constant threshold. However, because age-0 rainbow smelt were more abundant in shallow water, the overall density in the water column decreased by 17% when the appropriate thresholds were applied. In many lakes, fish occur close to the surface (e.g. Kubecka and Wittingerova, 1998; Knudsen and Sægrov, 2002) where smaller targets than the fish of interest can contribute substantially to S_v, causing bias in the overall fish density. Therefore, we recommend using a range-dependent S_v threshold for fresh-water surveys.

In situ TS algorithms

In situ TS depends on the SED algorithms, correct angle detection within the beam and the beam-compensation algorithm (Ona and Barange, 1999). Ideally, the SED algorithm should remove echoes from multiple fish from the distribution of *in situ* TS. These algorithms include (i) limits on the ratio of echo- and transmitted-pulse lengths, (ii) the s.d. of the angle determinations from the samples within the echo pulse (SD$_{angle}$), and (iii) the angle of the target from the centre of the beam (Soule *et al.*, 1996; Ona and Barange, 1999). The effect of these settings will vary among lakes and survey conditions, which complicates standardizations. For an alewife population of mainly age-3 fish (Onondaga Lake, New York, in 2005, data collected with a 70 kHz Simrad EY500 echosounder with 11.4° beam width and 0.2 ms pulse duration), the mean *in situ* TS was most sensitive to SD$_{angle}$. Mean TS increased from −42.55 dB for SD$_{angle}$ = 0.6° to −41.73 dB for SD$_{angle}$ = 5° (Table 3). This difference (0.82 dB) is equivalent to a 20% change in the estimated fish abundance. Mean *in situ* TS also increased with higher beam compensation (Table 3), but this difference was small. For the 2005 Onondaga Lake survey, the mean TS was −42.58 dB with 3 dB beam compensation and −42.41 dB with 12 dB beam compensation (at SD$_{angle}$ = 0.6°); a difference of 0.17 dB and a 4% difference in estimated fish density. The effect of changing the acceptable lower echo-length limit from 0.6 to 0.8 times the initial pulse length was a 0.3 dB decrease in *in situ* TS and the accepted targets decreased sixfold, from 2976 to 466. Decreasing the upper echo-length ratio limit from 1.5 to 1.2 had no effect (Table 3). The maximum TS difference in this case implies a 20% change in estimated fish density; a result of similar magnitude to several other sources of uncertainty associated with acoustic surveys (Simmonds *et al.*, 1992). The GL-SOP recommends a maximum beam compensation of 6 dB, as long as sufficient echoes are obtained (i.e. several hundred), and a maximum acceptable SD$_{angle}$ of 0.6°. A higher SD$_{angle}$ may allow some multiple-fish echoes to pass the SED filter and could also accept more noise spikes as single targets.

In situ TS in dense fish aggregations

When fish are too dense, they cannot be observed individually and *in situ* TS measurements are unreliable. As SED algorithms are not perfect, some echoes are falsely detected as single fish, especially in

Table 3. Mean TS calculated for targets stronger than −60 dB in the 2–10-m depth layer using different SED settings.

Beam compensation (dB)	Angle variance	Minimum echo length	Maximum echo length	Number of targets detected	Mean TS greater than −60 dB (dB)	ΔTS (dB)
3	0.6	0.6	1.5	1 567	−42.58	−0.03
6	0.6	0.6	1.5	2 976	−42.55	0
9	0.6	0.6	1.5	4 177	−42.44	0.11
12	0.6	0.6	1.5	5 235	−42.41	0.14
6	2.0	0.6	1.5	4 815	−41.97	0.58
6	5.0	0.6	1.5	6 172	−41.73	0.82
6	0.6	0.8	1.5	504	−42.86	−0.31
6	0.6	0.8	1.2	466	−42.82	−0.27
6	0.6	0.6	1.2	2 950	−42.55	0

All analyses are based on the same transect data. Data are from a survey with a Simrad 70 kHz echosounder (11.4° beam width, 0.2 ms pulse duration) in Onondaga Lake, May 2005. Data analysis done with EchoView version 4.4, method 1 [equivalent to the Soule *et al.* (1996) algorithm used by Simrad (Myriax, 2007)]. ΔTS is the difference in mean TS for targets greater than −60 dB compared with standard recommended settings (row 2, mean TS of −42.55 dB).

dense aggregations (Soule *et al.*, 1997). Accepting these echoes as valid *in situ* TS measures can lead to a substantial error in mean TS and therefore in fish-abundance estimates. A clear example of this was observed in Lake Erie via a concentration of age-0 rainbow smelt in the thermocline, on 21 July 2006 (Figure 3). The number of small targets declined drastically in the densest area (between 19- and 21-m depth), whereas the number of larger targets increased (Figure 3). We interpret this as an effect of multiple-fish targets being accepted as single targets in the dense region. This conclusion is supported by the absence of similar large targets in the same depth layer in areas with lower densities.

To recognize when fish are too dense to calculate unbiased *in situ* TS data, the GL-SOP recommends that users routinely calculate the Sawada index (N_v, Sawada *et al.*, 1993; see also Gauthier and Rose, 2001), which estimates the average number of fish present in the sampling volume given a random distribution of fish in space. i.e.

$$N_v = \frac{c\tau\psi R^2 \rho_v}{2}, \tag{2}$$

where c, τ, ψ, and R have been defined previously, $c\tau\psi R^2/2$ is the sampling volume (in m^3), and ρ_v the fish density (number of fish m^{-3}). All of these parameters, except ρ_v, are known or easily measured. Density is generally obtained from the ratio of s_v to $\sigma_{\rm bs}$ but that approach is not valid in this case, because the *in situ* mean $\sigma_{\rm bs}$ is biased in dense regions. Therefore, we propose using $\sigma_{\rm bs}$ from surrounding depths where the fish density is lower. For the Lake Erie data in Figure 3, we calculated N_v by assuming that the fish in the dense layer (19–22 m) were the same fish as found at depths above and below this layer (17–18 and 23–24 m). There was a strong correlation between the N_v index and the measured mean TS (Figure 4, $r^2 = 0.85$). We propose accepting the apparent mean *in situ* TS only if $N_v < 0.1$ (Warner *et al.*, 2002; Rudstam *et al.*, 2003), otherwise replacing *in situ* TS in dense regions with a TS value from surrounding areas with lower fish density. In our example from Lake Erie, the estimated density of age-0 rainbow smelt in the 15–22-m depth layer increased from 2.7 fish m^{-2} when using mean TS, without accounting for multiple-fish biases, to 5.0 fish m^{-2} when based on the mean TS from surrounding regions where $N_v < 0.1$.

Detection limits

Detection limits are seldom discussed in fresh-water applications. Signals can only be detected without bias if the signal-to-noise ratio (SNR) is high enough. Because noise varies, spurious noise spikes can be mistakenly attributed to fish if the SNR is too low. Simmonds and MacLennan (2005) suggest that an SNR of 10 dB is adequate for fish assessment, representing a signal that is an order of magnitude higher than the average noise levels. If noise levels do not vary much, signals may be detectable without bias at a lower SNR.

There are two components to consider when determining appropriate SNR: the signal and the noise. We want to detect, without bias, the signal from a single fish with TS$_{\rm min}$ when located within some distance from the acoustic axis. As above, we suggest using the beam width. Within the beam width, TS$_{\rm u}$ is up to 6 dB lower than TS. For a fish with TS of -60 dB, we would need to detect a signal of -66 dB at some reasonable

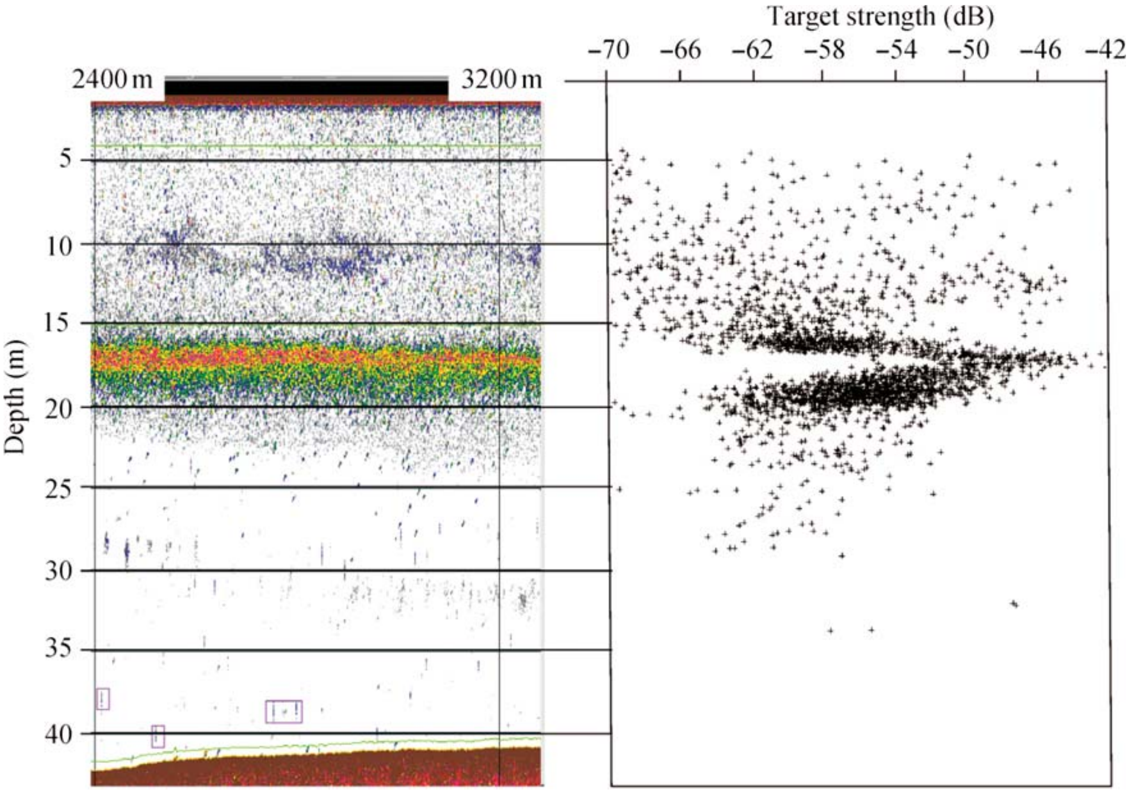

Figure 3. Example of *in situ* TS bias caused by high fish density (rainbow smelt in Lake Erie). Analysis is shown in Figure 4. Data collected by L. Witzel, Ontario Ministry of Natural Resources, and D. Einhouse, New York State Department of Environmental Conservation.

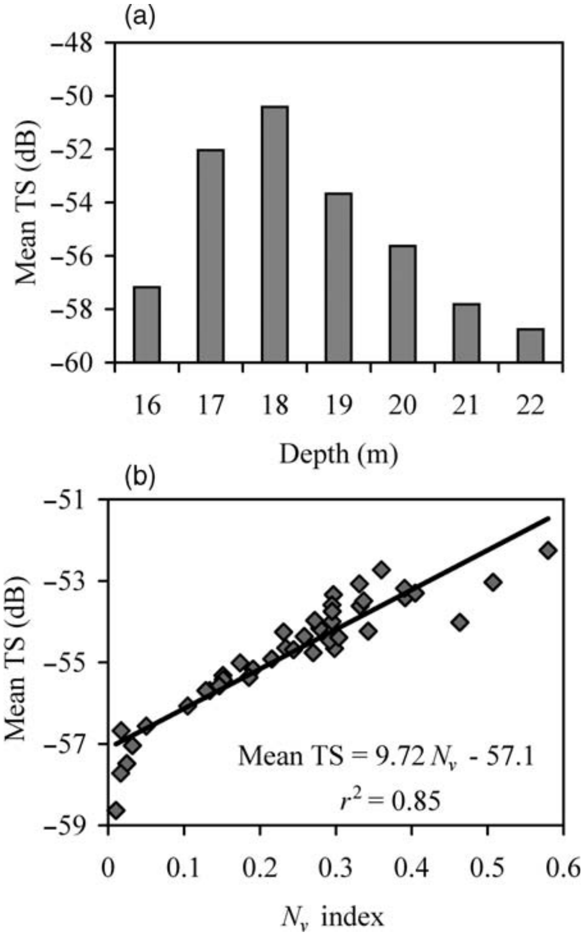

Figure 4. Mean TS as a function of depth for the data in Figure 3 (a) and as a function of the N_v index [b; Equation (2)]. The continuous increase in mean TS with N_v illustrates the bias from multiple targets included in the mean TS calculations. Single-target detection criteria were those recommended in the GL-SOP (Table 2).

SNR (e.g. 3 dB, a factor of 2). In this manner, we can detect fish of this size, without bias, down to a depth where the noise level, after amplification by the TVG, is −69 dB measured as $\mathrm{TS_u}$, i.e. −66 dB signal and an SNR of −3 dB. For *in situ* TS measures, the application of a normalized echo-length criterion at some distance from the peak, typically 6 dB lower, must also be considered. For unbiased *in situ* TS data, we therefore need the noise level to be 6 dB lower, or −75 dB for a minimum TS of −60 dB. The range (R) at which the noise level (in $\mathrm{TS_u}$ units) is −75 dB can be calculated given the noise levels at 1 m ($\mathrm{TS_{u,1}}$):

$$\mathrm{TS_u} = -75 = \mathrm{TS_{u,1}} - 40\log_{10}(R) - 2\alpha R, \tag{3}$$

where α is the acoustic-absorption coefficient in dB $\mathrm{m^{-1}}$. As an example, the noise $\mathrm{TS_{u,1}}$ for a Lake Ontario survey in 2005 was −150 dB (equivalent to $S_v = -125$ dB for this case; Rudstam *et al.*, 2008). The limit for unbiased detection of a −60 dB target at that noise level is 101 m. Noise levels in 2006 were slightly higher ($\mathrm{TS_{u,1}} = -145$ dB) and the limit for unbiased detection of the same target was therefore 58 m in 2006 (Figure 5). As most fish in Lake Ontario are found at depths <60 m, noise levels were acceptable for unbiased target detection for targets stronger than −60 dB in both 2005 and 2006. It must be emphasized that changes in noise levels (in dB) are not linearly related to detection range. Additionally, targets of a given strength (e.g. −60 dB) can be detected in deeper water when they are located closer to the centre of the beam, but the number of such targets detected will be biased low.

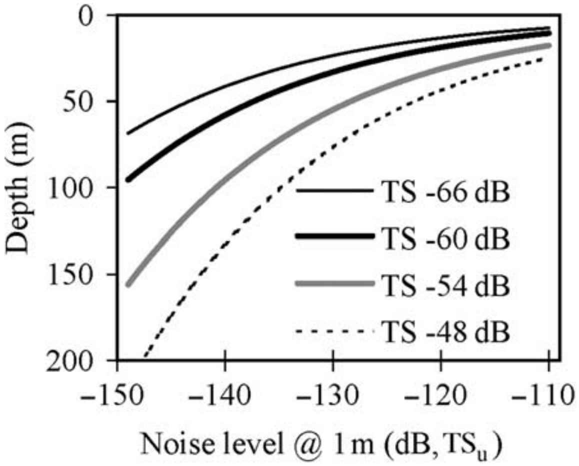

Figure 5. Depth at which fish detection for a given TS becomes biased. These "detection limits" are calculated for four TS values as a function of noise levels at 1-m depth for a 120 kHz echosounder; acoustic absorption calculated for 10°C. The detection limit is assumed to be where the SNR is 3 dB for a target located on the edge of the beam width ($\mathrm{TS_u}$ 6 dB below the minimum TS of interest).

Reports

Acoustic-survey reports typically include information on basic parameters such as beam width, pulse duration, and ping rate, but seldom include a detailed rationale for selecting minimum TS values, the number of areas with $N_v > 0.1$ that can bias *in situ* TS values, and detection limits. To improve comparisons between studies, we suggest that the following information be included in primary reports presenting acoustic data: (i) hardware and software used, including version; (ii) ping rate, pulse duration, field-calibration details, and beam width; (iii) SED parameters and method; (iv) the minimum threshold level that is considered to represent the fish of interest and the method used for noise removal; (v) the noise level at 1 m (S_v preferred); (vi) the detection limit (range) for the smallest fish of interest; (vii) the number of analysis cells with high N_v values; (viii) a graph of representative TS distributions for layers with different TS features or a graph of mean TS vs. depth; (ix) information on decision rules for allocating fish density to different species; (x) mean and variance of the fish density and the calculation method used (geostatistics, cluster analysis, etc.); (xi) estimates of uncertainty, including identification of factors that were included in the estimates; and (xii) a map of the spatial distribution of fish density along transects to illustrate spatial patterns and variability.

Acknowledgements

We thank the members of the study group for stimulating discussion and input to the GL-SOP, specifically D. Mason, T. Schaner, M. Jech, L. Witzel, D. Einhouse, D. Yule, and T. Hrabik, the invited participants (J. Simmonds, J. Horne, H. Balk, F. Knudsen), and the thoughtful reviews of the GL-SOP by H. Balk and I. Higginbottom. This work was supported by a Great Lakes Fishery Commission grant to LGR and Doran Mason, and by New York Sea Grant project R/CE funded under award NA16RG1645 from the National Sea Grant College Program of the US Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) to the Research Foundation of State University of New York on behalf of New York Sea Grant. Contribution #263 from the Cornell Biological Field Station.

References

Balk, H., and Lindem, T. 2007. Sonar4 and Sonar5-Pro Post Processing Systems. Operator Manual, version 5.9.7. Balk and Lindem Ltd, Oslo, Norway.

Brooking, T. E., and Rudstam, L. G. Hydroacoustic target strength distributions of alewife in a net cage compared to field surveys: deciphering target strength distributions and effect on density estimates. Transactions of the American Fisheries Society, in press.

Frouzova, J., Kubecka, J., Balk, H., and Frouz, J. 2005. Target strength of some European fish species and its dependence on fish body parameters. Fisheries Research, 75: 86–96.

Gauthier, S., and Rose, G. A. 2001. Diagnostic tools for unbiased *in situ* target strength estimation. Canadian Journal of Fisheries and Aquatic Sciences, 58: 2149–2155.

Heist, B. G., and Swenson, W. A. 1983. Distribution and abundance of rainbow smelt in western Lake Superior as determined from acoustic sampling. Journal of Great Lakes Research, 9: 343–353.

Horne, J. K., and Jech, J. M. 2005. Models, measures, and visualizations of fish backscatter. *In* Sounds in the Sea. From Ocean Acoustics to Acoustical Oceanography, pp. 374–397. Ed. by H. Medwin. Cambridge University Press, Cambridge, UK.

Korneliussen, R. J., Diner, N., Ona, E., Berger, L., and Fernandes, P. G. 2008. Proposals for the collection of multifrequency acoustic data. ICES Journal of Marine Science, 65: 982–994.

Knudsen, F. R., and Sægrov, H. 2002. Benefits from horizontal beaming during acoustic survey: application to three Norwegian lakes. Fisheries Research, 56: 205–211.

Kubecka, J., and Wittingerova, M. 1998. Horizontal beaming as a crucial component of acoustic fish stock assessment in freshwater reservoirs. Fisheries Research, 35: 99–106.

Lurton, X. 2002. An Introduction to Underwater Acoustics: Principles and Applications. Springer Verlag, London, UK.

Mason, D. M., Goyke, A., Brandt, S. B., and Jech, J. M. 2001. Acoustic fish stock assessment in the Laurentian Great Lakes. *In* The Great Lakes of the World Food-Web, Health and Integrity, pp. 317–340. Ed. by M. Munawar, and R. E. Hecky. Backhuys Publishers, Leiden, The Netherlands.

Myriax 2007. Echoview 4.4. Myriax Ltd, Hobart, Tasmania, Australia.

Ona, E., and Barange, M. 1999. Single target recognition. *In* Methodology for Target Strength Measurements (with Special Reference to *In Situ* Techniques for Fish and Mikronekton). Ed. by E. Ona. ICES Cooperative Research Report, 235: 28–43.

Parker-Stetter, S. L., Rudstam, L. G., Stritzel-Thomson, J. L., and Parrish, D. L. 2006. Hydroacoustic separation of rainbow smelt (*Osmerus mordax*) age groups in Lake Champlain. Fisheries Research, 82: 176–185.

Parker-Stetter, S. L., Rudstam, L. G., Sullivan, P. J., and Warner, D. M. 2009. Standard operating procedures for fisheries acoustic surveys in the Great Lakes. Great Lakes Fisheries Commission Special Publication, 2009-01.

Peterson, M. L., Clay, C. S., and Brandt, S. B. 1976. Acoustic estimates of fish density and scattering function. Journal of the Acoustical Society of America, 60: 618–622.

Rudstam, L. G., Parker, S. L., Einhouse, D. W., Witzel, L. D., Warner, D. M., Stritzel, J. L., Parrish, D. L., *et al.* 2003. Application of *in situ* target strength estimations in lakes: examples from rainbow-smelt surveys in Lakes Erie and Champlain. ICES Journal of Marine Science, 60: 500–507.

Rudstam, L. G., Schaner, T., Gal, G., Boscarino, B. T., O'Gorman, R., Warner, D. M., Johannsson, O. E., *et al.* 2008. Hydroacoustic measures of *Mysis relicta* abundance and distribution in Lake Ontario. Aquatic Ecosystem Health and Management, 11: 355–367.

Sawada, K., Furusawa, M., and Williamson, N. J. 1993. Conditions for the precise measurement of fish target strength *in situ*. Journal of the Marine Acoustical Society of Japan, 20: 73–79.

Simmonds, E. J., Williamson, N. J., Gerlotto, F., and Aglen, A. 1992. Acoustic survey design and analysis procedures: a comprehensive review of current practice. ICES Cooperative Research Report, 187.

Simmonds, E. J., and MacLennan, D. N. 2005. Fisheries Acoustics. Theory and Practice, 2nd edn. Blackwell, Oxford, 437 pp.

Soule, M., Barange, M., Solli, H., and Hampton, I. 1997. Performance of a new phase algorithm for discriminating between single and overlapping echoes in a split-beam echosounder. ICES Journal of Marine Science, 54: 934–938.

Soule, M., Hampton, I., and Barange, M. 1996. Potential improvements to current methods of recognizing single targets with a split-beam echo-sounder. ICES Journal of Marine Science, 53: 237–243.

Warner, D. M., Rudstam, L. G., and Klumb, R. A. 2002. *In situ* target strength of alewives in freshwater. Transactions of the American Fisheries Society, 131: 212–223.

doi:10.1093/icesjms/fsp014