STANDARD OPERATING PROCEDURES FOR FISHERIES ACOUSTIC SURVEYS IN THE GREAT LAKES

Great Lakes Fishery Commission

SPECIAL PUBLICATION 09-01

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January 2009

STANDARD OPERATING PROCEDURES FOR FISHERIES ACOUSTIC SURVEYS IN THE GREAT LAKES

Prepared for the Study Group on Fisheries Acoustics in the Great Lakes, Great Lakes Fishery Commission

Sandra L. Parker-Stetter[1], Lars G. Rudstam[2], Patrick J. Sullivan[3], David M. Warner[4]

Citation: 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 Fish. Comm. Spec. Pub. 09-01.

Great Lakes Fishery Commission
2100 Commonwealth Blvd., Suite 100
Ann Arbor, MI 48105-1563

January 2009

ISSN 1090-1051

[1]**S.L. Parker-Stetter**. School of Aquatic and Fishery Sciences, University of Washington, Box 355020, Seattle, WA, 98195-5020, U.S.A. (e-mail: slps@u.washington.edu).

[2]**L.G. Rudstam**. Department of Natural Resources and the Cornell Biological Field Station, Cornell University, 900 Shackelton Point Road, Bridgeport, NY, 13030, U.S.A. (e-mail: lgr1@cornell.edu).

[3]**P.J. Sullivan**. Department of Natural Resources, Cornell University, Fernow Hall, Ithaca, NY, 14850, U.S.A. (e-mail: pjs31@cornell.edu).

[4]**D.M. Warner**. USGS Great Lakes Science Center, 1451 Green Road, Ann Arbor, MI, 48105, U.S.A. (e-mail: dmwarner@usgs.gov).

Printed on recycled paper.
SP09-01/01-2009/900

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1. INTRODUCTION

1.1 Background on the Study Group on Fisheries Acoustics in the Great Lakes

The Study Group on Fisheries Acoustics in the Great Lakes (hereafter, Study Group) was formed in 2002 through a grant from the Great Lakes Fishery Commission (GLFC). Members of the Study Group were from agencies and institutions associated with all the Great Lakes and Lake Champlain, as well as experts working with marine acoustics. The Study Group had two primary tasks. The first task was to hold workshops on acoustics in the Great Lakes to introduce agency biologists and scientists to the advantages of acoustic-survey methodology. Workshops were held at the Cornell University Biological Field Station in Bridgeport, New York, and at the U.S. Geological Survey, Great Lakes Science Center (USGS/GLSC) in Ann Arbor, Michigan, during 2002-2006. The workshop in 2002 reviewed acoustics surveys in the Great Lakes. The 2003 workshop focused on survey design (with John Simmonds, Fisheries Research Services Marine Laboratory, Aberdeen, Scotland). The workshop in 2004 focused on target strength (with John Horne, University of Washington, Seattle, Washington, U.S.A.). The workshop in 2006 focused on multi-frequency analysis (with Frank Knudsen, Simrad and Helge Balk, University of Oslo, Norway). In addition, we organized a symposium on fisheries acoustics in the Great Lakes at the International Association for Great Lakes Research annual meeting in Ann Arbor, Michigan, in 2005. The second Study Group task, which resulted in this document, was to develop standard operating procedures (SOPs) for collecting, processing, and analyzing acoustic data collected in the Great Lakes. At present, many of the procedures used in fisheries acoustic surveys vary among the Great Lakes. The Study Group felt that documentation of these procedures and recommendations for their standardization were needed. Our recommendations are based on discussions at the workshops and reviews by members of the Study Group, Ian Higginbottom at Myriax (Echoview), and Helge Balk at the University of Oslo (Sonar5). The Study Group was organized by Lars Rudstam (Cornell University) and Doran Mason (National

Oceanographic and Atmospheric Association (NOAA), Great Lakes Environmental Research Laboratory) and included members from all the Great Lakes and Lake Champlain, as well as experts working with marine acoustics from the National Marine Fisheries Service (NMFS) (Michael Jech and William Overholtz) (Appendix). We are grateful to all participants and reviewers for suggestions that improved the text. Funding was provided by the GLFC with additional support from New York Sea Grant and from the USGS/GLSC.

This Great Lakes SOP should be updated, as needed. Current and older versions are available through the USGS/GLSC website in Ann Arbor and supported by Dr. David Warner. The link for that site is http://www. glsc.usgs.gov/main.php?content=research_DWS_acrosslakes_acousticS OP&title=Across%20Lakes0&menu=research_DWS_acrosslakes.

We also recommend using the website www.acousticsunpacked.org that is maintained by P. Sullivan and L. Rudstam and housed at Cornell University. This website includes small programs to use the examples presented in this SOP. Some of the procedures presented in this document are unique to the Great Lakes, whereas some are modifications of acoustic SOPs developed in 2003 by the NOAA/NMFS science centers and published as "NOAA Protocols for Fisheries Acoustics Surveys and Related Sampling" (Advanced Sampling Technologies Working Group 2003).

1.2 Great Lakes Basin Acoustic Surveys

The goal of fisheries acoustic surveys in the Great Lakes is to provide estimates of species-specific biomass and abundance of forage fish (primarily alewife (*Alosa pseudoharengus*), rainbow smelt (*Osmerus mordax*), and coregonines (*Coregonus* spp.). Acoustic surveys are currently being conducted on all of the Great Lakes and some inland lakes, including Lake Champlain. Techniques and equipment reflect differences among the surveys with respect to target species and agency assessment goals, as well as site-specific history of equipment availability.

1.2.1 Lake Ontario

The Lake Ontario acoustic program began in 1992. Target species are alewife and rainbow smelt. The New York State Department of Environmental Conservation research vessel (RV) “Seth Green” (50’ length) is the current survey vessel, although, in the past, chartered commercial vessels were used. Acoustic equipment used in 2006 was a BioSonics DtX 120 kHz split-beam echosounder on a towed body and Echoview software. A 120 kHz EY500 split-beam Simrad echosounder and a 420 kHz dual-beam BioSonics echosounder were used in the past.

1.2.2 Lake Erie

The Lake Erie acoustic program began in 1993 and the current survey design has been used since 1998. Rainbow smelt is the primary target species. The acoustic-survey vessel is the Ontario Ministry of Natural Resources RV “Erie Explorer” (62’ length). Acoustic equipment used in 2006 was a pole-mounted Simrad EY60 120 kHz split-beam echosounder and Echoview software. A 120 kHz split-beam Simrad EY500 echosounder and a 70 kHz single-beam Simrad EY-M echosounder were used in the past.

1.2.3 Lake Huron

Annual acoustic surveys in Lake Huron began in 2004. Surveys have been conducted from the USGS/GLSC RV “Sturgeon”(100’ length), the USGS/GLSC RV “Grayling” (75’ length), and the Michigan Department of Natural Resources (DNR) RV “Steelhead” (67’ length). Target species are alewife, rainbow smelt, bloater (*C. hoyi*), threespine stickleback (*Gasterosteus aculeatus*), and cisco (*C. artedi*). Acoustic equipment used in 2006 was a BioSonics DtX 70 kHz split-beam echosounder on a towed body and Echoview software.

1.2.4 Lake Michigan

Annual acoustic surveys in Lake Michigan began in 1991. The USGS/GLSC RV “Sturgeon” (100’ length) and the Michigan DNR RV “Steelhead” (67’ length) are used for the surveys, but the USGS/GLSC RV “Kiyi” (107’ length) has also been used. Target species are alewife, rainbow smelt, bloater, threespine stickleback, and cisco. Acoustic equipment used in 2006 was a BioSonics DtX 120 kHz split-beam echosounder deployed with a sonar tube or hull mounted and Echoview software.

<u>1.2.5 Lake Superior</u>

Regular acoustic surveys in Lake Superior began in 1996. Initial surveys were conducted using the University of Minnesota-Duluth's RV "Blue Heron" (86' length). All recent surveys have been done by the USGS/GLSC using the RV "Kiyi" (107' length). Target species are rainbow smelt, cisco, bloater, and kiyi (*C. kiyi*). A BioSonics DtX 120 kHz split-beam echosounder on a towed body and Echoview software have been used since 2005.

<u>1.2.6 Lake Champlain</u>

The Lake Champlain acoustic program began in 1993 and was expanded in 2004. The target species is rainbow smelt. Although the historical focus was on yearling and older rainbow smelt, the 2004 assessment also included young-of-the-year (YOY) rainbow smelt and the alewife that has recently invaded the lake. Surveys are currently conducted on the Vermont Fish and Wildlife Department RV "Doré" (31' length). The University of Vermont RV "Melosira" (45' length) was used previously. Acoustic equipment used in 2006 was a BioSonics DtX 120 kHz split-beam echosounder on a towed body and Echoview software. A 200 kHz Simrad single-beam echosounder and a 70 kHz Simrad split-beam echosounder have been used in the past.

2. SUMMARY OF STANDARD OPERATING PROCEDURES

This summary assumes use of a split-beam echosounder (likely a BioSonics or Simrad unit using a frequency of 120 or 70 kHz), and a data-processing software package, such as Echoview (EV) or Sonar5 (S5). Numbers in parentheses refer to sections in this document.

In preparation for an acoustic survey, the following steps should be taken:

1. Choose a deployment method (4.4).
2. Choose a survey design (5).
3. Calibrate the echosounder in both S_v and target strength (*TS*) domain with settings used during the survey (pulse duration, power settings) (6).
4. Run the acoustic equipment during standard operating speed and use of other onboard equipment (e.g., trawl winches) to look for noise and spurious echoes, as well as performance of towed bodies and pole mounts. Attempt to minimize noise (8.6).
5. Record passive data during standard survey speed (8.7).
6. Consider collecting stationary data to test for bubbles and get a range of *TS* values from single fish (8.4).

During data collection, there are a number of collection settings that cannot be changed later during analysis. These settings are listed here with suggested values:

1. Collect raw data to below the bottom or maximum range of usable data (8.2).
2. Set pulse duration to 0.4 msec (0.2 to 0.6 msec is acceptable; 0.256 or 0.512 msec on Simrad) (7.2).
3. Set power to 300 W or lower for Simrad; default for BioSonics (7.4). If operating at higher frequencies than 120 kHz, use lower power settings.

4. Set the ping rate slow enough to avoid shadow bottom (0.5-4 pings•sec^{-1}) (7.2).
5. Set the collection threshold to -100 dB or lower (squared threshold in BioSonics) (7.2).
6. There are a number of other collection settings for Simrad and a few more for BioSonics; these settings are not critical, because they can be changed during data analysis (7.6).

SOPs for data analysis (also referred to as post-processing) are listed next. The order of implementation varies somewhat among analysis programs. Statements related to Echoview (Myriax, SonarData) are designated with EV, statements related to Sonar5 (Balk and Lindem 2000, 2007) with S5. When using S5, follow the "Biomass estimation guide for vertical mobile lake surveys" tool (Analysis/SGA) that is based on this document.

1. Enter sound speed, absorption coefficient, and system calibration settings (9.1.2). Calculate the average sound speed and absorption coefficient using the software calculator, given the depth of the fish of interest and the measured temperature gradient.
2. Adjust transducer depth. Add the depth of the transducer so all depths are relative to the surface
3. Synchronize time. If multiple echosounders are used, make sure the times and depths are synchronized. Time synchronization can be achieved by aligning a distinguishable point on the echograms from both units.
4. Add a surface exclusion line (9.1.3). Add a surface line at a depth of at least twice the transducer near-field and exclude data above that line. Larger surface exclusion zones may be needed if there is a lot of surface noise. Note that the surface line should encompass the near-field and the depth of the transducer.

5. Detect and correct the bottom (9.1.4). Run the bottom-detection algorithm of your software using default parameters. The bottom line should be set slightly higher than the detected depth to avoid including data from the bottom dead zone and poorly defined bottoms. We suggest 0.5 m (0.2 to 1 m is acceptable). Inspect all data for accurate bottom detection and redefine, as needed.
6. Scrutinize echograms for bad data and remove from the analysis (9.1.5). Mark (EV) or erase/threshold (S5) bad-data regions and exclude from the analysis. Note that the assumption about fish density in bad-data regions is important if these regions are large.
7. Remove ambient noise (9.1.5). Calculate noise at the 1-m depth in the S_v domain. Remove noise by applying the noise-subtraction algorithm (S5) or by integrating noise and subtracting it from the data after data export (EV). Noise at 1 m is different for *TS* and S_v data, but noise can be calculated from each other.
8. Extract *TS* data from single-echo detection (9.2). Run single-echo or target-detection algorithms. Use the same method when measuring *TS* of the calibration ball (EV). This step is done in the initial conversion step in S5. Suggested initial settings are -75 dB for lower threshold, 0.6 and 1.5 for minimum and maximum pulse-duration multiplier, determination of echo length at -6 dB from peak value, 6 dB for maximum beam compensation (2-way (EV), 3 dB for 1-way (S5)), and a maximum phase deviation of 0.6 in both directions (mechanical degrees).
9. Study the *TS* distribution at different depths (9.4). Use the *TS* versus depth graph (e.g., Fig. 16). Note that changes in *TS* distribution with depth may indicate a change in fish species or age-group composition or a bias related to the sampling volume and number of targets. Compare *TS* distribution in different zones of the lake (nearshore, offshore). Define depth layers for analysis based on this *TS* graph. The data should be analyzed in depth layers with fish species and size structure as homogeneous as possible. Different depth layers may have to be used in different regions of the lake.

10. Set the minimum *TS* of interest (9.4.2 and 9.4.3). Based on the measured *TS* distribution and/or known *TS* distribution of the fish species of interest, set the minimum *TS*. Check the *TS* distribution down to -75 dB to see if smaller targets are likely to be included in this range. Common values for minimum *TS* of interest range from -65 to -5 dB, but this depends on the species and age-class of that species.
11. Set the integration threshold (9.4.4). The integration threshold should be set to 6 dB below the minimum *TS* threshold (in the *TS* domain) to account for observations of all targets above the minimum *TS* within the half-power beam width. Set this threshold in the Amp echogram representing $40 \bullet \log_{10}(R)$ data (S5) or use the minimum *TS* threshold in the S_v echograms (EV, version 4.4 and greater). Include any difference between calibration in S_v and *TS* (EV). If it is not possible to set a *TS*-based threshold for integration, choose a lower S_v threshold of -80 dB.
12. Calculate the detection limit (3.6, 9.1.5). Calculate the depth for which detection of the minimum *TS* of interest is unbiased. This depth depends on the signal-to-noise ratio and the size of the targets.
13. Choose the size of the analysis cell (9.3). This should include 20 to 50 single-fish echoes in most cells. We suggest 200- to 500-m long horizontal bins. Depth (also referred to as “range”) layers need to be chosen given the fish distributions (see step 10). Integration bins can be shorter if fish are abundant or longer if few fish are present. If the depth layers are small, the horizontal distance may need to be increased to get a sufficient number of targets in the analysis cells.

14. Export integration and *TS* data (9.5). S_v and *ABC* are obtained from the Amp echogram (S5) or the S_v echogram (EV). *TS* distribution and mean σ_{bs} are obtained from the single-target-detection echogram if using EV or from the SED echogram if using S5. Apply the lower *TS* of interest (e.g., -60 dB) as the lower data threshold. EV requires 3 separate export runs (for S_v, mean *TS*, and *TS* distribution). Merge these data in a database. S5 exports all information in several table formats.
15. Check for bias in *in situ TS* (10.2). Test if *in situ TS* can be used for density estimates in each analysis cell using the N_v index. Use the average σ_{bs} by depth layer to calculate the N_v index. If N_v is >0.1, replace the average σ_{bs} in that cell with the average σ_{bs} in surrounding cells or an average from the appropriate depth layer.
16. Calculate total fish density (10.3, 10.4). Calculate fish density by dividing *ABC* with mean σ_{bs} for each analysis cell. This calculation yields a density in units of fish•m^{-2} for each depth layer. A density-per-unit surface area is obtained by summing over all layers in each bin. Fish•ha^{-1} is obtained from fish•m^{-2} by multiplying by 10,000. Be careful if using *NASC* to include the 4π term (Table 1).
17. Apportion the acoustic fish density to different fish species (10.5). This is a critical step that should be based on temperature profiles, known temperature preferences of the target species, and the most current catch data. Catch data can be incorporated in S5 to directly export density by fish species. Inspection of *TS* distributions can also help.
18. Make assumptions about fish density and species composition in surface and bottom exclusion zones that are not sampled with acoustics (9.1.4). Decide how to deal with fish present in the surface and bottom exclusion zones (3.6.3). Data reports should be specific about what assumptions are made for these zones and if the choice was to exclude these areas from analysis.

19. Calculate fish density by species (10.4, 10.5). Calculate average fish density by species with the appropriate statistics for the survey design used.
20. Calculate uncertainty (10.6). Calculate uncertainty of the estimate, including all aspects of uncertainty that are known at the time. List the sources of uncertainty included in these calculations, such as uncertainty in calibrations, mean σ_{bs}, and species allocations, as well as the method used to calculate sampling variance (e.g., cluster analysis and geostatistics).

Table 1. Definition of symbols and their associated units presented in this procedure manual for acoustic surveys in the Great Lakes.

Symbol	Definition
a	Transducer active radius (m)
A	Survey area (m^2)
BD	Water column depth (bottom depth, m)
$b(\theta)$ or $B(\theta)$	Transducer directivity defined by angle θ and Φ (linear or dB scale)
c	Sound speed ($m \cdot sec^{-1}$)
D	Cruise track length (Distance, m)
E-lost-down	Acoustic energy lost en route to the target (dB)
E-lost-up	Acoustic energy lost after hitting the target and returning to the transducer (dB)
EL	Echo level of the returned acoustic signal (dB)
f	Frequency (Hz or kHz)
h_{eq}	Height of the bottom deadzone (m)
i	Ping interval (sec)
k	Wave number ($k = 2\pi/\lambda$)
L	Target scattering size (e.g., body length or swimbladder length) (cm or m)
R	Range between two targets or between a target and the transducer (m)
R_{nf}	Near-field range (m)
s^*	The point location (with x- and y-coordinates) used in kriging
s_a, *ABC*	Area backscattering coefficient ($m^2 \cdot m^{-2}$)
s_A, *NASC*	Nautical area backscattering coefficient ($s_A = s_a/(1852)^2 \cdot 4\pi$), unit $m^2 \cdot nmi^{-2}$)
S_a	Area back scattering strength ($S_a = 10 \cdot \log_{10}(s_a)$, dB)
s_v	Volume backscattering coefficient ($m^2 \cdot m^{-3}$)
S_v	Volume back scattering strength ($S_v = 10 \cdot \log_{10}(s_v)$, dB re:1 m^{-1})
SL	The acoustic source level for transmitted acoustic energy (dB)

Table 1, continued.

Symbol	Definition
T	Temperature (ºC)
TL	Transmission loss (in dB)
TS	Target strength ($TS = 10 \cdot \log_{10}(\sigma_{bs})$, dB re:1 m^2)
TS_u	Measured value in the TS echogram (dB). Often referred to as "uncompensated TS."
V	Sampling volume (m^3)
w	Fish mass (g)
W	System transmit power (W)
α	Absorption coefficient ($dB \cdot m^{-1}$ or $dB \cdot km^{-1}$)
ψ *or EBA*	Equivalent beam angle (steradians or dB re: 1 sr)
λ	Wavelength (m)
σ_{bs}	Backscattering cross section (m^2)
$<\sigma_{bs}>$	Average backscattering cross section (m^2)
θ_{3dB}	Beam angle between the two -3 dB points (º)
Λ	Degree of coverage (no units)
ρ_v	Volumetric fish density ($\# \cdot m^{-3}$)
ρ_a	Areal fish density ($\# \cdot m^{-2}$)
τ	Pulse duration (msec or sec)

We also recommend, as a final check of the data, an investigation of any unusually high density estimates against the echogram. This investigation should reveal if there is bottom return included in volume backscattering or some noise problems.

Reports presenting fish density derived from acoustic data should include the following information:

- Hardware and software used, including version
- Ping rates, pulse duration, field calibration information, and beam width
- Single-echo detection parameters
- The minimum threshold level that is considered to represent the fish of interest and the method used for noise removal
- The detection range for unbiased detection of fish of interest.
- The noise level at 1 m (S_v domain preferred) and the detection limit (range) for the smallest size fish of interest
- Information on the number of analysis cells with high N_v values
- A graph of representative *TS* distributions for layers with differences in this distribution; alternatively, provide a graph of *TS* versus depth
- Information on decision rules for allocation of fish density to different species
- Average fish density and method used for calculations of average and variance (geostatistics, cluster analysis, etc.)
- Estimates of uncertainty, including identification of uncertainty factors that were included in the estimates
- Map of the spatial distribution of fish density along transects to visualize spatial patterns and variability

3. ACOUSTIC BACKGROUND

This section provides general background information on concepts relevant to fisheries acoustic surveys. Additional information may be found in acoustic texts, such as Simmonds and MacLennan (2005) and Brandt (1996). MacLennan et al. (2002) describe standard definitions, symbols, and units used in acoustical surveys. Symbols and units used in this manual are presented in Table 1.

3.1 Acoustic Theory and Use

Acoustics is a remote sensing technique with advantages over traditional fish and zooplankton sampling methods that include the ability to sample nearly the entire water column quickly (sound travels approximately 1450 $m \bullet s^{-1}$ in fresh water), to provide continuous areal sampling along a transect, and to provide high data resolution (less than a meter vertically and tens of meters horizontally). Limitations specific to acoustics include difficulty in determining identity of targets, variability in target strength, the inability to sample exclusion zones close to the transducer (near-field) and close to the bottom (bottom dead zone), and the inability to acquire biological data, age, sex, and diet. Fisheries acoustic surveys are typically integrated with other sampling methods, such as net catch and temperature data, to confirm target identity, to obtain biological data, and to estimate abundance.

Echosounders provide data based on the time delay between transmission and reception of the echo and the intensity of the returning echo (echo level). The time delay indicates the range or depth to the target. The echo level is the measure that is translated to abundance of fish in the water column. The echo level depends on the intensity of the transmitted sound (the source level), the loss in intensity as the sound spreads in the water and is absorbed by water (transmission loss), the reflectivity of the target (target strength, *TS*), the position of the target in the beam, and various losses in the echosounder associated with converting sound pressure to an electric voltage. These processes are combined in the SONAR (SOund NAvigation and Ranging) equation. It is necessary to know the different terms in this equation to correctly relate the measured echo level to fish density.

3.2 The SONAR Equation

3.2.1 General Equation

The SONAR equation relates returned energy (*E_return*) to transmitted energy (*E_transmitted*) through the generalized form (in logarithmic units):

(1) *E_return = [E_transmitted – E_lost_down] + E_reflected – [E_lost_up]*

where *E_lost_down* is the acoustic energy absorbed by the water as the beam travels away from the transducer, *E_reflected* is the amount of energy that is reflected by an acoustic target, and *E_lost_up* is the amount of energy that is absorbed by the water as the reflected sound travels from the target back to the transducer.

The full SONAR equation has energy transmission, loss, and reflection components but also accounts for the position of the target relative to the acoustic beam ($B(\theta)$). The equation is simple and takes the form:

(2) $$EL = [SL + B(\theta) - TL] + TS + [B(\theta) - TL]$$

which, by combining terms, is equivalent to:

(3) $$EL = SL - 2TL + TS + 2B(\theta)$$

where *EL* is the returning echo intensity (also referred to as echo level, dB), *SL* is the transmitted sound intensity (dB), *TS* is the reflectivity or target strength of the fish (dB), $B(\theta)$ is the beam directivity (intensity of the sound at angle θ), and *TL* is the transmission loss (dB). The *TL* depends on spreading and absorption. *TL* in one direction is:

(4) $$TL_{1-\text{way}} = 20 \bullet \log_{10}(R) + \alpha R$$

And, in two directions, is twice that, or:

(5) $$TL_{2-\text{way}} = 40 \bullet \log_{10}(R) + 2\alpha R$$

where R is the range to the target (m) and α is the absorption loss (dB•m^{-1}).

Substituting these into Equation 3, the logarithmic version of the SONAR equation becomes:

(6) $$EL = SL - 40 \bullet \log_{10}(R) - 2\alpha R + TS + 2B(\theta)$$.

This equation can also be written in the linear form as:

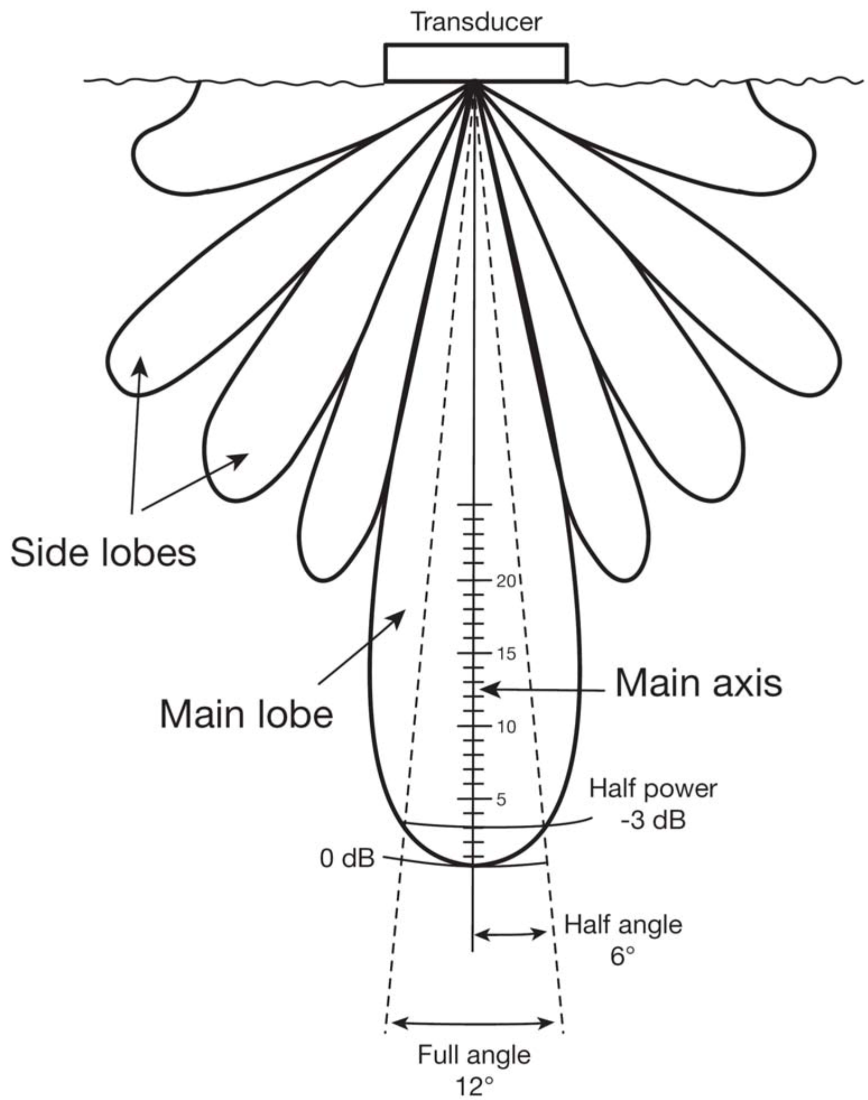
(7) $$I_{EL} = \frac{I_{SL} \bullet \sigma_{bs} \bullet b^2(\theta)}{R^4 \bullet 10^{\frac{2\alpha R}{10}}}$$

where I_{EL} is the intensity of the returning sound, I_{SL} is the intensity of the transmitted sound, σ_{bs} is the back-transformation of *TS* (m^2), b is the back-transformed directivity of the transducer in the direction (θ) of the target, and $R^4 \bullet 10^{\left(\frac{2\alpha \mathrm{R}}{10}\right)}$ is the back-transformation of the *TL*. Note that an addition or subtraction using logarithmic units is equivalent to multiplication and division in un-transformed units.

3.2.2 Beam Width or 3 dB Angle

The beam width or 3 dB angle are equivalent terms that refer to the angle between the lines that represent the half-intensity direction on either side of the main lobe axis, measured in degrees (Fig. 1). If the transducer beam is elliptical, both minor (athwart or transverse) and major (along or longitudinal) values exist. Values for the 3 dB angle are usually provided by the manufacturer and may be obtained during calibration. Some authors use half-beam angle, which is the angle from the center of the beam to the half-intensity direction and, therefore, half of the beam width used here.

Fig. 1. Schematic image of a transducer beam pattern (scaled in dB and reproduced from Johannesson and Mitson (1983)). The full angle is the 3 dB beam angle, which is defined as the angle between the lines that represent the half-intensity direction on either side of the main acoustic axis.



3.2.3 The Equivalent Beam Angle

The equivalent beam angle (ψ in steradians or EBA in dB) is also known as the reverberation angle. This value represents the angle at the apex of the ideal transducer beam (a transducer with beam directivity of 1 within and 0 outside the beam) that gives the same volume backscattering strength (S_v) values as the actual transducer, including side lobes (Simmonds and MacLennan 2005). Equivalent beam angle is defined as:

(8)
$$\psi = \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} b^2(\theta,\phi)\sin(\theta) \bullet d\theta\, d\phi$$

where θ and Φ are spherical polar coordinates used to determine the direction of a point (P) relative to the origin (O) of the transducer, θ is the angle of OP from the acoustic axis, ϕ is the azimuthal angle of OP projected onto the plane of the transducer face, and b is the beam pattern, defined in terms of intensity. The entire beam patterns is used in the integration, from $\theta = 0$ to π and from $\phi = 0$ to 2π. Values for ψ are supplied by some manufacturers and can be modified in analysis software. Some manufacturers report equivalent beam angle in steradians, while others use the dB format. The conversion between the two forms is:

(9)
$$\psi \text{ or } EBA\,(dB) = 10 \bullet \log_{10}(\psi)$$

Values of ψ or EBA can be calculated for a circular transducer with Equation 15. The beam pattern $b(\theta,\Phi)$ is squared to account for both the transmitting and the receiving beam patterns.

3.2.4 Volume Backscattering

The sampling volume is related to the volume of a half sphere in front of the transducer with a thickness of $c\tau/2$, where c is sound speed in water ($m \bullet sec^{-1}$) and τ is pulse duration (sec or msec). All fish within this volume contribute to the measured echo level received at any one time, but their contribution depends on their location in the beam. Therefore, we integrate the beam directivity over the whole half-sphere (Equation 8) to obtain the equivalent beam angle (ψ or EBA). The sampling or reverberation volume (V) also increases with range squared (R^2) due to spherical spreading:

(10) $V = \psi R^2 (c \cdot \tau /2)$

Fish density (ρ) and sampling volume (V) combine to yield the number of fish ($\rho \bullet V$) within the ideal beam that contribute to the volume backscattering. The total volume backscattering is this number of fish multiplied by their average backscattering cross section (σ_{bs}). The volume backscattering coefficient (s_v) is defined as fish density (ρ) multiplied with the average backscattering cross section ($<\sigma_{bs}>$):

(11) $s_v = \rho < \sigma_{bs}>$

Therefore, the total echo level is proportional to ($s_v \bullet V$), which is equivalent to [$s_v \psi R^2 \ (c\tau /2)$]. Equations 6 and 11 can be combined to calculate the echo intensity from an ensemble of fish (after dB transformations):

$$EL = SL + S_v + 10 \bullet \log_{10}(c\tau/2) + \Psi + 20 \bullet \log_{10}(R) - 40 \bullet \log_{10}(R) - 2\alpha R.$$

Combining terms yields:

(12) $$EL = SL + S_v + 10\bullet \log_{10}(c\tau/2) + \Psi - 20\bullet \log_{10}(R) - 2\alpha R.$$

In these equations, S_v is s_v in dB units (S_v = 10•log$_{10}$(s_v)). The same equation may be written in back-transformed units for the volume backscattering coefficient (s_v):

(13) $$I_{EL} = \frac{I_{SL} \bullet s_v \bullet \psi \bullet (c\tau/2)}{R^2 \bullet 10^{\frac{2\alpha R}{10}}}$$

All values in these equations are known from manufacturer-supplied transducer specifications or calibrations except s_v, which can be calculated. These values are used to translate acoustic data into fish density.

3.3 Acoustic Transducers

Transducers transmit a sound wave that is not uniform in all directions due to constructive and destructive interference patterns—the beam pattern (Fig. 1). Due to the directivity of a transducer, the echo level from an organism will be greater on-axis than off-axis. To measure the *TS* of the organism, the echo level must be compensated for the location of the organism in the acoustic beam. This compensation can be done with statistical analysis of single-beam data and directly from the phase deviation and beam pattern in split-beam transducers.

3.3.1 Beam Pattern

All transducers should have a measured beam pattern showing the magnitude of the main lobe and associated side lobes. Performed by the manufacturer, these transducer-specific measurements also provide measures for Ψ (equivalent beam angle) and the 3 dB angle used in data collection and processing. The active radius (a) of a circular transducer, the half-intensity beam angle (θ_{3dB}), and the equivalent beam angle (Ψ) are related and can be calculated from each other through the following equations (when ka>10):

(14) $$a = \frac{1.6}{k \bullet \sin(\frac{\theta_{3\text{dB}}}{2})}$$

where θ_{3dB} is the half-power beam angle (º), k is the wave number [$k = \frac{2\pi}{\lambda}$] and λ is the wavelength (m) and:

(15) $$\psi = \frac{5.78}{(ka)^2} \text{ in steradians, or } \psi = 10 \bullet \log_{10}\left(\frac{5.78}{(ka)^2}\right) \text{ in dB}$$

3.3.2 Near-Field and Far-Field

Transducers have both near-field and far-field regions. Within the near-field, wave fronts produced by the transducer are not parallel, and the intensity of the wave oscillates with range. For that reason, echo levels from targets within the near-field region can vary greatly with small changes in location, which invalidates the beam-pattern corrections and the equivalent beam angle. Once in the far-field, wave fronts are nearly parallel, and intensity decreases with range squared. Within the far-field, the beam is properly formed, and echo levels are predictable from standard equations.

3.4 Target Strength

Backscattering cross section σ_{bs}, or *TS* when expressed in dB, is an important scalar for converting s_v measurements to absolute numbers. In the Great Lakes, *in situ* σ_{bs} values, taken from fish observed during the survey, are commonly used as the s_v scaling factor. For that reason, σ_{bs} data must be collected with the goal of gaining a representative distribution. Fish *TS* is primarily dependent on swimbladder size, but also on swimbladder shape and compression, the state of maturity, and the fat content (Ona 1990; Horne 2003). The *TS* is also strongly affected by the orientation of the fish relative to the transducer beam (often referred to as aspect). The aspect depends on behavior, such as vertical migration, swimming, and feeding behavior. In addition, pressure changes during vertical migration can affect *TS*. In the case of fish with swimbladders, maximum *TS* occurs when the major axis of the swimbladder is aligned perpendicular to the transducer beam and decreases significantly as the axis aligns parallel to the beam axis. The *TS* of a fish can vary over 30 dB due to different tilt and roll angles (Reeder et al. 2004; Frouzova et al. 2005). Note that all calculations of fish density should be done with σ_{bs}, including calculations of averages. When referring to mean *TS*, this is the dB transformation of mean σ_{bs} ($<\sigma_{bs}>$).

3.5 Volume Backscattering

Volume backscattering (S_v in dB or s_v in $m^2 \bullet m^{-3}$) is the summation of the backscattering from all targets within a sampling volume scaled to 1 m^3. Total-area backscattering (S_a in dB or s_a in $m^2 \bullet m^{-2}$) is the summation of s_v over all depths and therefore scaled to 1 m^2. S_v is a measure of the density of organisms and the primary measurement for acoustically estimating fish densities and abundance. The volume backscattering coefficient s_v is defined in Equation 11 as $s_v = \rho \bullet <\sigma_{bs}>$, and this equation is the basis for estimating fish density from acoustics.

3.6 Detection Probability

The detection probability is the likelihood of detecting echoes from individual organisms. Single-target detection probability is dependent on the imposed thresholds and the behavior of the organisms. Organism orientation strongly affects *TS*, as does the vertical distribution. Organisms on the edge of the beam will have lower detection probabilities due to the acoustic beam pattern. The echo level from a fish located at the 3 dB beam angle will be 6 dB lower than if the fish is located in the center of the beam (-3 dB for transmitting and -3 dB for receiving the signal in that direction). Organisms near the bottom will have lower detection probabilities due to the bottom dead zone (3.6.3). Organisms close to the surface will not be detected if they are above the depth of the transducer and will give unstable returns if in the near-field. Fish near the surface may also have higher avoidance reactions to the survey vessel (3.6.3).

Uncertainty in detection probabilities of a single fish affects interpretation of S_v measurements and the efficacy of data-analysis techniques. Systematic and random changes in detection probabilities during the survey will have linear and non-linear effects on S_v measurements. A systematic change in fish orientation, for example, from a horizontal to a more-vertical position during vertical migration, will cause a decrease in individual fish *TS* and, therefore, also in S_v. If factors, such as orientation, are not taken into account, it might appear that there are fewer or smaller fish. For that reason, surveys should avoid periods of vertical migration.

3.6.1 Signal-to-Noise Ratio (SNR) and Detection Limits

The echo level (the returning signal) must be higher than the noise level to be detected and to provide interpretable data. This is referred to as the signal-to-noise ratio (SNR). Although noise does not increase with depth, the signal decreases with depth due to spreading and absorption. Therefore, the SNR decreases with depth until the signal is too weak to be reliably separated from noise. This depth defines a detection range for the target size in question. How small the SNR can be depends on the consistency of the noise. As a general rule, Simmonds and MacLennan (2005) suggested a SNR of 10 dB to be acceptable (a factor of 10). At lower SNRs, the chances increase that spurious noise spikes are detected as fish (Simmonds and MacLennan 2005). Noise can change during a survey, and there are methods being developed to dynamically adjust noise levels when analyzing data (DeRobertis and Higginbottom 2007). However, it is important to remember that this method will also change the SNR and, therefore, detection ranges. In practice, an indication of the noise level is obtained by observing the increase in noise levels with depth as it is amplified through the time-varied gain (TVG). We recommend collecting passive data during the conditions of the survey to measure noise level. It is important to know the depth limitations for detecting targets of interest to avoid biased results for fish abundance and distribution.

The depth (or range) limit for unbiased detection of a given target can be calculated given certain assumptions. We want to detect without bias the signal from the smallest target of interest located within some distance from the acoustic axis. A reasonable distance may be the 3 dB beam angle where TS_u (uncompensated *TS*) is 6 dB lower than the *TS* of the target in the center of the beam. For a target having a *TS* of -60 dB, we would need to detect a signal of -66 dB with some confidence (for example, with a SNR of 3 dB, a factor of 2). Therefore, we can detect the volume backscattering (S_v) of this size fish with minimal bias down to a depth where the noise level (after being multiplied by the time-varied gain) is -69 dB (measured as TS_u -66 dB signal and a SNR of 3 dB). The corresponding S_v value can be calculated using Equation 24. For *in situ TS* measures, the application of a criterion for pulse length 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 than -69 dB, or -75 dB. Thus, volume backscattering from a -60 dB fish can be detected with minimal bias in deeper water than where we can detect the *in situ TS* without bias. For a concrete example, the noise TS_u at 1-m depth ($TS_{u,1}$) for the Lake Ontario survey in 2005 was -150 dB (equivalent to a S_v of -125 dB for this unit (Rudstam et al. 2008b)). The limit for unbiased detection of volume backscattering from a -60 dB target at those noise levels is 101 m. Noise levels in 2006 were slightly higher ($TS_{u,1}$ -145 dB), and the limit for unbiased detection of this target was therefore 58 m in 2006. In both years, this unbiased detection limit should be sufficient, as most small fish are found in shallower water in Lake Ontario.

3.6.2 Vessel Noise and Avoidance

All vessels radiate underwater noise. Fish are able to detect this vessel noise over a range of frequencies from tens to at least several hundred Hz and respond by exhibiting avoidance behavior, which reduces their probability of detection (Mitson 1995; Handegard et al. 2003). Avoidance behavior typically occurs when fish are 100-200 m from the vessel, but particularly noisy vessels may elicit avoidance at distances as great as 400 m (Mitson 1995). Vessel lighting and trawling may cause avoidance reactions as well (Ona and Godø 1990). In addition to vessel avoidance, some fish, such as alewife, avoid broadband sound pulses at the frequencies (>100 kHz) used in typical scientific echosounders (Ross et al. 1996).

Fish may react to a survey vessel by swimming away from the vessel or by diving. Horizontal avoidance includes herding, which results when fish respond to the sound field of an approaching vessel by swimming ahead of the vessel on the vessel track. This fish response may occur as fish move into a null in the emitted vessel sound field that exists ahead of the vessel (Aglen 1994). Fish remain in this null until the vessel is visible, at which time they may swim perpendicular to the vessel track to avoid it or they dive vertically (Soria et al. 1996; Vabø et al. 2002). The degree of horizontal avoidance varies among and within species, age-classes, time of day, season, and even within a single survey of the same aggregation of fish. Vertical avoidance may be dependent on fish depth distribution, with no response occurring below a given depth (Vabø et al. 2002). In addition to affecting estimates of depth distribution, vertical avoidance can also affect density/biomass estimates in two ways. First, active head-down swimming will increase tilt angle and decrease scattering strength for individual fish. Second, change in pressure, resulting from rapid changes in depth, can reduce swimbladder volume, also leading to a decrease in *TS*. On the other hand, fish attraction to survey vessels has also been observed, which would induce an opposite bias (Røstad et al. 2006). In the Great Lakes, avoidance or attraction of fish caused by survey vessels has received little attention.

3.6.3 Near-Surface and Near-Bottom Dead Zones

Although acoustic methods are efficient for water-column measurements, they are less effective at measuring backscattering by organisms near the sea surface or sea floor. Near-surface and near-bottom dead zones (Ona and Mitson 1996) inherent in the design and application of typical echosounders are important limitations in many survey areas. Fish that are near the surface are not observed with echosounders, as vessel-mounted or surface-towed downward-looking transducers do not sample the water column above the depth of the transducer. Additionally, data within the transducer near-field are not valid for survey estimates. For data analysis, a surface exclusion zone is selected, accounting for both transducer depth and the near-field. Surveys interested in near-surface species should consider horizontally oriented echosounders or sidescan and multibeam sonars.

The near-field distance (R_{nf}) may be calculated as:

(16)
$$R_{nf} = \frac{(2a)^2}{\lambda}$$

where a is the radius of the active elements of the transducer (m), and λ is the wavelength (m). To be safely in the far-field region, we need to double (Simmonds and MacLennan 2005) or triple (Medwin and Clay 1998) the calculated near-field distance. Example 1 provides a sample calculation for determining the near-field depth.

Example 1. If using a 120 kHz transducer with $a=\theta_{3dB}$ = 7° and c=1450 m•sec^{-1}, then from Equation 14 a = 5.2 cm and λ:

$$\lambda = \frac{c}{f} = \frac{1450}{120000} = 0.0121\,\mathrm{m}$$

and:

$$R_{nf} = \frac{(0.10)^2}{0.0121} = 0.9\ \mathrm{m}$$

Data from within 1.8 m (2•R_{nf}) of the transducer face should not be included in the analysis.

The bottom dead zone is important in the Great Lakes because bloater, kiyi, rainbow smelt, and alewife in some of the lakes are often closely associated with the bottom during the day (Janssen and Brandt 1980; Tewinkel and Fleischer 1998; Yule et al. 2007). The detection of a fish close to the bottom is not possible after the pulse first strikes the bottom, as this generates a much stronger echo than any fish. Because the beam is circular, a fish located at the angle θ relative to the acoustics axis cannot be detected if it is closer to the bottom than the bottom depth (BD) multiplied by (1-cos(θ)) (Ona and Mitson 1996). In addition, fish will be only partially integrated when closer to the bottom than the acoustic resolution distance ($c\tau$/2). The distance from the bottom at which there is a bias ($H_{BotBias}$) associated with both the bottom dead zone and then partial integration zone therefore depends on pulse duration, angle to the fish, and depth (Ona and Mitson 1996) as follows:

(17) $$H_{BotBias} = BD \bullet (1 - \cos(\theta)) + c\tau / 2$$

In Example 2, we evaluate this for the half-power beam angle, as an indication of distance from the bottom where we can expect a bias. For a typical 7° transducer operating with 0.4 msec pulse length, the $H_{BotBias}$ is 0.5 m at 100 m depth (Example 2). The bottom dead zone increases to 0.76 m with a half-power beam angle of 11°. Ona and Mitson (1996) present the theory behind near-bottom echo integration, as well as the equations needed to correct for this bias.

Example 2. If sampling to a depth of 100 m using a 120 kHz with a 7º transducer, then:

$$\left(\frac{\theta_{3dB}}{2}\right) = \frac{7}{2} = 3.5^{\circ}$$

and:

$$H_{BotBias} = 100 \bullet (1 - \cos(3.5)) + 1450 \bullet 0.0004 / 2 = 0.48$$

S_v values from within 0.5 m of the bottom are biased.

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4. EQUIPMENT AND DEPLOYMENT OPTIONS

The main considerations before purchasing an echosounder, in addition to price and manufacturer, are frequency, beam width, and transducer configuration.

4.1 Frequency

The selection of optimal frequency, or frequencies, is not trivial and depends on a number of factors. The target strength (*TS*) of an animal depends on the size of the animal but also on the ratio of animal length to wavelength (Simmonds and MacLennan 2005). Higher frequencies have short wavelengths (λ) and, therefore, can detect smaller animals than lower frequencies (Table 2). But this detection is not always desirable, as invertebrates can produce considerable volume backscattering (S_v) at high frequencies (e.g. Knudsen et al. 2006; Rudstam et al. 2008a). Fish *TS* is more variable at higher frequencies, because the effects of tilt and roll (aspect) are greater. Higher variability makes it more difficult to identify species or age-groups in the *TS* distributions. Higher frequencies have higher absorption (α) and, therefore, reduced detection limits (Table 2). Taken together, this evidence suggests intermediate or lower frequencies (38, 70, or 120 kHz) are appropriate choices for fisheries assessment in the Great Lakes.

Table 2. Wavelengths (λ) and absorption (α) calculated for common fisheries acoustic frequencies in freshwater (c=1450 m•sec^{-1}).

Frequency (kHz)	**λ (cm)**	**Absorption (α, dB•km^{-1})**
38	3.82	0.45
70	2.07	1.52
120	1.21	4.47
200	0.72	12.41
420	0.34	54.72

Organisms must be sufficiently separated to be identified as individual targets to obtain valid *TS* measurements. Pulse duration (τ in sec) and sound speed (c in m•sec^{-1}) affect the separation of echoes through the relationship:

(18)
$$\Delta \mathrm{R} = R_2 - R_1 > \frac{c\tau}{2}$$

where ΔR is the range between two resolvable targets (R_1 and R_2 in m). Targets that are closer together than ΔR cannot be separated (Simmonds and MacLennan 2005). Although frequency is not a factor in the calculation of acoustic resolution, higher frequencies can generally operate at shorter pulse durations (e.g., 0.2-0.3 msec), thus allowing the resolution of targets closer together. Example 3 provides a sample calculation of target separation required for individual resolution. In Example 3, if pulse length was increased to $\tau = 0.0007$ sec (0.7 msec), targets would need to be at least 51 cm apart to be individually resolved. This difference suggests that higher frequencies that allow for shorter pulse lengths are preferable for applications using *in situ TS*.

Example 3. If data are collected at $c = 1450$ m•sec-1 and $\tau = 0.0003$ sec (≡0.3 msec),

$$R_2 - R_1 = \frac{1450 \bullet 0003}{2} = 0.22 \text{ m}$$

Targets must be separated by at least 22 cm to be individually resolved.

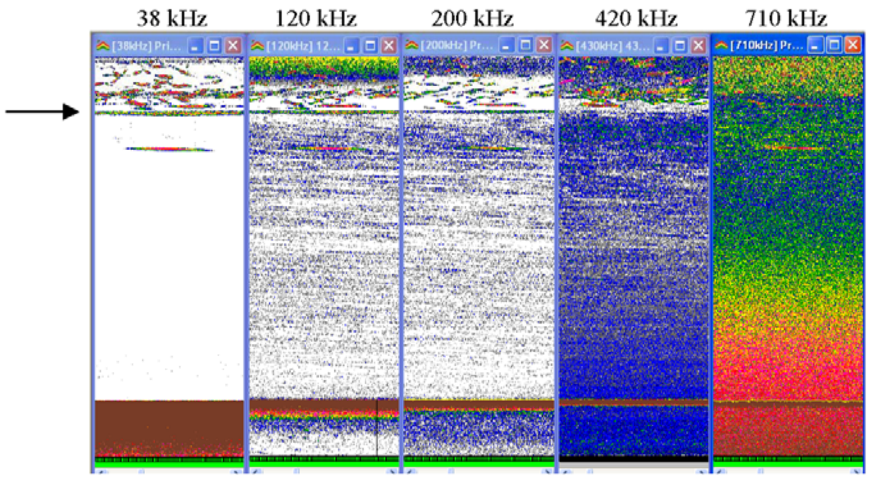
High-frequency transducers are smaller in physical size than low-frequency transducers (Fig. 2). This consideration is important for most transducer deployment options (See 4.4).

Fig. 2. Example of transducers made for different frequency output. Note that lower-frequency transducers are larger in physical size. Top row (L to R): Simrad 38 kHz, 70 kHz, 120 kHz, 200 kHz, and 710 kHz, all approximately 7^o beam width (70 kHz at 11^o). Bottom row (L to R): BioSonics 120 kHz (7^o beam width) and 430 kHz (6^o beam width). Photo by Tom Brooking, Cornell University Biological Field Station, Bridgeport, NY, 13030.

4.1.1 Great Lakes Frequencies

The most-common frequency used in the Great Lakes is 120 kHz. This frequency has a wavelength of 1.2 cm, can operate with short pulse durations (0.2 to 0.4 msec are common), and has relatively low absorption (around 5 dB•km^{-1} in fresh water (Table 2)). Unfortunately, mysid shrimp (*Mysis relicta*) give rise to relatively high volume backscattering at 120 kHz, less so at 38 and 70 kHz. In general, frequencies higher than 200 kHz are less appropriate for fisheries acoustic surveys in the Great Lakes because of higher absorption rates and higher reverberation from invertebrates (Fig. 3) (Rudstam et al. 2008a). Lower frequencies, like 38 kHz, have not yet been used in the Great Lakes, because this frequency has generally not been recommended for freshwater applications due to the large physical sizes of the transducer. Although the 38 kHz frequency has a larger near-field due to the larger size of the transducer, it has low backscatter from invertebrates and may be better for assessing fish abundance than a 120 kHz unit.

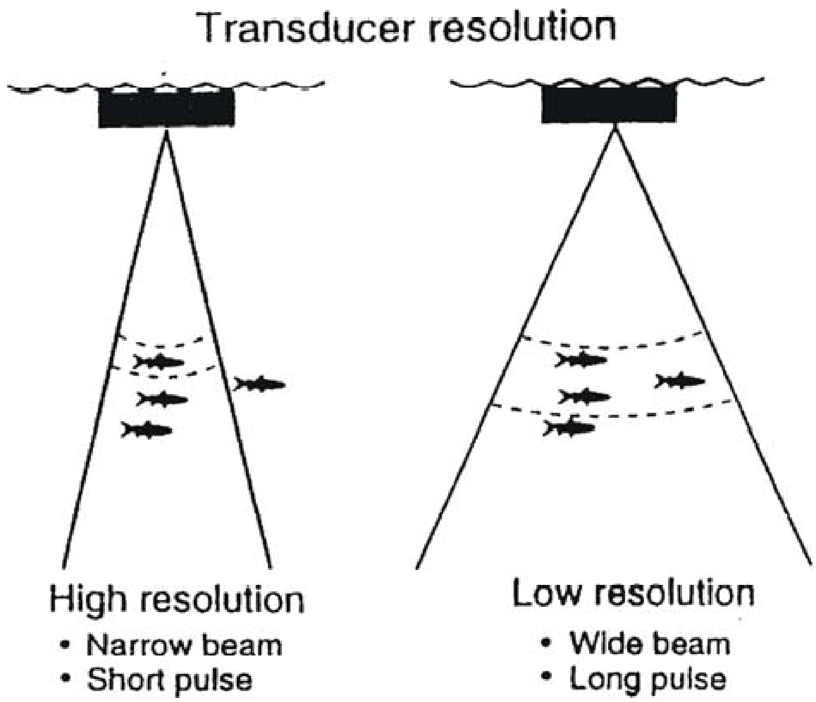
Fig. 3. Frequency-dependent volume backscattering (S_v) caused by fish (mostly alewife) and zooplankton above the thermocline (arrow) and the invertebrate *Mysis relicta* below the thermocline using 38, 120, and 200 kHz split-beam units and 710 kHz Simrad EY60 and 430 kHz BioSonics DtX single-beam units. Data were collected while stationary in Cayuga Lake, New York, in September 2006 (Rudstam et al. 2008a).



4.2 Beam Width

Choice of beam width depends on several considerations that can affect data collection or quality. First, narrow beams (smaller 3 dB beam width) increase horizontal resolution and improve the ability to separate echoes from individual fish (Fig. 4). Second, narrow beam width has smaller bottom dead zones. In Example 2, the wider beam width (120 kHz, 3 dB=7º, depth=200 m) had a bottom dead zone of 0.5 m, whereas a narrower beam (120 kHz, 3 dB=5º, depth=200 m) would have a dead-zone value of 0.3 m. Third, narrow beam width requires a greater active area of transducer elements than does a wide beam at the same frequency and, therefore, a narrow beam has a larger near-field. In Example 2, a 7º, 120 kHz transducer has an active radius of 4.5 cm and a near-field value of 1.4 m. A 4º, 120 kHz transducer would have an active radius of 8.9 cm and, therefore, a near-field value of 2.6 m. Fourth, wider beam widths allow for a greater sampling volume, an advantage when fish abundance is low, but they are more sensitive to omni-directional background noise than narrow beams (Simmonds and MacLennan 2005), making a narrow beam a better choice in noisy environments. Fifth, transducers with wider beam widths are smaller in overall size than narrow-beam-width transducers. This smaller size is a consideration for portable acoustic systems. Typical beam widths used in the Great Lakes are 6º to 12º.

Fig. 4. Transducer resolution and beam width. Fish within a pulse volume (delineated with dashed lines) cannot be resolved separately. More fish are within a pulse volume when the pulse duration is longer and when the beam is wider. Reproduced from Brandt (1996) with permission from the American Fisheries Society.

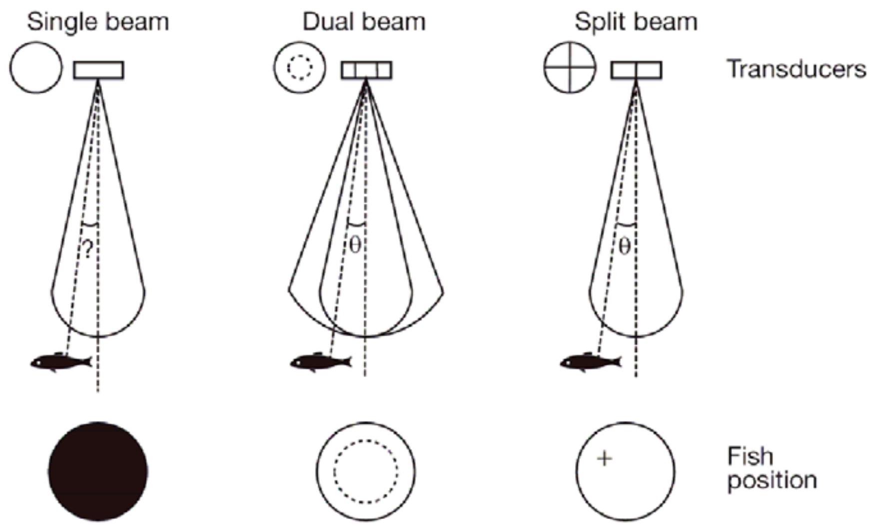


4.3 Beam Configuration

There are three different transducer configurations, the single-beam, dual-beam, and split-beam (Fig. 5). *TS* measurements are affected by differences in the processing of sound received in different portions of the transducer. Ona (1999) reviewed *in situ TS* measurements with all three configurations. For S_v, the three configurations are equivalent. Single-beam systems provide only target depth, and the measured echo level combines the effect of *TS* and location in the beam (Fig. 5). *TS* distributions need to be estimated from echo statistics. Dual-beam systems transmit sound on a narrow beam and receive the echo on both this narrow beam and a wide beam (Fig. 5). They provide information on depth and position relative to the beam axis. The ratio between the two echo levels is used to calculate the distance from the target to the center axis of the beam and allows for compensation for directivity in the calculation of *TS*. Finally, split-beam transducers calculate target location in three dimensions (depth, and the x and y coordinates of the location in the beam measured as angles in two directions) by comparing phase deviations of the returning signal in four sections of the transducer (Fig. 5). This calculation allows for compensation of directivity and calculation of *TS*, as well as calculation of fish swimming speed *in situ* (Arrhenius et al. 2000; Torgersen and Kaartvedt 2001). In addition, split-beam units can be elliptical, but dual-beam units are always circular.

Given current developments in both hardware and software, we recommend acquiring split-beam systems. While more expensive, the increased capabilities of a split-beam system are worth the cost.

Fig. 5. Single-beam, dual-beam, and split-beam transducer configurations. Single-beam transducers provide only one location dimension (depth), dual-beam transducers provide two dimensions (depth and distance from the acoustics axis), and split-beam transducers provide locations in all three dimensions (depth and both x and y coordinates for location within the beam). Reproduced by permission from Simrad Inc.



4.4 Transducer Deployment

Many options exist for transducer deployment. The most-common options are towed bodies, pole mounts, sonar tubes, and hull mounts.

4.4.1 Towed Bodies

Towed bodies are commonly used for transducer deployment in fisheries assessments. As the transducers are not affixed directly to the vessel, towed bodies have the advantages of reduced entrapment of bubbles, less pitch/roll in rough weather, and relatively easy installation and removal. Towed bodies present a greater risk for cable breakage than do hull mounted systems, and deployment/retrieval can be a safety hazard in rough sea conditions.

Deep towed bodies are used when the species of interest is found only in deep water. Deploying a transducer at a depth closer to the targets of interest improves spatial resolution of targets, reduces noise, and improves detection of the bottom in bathymetric areas, such as canyons. Although this approach is primarily used in marine systems, it may be useful for studies of deep-dwelling species in the Great Lakes (e.g., Lake Superior during the day) or in cases where there is a low SNR.

Two styles of towed bodies are currently used in the Great Lakes (Fig. 6). Each style is a suitable design for towing at 5-7 knots under typical survey and sea conditions. As with any towed body, the operator must ensure that the transducer face is parallel with the surface while at survey speed. If stationary sounding is to be performed, stabilizing lines may be needed.

Fig. 6. Two styles of towed bodies currently used in the Great Lakes. The towed body on the left is 4-ft long and the one on the right is 8-ft long.

4.4.2 Pole Mount

A pole-mounted transducer bridges the gap between towed bodies and hull-mounted systems. In this set-up, a pole is affixed to the vessel at a distance from the side, and the transducer is mounted on a plate at the base of the pole (Fig. 7). The location of the pole mount depends on the vessel size and wake pattern. Pole mounting provides greater transducer stability than towed bodies but more flexibility than hull mounting for deployment and removal. On small vessels, some pole-mount systems can consume critical deck space or present an obstacle if a stabilizing mount is used across the deck. Pole mounts have the same disadvantage as hull mounts—they are more susceptible to the pitch/roll of the vessel than towed bodies.

Fig. 7. Example of a pole-mounted transducer deployment.

4.4.3 Sonar Tube

A sonar-tube deployment is similar to a pole mount, but differs in that there is a tube that runs from the deck to the bottom of the vessel through which a transducer is deployed on a pole, pipe, or hydraulic ram. Currently, this deployment technique is used only on Lakes Michigan and Huron by the USGS. The tube itself is typically constructed of steel and has an opening with a hatch at the deck surface and is open to the lake at the hull. The sonar tube is generally installed amidships, with the fore/aft position of installation varying with the vessel. It is generally desirable to have the tube installed where the influence of vessel motion is minimized, but it may also be necessary to keep the tube away from the propeller(s), engines, and turbulence passing over the hull.

Advantages of this approach are that it is less susceptible to vessel movement than a pole mount, because the transducer is at the most-stable portion of the vessel, the transducer can be deployed and retrieved easily and quickly while under way at full speed, and the presence of paired sonar tubes allows for easy calibration, as a calibration sphere can be lowered down one tube while the transducer is in the other tube. Installation of paired tubes also allows for simultaneous deployment of multiple transducers.

4.4.4 Hull Mount

Hull-mounted systems have the advantage of reducing the frequency of cable breaks and of remaining safely deployed at all times. As a result, hull-mounted systems reduce deployment and removal times on vessels frequently used for acoustics. Data quality from hull-mounted transducers may be reduced in rough weather due to vessel pitch/roll and aeration. However, incorporating pitch/roll sensor data into data-analysis routines may minimize the effect of pitch/roll on the data. Many marine vessels use drop-keel systems instead of hull-mounted systems to reduce the probability that transducers will be damaged or lost if the vessel enters shallow-water zones and to allow lowering of the transducer below the bubble zone created by the RV.

4.5 Vessel Speed and Sea Condition

Most Great Lakes acoustic surveys are conducted at a vessel speed of 5-7 knots, depending on surface conditions (wind speed and wave height). As weather conditions worsen, vessel speed is often decreased to maintain data quality due to increased noise, the influx of bubbles across the face of the transducer, and increased vessel pitch and roll. At some point, as surface conditions worsen primarily due to wave height and precipitation, data quality cannot be maintained, and the survey should be postponed. Suspension of the survey in rough weather may be necessary if targets of interest are located sufficiently high in the water column to be affected by an increase in surface noise from bubbles. There is currently no set rule to determine when surveys need to be postponed in the Great Lakes because of sea state conditions. Experience in Lake Superior suggests that usable data can be obtained even during 25 knot winds if transects are aligned with the prevailing wind direction (D. Yule, personal communication, 2008).

5. SURVEY DESIGN

In designing an acoustic survey, the tenets of good survey design should be followed. The following recommendations for survey design are based in part on guidelines outlined by Scheaffer et al. (1996), and guidance in choosing among different statistical analysis techniques was taken from Rivoirard et al. (2000) and Simmonds and MacLennan (2005).

5.1 Defining Survey Objectives

The first step of survey design is to clearly define survey objectives (Pollock et al. 2002). For fisheries acoustic surveys, the objective is most often to estimate the relative or total fish abundance. Both of these objectives involve defining the area to be sampled, so that the population will be fully and fairly represented. Additional objectives (e.g., measuring changes in spatial distribution or assessing behavior) may require some changes to the survey design. These design components may compete with one another for survey and analysis time and may ultimately influence statistical confidence in the estimate.

5.2 Target Species or Groups

Important information on survey needs can be gained by clearly identifying the target(s) of interest, such as a specific species, age-group (YOY, age 1, yearling and older), or fish located in a particular bathymetric region (bays, open water). Identifying survey targets ahead of time will aid in identifying data limitations that may result from the survey design. For example, a survey designed to quantify open-water pelagic species will not provide valid estimates for species or age-groups that are commonly found in nearshore shallow waters. These restrictions should be made explicit for the sake of other researchers who may use the data in the future.

5.3 Survey Timing

Selection of survey timing is important to minimize bias and maximize species or age-group separation by taking into account seasonal, diel, or lunar patterns in fish behavior.

5.3.1 Seasonal

Great Lakes species and age-groups within species have different thermal and depth preferences (Brandt 1980; Brandt et al. 1980; Argyle et al. 1998; Parker-Stetter et al. 2006). Age-groups of bloater and rainbow smelt are often separated spatially, but this is not the case for alewife in all lakes. There are differences in adult alewife distributions among Lakes Michigan, Huron, and Ontario. Current information regarding the depth distributions of the major forage-fish species in the different lakes (summer-fall) relative to the thermocline are:

- Epilimnion: YOY rainbow smelt, YOY alewife, and YOY bloater, and adult alewife in Lake Ontario
- Metalimnion: adult alewife and adult rainbow smelt
- Hypolimnion: adult bloater, adult rainbow smelt, and adult alewife in Lakes Michigan and Huron

In addition, ciscoes are expected to be metalimnetic and threespine stickleback and shiners (*Notropis* spp.) to be epilimnetic. Mysids are expected to be below the thermocline. Although complete physical separation may not occur, acoustic surveys conducted during thermal stratification may improve our ability to isolate and estimate abundance of different species or age-groups. Direct sampling associated with acoustic surveys is needed to confirm the thermal distributions of target and nontarget species.

Another seasonal consideration for survey timing is schooling associated with spawning migrations. In alewife, adults move inshore during late spring and early summer into water too shallow to survey acoustically with large vessels. This movement would cause a large proportion of the adult population to be missed during a spring survey.

A final seasonal consideration is the timing of YOY recruitment to direct-sampling gear. If nets, such as midwater trawls, are used for target identification or collection, sampling should occur when the majority of YOY are available and vulnerable to the gear used.

5.3.2 Diel

Diel vertical migration (DVM) has been documented in four primary Great Lakes forage species (bloater, kiyi, rainbow smelt, and alewife) (Janssen and Brandt 1980; Tewinkel and Fleischer 1998; Rudstam et al. 2003; Yule et al. 2007). Change in pressure during DVM can affect swimbladder size and, therefore, *TS*. Differences in swimming behavior between day and night may affect average tilt angle, which strongly influences the echo intensity returned by a fish. Day-night differences in *TS* due to tilt angle have been observed in marine surveys (Hjellvik et al. 2004).

Fish releasing bubbles during DVM may also bias density estimates. In Lake Erie, migrating rainbow smelt produce more bubbles at dusk than during the night, and these bubbles have a *TS* similar to small fish. Surveys that began after dusk minimized the inclusion of bubbles in the acoustic data (Rudstam et al. 2003).

5.3.3 Moonlight

The presence or absence of moonlight affects behavior and DVM and can affect abundance estimates (Luecke and Wurtsbaugh 1993). Alewives form schools during periods of sufficient light intensity, and, although this behavior is typically observed during the day, it has also been observed under bright moonlight (D. Warner, personal observation, 2005). Moonlight may attract alewife to the surface and allow them to feed by sight. Moonlight can increase the visibility of direct-sampling gear and thereby decrease catches.

5.4 Survey Components

In order to meet project objectives, acoustic surveys may include other components, such as areal surveys, stationary sounding, trawling, and environmental-data collection. Some of these components will provide critical data, whereas others will provide supplementary information on the species or system.

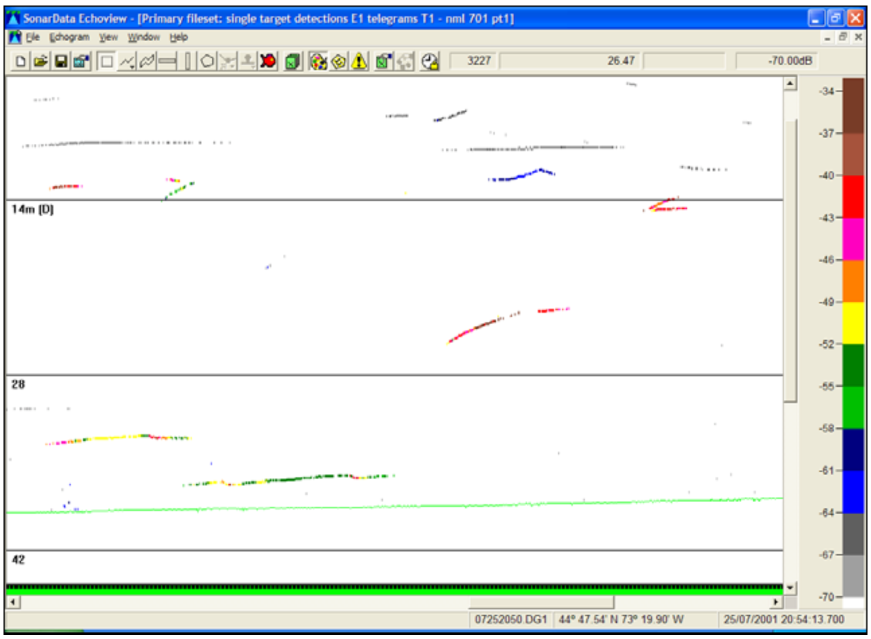
5.4.1 Areal Survey

Areal surveys may include both systematic and adaptive components. The systematic survey is generally the primary effort in an acoustic assessment and refers to the area-wide acoustic survey that follows predetermined transects. Conversely, the purpose of an adaptive acoustic survey is to increase sampling effort when a region of high fish density is detected on systematic transects (Conners and Schwager 2002). Adaptive survey transects are performed at a higher resolution than systematic ones and aim to characterize the full extent of an observed aggregation. This information may be used in density/abundance estimates (Conners and Schwager 2002) or to gain insight on the spatial attributes of fish aggregations.

5.4.2 Stationary Sounding

Stationary sounding produces elongated single-fish tracks that represent multiple detections of the same fish (Fig. 8). These tracks may be used to determine the range of *TS* values expected from a single fish.

Fig. 8. Elongated single-fish tracks resulting from multiple detections of likely adult rainbow smelt during stationary sounding in Lake Champlain.



5.4.3 Trawling

Trawl collections serve multiple purposes during an acoustic survey. They may be performed to:

- Identify the insonified targets
- Partition backscatter into species or age-group composition
- Collect specimens for *TS* versus length estimates
- Collect specimens for supplementary information (e.g., age, diet, maturity, or sex)

Trawling may represent a significant amount of time during a survey, so it is essential that trawl time be considered during the survey design phase. If the variances in trawl catches and acoustic surveys are known, Simmonds and MacLennan (2005) provide recommendations on balancing the trawling and survey components to minimize variance. Adams et al. (2006) propose a method for stratification of trawl and acoustic samples in Great Lakes surveys.

5.4.4 Environmental Data

Environmental data are needed for the calculation of data-analysis parameters and may be useful in characterizing the location of targets of interest. Temperature is required for the calculation of sound speed (c in m•sec^{-1}) and the acoustic absorption coefficient (α in dB•km^{-1}). As temperature may vary across the survey area, measurements should be taken regularly. Depending on survey objectives, other environmental data, such as dissolved oxygen or fluorescence, may be useful for classifying analytic regions based on target-species preferences. Consideration should be given as to how the environmental data will be used in analyses (e.g., correlation with density distribution and analysis cell definition), as a greater number of samples may be needed to meet this objective. Although water-column profiles are necessary, continuous surface-temperature measurements could be useful surrogates in areas lacking environmental sampling.

5.4.5 Supplementary Information

Supplementary information collected during stationary sounding, trawling, or environmental-data collection may include fish life-history information (diet, age, fecundity, etc.); measurements of single-fish *TS*, orientation, and movement; or depth, temperature, thermocline depth, nutrients, or water clarity. Taking time to collect this information may reduce time available to acoustic sampling, so it is important to acknowledge costs and benefits of supplementary information at the same time that survey design is being considered. There are no simple formulae for weighting effort between collecting supplementary information and collecting the acoustic samples themselves. However, the same considerations made for acoustic sampling (e.g., stratifying the collection of supplementary information and increasing sampling of supplementary information to increase precision) should be used when determining how and how much supplementary information should be collected.

5.5 Time Budget

Generating a time budget is a necessary step in the survey design process. With a detailed budget, you can quickly determine if additional time is needed to meet survey objectives or if achieving multiple objectives is not feasible within the available time. Necessary considerations or inputs include:

- Amount of total time available (if fixed), including any diel considerations
- Logistics constraints associated with docking, accommodations, etc.
- Optimal vessel speed during the acoustic survey and transit
- Time required for individual tasks (e.g., trawling and stationary sounding)

5.6 Sampling Effort

An elementary sampling unit (ESU) is a unique object or area from which survey data are drawn. In the case of acoustic estimates, this ESU may correspond to non-overlapping whole transects or transect segments. If the total number of possible ESUs is known, corrections to variance estimates for the finite sampling frame can be made and the variance reduced. However, for most applications in the Great Lakes, the number of possible ESUs is so large that such corrections are not helpful.

The sampling frame is defined as the total number of ESUs that exist within the area to be surveyed. The survey area should be accurately defined with the survey objectives in mind. Examples of defined survey areas in the Great Lakes might be the open lake beyond the 20 m contour or bays and nearshore waters between the 10 and 30 m contours.

Creating the sampling frame and identifying the ESUs confronts the issue of selection probability. Random sampling methods assume that each sampling unit has an equal probability of selection and, therefore, no one sampling unit should have a higher probability of being sampled than any other. Although a logistically attractive design, zig-zag transects may over-sample certain areas and under-sample others, even if random starting positions are used. The identification of the sampling frame and units is an important step also for geostatistical methods, for which a zig-zag design may be appropriate, to ensure unbiased and efficient estimates.

A conscientious definition of the sampling frame is required when choosing to extrapolate density estimates to absolute abundance. The extra step of expanding a density per sampling unit (e.g., a transect) to total abundance in the sampling frame (e.g., the lake) may seem trivial, requiring only a scaling by area, but decisions must be made, such as:

- Should the extrapolation be based on area or volume?
- Should embayments or deepwater areas be included?
- What is the horizontal distribution of target species? How close to shore should we reasonably expect offshore fish to be?
- What is the bathymetric distribution of the target species?

All of these issues affect how the total sample area or volume is interpreted, and care should be taken in defining this density multiplier, as it will influence total-abundance estimates.

5.7 Estimates of Quality

The quality of acoustic-survey estimates is typically evaluated by the variance of the estimate. We can control quality by reducing variance through selecting the appropriate units (sampling design) and number of units (sample size) within the sampling frame. The choice of sampling design and sample size will depend on how and by how much the population varies and the desired level of precision (confidence) of the estimate. The Catch-22 is that acoustic surveys cannot be adequately designed without knowledge of population variance, but this variance is unknown until sampled. Estimates of variance for the initial design of an acoustic survey may be obtained from a pilot or exploratory survey or from similar surveys conducted elsewhere.

5.7.1 Degree of Coverage (Λ)

In designing a pilot or exploratory survey, a preliminary calculation of necessary sampling effort is the degree of coverage (Aglen 1983). Degree of coverage (Λ) is defined as:

(19)
$$\Lambda = \frac{D}{\sqrt{A}}$$

where D is the transect length sampled, and A is the size of the survey area.

Errors associated with abundance estimates decrease as Λ increases. Aglen (1983) presents an empirical relationship between the CV (SE/mean) and Λ as:

(20)
$$CV = \frac{0.5}{\sqrt{\Lambda}}$$

Example 4 provides an example of degree of coverage for Oneida Lake.

Example 4. If you wish to sample a 200 km^2 area (Oneida Lake) with a CV of 25%, Λ needs to be a least 4 (from Equation 20: $\Lambda = (0.5/\mathrm{CV})^2$), and, therefore, the survey length D can be calculated from Equation 19:

$$D = 4 \bullet \sqrt{200} = 57$$

A total survey length of 57 km is an acceptable starting point for pilot survey design. Current transect design in Oneida Lake results in approximately 65 km of transects and a CV range from 8% to 26% (Rudstam et al. 2002).

5.7.2 Standard Error

The predicted effect of using particular designs, sample sizes, and sampling allocations (i.e., among strata) should be examined prior to conducting the survey. A calculation of the likely standard error of the estimate should be made using population variance from a pilot/exploratory survey or assumed population variance levels from a similar survey elsewhere. An optimal sampling allocation to different strata given the assumption of variance in these strata can be made using sampling theory (Scheaffer et al. 1996). Total sampling effort required to reach a desired standard error can also be calculated using power analysis.

5.8 Analysis Expectations

Although it is easy to get caught up in logistical considerations (how long? lunar phase? equipment issues?) before a survey, it is essential to know that the collected data will answer the primary survey questions. Scheaffer et al. (1996) suggest visualizing the final report before conducting the survey. This reflection on survey and project objectives should be done throughout survey design and frequently while conducting the survey. By frequently reviewing survey objectives, priorities can be established or reordered should it appear that key project questions are not being answered. Visualizing the final report also puts analysis options into perspective while the survey is being designed. For fisheries acoustic surveys, both classical and geostatistical approaches may be used:

- Classical, or design-based, analyses follow random sampling theory; the use of randomly selected sampling units facilitates computation by allowing the samples to be treated as independent variables
- Geostatistical, or model-based, analyses can make use of the information that exists in how organisms are distributed; an underlying spatial pattern is detected from survey observations and that pattern is modeled to deduce the density distribution of the organisms elsewhere in the survey

Both design-based and model-based methods benefit from the appropriate allocation of samples across all possible elementary sampling units (i.e., the distribution of samples across the area to be surveyed).

5.9 Types of Survey Designs

Population distribution within different regions should be considered when choosing among survey designs. For fisheries acoustic surveys, the most common designs are:

- Simple random with parallel transects
- Systematic with parallel transects
- Stratified systematic with parallel transects
- Zig-zag with parallel zigs and parallel zags

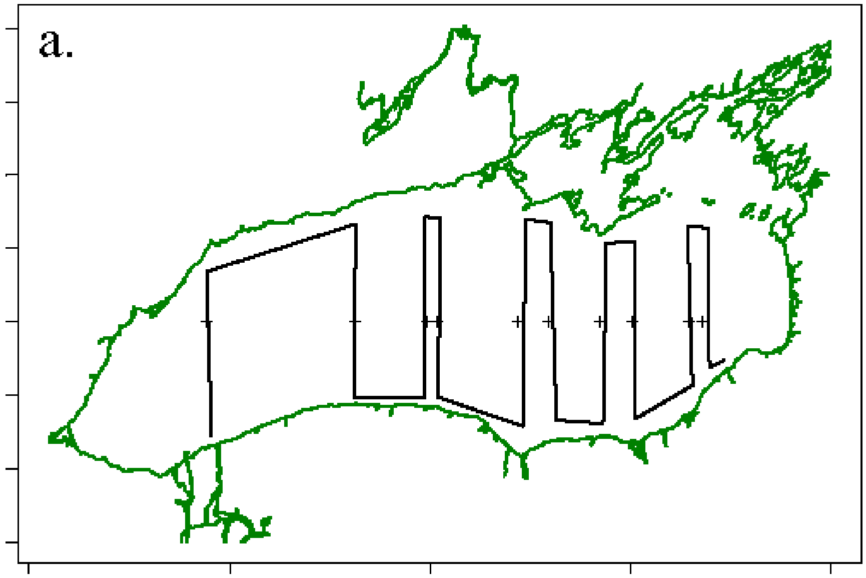
Below are graphical examples of these sampling designs with commentary about when they might be used and what computations would follow. See Survey Calculations (10) for specific calculations. Here we use Lake Ontario as an example for the designs.

5.9.1 Simple Random Sampling with Parallel Transects

<u>5.9.1.1 Layout</u>

Parallel transect location is determined by randomly selecting nearshore starting points within the sampling frame along the south shore (Fig. 9a). Number of transects (sampling effort) is determined based on variance calculations, time constraints, or degree of coverage for pilot studies. This design, although not as statistically efficient as the others discussed below, relies on the most-general set of assumptions and, thus, as the name would imply, is the simplest statistically to implement.

Fig. 9a. An example of a simple random survey design with parallel transects using Lake Ontario as a template.



5.9.1.2 Advantages and Limitations

The simple nature of this design facilitates both implementation and analysis. However, with this simplicity often comes a loss of statistical efficiency in that the long-term variance will tend to be higher than it would be under some other survey designs, such as stratified or systematic sampling. A concern when using this random sampling approach is that a sample taken in any one year might be assumed to be biased because, by chance, several of the transects fall into high-density (or alternatively low-density) areas, thus causing the estimates to be higher or lower than average for that year. But this is not bias, at least not in the long run, because chances are, over many survey years, that the resulting estimates will be distributed around the true mean. So do not mistake variation for bias. Finally, note that the efficiency of the random sampling approach will depend on the degree of variation (patchiness) of the system being surveyed.

5.9.1.3 Analyses

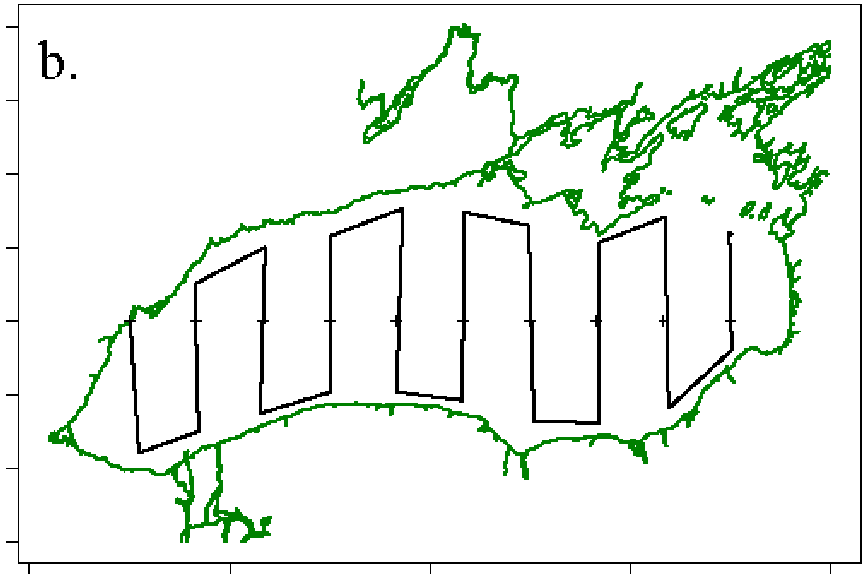
Simple random sampling typically treats the transect as the elementary sampling unit upon which a classical analysis is conducted. If the sampling units are fixed integrated intervals along the transect, analysis can also be conducted using a cluster-sampling or a geostatistical approach as described under survey sections below.

5.9.2 Systematic Sampling with Parallel Transects

5.9.2.1 Layout

Starting points for parallel transects are evenly spaced across the sampling frame along the south shore (Fig. 9b). The number of transects (sampling effort) is determined based on variance calculations, time constraints, or degree of coverage for pilot studies. This design is appropriate if we anticipate no periodicity in distribution of the target species during our survey. It is hard to imagine a periodicity in the fish distributions that would be of the same scale as the spatial distance between transects. Therefore, this design is currently favored in many systems because of guaranteed better coverage than randomly allocated transects.

Fig. 9b. An example of a systematic design with parallel transects using Lake Ontario as an example.



<u>**5.9.2.2 Advantages and Limitations**</u>

This design spreads sampling effort evenly and may be logistically simple to carry out.

<u>**5.9.2.3 Analyses**</u>

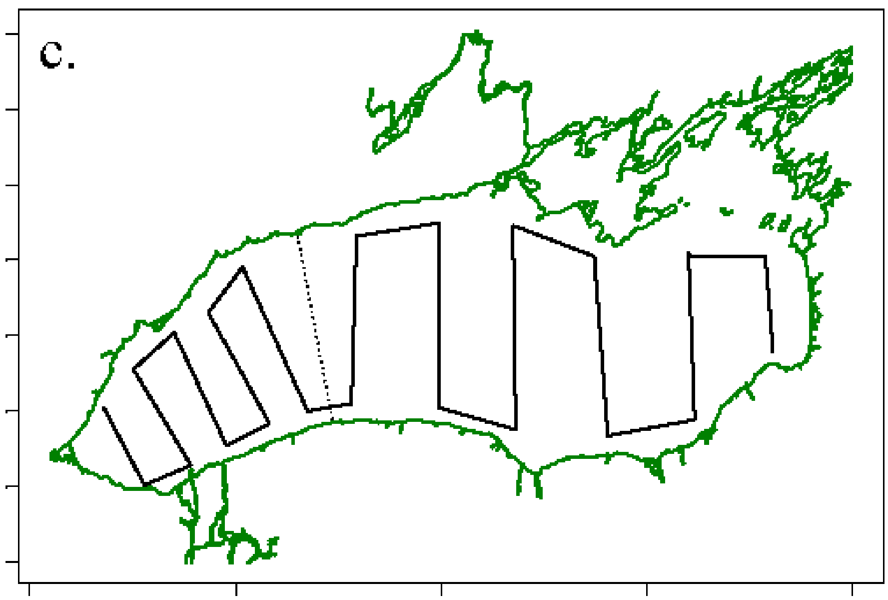
Survey data from this design may be analyzed using classical, geostatistical, or cluster-sampling approaches.

5.9.3 Stratified Sampling with Systematic Samples Nested within Strata

5.9.3.1 Layout

Parallel transects are placed (randomly or systematically) within the sampling frame based on expected variability or where the means may be different (Fig. 9c). Stratification can be based on bathymetric criteria (e.g., shallower and deeper than a given depth contour) or regionally (e.g., east versus west or bays versus open water). Number of transects (sampling effort) is determined based on variance calculations, time constraints, or information from pilot studies.

Fig. 9c. An example of a stratified design with systematic samples nested within eastern and western strata using Lake Ontario as a template.



5.9.3.2 Advantages and Limitations

This design will reduce overall variance by stratifying the sampling frame into more-homogenous areas.

5.9.3.3 Analyses

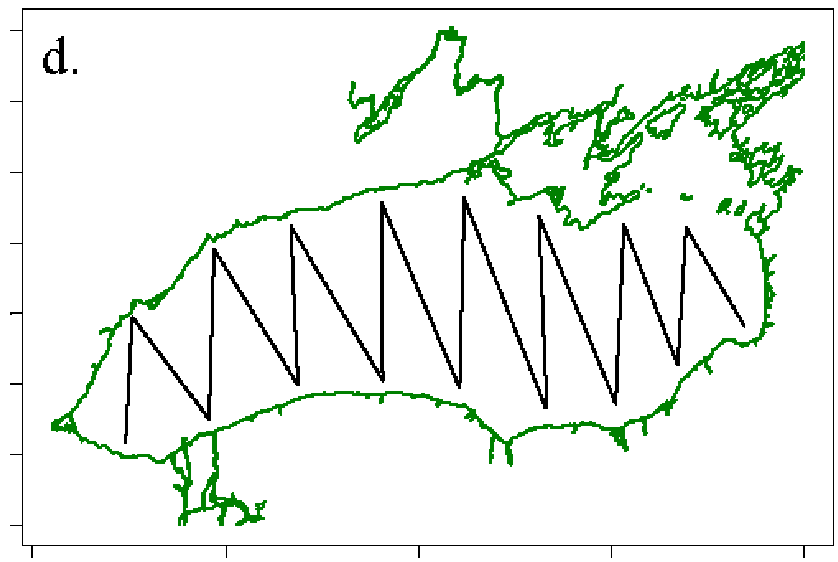
Data from stratified surveys may use classical, geostatistical, or cluster-sampling approaches.

5.9.4 Zig-Zag Design with Parallel Zigs and Parallel Zags

5.9.4.1 Layout

Parallel zigs and parallel zags are distributed throughout the sampling frame (Fig. 9d). Placement is generally systematic (evenly spaced) with a fixed or random transect start.

Fig. 9d. An example of a zig-zag design with parallel zigs and parallel zags using Lake Ontario as a template.



5.9.4.2 Advantages and Limitations

This survey design maximizes the amount of transect sampling time relative to transit time, but if you are planning to use the classical analysis approach (analysis assuming random sampling), then you will only be able to utilize every other transect, thus decreasing the effectiveness of the survey by half. A geostatistical analysis, however, would allow use of all the data available, provided one is willing to use this model-based approach. The reason for this difference in how the data may be used is that the zig-zag design results in sections of one transect being highly correlated to that of the adjacent transect at the intersecting vertices. Leaving out every other transect diminishes the effect of this small-scale correlation and makes classical analysis possible. Leaving in every other transect provides a mechanism to better characterize small-scale variation as it is used in a geostatistical analysis.

5.9.4.3 Analyses

Geostatistical approaches are typically applied for this type of design, thus, all the data are utilized (i.e., both zigs and zags). Classical or cluster-sampling approaches may only be applied to alternate parallel transects (zigs or zags) because of the spatial autocorrelation of data near the intersection of zigs and zags.

5.10 Logistics of Survey Design

If the person conducting the survey is not the person who designed the survey, it is helpful to have the designer on board for at least the first part of the survey, especially if this is the first time the survey is to be conducted or if a major change in the survey is planned. With the survey designer on board, unforeseen complications can be dealt with immediately without loss or decreased integrity of the data.

6. SYSTEM CALIBRATION

6.1 Background

Calibrations are conducted by the manufacturer and user to verify that the echosounder and transducer are operating properly and to ensure system stability over time. Calibrations characterize system parameters relative to expected standard values. Calibration data should be documented as meticulously as survey data.

Echosounder calibrations conducted in most Great Lakes surveys use the standard-target method (Foote et al. 1987), which relates acoustical energy to an absolute standard. The standard-target method calibrates the overall acoustic system (echosounder, transducer, and cable) and consists of two parts: on-axis sensitivity and beam-pattern measurements. On-axis target strength (*TS*) and area backscattering coefficient (s_a) measurements calibrate gain parameters, and beam-pattern measurements supply beam width and angle-offset values. They are not independent.

6.2 Calibration Issues

6.2.1 Echosounder Calibration Programs

Simrad provides the Lobe software program to measure echosounder beam patterns. Due to concerns about circularity in the beam-width measurement process, marine and freshwater groups are divided on how or whether to apply the beam-width results. However, the target strength gain given by the Lobe program is valid. This gain can be checked by an on-axis calibration. As a result, no consistent approach has been adopted, and discussions among users and the manufacturer continue. BioSonics does not provide a similar program.

6.2.2 Environmental Effects

Variability in system parameters due to environmental conditions, primarily temperature, has been observed in the Simrad EK500. Temperature appears to influence the 120 and 200 kHz transducers more than lower frequencies, and the effect is observed even when absorption and sound speed are properly established. This effect is believed to be a transducer design issue. We have no data on this for BioSonics transducers.

6.3 Standard Values

Table 3 provides a list of common standard values for calibration. The calibration sphere *TS* is dependent on the water temperature and salinity (i.e., sound speed dependent). The copper spheres specified for each frequency have been shown to be "optimal" in that the *TS* of the specified spheres vary minimally for a normal range of temperatures and salinities (Foote et al. 1987). However, many groups use a single tungsten carbide sphere to calibrate multiple frequencies (Foote 1990).

Table 3. Target strength (*TS*) of some standard calibration spheres used in the Great Lakes Region. Values are given for 1430, 1460, and 1490 m•sec^{-1} sound speed. "Cu" denotes copper and "WC" denotes tungsten carbide. Calculations for the WC spheres are from Foote (1990) (38.1 mm, bandwidth about 3 kHz) or from the manufacturer's data sheet (BioSonics and Simrad, other sizes).

Frequency (kHz)	**Calibration-sphere diameter**	**Nominal *TS* (dB)**		
		1430 m•sec^{-1} (6ºC)	**1460 m•sec^{-1} (13ºC)**	**1490 m•sec^{-1} (23ºC)**
38	38.1 mm WC	-41.78	-42.14	-42.33
70	32.1 mm Cu	-39.34	-39.16	-39.16
70	38.1 mm WC	-40.24	-40.75	-41.26
120	23 mm Cu		-40.40	
120	38.1 mm WC	-40.22	-39.68	-39.49
120	33 mm WC	-41.10	-40.80	-40.60
200	13.7 mm Cu		-45.00	
200	38.1 mm WC	-39.22	-39.52	-39.24
420	17 mm WC	-46.40	-46.00	-45.90
420	21 mm WC	-43.60	-43.50	-43.70

6.4 Conditions for Calibration

Before conducting a calibration, important issues to consider are:

- The calibration should be conducted in the same environmental conditions (water temperature and salinity) as experienced during the survey
- Water depths must be sufficient to exceed near-field limitations and/or system limitations for the echosounder frequencies to be calibrated
- Calibrations must be conducted before the survey begins to establish proper echosounder operation, and after or near the end of the survey to ensure no significant changes have occurred; additional calibrations during the survey are valuable for maintaining system performance and ensuring high-quality data
- Calibrations must be conducted with the same pulse durations, transmit powers, and bandwidths used during the survey; a relatively fast ping rate, such as 5 pings•sec^{-1}, is often used to increase the number of sphere observations
- If multiple frequencies will be operating simultaneously during collection, run all frequencies while calibrating each single frequency to include any effects from the other units and to determine if there is acoustical interference between systems; some manufacturers recommend calibrating each frequency separately

The standard-target method for calibrating echosounders is used to calibrate the overall acoustical system (combined transmit and receive echosounder components, transducer, transducer cable, and the electrical supply) to an absolute standard. Thus, the calibrations reflect an integration of the echosounder, transducer, and shipboard electrical system. If changes to any component of this system occur (e.g., the shipboard electrical system or transducer cable length) during the survey, the echosounder must be recalibrated (Advanced Sampling Technologies Working Group 2003).

6.4.1 Standard Calibration-Sphere Preparation

The standard calibration sphere should be suspended in a monofilament cradle (see the figure in “standard sphere preparation,” www.acousticsunpacked.org). In order to reduce the presence of air bubbles, the cradle knots should be tied tightly. Prior to deployment, the sphere should be dipped in liquid dish soap to further reduce the likelihood of air-bubble entrapment.

6.4.2 Optimal Sphere Depth

The calibration sphere must be positioned below the transducer outside of the transducer near-field zone, making a minimum distance for the standard target of more than three times the near-field range calculated with Equation 16. For most cases, a distance between transducer and target of 5-10 m is sufficient, but distances greater than 10 m may be optimal to minimize the effect of sphere motion.

6.4.3 Temperature

A vertical temperature profile should be obtained to calculate sound speed prior to every calibration. The profile must encompass the calibration depths. This profile should be compared to temperature profiles obtained during the survey to ensure similar physical environmental conditions between the calibration exercise and the survey. Calculate sound speed and absorption from the average temperature between the transducer and the target. The *TS* of standard targets has a small dependency on temperature and, therefore, should be corrected for temperature at the calibration sphere.

6.4.4 Software

Echosounder manufacturers provide detailed instructions for calibrating their systems. These instructions must be followed to ensure proper calibration and system stability. The manufacturers may also provide calibration software, such as Simrad’s Lobe program. However, we recommend that the software used for analysis of survey data be used for analysis of calibration data. For example, different methods for single-target detection are implemented in EV software and will give slightly different values. Therefore, use the same method to analyze the calibration ball and to analyze fish echoes. Because software upgrades occur, software version identification (both calibration software and echosounder software) should be documented.

6.5 Calibration Procedures

To ensure system stability, allow a 5-minute warm-up period prior to calibration data collection. Douse (or soak) the sphere with liquid soap to prevent adherence of bubbles to the target.

6.5.1 Sphere Deployment

6.5.1.1 Towed-Body Transducer

A fishing pole is the most convenient tool for the calibration of a towed transducer. The calibration-sphere cradle is tied to the loose end of the fishing-pole line and lowered in to the beam. One challenge with this method is keeping the sphere stationary when performing the on-axis calibration. If a mounting bracket that would allow the sphere to be positioned near the acoustic axis is available, higher-quality data can be collected. An alternative approach, commonly used for small-boat deployments, is to keep the sphere stationary and move the transducer relative to the sphere. When using this technique, care must be taken to avoid introducing bubble noise at the transducer face.

6.5.1.2 Hull-Mounted Transducer

To calibrate a hull-mounted transducer, it is necessary to construct a three-point tethering system to position the sphere under the vessel and ultimately under the transducer. Foote et al. (1987) describe this method in detail.

6.5.2 On-Axis Calibration

On-axis sensitivity is measured by positioning the calibration sphere on the acoustic axis of the transducer. The *TS* gain is derived from the measured on-axis *TS* relative to the known *TS* of the calibration sphere. Similarly, S_v gain is also calibrated by measuring the S_v of the calibration sphere relative to the theoretical S_v value. By measuring S_a values instead of S_v values, we sum all backscattering from the calibration sphere given the pulse duration, and we do not have to account for the height of the selected region. The calibration constant for S_v and S_a are the same. Theoretical S_a is based on the *TS* and range to the calibration sphere. With the sphere in the middle of the beam, theoretical S_a can be calculated from:

(21)
$$S_a = 10 \bullet \log_{10}\left(\frac{\sigma_{bs}}{\psi \bullet R^2}\right) = TS - \psi - 20 \bullet \log_{10}(R)$$

To perform an on-axis calibration for either towed-body or hull-mounted transducers:

1. Note the temperature, echosounder, pulse duration, and ping rate (a fast ping rate is fine (e.g., 5 pings•sec^{-1}) on your calibration sheet.
2. With Simrad units, use the single-target detection window or the oscilloscope to center the sphere on the acoustic axis. With BioSonics units, observe the oscilloscope display of angle data on the computer screen and center the ball by minimizing both angles. This centering should maximize the voltage return.
3. Begin recording data, and note the time.
4. Watch that the sphere remains in the center of the beam most of the time. Do not adjust the vertical location of the sphere. If the sphere moves and stays off-axis, begin at Step 1 in the new position.
5. Collect data for approximately 5-10 minutes.

6. Note the time when stopped recording. Make any changes for additional calibrations (e.g., another pulse duration), and start again at Step 1.

It is possible to isolate on-axis data during data analysis to obtain on-axis values for both S_v and *TS* calibrations.

6.5.3 Beam-Pattern Measurement

Beam-pattern measurements are acquired by positioning the calibration sphere at many different angular locations within the acoustic beam. For split-beam transducers, echo strength is compensated by the angular location of the target in the acoustic beam. Some manufacturers provide software to collect beam-pattern measurements, but the use of this software is not universally accepted and applied by acoustic users (see 6.2). Simrad recommends a minimum of 100 pings per quadrant for a good beam-pattern measurement, with many hits registered near the acoustic axis.

6.6 Tolerance and Calibration Adjustments

When should gains be adjusted based on calibration results? Gains are sometimes not adjusted when differences are sufficiently small that the error inherent in the calibration is larger than the suggested adjustment. Foote (1981) and Simmonds and MacLennan (2005) suggest that calibrations should be able to give gain values for on-axis *TS* measurements of ±0.2 dB for a 38 kHz transducer. If this holds for the higher-frequency transducers, calibration results within 0.2 dB may be considered an indication that the unit is working properly and that no changes are required. Calibrations of the Cornell University units, done in conjunction with the surveys, have generally resulted in differences larger than 0.2 dB, and, therefore, gains are generally adjusted according to the calibration even if the differences are small. Since 1996, calibrations of Cornell University's 70 kHz split-beam Simrad transducer (EY-500) with a 0.2 msec pulse duration has resulted in a measured *TS* of the calibration sphere spanning 3.4 dB (±1.7 dB). Of 29 calibrations considered acceptable, 27 were within ±0.8 dB of the overall mean, but since this is larger than the ±0.2 dB calibration error, calibrations should be done for each survey. Calibrated gains also vary with pulse duration—*TS* of the sphere with a default setting was 2.2 dB lower with a 0.6 msec pulse duration than with a 0.2 msec pulse duration. For the Cornell split-beam 120 kHz BioSonics Dt-X unit, calibrations in 2005 and 2006 ranged ±0.5 dB and also varied with pulse duration—higher *TS* values were measured at 0.2 msec than at 0.4 msec for the same sphere (-39.01 dB at 0.2 msec and 40.22 dB at 0.4 msec for a -40.4 dB calibration sphere). However, this unit did give the same values for the sphere for 0.4 to 0.8 msec pulse durations. Somewhat higher variation has been observed for BioSonics equipment used by USGS/GLSC, and a somewhat lower variation has been observed for BioSonics equipment used by Vermont Fish and Wildlife during 2007 (5 calibrations within ±0.3 dB). Since the calibration constants stored in the BioSonics transducer are for the default pulse duration of 0.4 msec, gain offsets are needed when analyzing data collected with pulse durations other than 0.4 msec, especially shorter pulse durations. Therefore, it is imperative to calibrate all units at all pulse durations used in the surveys. Because there are differences between analysis programs, we recommend using the same methods and software for calibration as is used for data analysis.

6.7 Data Management and Archiving

Documenting and archiving calibration data and supporting information is critical. In addition to data and derived values acquired from the calibration software, echosounder data should be recorded and archived immediately after conclusion of the calibration. A single calibration analysis worksheet should be created to archive the results of each calibration done with a given transducer. An analysis file allows the operator to compare the current calibration with past values and provides a means to assess system flux/stability over time.

7. DATA COLLECTION

7.1 Data Management

A plan must be made for the storage and backup of all data that includes:

- How data are to be collected, backed up, and stored during the survey
- Who is responsible for collection and quality assurance
- What metadata are to be collected (e.g., date and time of cruise, vessel name and survey leader and crew names, and weather conditions)
- Where the primary data will be stored after the survey
- Where backup copies will be housed

It is essential to document all initial echosounder parameter settings and any changes made to them during data collection in a survey log. Record the old and new value, date, and time of modification so that the data collected prior to the modification can be reprocessed using a data-analysis software package. The survey log should also include identification of personnel involved and environmental (weather and sea) conditions. The collection settings (see below) that can be changed in the field vary between Simrad and BioSonics units. Both units have collection settings that cannot be modified during analysis and a number of other settings that can be modified if raw data are collected. If multiple surface units and/or transducers are available, the serial number(s) of the unit(s) being used should be recorded.

7.2 Collection Settings

7.2.1 Pulse Duration

Choice of the pulse duration (τ), sometimes referred to as pulse length, is dependent on the objectives and conditions of the survey. A shorter pulse duration is necessary for higher resolution of individual targets, whereas a longer pulse duration is desirable for greater ranges because of a higher

SNR ratio. The echosounder must be calibrated at the pulse duration used during a survey. Pulse durations used in the Great Lakes range from 0.2 to 0.6 msec. Most of the standard surveys are done with 0.256 msec (Simrad default) or 0.4 msec (BioSonics default). Pulse duration is a collection setting and, therefore, cannot be modified after a survey.

7.2.2 Ping Interval and Rate

Ping interval (*i,* sec, the time delay between sequential pings) and ping rate (pings•sec^{-1}, the number of pings sent out per sec) are related (ping rate = 1/(ping interval)). In choosing a ping interval, the goal is to select the smallest interval that will not cause shadow bottoms in the data and is within the processing speed of the echosounder. To avoid a shadow bottom originating from the "third" bottom return, the minimum ping interval (*i*, sec) is:

(22)
$$i = \frac{3 \bullet 2 \bullet BD}{c}$$

where *BD* is the expected maximum bottom depth (m), and *c* is the speed of sound in water (m•sec^{-1}). The factor "3" is related to the third bottom signal, and the factor "2" is related to the sound traveling from the transducer to the bottom and back to the transducer.

Example 5 provides an example of minimum ping interval.

Example 5. For *BD*=100 m and *c*=1450 m•sec^{-1},

$$i = \frac{3 \bullet 2 \bullet 100}{1450} = 0.4$$

The minimum ping interval is 0.4 sec or 2.5 pings•sec^{-1}.

Ping interval is a collection setting and cannot be changed during analysis, although the data can be "resampled" to a slower (but not faster) rate in analysis software. Ping rates used in the Great Lakes range from 0.25 to 1 pings•sec^{-1}. The acquisition software often warns the user of ping rates that are too high, but some units may adjust to lower ping rates without warning (e.g., Simrad EK60).

7.2.3 Raw-Data Depth

The collection of raw data is essential. The raw-data depth setting defines how deep data will be collected. If it is set too shallow, data from the bottom of the water column will be missed. Unless better information is available, set the raw-data depth to the maximum depth of the lake area within the sampling frame or the maximum depth with interpretable data. Raw-data depth is a collection value, and data will not be collected beyond that point.

7.2.4 File Size

Reasonable acoustic-survey file sizes are 10-20 MB or 10-15 min. Large file size causes some data-analysis software packages to run slowly. More importantly, if there is a file corruption, less data are lost when using a number of smaller–sized files rather than one large file. Files can be merged during the analysis.

7.2.5 Transducer Depth

The transducer depth (depth from the water surface to the transducer face) should be measured and recorded on your survey log. However, for data collection during the survey, set the transducer depth to 0, as all measurements will then be relative to the transducer face. This clarification is important if the echosounder output is to be used by the vessel captain for bottom sounding. In data-analysis software, enter the measured depth to the transducer face. When data are exported, depth will then be referenced to the water surface.

7.2.6 Collection Thresholds

In Simrad systems, raw-data collection does not require the application of a threshold. However, if Simrad telegram data that have undergone some processing by the Simrad software are to be collected, S_v and *TS* thresholds must be entered. We recommend collecting raw data to make these thresholds settings less important. For BioSonics systems, one threshold and a threshold model must be selected. Entering a threshold that is equivalent to the noise value at 1 m (likely at -120 to -130 dB) will ensure that all data are recorded, but this threshold will increase the size of the files. A threshold of -100 dB is sufficient for identifying echoes from mysids. The threshold should always be low enough to allow for measurement of noise levels on the recorded data. BioSonics provides three threshold models: a constant threshold, a linear threshold, and a squared threshold. Although the choice of model is not important as long as the threshold is low enough to include data below the noise level, most Great Lakes users apply the squared-threshold model. In data analysis, thresholds may be set to exclude unwanted echoes, but they cannot be adjusted to include data below the threshold set in the field. Analysis thresholds are discussed in the Data Processing and Analytic Decisions section.

7.2.7 Bottom Backstep

Simrad echosounders include a bottom "backstep" used to detect and define the bottom. In rough topography or rough seas, the bottom-detection algorithm fails more frequently, and bottom echoes will intrude into the water column. The default bottom-detection value (-50 dB) is appropriate for most surveys. BioSonics units do not do bottom detection during data collection.

7.2.8 Single-Fish Recognition

Default settings for single-fish recognition are appropriate for viewing during most surveys, but the settings can be modified if more-specific detections are desired. BioSonics does not have single-fish viewing capabilities during data acquisition. Suggested values for single-echo detection parameters are presented in section 9.2.

7.3 GPS

Global positioning system (GPS) data are critical for acoustic estimates of population size. GPS data should be sent to the echosounder and stored with the acoustic data string. All units currently used in the Great Lakes have that capability. GPS data are required for measurements of species spatial distribution and for determining vessel location relative to physical oceanographic conditions and topographic features. To ensure proper integration of GPS in the survey, monitor GPS output during data collection, document the type of GPS data used, and document data-storage and retrieval procedures.

7.4 System Settings

7.4.1 Transducer Gain

The transducer, or through-system, gain is a measure of amplification related to the receiver sensitivity of the echosounder. Transducer gain is calculated from calibration data relative to a known standard. Simrad units come with factory default values, but these are not adequate for data processing, so transducer gain must be determined from a calibration. BioSonics units come with the factory calibration values stored in the transducer. For BioSonics units, the correction constant is the difference between this factory-installed gain and the gain from a calibration. Gain constants can be modified in data-analysis software.

7.4.2 S_a Correction

The S_a correction (dB) in Simrad units is needed to account for differences in *TS* and S_v calibrations. This value is calculated from calibration data relative to a known standard. The Simrad S_a correction is equivalent to the difference between the *TS* and S_v gains in the older EY500 systems. Similarly, a calibration offset can be specified for BioSonics units post-processing that may be different for S_a and *TS* data. For BioSonics units, we recommend using default values in the field and applying any needed adjustment as calibration offsets during post-processing, because only one offset can be specified during data collection. S_a correction can be modified in data-analysis software.

7.4.3 Equivalent Beam Angle (ψ) and Beam Width (3 dB Angle)

The equivalent beam angle (EBA) and beam width (3 dB angle) are related (Equations 14 and 15). The values are supplied by the manufacturer or can be calculated if beam width is adjusted following calibration. The beam width is also referred to as the half-intensity angle, because it represents the angle between the half-power (3 dB) points on either side of the main lobe, measured in degrees. 3 dB angles and EBA can be modified in data-analysis software.

7.4.4 Output Power

For 120 and 200 kHz transducers, we recommend that maximum output power be limited to 300 W (120 kHz) and 100 W (200 kHz) to avoid harmonic distortion (Simrad 2002, Tichy et al. 2003). Harmonic distortion results in two errors. First, the sound level does not increase proportionally with increasing input power. Second, the transducer beam pattern shifts toward a flatter, wider main lobe and increased side lobes.

The combination of these two errors results in incorrect *TS* and integration values. Power output can be reduced on the BioSonics transducer by about 10 dB, but most users apply the default setting. If reduced-power output is used, calibration should be done with the same reduced-power setting. Output power cannot be modified in data-analysis software.

7.5 Environmental Settings

Conductivity-temperature-depth (CTD) sensors measure salinity (computed from conductivity), temperature, and depth. Lowering and raising the CTD at a station provide a vertical temperature and salinity profile. Temperature data are necessary for calculations of sound speed and absorption and may also be useful for identification of targets if they are thermally separated.

7.5.1 Sound Speed (*c*)

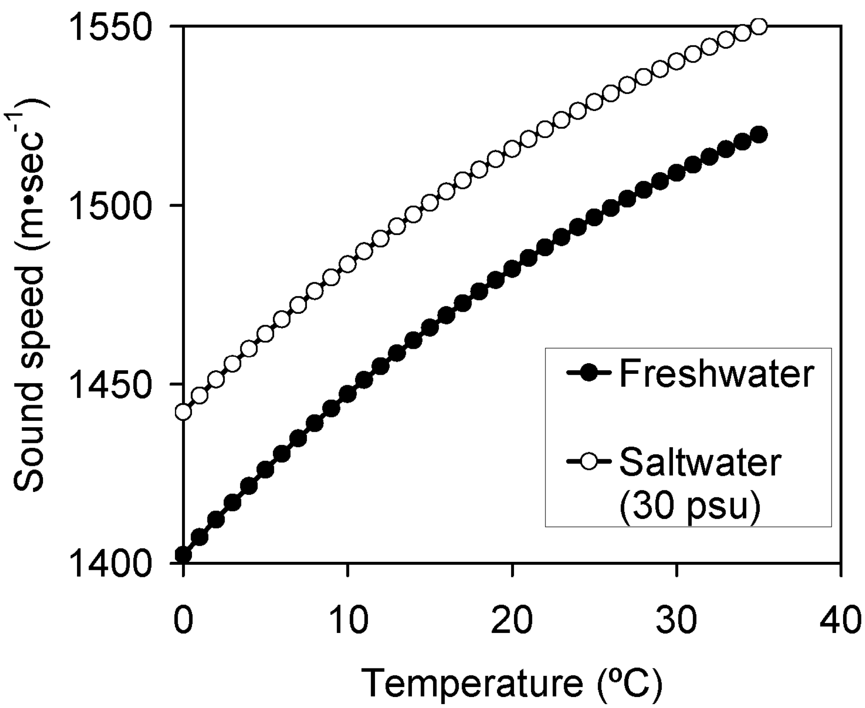
Sound speed (*c*) is dependent on water temperature and salinity, so setting the sound speed requires prior knowledge of the environmental conditions expected during the survey. Setting an appropriate sound speed is essential, as the selected value will influence bottom depth and range to targets. Sound speed increases as temperature increases. In the Great Lakes, where temperatures can range from 0ºC to near 30ºC, sound speeds range between 1400 and 1500 $m \bullet sec^{-1}$ (Fig. 10). Sound speed (c, $m \bullet sec^{-1}$) may be calculated for fresh water using the equation from Chen and Millero (1977):

(23) $$c = 1402.388 + 5.03711 \bullet T - 0.0580852 \bullet T^2 + 0.3342 \bullet 10^{-3} \bullet T^3 - 0.1478 \bullet 10^{-5} \bullet T^4 + 0.315 \bullet 10^{-8} \bullet T^5$$

where T is temperature in ºC.

The sound speed value should be based on the mean water temperature of the water column between the transducer face and the depth at which the fish of interest are located. As sound speed varies with temperature (Fig. 10), selecting this value in stratified systems should be done consistently and with consideration of the possible biases selection may introduce. Sound speed can be modified in the data-analysis software. S5 can adjust for variable sound speed and attenuation with depth if detailed temperature profiles are available. Temperature values are particularly important in the calculation of absorption coefficients (α) for high (>200 kHz) frequencies.

Fig. 10. Effect of temperature on sound speed in fresh water and salt water. Freshwater sound speed calculated from Chen and Millero (1977) and saltwater sound speed from Mackenzie (1981).



7.5.2 Absorption (α)

Sound absorption (α in dB•km^{-1}) and acoustic spreading combined are equal to the total transmission loss. Sound absorption is dependent on the acoustic frequency, water temperature, and salinity. Similar to the sound speed, setting α requires prior knowledge of environmental conditions. If significant environmental changes occur during the survey, the absorption parameter and sound speed should be recalculated and set for those conditions. Absorption coefficients can be modified in the data-analysis software.

7.6 Correction of Incorrect Settings

It is important to remember which system and data-collection settings may be changed in data analysis. Table 4 is a summary of system settings, collection settings, and which settings can be modified in data analysis.

Table 4. Modification status of system and field-collection settings for acoustic surveys using Simrad and BioSonics units.

	Entered at data collection		
Setting	**Simrad**	**BioSonics**	**Modifiable in data-analysis software**
Transducer gain	X	X	X
Pulse duration	X	X	
Ping rate	X	X	
Raw data depth/range	X	X	
File size	X	X	
Transducer depth	X	X	X
Collection thresholds[1]	X	X	
Sound speed	X	X	X
Absorption	X	X	X
Power setting[2]	X	X	
S_a correction	X		X
Equivalent beam angle	X		X
3 dB angle	X		X
Bottom backstep	X		X
Threshold model[3]		X	

[1] This does not apply to Simrad raw data.

[2] Power settings can be selected to different values for Simrad EY60 units and as a choice of full or reduced power for BioSonics units.

[3] Threshold model is only important when thresholds are set high. Data below the threshold will not be recorded.

8. SURVEY PROTOCOLS

8.1 Conditions for Data Collection

Acoustic data collected in high wind or poor sea conditions may suffer from bubble entrainment and/or noise from waves. Little can be done to reduce this problem other than to conduct surveys under the best conditions possible. It is possible to minimize this problem by deploying transducers at deeper depths (either on a towed body or a drop keel). However, it is likely that high wind conditions (>15 knots) will still reduce the quality of acoustic data (Knudsen 2001). These conditions can occur at any time, but are most likely in fall and winter.

Excessive transducer motion is a problem for all deployment styles, but particularly for hull-mounted transducers that pitch and roll with the vessel. The most-obvious indication of transducer motion is excessive surface noise and poor bottom quality (Figs. 11a, 11b, 11c). Early diagnosis of this problem is critical due to the effect of transducer motion on quantitative results. In Lake Superior, useful data are collected at winds up to 25 knots (with a 100-foot vessel) when heading either into the wind or with the wind, and heading with the wind also allows for midwater trawling (D. Yule, personal communication, 2008).

Fig. 11a. Echogram showing high noise detected at the surface and sharp fluctuations of the bottom (data collected in Lake Champlain in 2001 with a 70 kHz 11.4º split-beam unit by Sandra Parker-Stetter).

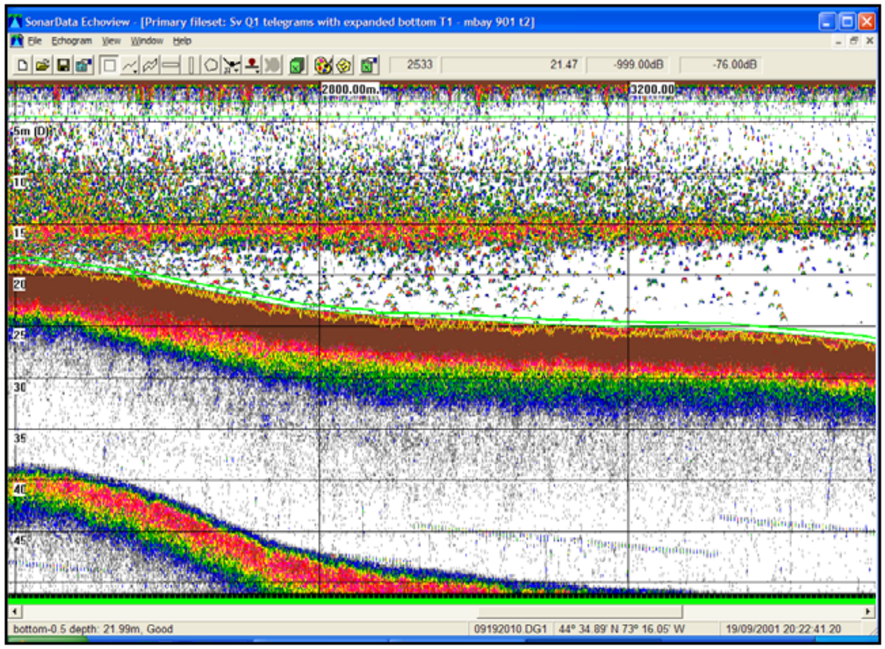


Fig. 11b. Expanded echogram showing high noise detected at the surface.

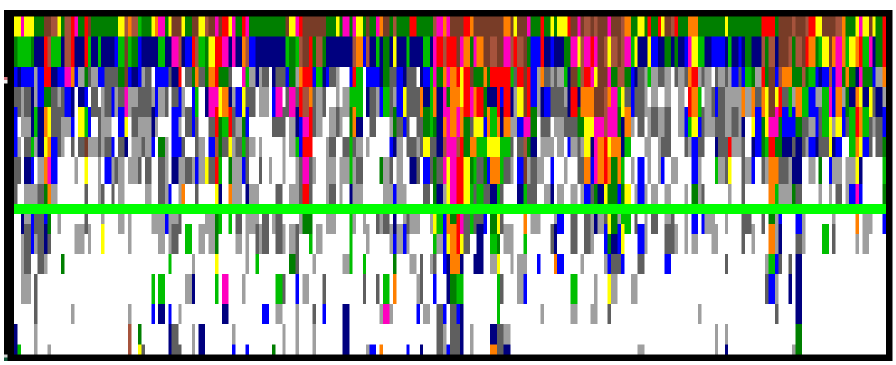
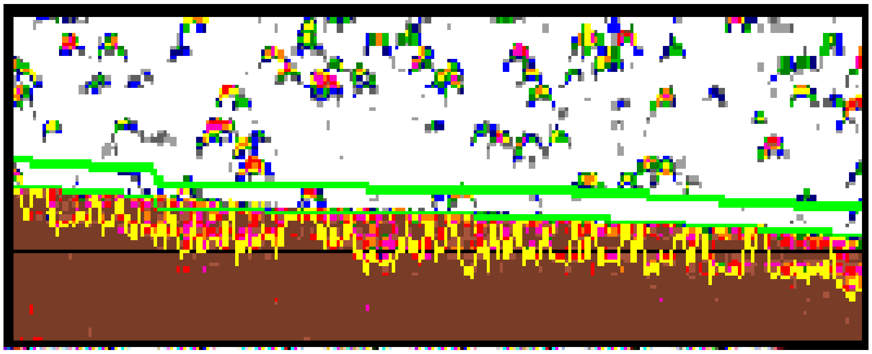


Fig. 11c. Expanded echogram showing sharp fluctuations of the bottom (indicated by the yellow jagged line representing the sounder-detected bottom). The lower solid green line is the bottom line, as detected by the software.



Transducer motion results in a change in the orientation of the transducer beam, relative to the insonified targets, between transmission and echo return. Targets insonified on-axis may be received off-axis or vice versa. Similarly, the return signal from targets insonified at the edge of the beam may be lost. The effect of transducer motion on data is complex, but includes:

- Echo integration (S_v) values that will be lower than expected (Stanton 1982)
- Single-target *TS* values that may be higher or lower than expected (Furusawa and Sawada 1991)
- Significant errors in tracking single-target *TS*, although the mean backscattering cross section across a range of random targets is less affected (Furusawa and Sawada 1991)
- Application of single-target detection criteria (angle or *TS*) may result in the rejection of otherwise valid echoes
- Effects on S_v and *TS* data will be greatest for narrow beams (i.e., <10º) (Stanton 1982; Furusawa and Sawada 1991)
- Errors will increase at depths >50-100 m (Furusawa and Sawada 1991)

In the case of common Great Lakes surveys using narrow-beam transducers (~7º) and *in situ* or theoretical *TS*, transducer motion could result in a significant underestimation of density. High-resolution pitch/roll data recorders, standard on most marine RVs, can be used to compensate for these errors.

8.2 Data Management and Recording

8.2.1 Survey Activities

Events that occur during an acoustic survey, such as transect turns, CTD measurements, trawl deployment, or interesting echoes should be documented on a survey log. These events should be noted with time and/or file name and transect and can be delineated using consecutive "event numbers." The survey logs should provide a space for comments regarding the event, and other data that should be included are date, vessel, and survey location.

Inserting breaks into data files at key events is a useful technique for recording transect changes. For systematic surveys, file breaks at the end of one transect and the beginning of the next will allow data from the turn to be easily excluded in data analysis. This insertion of file breaks may be especially helpful if data analysis will utilize individual transects. Similarly, this approach simplifies the identification of specific components of the survey (e.g., specific transect and data collected during a trawl tow). Be sure to note the significance of any inserted file breaks in the survey log.

Although not currently used in the Great Lakes, Simrad commercial ES60 systems have a periodic "dither" that must be removed during data analysis. This dither alters (increases or decreases) backscatter values in a predictable pattern. As dither removal is based on establishing the sequence of pings between each introduced error, the process is made more complicated by inserted file breaks, so manual file breaks should be minimized. Open-source software (ES60Adjust) (Keith et al. 2005) is available to remove this dither.

8.2.2 Data Archiving

All acoustic and associated metadata should be routinely archived during the survey. If a break in the survey occurs, data should also be backed-up to shore-based computers. We recommend bringing a high-capacity portable hard drive into the field and backing up all data after each survey day.

8.3 Environmental-Data Collection

The quantity and type of environmental data collected during a survey should reflect its purpose in the survey objectives. At a minimum, temperature profiles should be made at the beginning of each survey day to establish whether sound speed and absorption coefficients will need adjusting during data analysis. Other data (e.g., dissolved oxygen, fluorescence, and light intensity) may also be collected to meet survey objectives. Record the location of all collection sites and collection times in the survey log for later reference.

8.4 Stationary Sounding

Stationary data may be collected while anchored or drifting. Towed bodies may need stabilizing, typically by adding ropes to the nose and tail to prevent motion, to ensure that the transducer face is parallel with the surface. Stationary data are useful for tracking fish and measuring variability in *TS* within single-fish traces (Warner et al. 2002; Rudstam et al. 2003; Parker-Stetter et al. 2006). Record the beginning and end of all stationary-sounding periods in the survey log. If the transducer is adjusted, record this also. Remove rope stabilizers prior to recommencing the mobile survey.

8.5 Target Identification

Fisheries acoustic surveys are designed to provide fish-density and abundance estimates, usually age- or length-based, for one or more target species. Identification of the target species can be done based on prior knowledge of echogram characteristics (depth distribution, shape of schools, and layer structure). *TS* distribution and its change with depth is a good indication of changes in species or age composition (Parker-Stetter et al. 2006). Mysid echoes can be identified by comparing echograms with and without light on board (Rudstam et al. 2008b). However, the main method of identifying the species, age, and size composition of organisms in the echogram is by direct sampling, primarily with midwater trawls. Vertical gillnets have also been used in the Great Lakes, and underwater video is another potential source of validation.

8.5.1 Trawling

8.5.1.1 Gear Requirements

Trawls are the best available method of obtaining relatively unbiased estimates of species and size composition (Simmonds et al. 1992). The goal of trawling is to obtain catches that are representative of the species composition and the length-frequency distribution of organisms detected acoustically (McClatchie et al. 2000), but other data, such as age, weight, and reproductive status, can also be obtained. Obtaining this representative sample is difficult to accomplish, because all biological sampling methods are species and size selective. There has been little work on trawl selectivity in the Great Lakes. To increase sampling effectiveness, trawls can be outfitted with sensor instrumentation (e.g., depth and/or temperature at doors, head-rope or foot-rope) to ascertain location, depth, and volume of water sampled relative to specific echogram aggregations. It is important to maintain consistency in trawl procedures between and within surveys and especially important to measure sampling depth. In recent years, depth and temperature sensors have been used during most Great Lakes surveys.

All Great Lakes surveys use conventional midwater trawls for direct sampling. Because these trawls sample continuously throughout a deployment and are open on descent and ascent, samples from targeted deeper midwater strata may contain fish caught in shallow strata. Switching to new trawls that can be remotely opened and closed will result in catches that better represent the species and size composition in the targeted strata. Trawls are selective and both small and large fish may be under-represented in the catch. A cod-end mesh of 10-13 mm (stretch) will likely select against fish smaller than 5 cm, but the selectivity is complicated because the mesh size of the trawl body also must be considered.

Fish behavior in temperature gradients is predictable and will not change dramatically between years. Therefore, the accumulated information from many years of depth- and temperature-stratified sampling can be used to help in target identification. Relying on past experience is common practice but target identification would benefit from a formal analysis.

8.5.1.2 Frequency, Location, and Timing

The number, locations, and timing of trawl tows are dependent on the objectives of the survey. In the Great Lakes, target species are stratified by temperature. Different temperature strata should therefore be sampled. Most Great Lakes surveys are done at night when fish are off the bottom and more likely to be associated with their preferred temperature. During the day, schools may form that are composed of single species or single-sized fish, and, therefore, sampling a single school would not be representative of the fish in an area. For this reason, trawl tows should sample more than one school.

8.5.1.3 Catch Processing

In many cases, trawl catches are too large to sample in their entirety and must be sub-sampled. Even when an entire catch is processed for species composition by weight and number, additional information, such as age, fish length, and sex, cannot normally be taken from all captured specimens and must be estimated using a random sub-sample.

Determination of the sub-sample size should be guided by statistical principles.

8.5.2 Underwater Video

Although not currently used in any Great Lakes acoustic surveys, underwater video and low ambient light level still-camera systems provide visual identification of species and have the potential to document behavior. Because of the limited light penetration in water, cameras must be positioned near the targets of interest, and artificial lighting often must be used. These two factors complicate acquisition of visual data for species identification and potentially alter the behavior of the organisms. Another promising technique for species identification is the DIDSON acoustic camera that uses multiple beams and high frequency to create a picture of the fish. The DIDSON so far has been used mostly in rivers (Holmes et al. 2006).

8.6 System Performance and Data Quality

Factors affecting performance and data quality may be internal or external to the system, but, regardless, early detection and remediation is critical.

8.6.1 Noise

Many types of noise can be eliminated during data collection or data analysis. Noise removal during data collection is preferable. Noise that cannot be removed will be added to S_v measurements, increase SNR and detection limits, and bias *in situ TS* measurements, leading to errors in fish-density or biomass estimates. Collect passive data during regular operating conditions to record the noise levels present during the survey (see below).

Some instruments output noise levels at 1-m depth and these noise levels should be recorded. We recommend recording the noise levels or the SNR at the deepest depth included in the analyses. Remember that noise levels at 1 m are different if expressed as TS_u or S_v data. This difference is because S_v values include a term for the equivalent beam angle and sampling volume, whereas uncompensated target strength (TS_u) values do not (compare Equations 6 and 12). Therefore, the difference between TS_u and S_v data is depth dependent. Note that *TS* refers to the target strength of the fish and TS_u refers to the measure of echo level with a $40 \cdot \log_{10}(R)$ TVG function ($TS_u = TS + 2B(\theta)$), also sometimes called non-adjusted *TS*. This distinction is important and not clear in some existing software. Combining Equations 6 and 12, we get:

$$TS_{u\ noise\ at\ 1\ m} = S_{v\ noise\ at\ 1\ m} + \Psi + 10 \cdot \log_{10}(c\tau/2) + 20 \cdot \log_{10}(R) \tag{24}$$
$$\text{or } TS_{u\ noise\ at\ 1\ m} = S_{v\ noise\ at\ 1\ m} + 10 \cdot \log_{10}(V)$$

where V is the sampling volume (Equation 10, $V = \psi R2\ (c\,\tau/2)$).

Example 6 provides a calculation of noise using Equation 24.

Example 6. A noise level measured in the S_v domain as -120 dB at 1 m depth (with a 120 kHz, 7.8º transducer and, therefore, a Ψ of -20.4 dB, a sound speed of 1450 $m \cdot sec^{-1}$, and a pulse duration of 0.4 msec) is -146 dB in the TS_u domain at 1 m ($20 \cdot \log_{10}(1) = 0$):

$$TS_{u\ noise\ at\ 1m} = S_{v\ noise\ at\ 1m} + \Psi + 10 \cdot \log_{10}(c\tau/2) + 20 \cdot \log_{10}(R)$$
$$= (-120 - 20.4 - 10 \cdot \log_{10}(1450 \cdot 0.0004/2)) + 0$$
$$= -146$$

8.6.1.1. Acoustic Noise

A common type of acoustic noise is a discreet spike caused by another echosounder or sonar operating within the frequency bandwidth or a harmonic of the scientific echosounder (Figs. 12a, 12b). The solution is to identify the source of the interference and shut it down. Interference can also be eliminated if acoustical instrumentation essential for safe ship operation is synchronized with the survey echosounder. Removal of acoustic noise during data analysis is sometimes possible, but difficult, so eliminating it during the survey is always preferable (Advanced Sampling Technologies Working Group 2003).

Fig. 12a. Example of acoustic interference (cross-talk) between two frequencies (diagonal lines, indicated by arrow): a 70 kHz scientific transducer and 50 kHz on-boat depth-sounder.

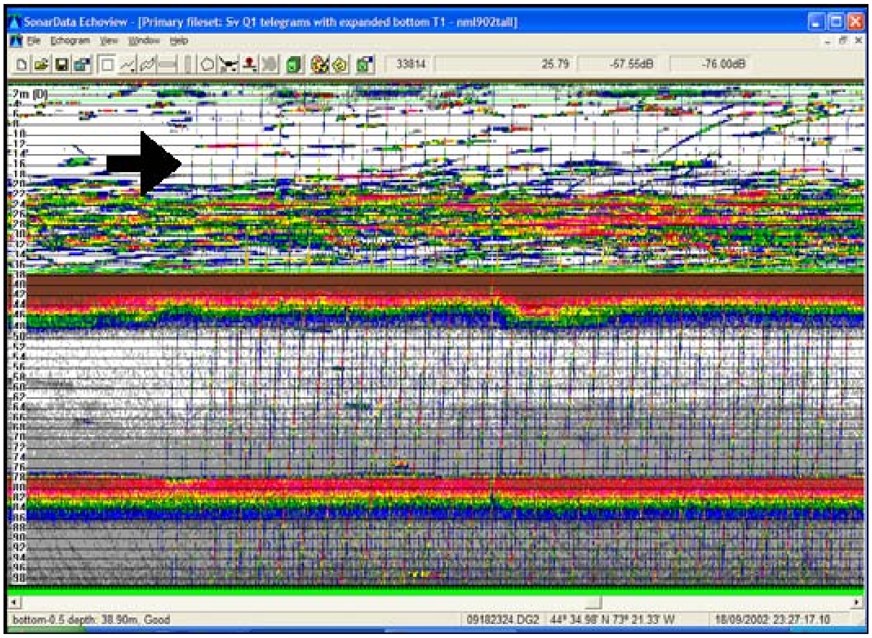
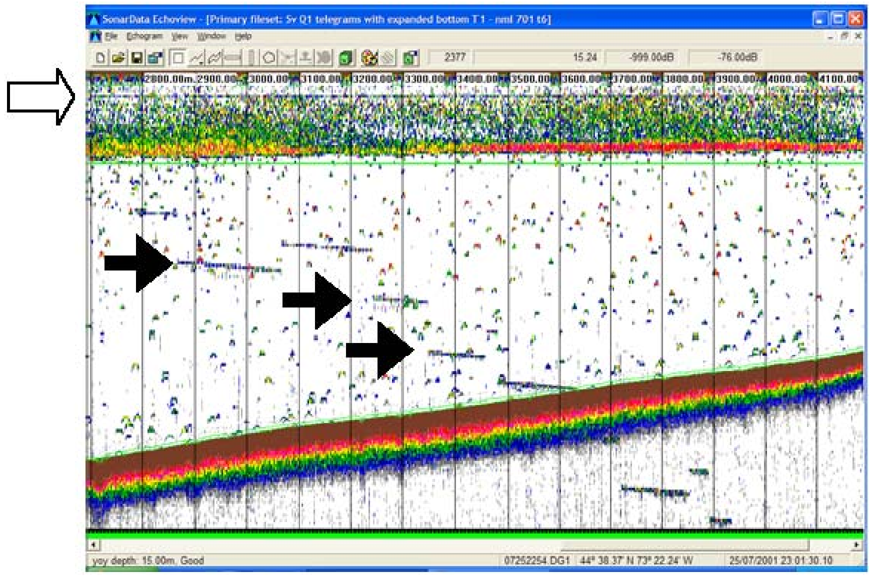


Fig. 12b. Example of acoustic interference (cross-talk) between two frequencies (unsynchronized 70 and 200 kHz scientific echosounders). The black arrows indicate the appearance of cross-talk (horizontal lines) and the hollow arrow indicates an echo return from side lobes hitting the hull of the survey vessel (solid, horizontal line in the upper water column).



8.6.1.2 Electrical Noise

Electrical noise (interference, Figs. 13a, 13b) can be caused by improper grounding of the survey echosounder or other components of the electrical system and can result in low-level voltage interference, spikes, or cyclical interference. There is also some internal noise generated by the electronics in the echosounders themselves. A low-level voltage introduced to the echosounder will be amplified with range by the TVG function and pose a problem, mainly in the greater depths of the survey area. Hydraulic pumps or winches may cause dramatic increases in noise during operation and should be checked to ensure that they do not generate noise during standby. It is advisable to test acoustics equipment under various operational scenarios (e.g., winch operation, trawling, coffee maker turned on, galley fans, etc.) prior to the commencement of a survey. It is also good practice to test equipment after significant modifications to the vessel (e.g., winch, propeller, or generator replacement/repair). The magnitude of these noise sources can change with vessel speed (see below). Electrical noise can be reduced or eliminated by:

- Ensuring proper grounding of the scientific echosounder
- Using an uninterruptible power supply for the scientific echosounder
- Placing transducer cables and data ethernet cables away from possible electric fields, such as fluorescent lights

Electrical interference not eliminated during data collection (Figs. 13a, 13b) should be removed during data analysis, either manually or with signal processing techniques. Manual removal of noisy regions and excluding them from the analysis should not affect results, as long as these regions are relatively small. Automated techniques may be possible but probably require specialized software. If signal-processing techniques are used, care should be taken to ensure that data are not modified or correction factors may be required.

Fig. 13a. Common noise pattern as seen on a 70 kHz acoustic echogram showing electrical interference (arrow indicating the electrical wave-like pattern throughout much of the water column).

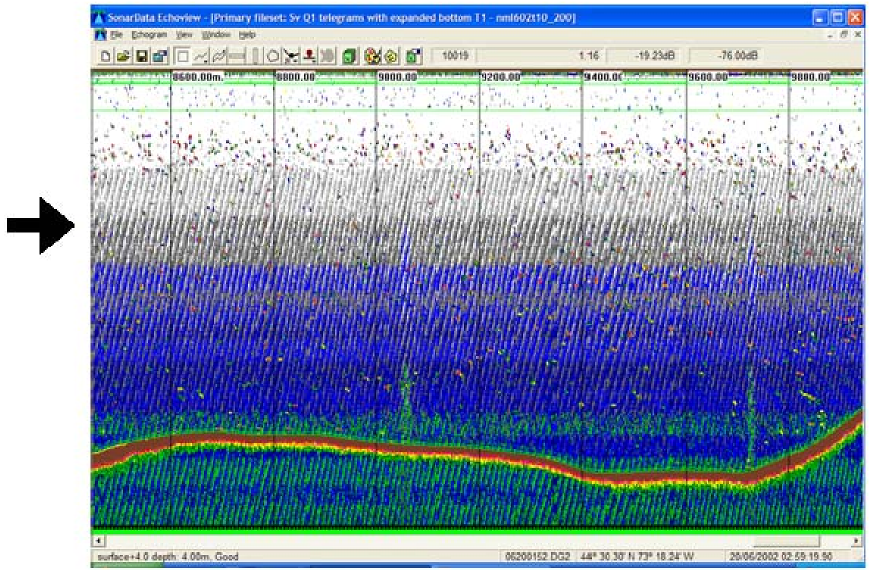
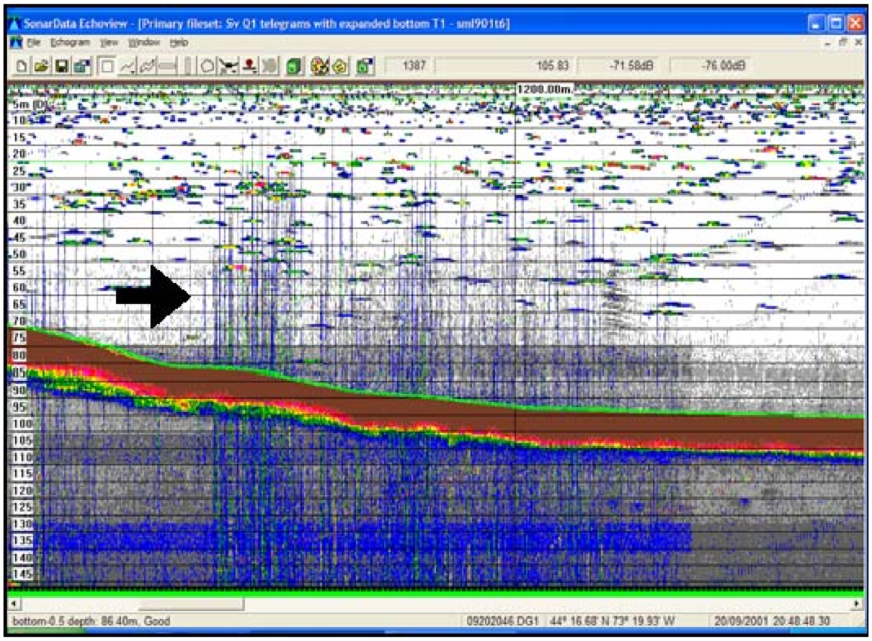


Fig. 13b. Common noise pattern as seen on a 70 kHz acoustic echogram showing noise from hydraulic winches (arrow indicating vertical spikes) during trawl deployment.



8.6.1.3 Bubble Attenuation

Bubbles, because of the high impedance between air and water, can have a strong effect on propagation and transmission of sound. Bubbles near the sea surface are generally produced by an increased sea state and/or the position of the transducer relative to the vessel's hull. The transducer location on the hull must be chosen to minimize potential problems caused by wake-produced bubbles. To prevent bubble-induced degradation of survey data, it is necessary to slow vessel speed or suspend acoustic survey operations when sea state causes unacceptable loss of signal strength. Bubble backscattering can be removed from data during data analysis by removing a portion of the data near the transducer face, but this will not correct for signal loss from targets of interest.

8.6.1.4 Propeller Cavitation

Cavitation is the formation of gas bubbles caused by low-pressure areas created as water accelerates and moves past the surface of vessel propeller blades. Faster propellers create lower pressure regions, and therefore, more bubbles than slower propellers. The noise that is detected on acoustic systems results from the sudden collapse of these bubbles. In addition to causing detectible noise, cavitation can also degrade propeller blade surfaces, thus increasing the amount of noise generated. The amount of cavitation can be influenced by propeller design or by flow patterns resulting from vessel design (e.g., hull shape) or from damage to the propeller. Propellers should be visually inspected prior to a survey to ensure that blades are not damaged. Replacement of the propeller or modification of the vessel hull may be necessary if cavitation is excessive.

8.6.1.5 Other Vessel Noise

Vessel engines and gearboxes may also generate noise that is detected by the echosounder (reviewed by Mitson and Knudsen 2003). Depending on vessel design, engines and gearboxes may cause the hull to vibrate and generate pressure waves. Vibrations will cause an increase in noise, particularly in shallow water with hard bottoms. Additionally, gearboxes are known to “whine” at frequencies that may be audible to acoustics.

8.6.1.6 Hull Interference

When a transducer is mounted on a shallow towed body or pole mounted, it is possible to receive backscatter from side lobes hitting the vessel hull. When side lobes hit the side of the boat, a solid band of backscatter at a distance from the surface is visible on the echogram (Figs. 12a). Deep-hulled vessels exacerbate this condition. This interference can be reduced or eliminated by deploying the transducer, whether towed body or hull mounted, deeper. However, deeper deployment can result in a loss of near-surface data. Data that includes hull interference should be removed from analysis.

8.6.2 Degradation

8.6.2.1 Bio-Fouling

Bio-fouling results from the accumulation of biological material (e.g., algae and small invertebrates) on the face of the transducer, causing a systematic degradation in echosounder performance as the bio-fouling increases. Bio-fouling can occur on hull-mounted transducers or protective coverings that stay in the water for long periods of time. Accumulation of material on the transducer will reduce transmission and reception sensitivity. The loss of sensitivity may not be recognized by system performance procedures, although it should be detected by calibration. Hull-mounted transducers and protective coverings should be regularly checked and cleaned, at least before each field season. Bio-fouling is less of a problem for towed-body and pole-mount transducers, as these are normally removed from the water when not in use.

8.6.2.2 Cable Breaks

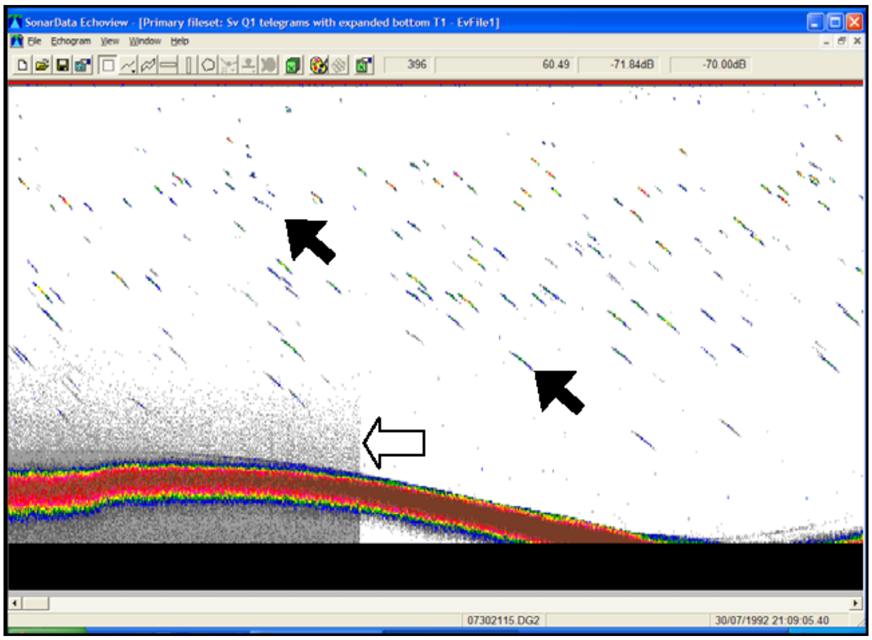
Cable breaks are of concern because they can cause a loss of signal, and once the cable housing is breached and water penetrates the cable and moves into the transducer, the transducer is irreparable. Transducers mounted on towed bodies are most susceptible to cable breaks given the distance between transceiver and transducer. Cable breaks may occur during storage, transport, or survey. Cables should be inspected for cable-housing breaks prior to each use. Breaks within the cable housing can result in a periodic loss of signal, or for a split-beam transducer, loss of specific quadrants.

8.6.3 Improper Towed-Body Weighting

Data quality can be degraded when the transducer face is not parallel to the surface of the water. This commonly occurs when towed bodies are improperly weighted, either nose-up or tail-up in the water. Fig. 14 illustrates an example of a towed body that is nose down, resulting in single-fish echoes that appear to be elongated downward rather than approximately cup-shaped. Improper weighting can result from:

- Sub-optimal speed (too high or too low)
- Towed-body placement within hull wake
- Transducer placement on the towed body
- Improper counterbalance weighting of the towed body

Fig. 14. The effect of improper towed-body weighting on single-fish echoes. In this case, the towed body was tipped nose-down, resulting in diagonal fish tracks (examples are indicated by solid arrows). Also note on this echogram that noise levels (indicated by the hollow arrow) changed during the transect, likely due to reestablishing a proper electrical ground.



The effects of this problem include inaccurate bottom-depth and target-depth measurements and possible lost data pings. A tilted transducer also causes the fish to appear tilted relative to the transducer. This tilt will result in differences in *TS* between surveys making identification of *TS* distributions difficult. S_v values will be biased relative to theoretical *TS* measurements for the size of fish sampled. This bias is less of a problem if using *in situ TS* measurements, but be aware that the *TS* distributions will be affected by the resulting tilt angle of the fish relative to the transducer. Comparisons of *TS* distributions between years and sampling frames within the lake may be affected.

Improper towed-body weighting can be diagnosed by direct observation and inspection of the echogram. It is advisable to conduct pre-survey trials to determine the proper weight placement on the towed-body, its deployment in the vessel wake, and optimal vessel speeds.

8.7 Diagnosis of System Performance

Echosounder manufacturers should provide detailed diagnostic and evaluation routines. General diagnoses for the Simrad EK500 or EY500 are as follows.

8.7.1 Test Data

A "test" value for Simrad transducers measures transducer performance through an internal oscillator routine. Test values should be checked at the beginning of each survey day. This feature is not available on the BioSonics units. A "test" value outside the specified tolerance (-55 ±2 dB for Simrad split-beam transducers and -61 ±2 dB for Simrad single-beam transducers) is an indication of a broken connection in one or more of the wires to the transducer or a faulty transceiver board. However, changes in the test values relative to values when the system was working properly that are important. The specified tolerance limit of ±2 dB may be too broad to detect problems. A change from -55.5 dB to -53.5 dB indicated a cable break in the Cornell Simrad EY500 unit. If the "test" signal is changing and/or outside of tolerance values:

- Check all transducer connections
- Measure transducer impedance (should be 60 Ω)
- Measure transducer impedance while moving sections of the transducer cable to detect any weak sections

The cause of an unacceptable test signal should be determined and rectified. If connections and transducer impedance are not the problem, then a full set of diagnostics must be completed on the echosounder. The survey should not continue until the problem is rectified. If individual targets do not appear in all quadrants, survey operations should be suspended and the problem diagnosed (Advanced Sampling Technologies Working Group 2003).

8.7.2 Passive Data

When a transducer is switched to “passive” mode, it listens but does not transmit. This function allows the user to measure ambient background noise or to determine the source of detected noise. Passive mode should be used prior to the commencement of a survey to determine if vessel noise levels are acceptable. In general, stationary noise levels of -140 dB (*TS* domain) or less are attainable with proper grounding. Procedures for the collection of vessel noise data are available from the manufacturers. Recommendations from Mitson (1995) and Simrad suggest that passive data should be collected under the following conditions:

- Vessel stationary and running
- Incrementally increasing the vessel to survey speed
- Vessel running at survey speed
- Incrementally decreasing the vessel to stationary
- Towing the trawls (midwater and/or bottom) to be used during the survey

If increasing noise is observed with increasing speed, and vice versa with decreasing speed, the engine or propeller is causing the noise. It is then also advisable to collect passive data under different RPMs, and propeller pitch and speeds. A minimum of 2-5 minutes of passive noise collection under each condition/speed is recommended.

By using the echogram color scheme, the user may evaluate whether noise levels will mask the targets of interest (Example 7).

Example 7 (taken from the Simrad EK60 Manual). If the desired lower S_v limit is -70 dB, and an SNR of 10 dB is required, set the minimum color scale for the $20 \cdot \log_{10}(R)$ TVG to -80 dB. The point at which shading in the echogram (e.g., gray) begins is the depth at which the S_v limit is obtained with the 10 dB SNR. The same can be done using the $40 \cdot \log_{10}(R)$ TVG echogram for TS_u.

Noise levels at 1 m (S_v at 1 m) observed during survey conditions should be recorded and reported in papers that utilize the survey data. Note that noise level measured in the *TS* domain is not the same as noise levels in the S_v domain (Equation 24).

9. DATA PROCESSING AND ANALYTIC DECISIONS

Data-collection parameters are set to acquire data that can be used for a variety of purposes, whereas data-analysis parameters and techniques are often optimized for single species. In other words, data collection attempts to maximize the detection probability for a wide variety of organisms, whereas data analysis attempts to maximize the detection probability for the species of interest and minimize the detection probability for all other organisms (Advanced Sampling Technologies Working Group 2003).

9.1 File Preparation

Prior to data export with a data-analysis package, several quality checks and processing decisions must be made.

9.1.1 Data Files

Depending on the analysis to be used, data files may be created to contain single transects, strata, or the entire survey. An analysis using transects as sampling units might benefit from keeping them separated during processing. Additionally, smaller, time- or location-referenced files make identifying specific sections of surveys easier. The components of an individual data file should also be chosen with file size in mind, because some data analysis packages slow considerably with increasing file size. If file processing speed is not a problem, it is straightforward to define each transect as a separate region in a file within the whole survey.

9.1.2 System and Other Settings

All system and collection settings must be input to each data file or a file template. Use the note fields to add comments and information on the surveys. Calibration and environmental settings are entered in calibration tabs for each variable (also check derived variables) and for the transducer. In EV and S5 software, calibration parameters are obtained directly from the data string for some echosounders. Typical calibration settings include gains (*TS* and S_v), equivalent beam angle, beam width, beam offset, and number of samples per meter.

Calculate average sound speed and absorption coefficient given the depth of the fish of interest. A calculator is available in most software, but temperature (and salinity) must be provided by the user. If all fish are found in water shallower than a given depth (e.g., 30 m), use average temperature between the surface and that depth (e.g., surface to 30 m). Alternatively, a measured temperature gradient can be entered to change sound speed and alpha dynamically with range (S5). Sound speed must be set to the same value in all analysis variables (echograms), or the data will not align properly (EV).

If settings have changed during the survey, be sure to make these changes in the data-analysis file. Make separate files for sections with different settings; however, separate files are not necessary for changes in ping rate, because variable ping rate is not a large problem in the analysis. Decisions about keeping sound speed and absorption values consistent for the survey or to vary with location (if sampling over a large area or one with very different values) are necessary at this stage of the analysis.

9.1.3 Surface Exclusion Zone

Selection of a surface exclusion zone should take into account:

- Extent of the near-surface dead zone, including the near-field of the transducer
- Transducer depth
- Surface conditions due to weather
- Vertical distribution of species or group(s) of interest

The purpose of the surface exclusion zone is to remove unreliable data while maintaining information about the survey targets. In the case of surface conditions, it is advisable to apply noise removal (see 9.1.5 below) and/or biological thresholds (see section 9.4 below) before selecting a surface exclusion zone, as these thresholds may remove or reduce the effect of bubbles on the data.

9.1.4 Bottom-Detection and Bottom-Exclusion Zone

Echosounders and data-analysis software use algorithms to detect the seabed. Depending on bottom type and topography, performance of these algorithms varies. The algorithms perform well on hard, flat substrate, but their ability to detect the bottom degrades on soft substrate or rugged topography. Echo strength from the seabed is typically orders of magnitude greater than the echo strength from biological organisms, thus, eliminating seabed echoes from the water-column data is imperative.

Improper bottom detections are found and corrected manually through inspection of the echograms or through automated algorithms. Failure to verify bottom detection could result in increased S_v values due to bottom inclusion. Bottom detection can also exclude echoes from dense fish schools. A detailed pixel-by-pixel check of the bottom definition is possible in the software.

The bottom-exclusion zone is selected to remove data within the near-bottom dead zone. However, targets of interest within this exclusion zone are also removed from analysis. Although Ona and Mitson (1996) propose extrapolating integration and *TS* values from the region immediately above the dead zone into the volume represented by the dead zone itself, this approach is not without bias (Simmonds and MacLennan 2005). If targets of interest are within the dead zone, it is advisable to acknowledge the bias that is introduce by the bottom-exclusion zone and only proceed with an extrapolation-based correction factor if the nature of near-bottom distribution is well known.

9.1.5 Noise Removal

Areas of an echogram with discrete spikes, diagonal lines, or horizontal lines resulting from acoustic (Figs. 12a, 12b), electrical (Fig. 13a), or trawl noise (Fig. 13) may be manually excluded as “bad-data regions,” but data associated with the noise will also be removed from analyses. Note that the assumption about fish density in bad-data regions is important if these regions are large. Two options are currently available:

1. Exclude bad-data regions from analysis (this will result in correct average S_v values, but S_a values will be biased low).
2. Assume bad-data regions have 0 acoustic scattering (this will lead to both S_v and S_a values being biased low).

The amount of bias depends on the size of the bad-data region. The assumption that bad-data regions have the same fish density as the surrounding water is not implemented directly in either S5 or EV software**,** but fish density can be calculated from the exported S_v data if the size of the analysis cell is known (export cell height while including bad-data regions in EV, and use that height to calculated S_a values from the measured S_v).

There is always ambient noise that is amplified by the TVG function and, therefore, appears to increase with depth. This noise is additive to the signal and can be removed with a threshold or by subtraction. A threshold removes noise by only accepting echoes larger than the threshold. This method will not account for noise added to the accepted signal, but this should not be a problem as long as the signal is an order of magnitude higher than the noise. But, if data with smaller SNR is to be used, then subtraction is the best approach (Watkins and Brierley 1996; Korneliussen 2000).

To remove ambient noise, measure S_v values in an area where only noise is expected, ideally from passive data. One such area is below the bottom signal or in deep water. Although the noise level is the same, the values expressed as TS_u or S_v are different because S_v values include the effect of the pulse volume (Equation 24, Example 6). Noise levels at any depth, including at 1 m, can be calculated from a measure of noise at a given depth (Equation 25 and 26) or directly from data collected in passive mode. Subtraction of noise in EV is done by either modeling the noise S_v value (at 1 m) using a virtual variable and then subtracting this virtual variable from the data, or by integrating noise and subtracting it from the data after data export. S5 calculates average noise levels from a user-defined region in any echogram (active or passive) and provides a plot of noise for all depth layers. This depth-dependent noise level can then be subtracted from any echogram.

Noise levels at 1 m (TS_{uN1} in TS domain and Sv_{N1} in S_v domain) can be calculated from the following equations:

(25) $$TS_{uN1} = TS_{uNZ} - 40 \bullet \log_{10}(R) - 2\alpha R$$

(26) $$S_{vN1} = S_{vNZ} - 20 \bullet \log_{10}(R) - 2\alpha R$$

where TS_{uNZ} and S_{vNZ} are the noise levels in dB measured at range R in the TS and S_v domains, respectively. The TS_u and S_v values are related—recall equation (24) $TS_{uNZ} = S_{vNZ} + 10 \bullet \log_{10}(V)$. Alternatively, the noise level can be obtained from measurement at many depths by minimizing the difference between a theoretical curve (from Equation 25 or 26) and several noise measurements. This minimization can be done with non-linear estimation in any statistical package, including Excel's solver routine.

9.2 Single-Echo Detection

Measures of TS of the organisms present are useful for scaling echo integration data to absolute abundance estimates and for interpreting the observed echoes. However, these measures are biased if fish are not sufficiently separated to be observed as single targets. Analysis software packages include algorithms for filtering out single echoes. The most commonly used algorithm is derived from Soule et al. (1997). Single targets (echoes) are detected following these general steps:

1. Peak amplitudes are selected above a single-echo detection threshold (SEDT).
2. The echo width (either time- or range-based) is measured.
3. The echo width is compared to the pulse duration.
4. Phase-jitter (angle standard deviation) should be smaller than a certain value.
5. The calculated beam compensation should be smaller than a certain value.

The threshold in step 1 should be small enough to observe the lower range of the *TS* distribution. Examination of this distribution is the basis for setting analysis thresholds in both the S_v and TS_u domains (see below). The chosen threshold for analysis will be higher than the initial SEDT. In addition, S5 provides a different approach for detecting traces (cross-filter detector) (Balk and Lindem 2000), but this feature has not yet been tested for *in situ TS* measurements on the Great Lakes.

For the Great Lakes, we recommend using an initial SEDT of -75 dB, a maximum beam compensation of 6 dB (two-way, 3 dB one-way), an echo duration of 0.6 to 1.5 times the pulse duration, and a maximum standard deviation of both angles of 0.6. These settings are similar to software default settings except that the default lower *TS* threshold is often set at -50 dB, which is too large for Great Lakes applications. The recommended limits for echo duration are also slightly wider than default, which is important when using short pulse durations. The choice of acceptable echo duration for single targets is partly dependent on the shape of the pulse, and it may be possible to make those limits more stringent with newer transducers and longer pulse durations. In shallow lakes (western Lake Erie) or in lakes with few targets (e.g. Lakes Superior and Huron), we recommend using a larger beam compensation to increase the number of detected single-fish echoes. Our analysis shows less than a 1 dB difference when beam compensation is increased from 3 to 12 dB. This potential bias has to be weighed against the increase in the precision of *in situ TS* measures due to more identified targets.

Different echosounder manufacturers and data-analysis software packages may apply single-target detection methods differently. It is important to understand the specific methods used to ensure that they are consistent and comparable with other studies. EV software presents two methods (referred to as methods 1 and 2) and a Simrad and a BioSonics single-fish filter. The two methods give slightly different *TS* values, although the difference is small. Even so, it is recommended that the same method be used for analysis as was used during calibration. Check the software for the method recommended for different echosounders.

A survey from Onondaga Lake collected at 70 kHz with a Simrad EY500 split-beam unit (0.2 msec pulse duration, 11.4^{o} beam width, (Table 5)) provides an example of single-fish detection settings. The open-water fish population was dominated by one age-group of alewife with an average length of 148 mm. Echoview suggests using single-target detection method 1 for EY500 data. When methods 1 and 2 were compared, differences were small—in the order of 0.1 dB. Since this difference is present also in calibration data, the two methods are essentially identical after correcting for differences in calibration. We present data only for method 1 in Table 5. This survey had relatively high noise levels, and some noise spikes were present in water deeper than 10 m. These spikes were often accepted as single-fish echoes when the angle standard deviation was high, resulting in a decrease in *in situ TS* of more than 1 dB. When the analysis was restricted to water depths of 2 to 10 m, the effect was less. Mean *TS* increased from -42.55 dB for an angle standard deviation of 0.6 to -41.73 dB for an angle standard deviation of 5 (both at 6 dB beam compensation). This difference of 0.82 dB is equivalent to a 20% difference in fish abundance. Mean *in situ TS* also increased with higher beam compensation (Table 5), but this increase was small. For this survey, the mean *TS* was -42.58 dB with 3 dB beam compensation and -42.41 dB with 12 dB beam compensation (at a angle standard deviation of 0.6)—a difference of 0.17 dB (and a 4% difference in estimated fish density). The effect of changing an acceptable lower limit for the normalized pulse length from 0.6 to 0.8

times the initial pulse length was a 0.3 dB decline in *in situ TS* and a sixfold decrease in number of accepted targets (from 3000 to 500). Decreasing the upper pulse length limit from 1.5 to 1.2 had no effect. Although a difference of less than 0.8 dB in mean *TS* may be considered relatively small, such differences do result in an up to 20% change in estimated fish density, which is of similar magnitude to several other components of uncertainty associated with acoustic surveys (Simmonds et al. 1992).

Table 5. Mean *TS* calculated for targets larger than -60 dB in the 2-10 m depth layer using different single-echo detection settings. The data are based on a survey with at 70 kHz (11.4^{o}, 0.2 msec pulse duration) in Onondaga Lake, NY, May 2005, when an age-3 alewife year-class dominated and constituted over 95% of the catch). Data analysis is with Echoview, method 1. *ΔTS* is the difference in mean *TS* for targets >-60 dB compared to standard recommended settings (row 2), which had a mean *TS* of -42.55 dB. Angle variance is given in mechanical degrees; echo length is a multiplier of pulse length.

Beam compensation (dB)	**Angle variance**	**Minimum echo length**	**Maximum echo length**	**Number of targets detected**	**Mean *TS* > -60dB (dB)**	***ΔTS* (dB)**
3	0.6	0.6	1.5	1567	-42.58	-0.03
6	0.6	0.6	1.5	2976	-42.55	0.00
9	0.6	0.6	1.5	4177	-42.44	0.11
12	0.6	0.6	1.5	5235	-42.41	0.14
6	2.0	0.6	1.5	4815	-41.97	0.58
6	5.0	0.6	1.5	6172	-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	2950	-42.55	0.00

Another difference between EV SED methods 1 and 2 is the application of the *TS* minimum threshold. EV SED method 1 applies the minimum threshold to uncompensated targets, resulting in the loss of small targets that are above threshold after compensation for position in the beam. Conversely, method 2 accepts any targets are above the minimum threshold after compensation. If SED is performed in EV using method 1, we recommend using a *TS* minimum threshold 6-10 dB lower than the desired *TS* minimum threshold and then applying a data threshold to the compensated targets. If method 2 is used for SED, the desired compensated target strength threshold may be used directly in SED without a data threshold.

9.3 Size of the Analysis Cell

9.3.1 Vertical Bin Size

The selection of vertical bin size is generally a trade-off among:

- Known or observed biologically relevant strata
- Known or observed environmentally relevant strata (e.g., thermal and optical)
- Anticipated analysis structure
- Maintaining a minimum number of targets in each analysis bin

Definition of bins based on biologically relevant strata, environmentally relevant strata, and analysis structure all aim to isolate specific groups, acoustic structures, or conditions for analysis. However, prior consideration should be given to the resultant data output. Typical data-analysis programs output a single line of data for each analytic bin, unless a database format is used.

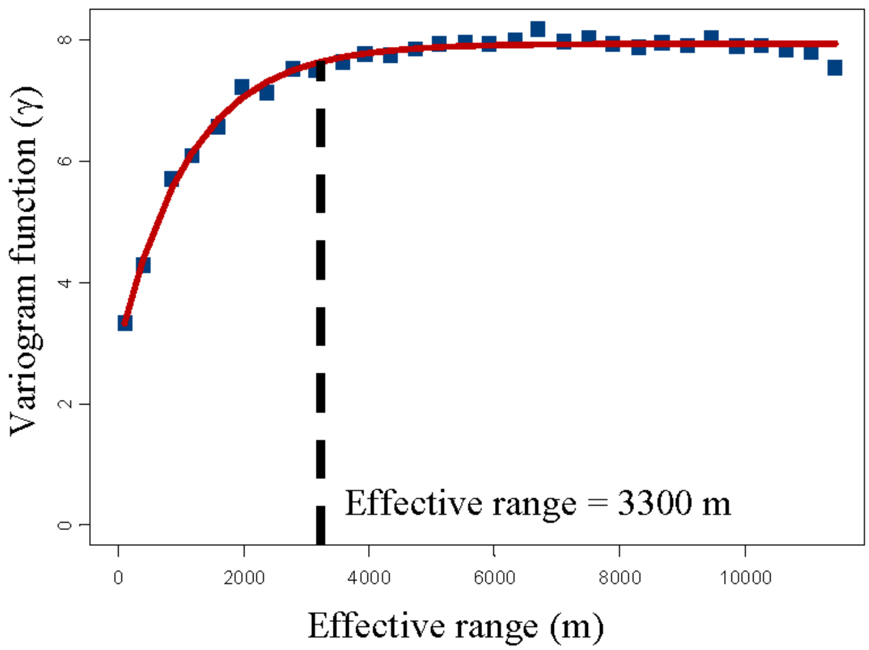
Note that the equation that relates S_v, σ_{bs}, and fish density only holds for a random distribution of fish within the beam. With only a few fish targets, deviations from a random distribution are likely, and the error in S_v and estimated fish density in an analysis bin increases when the number of targets is small. The standard deviation of the estimate of mean S_v is 9% of the beam when 10 similar-size targets are observed within the half-power beam width. Because of non-linear effects of fish size on *TS*, the effect may be larger when *TS* distributions are wide. More work is needed on the size of the sampling unit when using *in situ TS* to scale echo integration values.

9.3.2 Horizontal Bin Size

Horizontal bin size must take into consideration the objectives of the survey and future analysis. If classical statistical analysis is performed, the horizontal bin can be a whole transect without loss of precision. If a geostatistical approach is used, the horizontal bin size must be less than half the range of a variogram model of the data (Fig. 15) (Rivoirard et al. 2000). If density distribution is the survey objective, horizontal bins must capture the spatial structure of the underlying backscatter. To use a variogram to determine horizontal bin size:

1. Export data in a fine horizontal bin, such as 50 m.
2. Generate an empirical variogram model based on these data.
3. Fit a theoretical variogram model to this empirical data.
4. Determine the range (for spherical) or effective range (for exponential) at which the data are no longer autocorrelated in the theoretical model.
5. Select a bin size that is no more than half of this range.

Fig. 15. Empirical data (squares) and theoretical variogram model (smoothed line) for 120 kHz S_v data showing an effective range (the distance at which data are no longer autocorrelated) of 3300 m. In this example, a horizontal bin size of 250 m was selected, but 500 to 1000 m would also be appropriate.



The lower limit of horizontal bin size should be governed by:

- Data-processing power and needs
- Avoidance of the variogram "nugget zone," where observed spatial patterns may be related to measurement error or random error in the data
- Maintenance of a desired number of targets in each analytic bin

In maintaining a desired number of targets per bin, a trade-off is required with vertical bin size. Fine vertical bins may require larger horizontal bins.

9.3.3 Great Lakes Analysis Cell Sizes

Different horizontal and vertical bin sizes are used in Great Lakes surveys (Table 6). Bin sizes for Lake Champlain are under review but have not yet been established.

Table 6. Typical sizes (m) of horizontal and vertical analysis bins and ping rates (pings•sec^{-1}) for Great Lakes acoustical surveys. Layers in Lake Erie are determined by temperature profiles.

Lake	Horizontal bin	Vertical bin	Ping rate
Lake Ontario	2000 m	2 m	1 pings•sec^{-1}
Lake Erie	800 m	Epi-, meta-, and hypolimnion	0.5 pings•sec^{-1}
Lake Michigan	1000 m	10 m	0.5 to 1 pings•sec^{-1}
Lake Huron	1000 m	10 m	0.5 to 1 pings•sec^{-1}
Lake Superior	1000 m	10 m	0.5 to 1 pings•sec^{-1}

9.4 Separating Groups of Interest

Uncertainty in classifying and separating acoustic backscatter by target species from nontarget species or background noise is a potential source of error in acoustic estimates of density and abundance. Errors that may influence backscatter, *TS*, or vertical distribution data include (Advanced Sampling Technologies Working Group 2003):

- Misclassification (including nontarget or excluding target backscatter)
- Scaling acoustic data with unrepresentative fish length or age data
- Unrepresentative *in situ TS*
- Incorporating seabed echoes in water-column data
- Using inappropriate absorption or sound speed coefficients
- Improper calibration of echosounders and/or temperature sensors

Decisions must be made on how to separate target and nontarget species using one or more of several approaches:

- Spatial or temporal
- *In situ TS*
- S_v thresholds
- Partitioning by trawl catches

9.4.1 Spatial or Temporal Separation

The simplest way to separate target and nontarget species is to conduct a survey during a time (seasonal or diel) when the two groups are separated. For example, YOY rainbow smelt and alewife have different thermal preferences than yearling-and-older rainbow smelt and separate spatially during temperature stratification in the summer (Figs. 16a, 16b). Assessments in Lakes Ontario, Erie, Michigan, Huron, and Champlain take advantage of this separation by surveying in July to September.

Fig. 16a. Example of vertical separation of fish age-groups showing young-of-the-year and yearling-and-older rainbow smelt in Lake Champlain (redrawn from Parker-Stetter et al. (2006)). Shown is the distribution of individual fish targets. Location of the thermocline is marked with a solid black arrow.

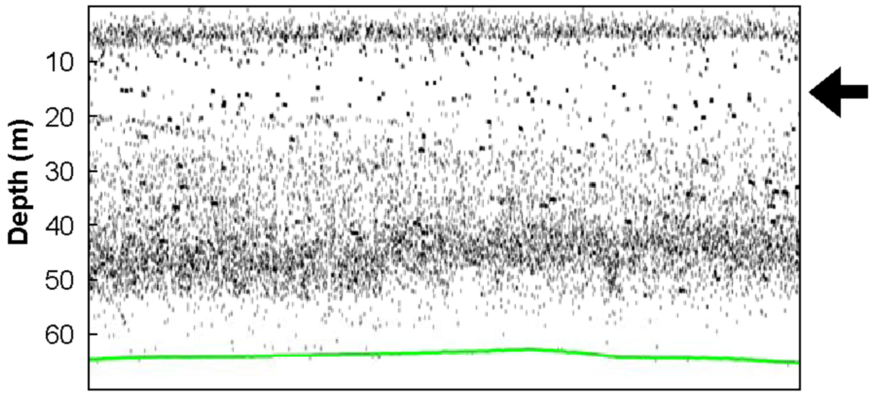
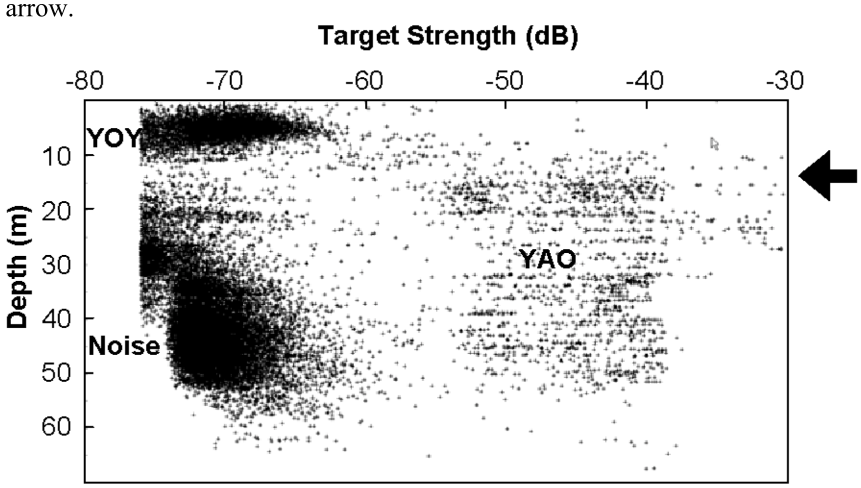


Fig. 16b. Example of vertical separation of fish age-groups showing young-of-the-year and yearling-and-older rainbow smelt in Lake Champlain (redrawn from Parker-Stetter et al. (2006)). Shown is the *TS*-depth distribution of the same targets. Location of the thermocline is marked with a solid black arrow.



9.4.2 Target Strength (*TS*)

9.4.2.1 *In Situ TS*

When individual fish can be resolved, *in situ TS* values can be obtained and used for calculating average backscattering cross sections, which can then be used to scale volume or area backscattering coefficients to fish density. When using *in situ TS*, it is important to analyze the data in depth regions with homogeneous fish groups, because the sampling volume increases with depth, and fish in deeper water will, therefore, be overrepresented in the data relative to their contribution to overall density. In many lakes, larger fish are found deeper and will be overrepresented in a *TS* distribution derived from the whole water column.

The *in situ TS* distribution can also be useful for separating age-groups and size groups. *In situ TS* ranges are best determined by observing the target group of interest in the absence of other potential scatterers, during normal activity (e.g., after diel vertical migration), and during the same month/season covered by the survey. If a range of "acceptable" *TS* can be defined, values outside this range can be attributed to either large or small nontarget organisms or noise. For example, yearling-and-older (YAO) rainbow smelt *in situ TS* values fall between -60 and -35 dB (Parker-Stetter et al. 2006). In June, values below -60 dB are from YOY rainbow smelt. During all times, values larger than -35 dB are from large piscivores (e.g. lake trout (*Salvelinus namaycush*)). In Lake Superior, targets >-35.6 dB are considered to be large (>250 mm) cisco (Yule et al. 2007). If a range of acceptable *TS* values cannot be defined, an alternative is to fit several theoretical distribution curves to the *TS* distribution to separate contributions from different species or age-groups (Rudstam et al. 1987; Warner et al. 2002). The contribution of alewife in Lake Ontario is calculated that way. With this method, it is important to be aware of the possibility of multiple peaks in the *TS* distributions from a single size group, such as what has been observed for rainbow smelt (Rudstam et al. 2003; Parker-Stetter et al. 2006). Parker-Stetter et al. (2006) present a variant of this method for separating the contribution of YOY and YAO rainbow smelt during the period of spatial and *TS* range overlap in September. A similar approach for separating sockeye (kokanee) salmon (*Oncorhynchus nerka*) from large lake trout was proposed by Crockett et al. (2006). More work is needed to determine the appropriate functions to use for different species and age-groups.

In situ methods are advantageous because they incorporate behaviors and vertical distributions observed during the survey. A limitation to this approach is that fish have to be sufficiently dispersed to be observed as single targets**.** A systematic change in fish orientation, for example, from a horizontal to a more-vertical position during vertical migration, will cause a change in *TS*.

9.4.2.1.1 Great Lakes *In Situ TS* Ranges

Most Great Lakes surveys utilize *in situ TS* ranges to assist in the separation of species of interest. In many cases, vertical separation is also used. There is overlap of *in situ TS* ranges, and they vary with season for YOY fish. *TS* ranges in Lakes Ontario, Erie, and Champlain are different from Lakes Huron and Michigan because of differences in the timing of the surveys. Defined *in situ TS* ranges, as well as vertical analysis bins divided into epilimnion, metalimnion, and hypolimnion (Table 6), are currently used only in Lake Erie. *TS* ranges for July surveys in Lake Erie are:

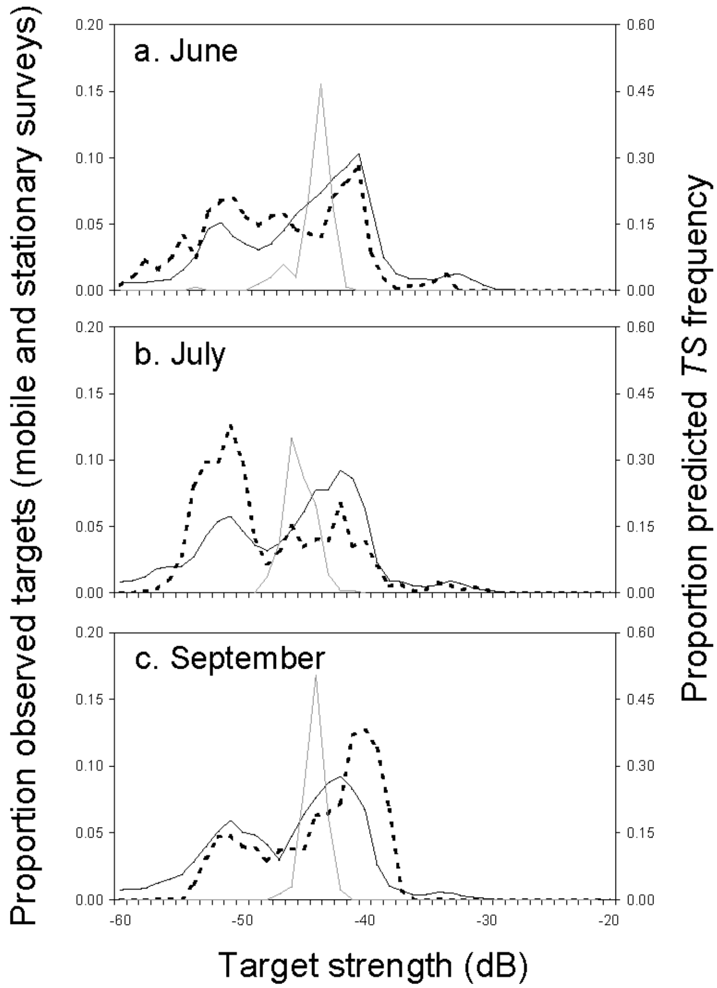
- YOY rainbow smelt: -70 to -59 dB
- YAO rainbow smelt: -59 to -40 dB
- Large fish other than rainbow smelt: -40 to -20 dB

In Lakes Michigan and Huron, the shape of the distribution of *in situ TS* between -76 and -20 dB are used to set the lower threshold using guidance from *TS–L* regressions (Warner et al. (2002) for alewife; Rudstam et al. (2003) for rainbow smelt). Species and length composition are based on trawl catches. Lake Ontario data are processed with a -64 dB *in situ TS* lower threshold, but densities are then prorated according to information in the *TS* histograms. Decisions are made individually for YAO rainbow smelt (hypolimnion, targets >-55 dB) and adult alewife (estimate targets belonging to a peak centered at approximately -39 dB).

9.4.2.1.2 Validation

In situ TS ranges should be validated or compared with other techniques. Direct sampling (trawling, etc.) to identify species and length composition is essential. Repeated observation of *TS* ranges will ensure that the distribution is representative. Parker-Stetter et al. (2006) compared *in situ* results from mobile surveys, *in situ* measurements from stationary-tracked single fish, and predictions based on length-frequency in trawls (Fig. 17). Note the similarity in range and shape of the *TS* distributions between stationary- and mobile-survey estimates of *TS*. Also note that those distributions are both much wider than expected from calculations of mean *TS* from *TS*–*L* regressions and the length distribution in trawl catches.

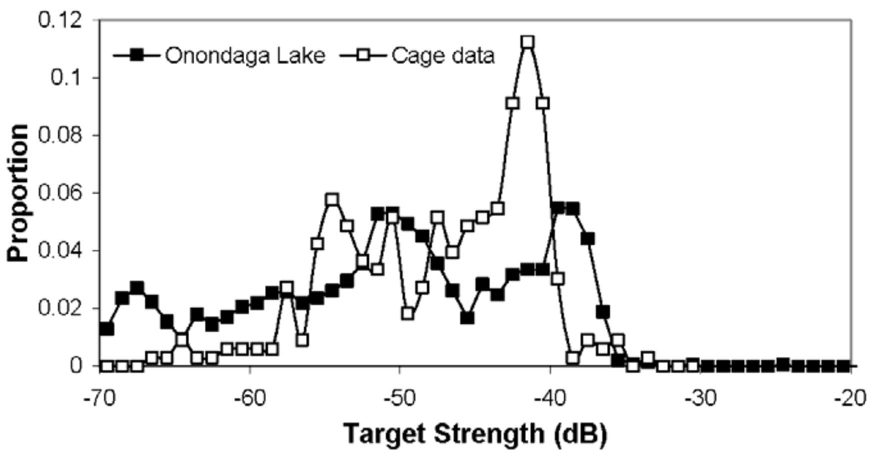
Fig. 17. Comparison of mobile survey (solid black), stationary survey (dashed black), and trawl capture (solid gray) estimates of *TS* for age-1 and older rainbow smelt in Lake Champlain during June, July, and September. The "trawl" target strength is calculated from the trawl catch and a *TS–L* regression (Parker-Stetter el al. 2006).



9.4.2.2 *Ex Situ TS*

Ex situ measurements in acoustic surveys are controlled or semi-controlled experiments where individuals or groups of known sizes are insonified. *Ex situ* measurements are often done on fish of known species and size suspended in a large cage, or individuals that are anesthetized and insonified suspended in a frame. An example of a *TS* distribution derived *ex situ* for alewife in a large net cage compared to *in situ TS* distribution is presented in Fig. 18. Disadvantages of *ex situ* measurements are difficulties in replicating *in situ* conditions and uncertainty in applying *ex situ* measurements to survey conditions.

Fig. 18. Alewife *TS* distribution (mean *TS* -42.8 dB) from Onondaga Lake in spring 2005, dominated by age-3 alewife (mean length 150 mm) compared to *TS* distribution (mean *TS* -43.8 dB) of alewife (mean length 130 mm) in a large net cage in summer 2005 measured at 70 kHz in both cases (T. Brooking and LGR, unpublished data).



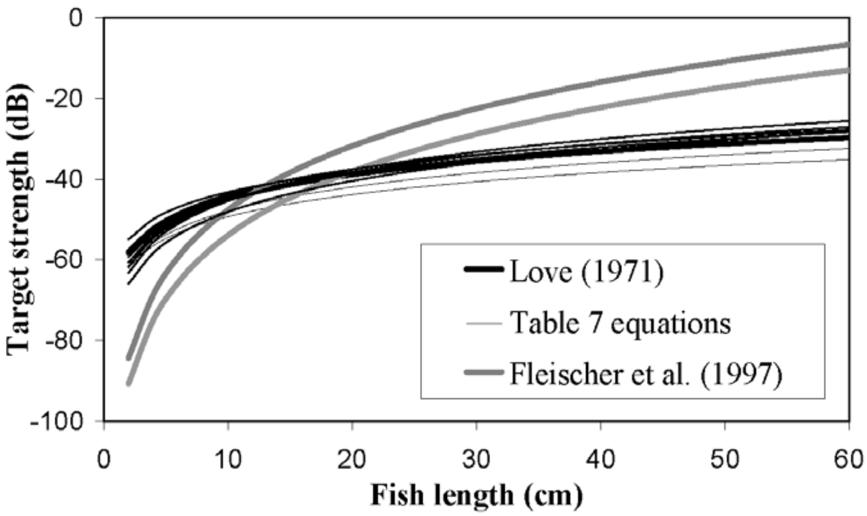
9.4.2.2.1 Deriving *Ex Situ TS* values

Deriving *TS* regressions for surveyed species requires a combination of *in situ* (if available) and *ex situ* measurements, and, if possible, theoretical predictions of individual backscatter. Additionally, these equations are frequency dependent and should incorporate behavior and vertical distribution of the target species. The empirically derived regression is typically in the form:

$$TS = A \bullet \log_{10}(L) + B \qquad (27)$$

where L is fish length (cm), and A is traditionally set equal to 20 (Foote 1987). *Ex situ TS* equations are based on mean *TS* calculated from mean $<\sigma_{bs}>$. The equation does not represent the distribution of expected *TS* (see Figs. 17, 18, 19). The lowest *TS* of interest in the analysis is substantially lower than the mean *TS* of the smallest fish of interest. Using a mean *TS* calculated from these equations to threshold data would result in the exclusion of target organisms that are located off their acoustic axes and/or happen to have a tilt angle that results in a smaller *TS*.

Fig. 19. Mean *TS* calculated from the *TS* fish-length regressions presented in Table 7. The black heavy line represents the multi-species regression from Love (1971). The heavy grey lines are from Fleischer et al. (1997), and the remaining thin lines are from various other sources presented in Table 7.



9.4.2.2.2 *TS* Length for Great Lakes Species

TS-length and *TS*-weight relationships have been developed for several Great Lakes species (Table 7, Fig.19). Relationships for similar species from the European literature are also included in Table 7. Given the variability observed among different studies, even for similar fish (e.g., the identically shaped European smelt (*Osmerus eperlanus*) and rainbow smelt), it is doubtful if the different species-specific equations represent any improvement over using the standard multi-species equation developed by Love (1971). Several authors have used the Love equation in the Great Lakes (Brandt et al. 1991; Goyke and Brandt 1993) and elsewhere (Burcynski and Johnson 1986; Guillard and Gerdeaux 1993; Parkinson et al. 1994; Mason et al. 2001; Rudstam et al. 2002; Frouzova et al. 2005; Crockett et al. 2006). Note that the equations for rainbow smelt and bloater presented by Fleischer et al. (1997) are very different for small and large fish compared to all other equations, but similar for fish in the middle of the size range. We believe the differences are due to the relatively large variance in the data used to build the equations in Fleischer et al. (1997). However, more work is needed before discounting these equations as the correspondence between direct-sampled size distribution and *TS* from the Fleischer et al. (1997) equations are reasonable for Lake Superior (Mason et al. 2005; Yule et al. 2006).

Table 7. Empirical target-strength (*TS*) relationships with length and weight of Great Lakes and similar European fishes. *L* is length (total length) in cm and *W* is weight in g.

Species	Relationship	Frequency (kHz)	*TS* of a 20 cm or 50 g fish (dB)	Source
Many species	$TS = 19.2 \cdot \log_{10}(L) + 0.9 \cdot \log_{10}(\lambda) - 62.3$		-39.0[1]	Love 1971; Brandt et al. 1991
Rainbow smelt and alewife	$TS = 18.2 \cdot \log_{10}(L) - 67.5$	120	-43.8	Argyle 1992
Rainbow smelt	$TS = 19.9 \cdot \log_{10}(L) - 67.8$	120, 70	-41.9	Rudstam et al. 2003
Rainbow smelt and alewife	$TS = 52.6 \cdot \log_{10}(L) - 100.2$	120	-31.6	Fleischer et al. 1997
Cisco	$TS = 21.9 \cdot \log_{10}(L) - 67.2$	70	-38.7	Rudstam et al. 1987
Bloater	$TS = 52.6 \cdot \log_{10}(L) - 106.5$	120	-38.0	Fleischer et al. 1997
Alewife	$TS = 20.53 \cdot \log_{10}(L) - 64.25$	70	-36.9	Warner et al. 2002

Table 7, continued.

Species	**Relationship**	**Frequency (kHz)**	***TS* of a 20 cm or 50 g fish (dB)**	**Source**
Lake trout	$TS = 20 \cdot \log_{10}(L) - 65.3$	120	-39.3	Middel 2005
Striped bass (*Morone saxatilis*)	$TS = 15.4 \cdot \log_{10}(L) - 56.3$	120	-36.3	Hartman and Nagy 2005
White perch (*Morone americana*)	$TS = 26.5 \cdot \log_{10}(L) - 69.4$	120	-35.0	Hartman and Nagy 2005
European smelt	$TS = 23.4 \cdot \log_{10}(L) - 68.7$	120	-38.1	Peltonen et al. 2006
Vendace (*Coregonus albula*)	$TS = 25.5 \cdot \log_{10}(L) - 70.9$	120	-37.7	Mehner 2006
Baltic herring (*Clupea harengus*)	$TS = 16.8 \cdot \log_{10}(L) - 60.0$	38	-38.1	Peltonen and Balk 2005
Baltic herring	$TS = 25.5 \cdot \log_{10}(L) - 73.6$	38, 70	-40.4	Didrikas and Hansson 2004
European fish[2]	$TS = 21.15 \cdot \log_{10}(L) - 63.8$	120	-36.3	Frouzova et al. 2005
Alewife	$TS = 6.98 \cdot \log_{10}(W) - 50.07$	70	-38.2	Warner et al. 2002
Rainbow smelt and alewife	$TS = 15.2 \cdot \log_{10}(W) - 60.24$	120	-34.4	Fleischer et al. 1997
Bloater	$TS = 15.2 \cdot \log_{10}(W) - 65.54$	120	-39.7	Fleischer et al. 1997

[1] Evaluated for 120 kHz

[2] Roach (*Rutilus rutilus*), perch, trout, carp (*Cyprinus carpio*), and bream (*Abramis brama*)

9.4.2.3 *TS* Model Values

Numerical and analytical models have been developed for zooplankton and fish to predict acoustic backscatter as a function of organism size, shape, anatomical characteristics, orientation, and acoustic frequency. The models range in complexity from approximating organism anatomy and morphometry as simple shapes to utilizing three-dimensional digital images of organism internal structures (Horne and Jech 2005).

Theoretical models have advantages and limitations when applied to different organisms. An advantage of *TS* models is that, once verified, predictions may be made over a wide range of conditions (i.e., acoustic frequency, behavior, and biological state, such as fat content and degree of maturation). Difficulties with applying models to survey data are obtaining accurate representations of *in situ* organism anatomy, morphometry, and orientation, and verifying the predictions. Models may be used to provide mean or minimum expected *TS* for S_v threshold calculations. Caveats on these two approaches are discussed under *in situ TS* above.

9.4.3 Partitioning Trawl Catches

In marine systems, groups of interest (species or size groups) are often analytically separated based on their representation in trawl catches and the known relationships between fish lengths and σ_{bs}. The main assumptions made by this approach are:

- Trawl bias is minimal or understood
- The *TS–L* regression used is valid for the survey conditions

Two ways to reduce biases introduced by this approach are:

- By using only in lake systems where the fish community is well understood from past sampling
- By sampling with a closing net to reduce contamination by fish in overlying water strata during deployment and retrieval of the trawl

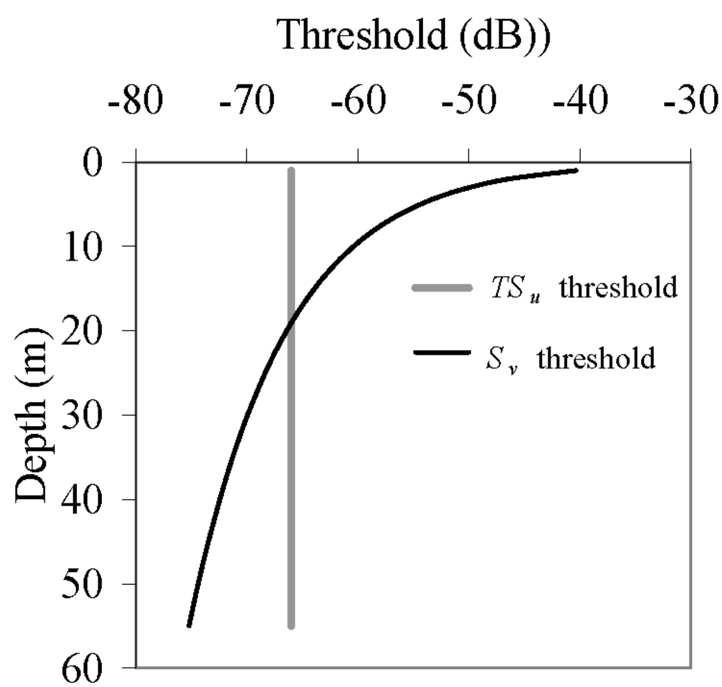
9.4.4 Thresholds

Acoustical backscatter by organisms with a gas-bearing structure, such as a swimbladder, is significantly greater than for organisms without a gas-bearing structure. This attribute can be used to reduce or eliminate the S_v from non-gas-bearing organisms by setting a volume backscattering threshold. No setting can discriminate between fish and plankton or between the target fish species and nontarget fishes with 100% accuracy. Some small fish targets are unavoidably discarded, just as some small amount of acoustic return from unwanted sources is included. The goal in choosing an S_v threshold setting is to find an optimal balance between eliminating nontarget species S_v and preserving the target species S_v (Advanced Sampling Technologies Working Group 2003). Because some error is involved in applying a threshold, it is important to maintain consistency between surveys, i.e., the data-collection threshold choices should be the same for all surveys in a time series (Advanced Sampling Technologies Working Group 2003).

Consider this example. The minimum *TS* of interest is determined to be -60 dB from observations of *in situ TS* distributions. A -60 dB target would be recorded as -66 dB in the TS_u variable if located in the direction of the half-intensity beam angle (-3 dB in both directions = -6 dB). Therefore, a reasonable compromise is to exclude volume backscattering from targets with a TS_u value smaller than -66 dB. The corresponding threshold in the S_v variable changes with depth due to the different TVG functions applied to the S_v and TS_u data (Fig. 20), and the correct S_v threshold for each depth can be calculated from Equation 24. In practice, this calculation is done either by setting this threshold in the amplitude echogram representing $40 \bullet \log_{10}(R)$ data and integrating on this echogram (S5), or by setting a minimum *TS* threshold in the S_v echogram data tab before integrating (EV, implemented in version 4.4). In earlier versions of EV, it was necessary to set the threshold in the TS_u echogram, convert the TS_u data that exceeds this threshold to S_v data, and integrate this data set. Additional correction factors have to be applied if the TS_u and S_v gains are different. S_v from the original S_v files should give the same values as the S_v derived from TS_u data when no thresholds are applied.

Our recommended threshold approach is also the one suggested by the European SOPs under development.

Fig. 20. The relationship of S_v threshold to depth using a 120 kHz transducer with *EBA* of -20 dB, sound speed 1450 m•sec^{-1}, and pulse duration of 0.4 msec that corresponds to a TS_u threshold of -66 dB (see text).



Finding the lower limit of the *TS* distribution of the smallest fish of interest is the key component of setting appropriate thresholds in the S_v domain. This minimum *TS* distribution is based on *in situ TS* distributions, *ex situ TS* distributions, or theoretical models. Thresholds should not be determined by converting the length of the smallest fish of interest to *TS* using a *TS–L* equation as in Table 7. The *TS* distribution of any fish is relatively wide, and using mean *TS* as the basis of a threshold would effectively remove half the echoes from the smallest fish of interest. After this minimum *TS* value is selected, follow the above procedure to calculate a depth-varying S_v threshold.

9.4.5 Challenges and Developing Approaches

9.4.5.1 Frequency Differencing

Multi-frequency approaches are in their infancy in the Great Lakes. Combined analysis of several frequencies could help differentiate fish from mysids (Rudstam et al. 2008a). Such approaches are common in marine systems (e.g., Cochrane et al. 1991; Swartzman et al. 1999). Frequencies lower than 120 kHz could be particularly useful—Rudstam et al. (2008a) have found that using 38 kHz resulted in a higher *TS* of alewife and a lower *TS* of mysids in Cayuga Lake. More frequencies can also help in single-fish detections (Demer et al. 1999).

9.4.5.2 Decomposition of the *TS* Distribution

Separation of species or age-groups within species from the *TS* distribution is difficult because of the large range of *TS* expected from each length group used to identify age-groups. There is considerable *TS* overlap, even between YOY and adult fish. Parker-Stetter et al. (2006) presented a method for separating age-groups of rainbow smelt in Lake Champlain based on measurements of the expected *TS* distribution from the two age-groups. However, at present, the error added by this method has not been reliably estimated. Crockett et al. (2006) presented a similar method for separating large lake trout from kokanee targets, and the expected *TS* distribution from YOY and adult alewife measured in net cages has been used to obtain age-specific density estimates from field *TS* distributions (T. Brooking and LGR, unpublished data).

9.4.5.3 Mysids and Zooplankton

Mysids and zooplankton could contribute substantially to S_v values in deeper waters without appropriate thresholds. The thresholds can also be reversed allowing for acoustic estimates of mysids by removing fish echoes, which has been applied successfully to Lake Ontario (Rudstam et al. 2008b). The use of acoustics for zooplankton estimates has also been done in Lake Superior (Megard et al. 1997; Holbrook et al. 2006). We need to further test and potentially modify these methods for the other Great Lakes.

9.5 File Exports

The EV software will export *TS* and S_v data in separate files, which are merged to scale S_v values using *in situ TS* measurements. In this software, each analytical cell is uniquely defined through intervals (horizontal bin) and layers (vertical bin). These interval/layer identifiers can be used to merge the data sets using standard data-base programs (Access, S-Plus). S5 exports fish density directly for each analysis cell defined through segments (horizontal bin) and layers (vertical bin). For each analytical cell, export s_v values, mean σ_{bs} (in EV transformed to *TS* in dB), and *TS* distribution in 1 dB bins. The database should include the following information: bin #, range/depth layer #, upper and lower depth of the layer, layer height, latitude and longitude in the middle of the interval/segment, file or transect name, S_v, s_a, σ_{bs}, and *TS* distribution in 1 dB bins.

10. SURVEY CALCULATIONS

10.1 Total Backscatter

Backscatter is presented as per unit volume (s_v) or per unit area ($ABC \equiv s_a$, $NASC \equiv s_A$). Depending on survey objectives, the following values may be needed for desired analyses:

- Average water-column backscatter
- Average depth-strata backscatter
- Distribution of backscatter throughout sampling frame

10.2 Backscattering Cross Section

When converting volume backscattering coefficients (s_v) to numeric densities (#•m^{-3}), s_v is scaled by σ_{bs} (backscattering cross section, Equation 11). This equation requires S_v and TS values in dB to be back-transformed before calculations. Calculations of fish density must be done using s_v (m^2•m^{-3}) and σ_{bs} (m^2), not in the dB scale (S_v and TS). The reciprocal relationships between the two values are:

(28)
$$\sigma_{bs} = 10^{\left(TS/10\right)} \text{ and } s_v = 10^{\left(S_v/10\right)}$$

and

(29)
$$TS = 10 \bullet \log_{10}\left(\sigma_{bs}\right) \text{ and } S_v = 10 \bullet \log_{10}\left(s_v\right)$$

In situ, *ex situ*, and theoretical models are the three general methods for obtaining an estimate of σ_{bs}.

10.2.1 *In Situ* Target Strength

In general, a mean σ_{bs} is calculated for each analytical cell. With most software (HTI's trackman excepted), the mean *TS* can be back-transformed to calculated mean σ_{bs} because mean *TS* is calculated based on mean σ_{bs}. By calculating a σ_{bs} value for each analytical cell, horizontal and vertical variations in *TS* are accounted for. However, if the analytical cells are too small, there is an increased risk of getting biased results. If small analytical cells are needed (e.g., for geostatistics), it is better to apply an *in situ* σ_{bs} from a larger region. The effect of using a small number of targets to calculate average *in situ* σ_{bs} needs to be investigated further. As a rule of thumb, try to get at least 20 targets from the fish groups of interest to calculate *in situ* σ_{bs}. For a discussion of the effect of single-echo detection criteria, see section 9.2.

10.2.1.1 Density Effects

When organism densities are very high, multiple scattering (echoes that have scattered off multiple individuals before returning to the transducer) and shadowing have non-linear effects on the summation of echoes within a sampling volume, and the effect on S_v is difficult to predict (MacLennan 1990; Toresen 1991). In the Great Lakes, fish are not sufficiently dense during the night to cause shadowing, but this may be a problem during daytime surveys, when fish tend to form large and dense schools (Appenzeller and Leggett 1992).

Under high-density conditions, reliable *in situ TS* values cannot be obtained. An example of high-density conditions is depicted in Fig. 21, along with caveats and procedures for dealing with the associated bias. Analysis bins that are unsuitable for *in situ* values should be identified and removed from σ_{bs} calculations. N_v (number of fish per acoustic sampling volume (Sawada et al. 1993)) is a common diagnostic tool for identifying high-density cells. It may be calculated as (see also Equation 10):

(30) $$N_v = \frac{c\,\tau\,\psi\,R^2\,\rho_v}{2}$$

where c is the sound speed (m•sec^{-1}), τ is the pulse duration (msec), ψ is the equivalent beam angle (steradians), R is the range (m), ρ_v is the density of targets (#•m^{-3}), calculated from Equation 11: $\rho = \frac{s_v}{\sigma_{bs}}$.

Example 8 below calculates N_v for common Great Lakes conditions. Warner et al. (2002), Rudstam et al. (2003), and Parker-Stetter et al. (2006) excluded cells with N_v >0.10 from *in situ* calculations. Gauthier and Rose (2001) concluded that N_v should not exceed 1.0.

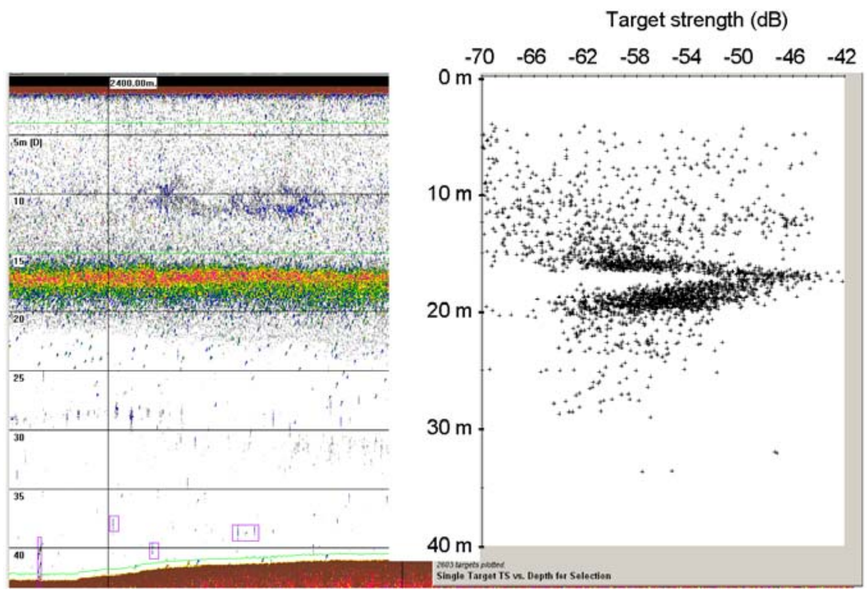
Example 8. Calculation of N_v for an analysis cell with c = 1450 m•sec^{-1}, τ = 0.0003 s (0.3 msec), ψ = 0.01 steradians (-20 dB re: 1 steradian), R = 20 m, S_v = -60 dB, and TS = -50 dB.

$$\rho = \frac{s_v}{\sigma_{bs}} = \frac{10^{\frac{S_v}{10}}}{10^{\frac{TS}{10}}} = 0.1$$

$$N_v = \frac{1450 \bullet 0.0003 \bullet 0.01 \bullet 20^2 \bullet 0.1}{2} = 0.087$$

Reliable *in situ TS* values could be obtained from this cell as N_v <0.1.

Fig. 21. An example of *in situ TS* bias caused by high-density conditions (rainbow smelt in Lake Erie). In this case, the single-target detection is set to a suggested standard setting but with a beam compensation of 12 dB (2-way). Mean *TS* in the dense layer (16-18 m) is -51.5 dB compared to -56.7 dB at a depth just above (14-16 m), and -56.0 dB at depth just below (18-20 m) the main layer. Assuming the correct *TS* is -56 dB, the corresponding N_v values are 0.03 (14-16m), 0.72 (16-18 m), and 0.09 (18-20 m). In this case, we would not accept *in situ TS* from the 16-18 m depth layer. Using the *in situ TS* data from the dense layer would underestimate the density of rainbow smelt in that layer by a factor of 2.9. Data were collected in Lake Erie on July 21, 2006, around 2000 h by Larry Witzel (unpublished data) and Don Einhouse (unpublished data).



10.2.2 *Ex Situ* Target Strength

Many marine surveys apply a σ_{bs} derived from *ex situ TS* estimates. This approach relies on target species being observed in cages, but measurements on caged Great Lakes fish are rare. *Ex situ TS–L* relationships may be applied to trawl catches for use in scaling density. Before applying σ_{bs} based on trawl proportions, the following must be considered:

- Species- or age-based trawl bias
- Contamination of trawl catches by fish shallower than the target depth range during trawl setting and retrieving
- Appropriateness of fishing depth(s) and whether to use discrete depths or stepped oblique trawls

10.2.3 Theoretical Model *TS*

A mean σ_{bs}, ($<\sigma_{bs}>$) may be calculated from theoretical *TS* modeling. The same validation concerns and caveats listed for *ex situ TS* apply.

10.3 Density

Density calculations may be the survey goal or may be needed for total abundance calculations. Either way, the calculation of density assumes that:

- Target species or groups have been separated from nontarget backscatter
- An appropriate σ_{bs} has been identified for each species, group, or depth layer

Two calculations are common:

- Average volumetric density within a vertical bin
- Areal density within a vertical bin

10.3.1 Density Per Unit Volume (ρ_v)

If density is expressed as #•m^{-3}, s_v and σ_{bs} are used to calculate average density (ρ_v, m^{-3}) by Equation 11. This method is sometimes referred to as S_v/*TS* scaling. Note that this density estimate is based on echo integration (s_v or s_a) values and an estimate of σ_{bs}. If fish populations are sufficiently sparse, such as in open-water areas of the upper Great Lakes, echo (or trace) counting is possible. Density based on echo counting is the number of single fish detected over an established minimum *TS* value divided by the total volume of water insonified (Kubecka et al. 1992; Mulligan and Chen 1998). However, in practice, not all fish echoes are accepted as single-fish echoes by the software, which will bias these estimates low. Also, such estimates should be made in relatively narrow depth layers as more water is sampled in deep than in shallow water. Any depth gradient in density will, therefore, also bias the estimates. Echo counting was not discussed as a standard method for the Great Lakes by the acoustic Study Group.

10.3.2 Density Per Unit Area (ρ_a)

For the calculation of stock size, a density estimate based on area is more useful. *ABC* ($\equiv s_a$) or *NASC* ($\equiv s_A$) may be used to calculate total density (ρ_a, in #•m^{-2} or #•nmi^{-2}) within the sampling frame:

(31)
$$\rho_a = \frac{ABC}{\sigma_{bs}} \quad or \quad \rho_a = \frac{NASC}{4\pi \bullet \sigma_{bs}}$$

(32)
$$ABC = \frac{NASC}{4\pi \bullet (1852)^2}$$

where *ABC* (s_a) is the area backscattering coefficient (•m^{-2}), *NASC* (s_A) is the nautical area scattering coefficient (•nmi^{-2}), and σ_{bs} is backscattering cross section (m^2).

10.4 Abundance

Estimates of abundance are often the goal of a survey. These estimates may be:

- Restricted to transects (sampling unit)
- Extrapolated to the entire area (sampling frame)

As outlined in the Survey Design section (5), some analytical techniques are more appropriate for some survey design layouts than others. We provide formulae and guidance for four approaches (simple random, stratified, cluster sampling, and geostatistics) and depict survey designs appropriate for these approaches in Figs. 9a, 9b, 9c, and 9d. Formulae included in each section assume that the area sampled is small compared to the sampling frame, meaning that there is no gain from attempting to correct variances for a finite sampling area. Doing such a correction would decrease variance. Formulae are in Scheaffer et al. (1996). However, even for a small lake (Oneida Lake, Example 4) with a survey length of 56 km and an area of 207 km^2, we only survey 0.03% of the total area (calculated based on the expected transect width of 1.2 m at 6 m depth). Therefore, this correction is very small for all practical applications in the Great Lakes.

10.4.1 Simple Random Analysis

Simple random analysis is appropriate for data collected via both simple random and systematic surveys with parallel transects (Figs. 9a, 9b). Each transect provides a single local estimate of fish density. Calculations of means and variance follow the standard methodology and assume that the randomly selected observations are independent and identically distributed.

We can compute the average density ($\overline{\rho}$) and variance (s_{ρ}^{2}) from the average density for each transect i (ρ_i) over all n transects:

(33) $$\overline{\rho} = \frac{1}{n}\sum_{i=1}^{n}\rho_i$$

(34) $$s_{\rho}^{2} = \frac{1}{n-1}\sum_{i-1}^{n}(\rho_i - \overline{\rho})^2$$

The standard error for the estimate of the average abundance per transect $(SE(\overline{\rho}))$ is:

(35) $$SE(\overline{\rho}) = \sqrt{\frac{s_{\rho}^{2}}{n}}$$

As discussed earlier, expansion of an estimate of average density per unit area (ρ_a) or per unit volume (ρ_v) to an estimate of the total population (N) requires additional knowledge and assumptions. Assuming the transects are representative of the whole area (A) and that this area is known absolutely (has no variance), the expansion is straightforward:

(36) $$N = A \cdot \overline{\rho}$$

where A is in units of total area or total volume, and $\overline{\rho}$ is in units of density per area or volume.

The corresponding standard error of the abundance estimate (*SE(N)*) would be:

(37) $$SE(N) = A \bullet SE(\overline{\rho})$$

10.4.2 Stratified Analysis

Stratified analysis is appropriate for surveys with systematic samples nested within strata (Fig. 9c). The approach is very similar to the calculations used for simple random sampling, but individual estimates are calculated for each stratum and then merged, based on the relative size of each stratum.

We can compute the average density $(\overline{\rho}_h)$ and between transect variance $\left(s^2_{\rho_h}\right)$ within each stratum h:

(38)
$$\overline{\rho}_h = \frac{1}{n_h}\sum_{i=1}^{n_h}\rho_{h,i}$$

(39)
$$s^2_{\rho_h} = \frac{1}{n_h - 1}\sum_{i=1}^{n_h}\left(\rho_{h,i} - \overline{\rho}_h\right)^2$$

where n_h is the number of transects in stratum h, and $\rho_{h,i}$ is average density on transect i in stratum h. The global mean for the stratified estimate ($\overline{\rho}_{str}$) is:

(40)
$$\overline{\rho}_{str} = \frac{1}{A}\sum_{h=1}^{L} A_h \bullet \overline{\rho}_h$$

where L is the total number of strata, A is the total area of all strata $\left(\equiv A_1 + A_2 + \ldots + A_L\right)$, A_h is the total area of each stratum h, and $\overline{\rho}_h$ is the average density within each stratum h.

The corresponding standard error for the stratified estimate ($SE(\overline{\rho}_{str})$) is:

(41)
$$SE(\overline{\rho}_{str}) = \sqrt{\left[\sum_{h=1}^{L}\left(\frac{A_h}{A}\right)^2\left(\frac{s_{\rho_h}^2}{n_h}\right)\right]}$$

where n_h is the number of transects in each stratum h, and $s_{\rho_h}^2$ is the between-transect variance in average abundance for stratum h. As above, assuming the transects are representative of each stratum and that the area of each stratum is known absolutely (has no variance), the expansion to total population is identical to the simple random survey calculations (Equations 36 and 37).

10.4.3 Cluster Sampling

Cluster sampling may be used for systematic or random parallel transects or for zig-zag transects using only parallel zig*s* or parallel zags (Figs. 9a, 9b, 9d). Cluster sampling is an appropriate design and analysis method to consider for acoustics, because clusters of observations are typically taken along a transect and are not, for example, independent 1-minute sample units randomly scattered throughout the population. The clustered nature of the samples often requires that additional attention be paid to the type of analysis used so that the most can be made from the number of samples collected. A major advantage of this method is that it will weigh estimates according to transect length. Since transect lengths are seldom identical, this is the recommended method for acoustics surveys in general when geostatistics is not being used (see below). In an acoustic example of cluster sampling:

- Transects are clusters
- Horizontal bins are elements within clusters

The first step is to compute an aggregate density estimate P_i across all the elements in each cluster i as follows:

(42)
$$P_i = \sum_{j=1}^{m_i} \rho_j$$

where m_i is the number of elements (bins) in cluster (transect) i, and ρ_j is density in horizontal bin j (#•m^{-2}). Notice that P_i is also in #•m^{-2}, but this is misleading, because P_i represents the sum of all densities and, therefore, is a function of the number of bins. Multiplying this aggregate density estimate by the average area per bin yields the total number per transect.

We can compute the average density:

(43)
$$\bar{\rho} = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} m_i}$$

where n is the number of clusters (transects) in the sample, P_i is the aggregate density observed in cluster i, and m_i is the number of elements (bins) in cluster i, with $i = 1,\ldots, n$.

The cluster variance (s_{clu}^2) and the standard error of the estimated average number per bin ($SE(\overline{\rho})$) may then be calculated:

(44)
$$s_{clu}^{2} = \frac{1}{n-1}\sum_{i=1}^{n}\left(P_i - \overline{\rho} \bullet m_i\right)^{2}$$

45)
$$SE\left(\overline{\rho}\right) = \frac{1}{\overline{m}}\sqrt{\frac{s_{clu}^{2}}{n}}$$

where P_i is the aggregate density in cluster I, $\overline{\rho}$ is the average number per bin over all clusters, m_i is the number of elements (bins) in cluster i, $i = 1,\ldots, n$, n is the number of clusters in the simple random sample, and $\overline{m}$ is the estimated average number of elements (bins) per cluster (transect), such that:

(46)
$$\overline{m} = \frac{\sum_{i=1}^{n} m_i}{n}$$

Cluster sampling estimates may be expanded to total population abundance (N) by simply multiplying average density by area:

(47) $$N = A \bullet \overline{\rho}$$

where A is the total area and $\overline{\rho}$ is the average density (#•m^{-2} area or #•m^{-3} volume).

The standard error of the population abundance is:

(48) $$SE(N) = A \bullet SE(\overline{\rho})$$

where, $SE(\overline{\rho})$ is the standard error of the estimated mean density derived from the cluster sampling method described above.

10.4.4 Geostatistics

Geostatistics is an appropriate approach to apply to data collected with zig-zag, systematic parallel, stratified parallel, or random parallel transect designs (Figs. 9a, 9b, 9c, 9d). This section provides only a brief overview of the theory of geostatistics. For further information about geostatistical theory and application of these techniques, readers are referred to Goovaerts (1997), Kaluzny et al. (1998) and Rivoirard et al. (2000). If there is reason to believe that the distribution of data follows some definable stochastic process, a geostatistical procedure would be used to obtain the estimates**.** A variogram is used to examine the correlation among sub-elements (horizontal bins) of transects. The variogram takes the form:

(49) $$2\hat{\gamma}(h) = \frac{1}{|N(h)|} \sum_{N(h)} \left(\rho(s_i) - \rho(s_j)\right)^2$$

where ρ is an observation (e.g., density) referenced to its location $s_i = [latitude, longitude]$, h is a distance vector separating the observations such that $s_i - s_j = h$, and $N(h)$ is the number of pairs of data locations that are a distance h apart.

The resultant empirical variogram (Fig. 15) is then fitted with a theoretical model with the components:

- Range: the distance at which the data are no longer autocorrelated
- Sill: representative of the maximum level of variance in data
- Nugget: the level of measurement error or microscale processes near $h = 0$

If correlation exists, the ordinary kriging predictor (an interpolation method) may be used to predict the distribution of S_v or density over the entire sampling frame. The ordinary kriging predictor is unbiased and fairly stable under different predictive conditions (Cressie 1993). The prediction of ρ at the point $s*$ is:

(50)
$$E\big(\rho(s^*)\big) = \sum_{i=1}^{n} \lambda_i \rho(s_i)$$

and the prediction variance is:

(51)
$$V\big(\rho(s^*)\big) = C(0) - \sum_{i=1}^{n(s^*)} \lambda_i(s^*) C(\rho(s_i) - \rho(s^*)) - m$$

where $C(0)$ is the variance at lag zero, $n(s^*)$ is the number of observations in a neighborhood of s^*, m is the Lagrange multiplier, and where:

$$\sum_{i=1}^{n} \lambda_i = 1$$

The vector of weights is given by:

(52)
$$\lambda' = \left(k + \mathbf{1}\frac{(1-\mathbf{1}'K^{-1}k)}{\mathbf{1}'K^{-1}\mathbf{1}} \right)' K^{-1}$$

These weights (λ) are based on a function of the variance-covariance matrix k between the observations and the point being estimated $\rho(s*)$ and the variance-covariance matrix K between each of the observations. These covariances may be computed using the variogram and the relation $C(h) = C(0) - \gamma(h)$ when the variation at lag zero, $C(0)$, estimated by the sill, is well defined.

10.5 Species-Specific Abundance and Biomass

Species-specific abundance and biomass estimates are the end result of fisheries acoustic surveys. Converting echo level to abundance is a multi-step procedure. Volume or area backscattering coefficients are scaled to numerical density (#•m^{-3} or # m^{-2}) by σ_{bs}. Values for σ_{bs} are obtained from *in situ* measurements and/or *TS*–*L* regressions. Densities are vertically integrated to give areal densities (#•m^{-2}) along the cruise track, and areal densities are scaled to the survey area. In freshwater surveys, areal density is typically given in #•ha^{-1}or sometimes in #•m^{-2}. In marine surveys, areal density is scaled to square nautical miles (1 $nmi^2 = (1852)^2$ m^2). The final step is to convert fish abundance to species-specific abundance and biomass, which requires separation of densities by species or age-groups through direct sampling, location, or *TS* distribution. Biomass is then calculated from these densities and observed weights or from a length to weight regression. Some approaches to separating acoustic density estimates by species are presented in this manual. This problem requires more attention as approaches to species estimation differ among the Great Lakes, and a consistent approach is needed to provide fishery managers with useful fish-abundance estimates. One of the main factors precluding good species-specific density estimates in the Great Lakes is an incomplete understanding of trawl selectivity.

Biomass can also be obtained directly from acoustic estimates using biomass-specific *TS* equations (e.g., Warner et al. 2002), or by converting *TS* values to fish lengths and then fish lengths to weight (e.g., Brandt et al. 1991). Using biomass-specific *TS* regressions to derive average σ_{bs}•g^{-1} fish will probably give reasonable numbers as long as the length distribution is relatively constant. Biomass calculated for small and large fish from *TS* equations will be biased because acoustics backscatter is related to the area of individual fish, not the mass of individual fish. The second method, converting *TS* values to fish lengths, introduces unknown biases associated with the wide distribution of fish *TS* obtained from a single fish (see Fig. 18) and the non-linearity in both length-weight regressions and *TS–L* regressions. Therefore, this method is not recommended, although it is possible that positive and negative biases will offset each other.

10.6 Uncertainty in Acoustic Surveys

The accuracy and precision of the acoustic survey is affected by numerous factors (Simmonds et al. 1992; Aglen 1994; Rose et al. 2000; Demer 2004). Many of these sources of error have been identified and discussed in this manual. Appropriate calculation procedures to account for all uncertainty are under development through a New York Sea Grant project by P. Sullivan and L. Rudstam (www.acousticsunpacked.org).

Estimates of the combined error require estimates of the error in each of the survey components. Some of the errors are additive (contribution from fish in the dead zones, fish avoidance, and noise), whereas, others are multiplicative (calibration, *TS*, and attenuation in schools). Also, some errors are known to bias the results in a particular direction. For example, transducer movement will, on the average, decrease the measured echo level (Simmonds et al. 1992). If we can make reasonable estimates of the distribution of the different error terms, it is possible to calculate the combined uncertainty in the estimate. This calculation of combined uncertainty is seldom done in the Great Lakes, and errors reported as uncertainty are generally limited to uncertainty associated with spatial sampling and patchiness. Simmonds et al. (1992) suggested that a typical coefficient of variation (SE/mean) is in the order of 26% for relative estimates (based on s_a alone) and 35% for absolute estimates (based on both s_a and σ_{bs}). They suggest that most uncertainty in relative estimates is due to spatial sampling, and uncertainty in *TS* may be of equal importance for absolute estimates with an unknown and potentially large component associated with avoidance. However, the main sources of uncertainty may vary between surveys. Rose et al. (2000) compared sources of variance for surveys with high and low assumptions on uncertainty of collection parameters. Not surprisingly, spatial variance in measured S_v values dominated, but variance in individual species identification, detectability, and target strength were also important when uncertainty in those parameters increased.

11. SUMMARY OF EQUATIONS

(1) E_return = [E_transmitted – E_lost_down] + E_reflected – [E_lost_up]

(2) $$EL = [SL + B(\theta) - TL] + TS + [B(\theta) - TL]$$

(3) $$EL = SL - 2TL + TS + 2B(\theta)$$

(4) $$TL_{1-\text{way}} = 20 \bullet \log_{10}(R) + \alpha R$$

(5) $$TL_{2-\text{way}} = 40 \bullet \log_{10}(R) + 2\alpha R$$

(6) $$EL = SL - 40 \bullet \log_{10}(R) - 2\alpha R + TS + 2B(\theta)$$

(7) $$I_{EL} = \frac{I_{SL} \bullet \sigma_{bs} \bullet b^2(\theta)}{R^4 \bullet 10^{\frac{2\alpha R}{10}}}$$

(8) $$\psi = \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} b^2(\theta, \phi) \sin(\theta) \bullet d\theta \, d\phi$$

(9) $$\Psi \text{ or } EBA\,(dB) = 10 \bullet \log_{10}(\psi)$$

(10) $V = \psi \mathrm{R}^2 (c\tau/2)$

(11) $s_v = \rho_v \langle\sigma_{bs}\rangle$ and $s_a = \rho_a \langle\sigma_{bs}\rangle$

(12) $$EL = SL + S_v + 10\bullet\log_{10}(c\tau/2) + \Psi - 20\bullet\log_{10}(R) - 2\alpha R$$

(13) $$I_{EL} = \frac{I_{SL} \bullet s_v \bullet \psi \bullet (c\tau / 2)}{R^2 \bullet 10^{\frac{2\alpha R}{10}}}$$

(14) $$a = \frac{1.6}{k \bullet \sin(\frac{\theta_{3\mathrm{dB}}}{2})}$$

(15) $$\psi = \frac{5.78}{(ka)^2} \text{ in steradians, or } \Psi = 10 \bullet \log_{10}\left(\frac{5.78}{(ka)^2}\right) \text{ in dB}$$

(16) $$R_{nf} = \frac{(2a)^2}{\lambda}$$

(17) $$H_{BotBias} = BD \bullet (1 - \cos(\theta)) + c\tau / 2$$

(18) $$\Delta\mathrm{R} = R_2 - R_1 > \frac{c\tau}{2}$$

(19) $$\Lambda = \frac{D}{\sqrt{A}}$$

(20) $$CV = \frac{0.5}{\sqrt{\Lambda}}$$

(21) $$S_a = 10 \bullet \log_{10}\left(\frac{\sigma_{bs}}{\psi \cdot R^2}\right) = TS - \Psi - 20 \bullet \log_{10}(R)$$

(22) $$i = \frac{3 \bullet 2 \bullet BD}{c}$$

(23) $$c = 1402.388 + 5.03711 \bullet T - 0.0580852 \bullet T^2 + 0.3342 \bullet 10^{-3} \bullet T^3 - 0.1478 \bullet 10^{-5} \bullet T^4 + 0.315 \bullet 10^{-8} \bullet T^5$$

(24) $$TS_{u\ noise\ at\ 1m} = S_{v\ \mathrm{noise}\ at\ 1m} + \Psi + 10 \bullet \log_{10}(c\tau/2) + 20 \bullet \log_{10}(R)$$

(25) $$TS_{uN1} = TS_{uNZ} - 40 \bullet \log_{10}(Z) - 2\alpha Z$$

(26) $$S_{v\ N1} = Sv_{NZ} - 20 \bullet \log_{10}(Z) - 2\alpha Z$$

(27) $$TS = \alpha \bullet \log_{10}(L) + \beta$$

(28) $$\sigma_{bs} = 10^{\left(TS/10\right)}$$

(29) $$TS = 10 \bullet \log_{10}(\sigma_{bs})$$

(30) $$N_v = \frac{c\ \tau\ \psi\ R^2\ \rho_v}{2}$$

(31) $$\rho_a = \frac{ABC}{\sigma_{bs}} \quad or \quad \rho_a = \frac{NASC}{4\pi \bullet \sigma_{bs}}$$

(32) $$ABC = \frac{NASC}{4\pi \bullet (1852)^2}$$

(33) $$\overline{\rho} = \frac{1}{n}\sum_{i=1}^{n} \rho_i$$

(34) $$s_\rho^2 = \frac{1}{n-1}\sum_{i-1}^{n} (\rho_i - \overline{\rho})^2$$

(35) $$SE(\overline{\rho}) = \sqrt{\frac{s_\rho^2}{n}}$$

(36) $$N = A \cdot \overline{\rho}$$

(37) $$SE(N) = A \cdot SE(\overline{\rho})$$

(38)
$$\overline{\rho}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} \rho_{h,i}$$

(39)
$$s_{x_h}^2 = \frac{1}{n_h - 1} \sum_{i=1}^{n_h} \left(\rho_{h,i} - \overline{\rho}_h\right)^2$$

(40)
$$\overline{\rho}_{str} = \frac{1}{A} \sum_{h=1}^{L} A_h \cdot \overline{\rho}_h$$

(41)
$$SE(\overline{\rho}_{str}) = \sqrt{\left[\sum_{h=1}^{L} \left(\frac{A_h}{A}\right)^2 \left(\frac{s_{\rho_h}^2}{n_h}\right)\right]}$$

(42)
$$P_i = \sum_{j=1}^{m_i} \rho_j$$

(43)
$$\overline{\rho} = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} m_i}$$

(44)
$$s_{clu}{}^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(P_i - \overline{\rho}\cdot m_i\right)^2$$

(45)
$$SE(\overline{\rho}) = \frac{1}{\overline{m}}\sqrt{\frac{s_{clu}{}^2}{n}}$$

(46)
$$\overline{m} = \frac{\sum_{i=1}^{n} m_i}{n}$$

(47) $N = A \bullet \overline{\rho}$

(48) $SE(N) = A \bullet SE(\overline{\rho})$

(49)

$$2\hat{\gamma}(h) = \frac{1}{|N(h)|}\sum_{N(h)}\left(\rho(s_i) - \rho(s_j)\right)^2$$

(50)

$$E\left(\rho(s^*)\right) = \sum_{i=1}^{n}\lambda_i \rho(s_i)$$

(51)

$$V\left(\rho(s^*)\right) = C(0) - \sum_{i=1}^{n(s^*)}\lambda_i(s^*)C(\rho(s_i) - \rho(s^*)) - m$$

(52)

$$\lambda' = \left(k + \mathbf{1}\frac{(1 - \mathbf{1}' K^{-1}k)}{\mathbf{1}' K^{-1}\mathbf{1}}\right)' K^{-1}$$

12. LITERATURE CITED

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13. APPENDIX

Members of the Study Group on Fisheries Acoustics in the Great Lakes, affiliation, and the freshwater or marine system they represented.

Organizers:	Lars Rudstam[1], Doran Mason[2]
Lake Ontario:	Ted Schaner[3], Steve LaPan[4]
Lake Erie:	Don Einhouse[4], Larry Witzel[3]
Lakes Huron and Michigan:	David Warner[5], Randy Claramunt[6]
Lake Superior:	Tom Hrabik[7], Jason Stockwell[5], Dan Yule[5]
Lake Champlain:	Bernie Pientka[8], Donna Parrish[9]
Small inland lakes:	Trevor Middel[3]
Marine system:	Michael Jech[10], William Overholtz[10]
Other members:	Sandra Parker-Stetter[1,11], Patrick Sullivan[1]

[1]Cornell University, Department of Natural Resources

[2]National Marine Fisheries Service, Great Lakes Environmental Research Laboratory

[3]Ontario Ministry of Natural Resources

[4]New York State Department of Environmental Conservation

[5]U.S. Geological Survey Great Lakes Science Center

[6]Michigan Department of Natural Resources

[7]University of Minnesota—Duluth

[8]Vermont Fish and Wildlife Department

[9]U.S. Geological Survey, Vermont Cooperative Fish and Wildlife Research Unit

[10]National Marine Fisheries Service, Northeast Fisheries Science Center

[11]University of Washington, School of Aquatic and Fishery Sciences

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