GREAT LAKES FISHERY COMMISSION

Project Completion Report[1]

Great Lakes Acoustics Workshop IV
Inter-Calibration of Scientific Echosounders in the Great Lakes

By:

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EXECUTIVE SUMMARY

Application of hydroacoustics for fisheries stock assessment and research is accepted worldwide and rapidly being accepted by resources managers in the Great Lakes. Resource managers and researchers from state, provincial and federal governments, as well as from universities in Canada and the United States, use hydroacoustics for the assessment, monitoring and scientific investigations of Great Lakes pelagic biota. In fact, all 5 of the Great Lakes support projects to various degrees that use and rely on hydroacoustics for estimates of the abundance and spatial distributions of pelagic fish. Currently, there is a minimum of 13 different scientific echosounders encompassing 8 models, 5 frequencies and 3 different manufacturers in use in the Great Lakes region. Comparisons of hydroacoustics data within lakes and between lakes are complicated by the unknown comparability between echosounders that differ in manufacturer, frequency, beam configuration (single-beam, dual-beam and split-beam), model and age. Furthermore, a standard for data acquisition and signal processing does not exist, adding to the complexity and confusion of comparing data and results between hydroacoustics systems, lakes and individual users. If we are to properly manage the Great Lakes ecosystem and fisheries, and provide information that is defensible in a court of law, we must have data, results and conclusions derived from techniques and instrumentation that are comparable and reliable.

Our primary objective was to compare estimates of abundance and size as determined from various fisheries acoustics systems currently being used in the Great Lakes basin. This report contains the results of that exercise. Moreover, this report also provides a brief history of fisheries acoustics applications in the Great Lakes, some technical background, and an appendix with definitions of terms used in this report. The brief history is provided as a historical context highlighting the evolution of fisheries acoustics technology with respect to development, application and acceptance in the Great Lakes basin. The technical information is provided so that the reader may understand exactly what was compared in the exercise. Lastly, definitions of acoustical terms are provided as an appendix for easy reference.

The primary conclusion from this study is that density estimates from 120 kHz systems are comparable between models and manufacturers of acoustic equipment. In addition, density estimates using the 120 kHz systems are comparable to other operating frequencies- 70 kHz and 200 kHz, but differences can occur depending upon instrument settings for data acquisition, and parameter settings in the post-processing software. The 420 kHz system, did not compare favorably to any other system, and should not be used for comparative studies. Lastly, differences in TS estimates were different within frequencies and between systems. Between frequency differences are explainable, however, causes for the differences observed within frequencies are unknown. The results of our study highlight the need to develop a standard protocol for the collection and processing of acoustic data within the Great Lakes basin. We recommend that a committee be formed to develop Standard Operating Procedures for Acoustic Surveys in the Great Lakes.

INTRODUCTION

Hydroacoustics is fast becoming one of the primary investigative tools in fisheries. The main advantage of hydroacoustics lies in its ability to quickly and relatively inexpensively sample large volumes of water, and provide detailed data on abundance and distribution of fish. Hydroacoustics is particularly suited for investigations of pelagic organisms in large bodies of water, and hence has quickly found numerous applications in the Great Lakes. Currently there are at least 13 hydroacoustic systems used by management agencies and universities around the Great Lakes. These hydroacoustics systems come from several manufacturers, and encompass a number of technologies and sound frequencies. Participants at the Great Lakes Acoustic Workshop III (Shackelton Point, N.Y) identified the lack of information on comparability of the systems as one of the chief obstacles in interpreting the results of hydroacoustics surveys and in comparing results within and between lakes. . It was proposed that the various systems be deployed in a common situation in order to assess their comparability. This report describes the results of the comparison. Moreover, this report also provides a brief history of fisheries acoustics applications in the Great Lakes, some technical background, and an appendix with definitions of terms used in this report. The brief history is provided as a historical context highlighting the evolution of fisheries acoustics technology with respect to development, application and acceptance in the Great Lakes basin. The technical information is provided so that the reader may understand exactly what was compared in the exercise. Lastly, definitions of acoustical terms are provided as an appendix for easy reference.

HISTORY OF FISHERIES ACOUSTICS IN THE LAURENTIAN GREAT LAKES

Early years: 1960s and 1970s

Applications of underwater acoustics in the Great Lakes can be traced back to the 1960's. These early studies focused on fish distributions at power plant thermal plumes (Spigarelli *et al.* 1973; Stuntz 1973), and on estimating zooplankton distribution and biomass (McNaught 1968). During these early years, data assimilation consisted of a paper chart recorder and an analog recording of output voltages on magnetic tape. Even with limited technology, McNaught (1969) was one of the first researchers, in marine or freshwater environments, to propose and develop a multi-frequency sonar system for size-class discrimination of zooplankton. Due to data storage and analysis limitations, these early studies were done on a localized scale. With technological improvements in electronic and computer technology, larger scale surveys were conducted on Lakes Michigan (Brandt 1975, 1978, 1980; Brandt et al. 1980; Janssen and Brandt 1980), Huron (Argyle 1982), and Superior (Heist and Swenson 1983) and provided the first quantitative estimates of fish abundance, density, and spatial distribution. Using a 50 kHz single beam scientific echosounder and deconvolution techniques (Peterson *et al.* 1976), Brandt (1980) studied the diel vertical migration, thermal ecology, and spatial segregation of various life stages of alewives in Lake Michigan. He found that alewife migrate to the thermocline at night and disperse, and that adult and young-of-the year (YOY) alewives thermally segregate. This information was the foundation for nighttime assessment of alewives in the Great Lakes. Heist and Swenson (1983) estimated rainbow smelt abundance in the western basin of Lake Superior during 1978-1980 to provide prey fish numbers used in re-establishing the native piscivore community and for assessing the impact of an expanding commercial fisheries. Their acoustics application was one of the first in the Great Lakes that focused on direct management applications.

Momentum building years: 1980s

Throughout the 1980s, acoustic hardware and data analysis techniques continued to progress, and the use of underwater acoustics for fisheries assessment gained wider acceptance. Multiple-beam transducers (Burczynski and Johnson 1986; Foote *et al.* 1986) allowed for direct, *in situ* measures of fish target strength and gave scientists better estimates of fish sizes. The first application of a multiple-beam acoustic system to a lake-wide acoustic survey was conducted on Lake Michigan in the spring and summer of 1987 (Brandt *et. al.*, 1991, Argyle 1992). In response to a declining alewife population, Brandt *et al.* (1991) initiated a lake-wide, multi-agency acoustic assessment of the pelagic prey fish community (alewife, rainbow smelt, and bloater). This first lake-wide acoustic assessment demonstrated the need for Great Lakes fisheries management to change from a program of stocking determined by hatchery production limitations to management based on food web and carrying capacity of the lake.

Recent years: 1990s

Following the work by Brandt *et al.* (1991) and Argyle (1992) in the late 1980s, fisheries acoustics has become a component of assessment programs throughout most of the Great Lakes. Assessment efforts are directed on pelagic prey species: alewife (*Alosa pseudoharengus*) and rainbow smelt (*Osmerus mordax*), as well as other species such as bloater (*Coregonus hoyi*) and lake herring (*Coregonus artedii*). On Lakes Erie and Ontario, the Ontario Ministry of Natural Resources (OMNR) and New York Department of Natural Resources (NYDEC) have combined trawling and acoustic efforts to assess population abundance of rainbow smelt and alewife (Schneider and Schaner 1995; Schaner and Lantry 1997; Rudstam *et al*. 1996). In an era of shrinking management budgets, an echosounder was purchased through a cooperative effort between the United States and Canada for common use by all fisheries agencies on Lake Erie (Witzel *et al.* 1995). Similarly, on Lake Ontario, the equipment and survey costs are shared by the State of New York and the Province of Ontario. The United States Geological Survey-Biological Research Division (USGS-BRD) now assesses populations of alewife, rainbow smelt, and bloater in Lakes Michigan and Huron using fisheries acoustics. There is also recent pressure to integrate acoustic assessment into the prey fish assessment program in Lake Superior.

Fisheries managers are also beginning to recognize that abundance estimates alone are not sufficient for successful management of fish populations. An understanding of the spatial and temporal distribution and ecology of both predator and prey species are needed. New areas of ecological research have developed in response to high spatial resolution data made available through advances in fisheries acoustics technology. One such area is the concept of spatially-explicit growth rate potential of pelagic predators (Brandt *et al.* 1992). This concept integrates spatial information of prey fish using fisheries acoustics, the thermal environment, bioenergetics theory, and foraging theory to quantify complex spatial habitat features of the pelagic environment. Thus, spatially-explicit growth rate potential quantifies an individual fish's growth response to non-uniform spatial distributions of prey resources and physical conditions. Applications of this technique have included a functional definition of habitat quality based on a species' physiological requirements (Mason *et al.* 1995), examination of spatial patterns of planktivory in the Chesapeake Bay (Luo and Brandt 1993), a map of seasonal patterns of predator growth rate potential in the Chesapeake Bay (Brandt and Kirsch 1993), and an examination of the importance of predator and prey spatial overlap with respect to the thermal environments in Lake Ontario (Goyke and Brandt 1993).

Current Status

Since the first application of hydroacoustics in the Great Lakes, the number of individuals using this technology for fish monitoring and research has grown rapidly. Currently, there are at least 13 different scientific echosounders encompassing 7 models, 5 frequencies and 3 different manufacturers in use in the Great Lakes region. Recently (yr 2000), the United States Geological Survey-Biological Resource Division (Ann Arbor, MI) acquired funds from the Great Lakes Fishery Trust to purchase 3 more acoustics systems. These systems are to be distributed around Lake Michigan to intensify the annual fall forage fish assessment for abundance estimates of alewife, rainbow smelt and bloater.

BASIC ACOUSTICAL PRINCIPLES

Acoustic system

The application of underwater acoustics for measuring fish abundance has been referred to as fisheries acoustics, hydroacoustics, underwater acoustics, and echosounding (Brandt 1996). Fisheries acoustics is the use of transmitted sound to detect fish. Sound travels quickly (~1450 m s^{-1} in freshwater) through the water and reflects from objects with density different from that of water. For fish, the primary reflecting organ is the swim bladder, as it has the greatest density differential from water. Gas filled swim bladders contributes 90% or more to the total returning echo from a fish (MacLennon and Simmonds 1992). Other secondary components of a fish's body that reflect sound include muscle, bone and fat tissue. The returning echoes contain information on fish sizes, spatial distributions and abundances.

Hardware

The basic acoustic system consists of an echosounder and a transducer. The echosounder produces electrical pulses which the transducer converts to sound energy and emits into the water. The sound travels through the water, reflects from a target, and travels back to be received by the transducer. The transducer converts the sound energy of the received echo into electrical energy which the echosounder then outputs to a computer for recording and processing.

Three primary types of echosounders are currently used for fisheries assessment in the Great Lakes: single beam, dual-beam, and split-beam. The primary difference between these echosounders is in the technique used to estimate acoustic size of individual fish. Transducers do not transmit or receive signals from all directions with equal efficiency. A fish will appear to have a larger acoustic size in the middle of the beam (on-axis) than it will on the edges (this is analogous to a flashlight where objects appear brighter in the beam than on the fringe). This effect must be corrected to accurately determine the acoustic size. Single beam transducers cannot directly measure the position of individual targets relative to the acoustic axis, and therefore require the statistical techniques of 'Echo Amplitude Probability Density Function (PDF)' and 'deconvolution' (Craig and Forbes 1969; Clay 1983; Lindem 1983; Stanton and Clay 1986; Rudstam et al. 1988) to correct for the beam pattern effect. This method requires a large number of targets, and hence integration over large volumes. Dual-beam and split-beam echosounders correct echoes from individual targets for the beam pattern by using multiple beams housed in a single transducer. Dual-beam echosounders use the ratio of the received echo intensities from a narrow and a wide beam to determine the off-axis position (Ehrenberg *et. al.* 1976; Traynor and Ehrenberg 1979). Split-beam echosounders divide the beam into four quadrants and use a phase relationship to determine the off-axis position (Foote *et al.* 1986). Split-beam echosounders have the advantage of being able to locate a target in 3-dimensional space (azimuthal angle, off-axis angle and range to transducer) (Ehrenberg and Torkelson 1996), while dual beam systems can measure only off-axis angle and range, and single beam systems can only measure range. Split-beam systems also provide improved target strengths estimates compared to single and dual beam systems (Ehrenberg and Torkelson, 1996).

Received echoes can be viewed on a paper chart recorder, an oscilloscope, or displayed on a computer attached to the echosounder. Raw data (received voltages) are typically saved to a file on a computer hard drive or to a digital recorder. The raw data can either be processed in real time (simultaneous with data collection) or processed later in the laboratory.

FISH ABUNDANCE ESTIMATES

Sonar Equation

Key for successful estimates of pelagic fish abundance resides in the application of the "sonar equation". The sonar equation is the fundamental starting point for fisheries acoustics with the mathematical description taking various forms. The sonar equation can be expressed in terms of sound pressure, voltage amplitude, or in a logarithmic form. Typically, the equation is expressed in logarithmic form because ranges of sound intensity are often times quite large. For example, the ratio of sound intensity reaching a fish to the sound intensity reflected from the fish can differ by factors of 10^3 to 10^6, depending on the size of the fish and whether or not the fish has a gas filled swim bladder. The decibel (dB) is the unit used to express the logarithmic differences in sound intensity. A decibel is a dimensionless unit used for expressions of ratios of sound intensities and is defined as 10 times the logarithm of the ratio of a measured sound intensity (I_M) to a reference sound intensity (I_R), $10\ LOG_{10}(I_M/I_R)$. For example, if the intensity of sound reflected from a fish is 4-orders less than the intensity of the transmitted sound intensity (0.0001), then the decibel equivalence would be $10\ LOG_{10}(0.0001)$ or -40 dB.

The sonar equation determines the echo level (EL, intensity of the returning echo from a fish) of a fish target. Echo level is the amount of energy returning from a fish and is a function of the amount of sound transmitted (source level-SL), the distance the fish is from the transducer, and the location of the fish relative to the transducer (i.e., distance from the transducer and location in the acoustic beam). The sonar equation incorporates this information in the following expression

$$EL = SL\ 40LOG_{10}(R) - 2\alpha R + TS + 2B \qquad (1)$$

where R is range from the transducer to the target, α is the attenuation coefficient (loss in intensity with absorption of sound in water), TS is the target strength (acoustic size) of an individual fish target, and B is the one way beam pattern factor (accounts for loss of echo intensity for targets off of the acoustics axis). For a more detailed descriptions and derivations of the SONAR equation see Forbes and Nakken (1972), Urick (1975), Clay and Medwin (1977), MacLennan and Simmonds (1992), Brandt (1996), Misund (1997), and Medwin and Clay (1998).

Acoustical Size

Acoustic size is the ability of the target to scatter sound back to the transducer and is the primary variable used to calculate numeric density, fish length, and biomass. A common form of the acoustic size given in fisheries acoustics literature is the acoustic backscattering cross-section, $\sigma_{bs,}$ and this is related to TS by the equation $\sigma_{bs,} = 10^{(TS/10)}$. The mean acoustic size, $\bar{\sigma}_{bs}$, can be obtained from a) concurrent *in situ* target measurements, b) previous knowledge, or c) derived from catch data. Derivations from catch data require a regression equation that relates σ_{bs} to individual targets [i.e. a TS-Length equation (Love 1971a, 1971b; Foote 1980; Foote 1991). TS-Length equations are often based on laboratory experiments where a series of individual fish are tethered, σ_{bs} is measured, and a regression equation is fit to σ_{bs} vs. length data. If one knows the length distribution from catch data, these lengths can be converted to $\bar{\sigma}_{bs}$ and then used in equation (3). When comparing catch data to acoustically derived size data, care must be taken to compensate for gear selectivity. *In situ* target data require targets that are sufficiently dispersed to be detectable as individuals. An advantage to *in situ* targets is that the distribution of acoustic sizes should be representative of the distribution of fish lengths. However, data must be collected when fish are not schooling or densely aggregated. In the Laurentian Great Lakes, TS has been converted to fish length using the empirical relationships developed by Love (1971a, 1971b, 1977) and/or Foote *et al.* (1987). Love's (1977) equation has been used to describe fish length vs. fish target strength relationship for pelagic fishes of the Great Lakes (Brandt *et al.* 1991), however, this relationship has recently been found to be less accurate for Great Lakes species (Fleischer *et al.* 1997). Fleischer et al. (1997) provides TS-length and TS-mass relationships explicitly developed for pelagic planktivores of the Great Lakes. An alternative to using acoustic size to estimate fish density is to relate s_v directly to density (Gerlotto *et. al.* 1994; Massé and Retiere 1995), or to biomass (Fleischer *et. al.* 1997).

Population Abundance

To estimate volumetric density (ρ) [# m^{-3}] for a fish population, we use volume reverberation (s_v), or the total backscattered energy from acoustic targets in a sampled volume (equivalent to EL in eq 1). Assuming incoherent addition of backscatter and linearity (Foote, 1983) we obtain s_v by integrating equation (1) over the volume sampled (i.e. Echo Squared Integration) and simplify to the form (Clay and Medwin, 1977)

$$s_v = \sum_i N(i)\ \bar{\sigma}_{bs}(i) \qquad (2)$$

where *N* is the number of targets of type *i* (e.g. zooplankton, fish with swimbladders, and/or fish without swimbladders) adjusted for echosounder variables, gains and corrections, and $\bar{\sigma}_{bs}$ is the acoustic backscattering cross-section, i.e., the linear form of TS (acoustic size). For detailed information on echo-squared integration see Thorne (1983), Powell and Stanton (1983), and Medwin and Clay (1997). Contribution to the total volume scattering for different types of targets is proportional to their abundance, and the *exact* solution requires a known $\sigma_{bs}(i)$ for each type of target (Foote, 1983). Equation (2) can be simplified to solve for numeric density (modified from eq. 7.3.13 in Clay and Medwin 1977):

$$\rho = \frac{s_v}{\bar{s}_{bs}} \quad (3)$$

where $\bar{\rho}$ [# m^{-3}] is the density estimate, and $\bar{s}_{bs}$ is the best estimate of acoustic size. To calculate density, we must have an estimate of s_v and mean acoustic size. *Echosounders with corresponding signal processing software estimate the total backscattered energy (s_v) from a group of targets and the mean acoustic size ($\bar{s}_{bs}$) from individual targets in the group, for the calculation of fish density.*

CROSS-COMPARISON

Introduction

Resource managers and researchers from state, provincial and federal governments, as well as from universities in Canada and the United States, use hydroacoustics for the assessment, monitoring and scientific investigations of Great Lakes pelagic biota. In fact, all 5 of the Great Lakes support projects to various degrees that use and rely on hydroacoustics for estimates of the abundance and spatial distributions of pelagic fish or macroinvertebrates (e.g., *Mysis relicta*). Currently, there is a minimum of 13 different scientific echosounders encompassing 8 models, 5 frequencies and 3 different manufacturers in use in the Great Lakes region (Table 1). Comparisons of hydroacoustics data within lakes and between lakes are complicated by the unknown comparability between echosounders that differ in manufacturer, frequency, beam configuration (single-beam, dual-beam and split-beam), model and age. Furthermore, a standard for data acquisition and signal processing does not exist, adding to the complexity and confusion of comparing data and results between hydroacoustics systems, lakes and individual users. If we are to properly manage the Great Lakes ecosystem and fisheries, and provide information that is defensible in a court of law, we must have data, results and conclusions derived from techniques and instrumentation that are comparable and reliable.

Acoustic estimation of fish abundance normally consists of two steps, the results of which are combined to produce an estimate of the number/density of targets:

1. Measurement of total backscattering from all targets (s_v, also referred to as relative density in this report)
2. Measurement of backscattering from representative individual targets to obtain mean target strength (TS)

Our experiment was designed to compare results of the two intermediate steps, as well as the estimate of fish target density ($s_v / \hat{s}_{bs}$, where $\hat{s}_{bs} = 10^{TS/10}$).

Several factors can lead to discrepancies between acoustic estimates:

1. Differences due to the fundamental acoustic technology (single vs. split beam)
2. Differences due to frequency
3. Mechanical/electronic differences between transducers of the same type and frequency
4. Differences due to details of data acquisition and processing (software) used by the various systems (e.g., filtering algorithms, single target detection)
5. Differences due to improper equipment calibration
6. Differences due to operator (data collection parameters).

Factors 1 through 4 were evaluated from the acquired data. Calibration effect (5) was eliminated through proper calibration prior to the inter-calibration exercise or shortly there after. Operator differences were evaluated by using standardized data acquisition and processing parameters and by allowing individual operators to use their best judgment and experience in processing the data.

Participants of the Great Lakes Acoustics Workshop III- Translation of Acoustic Data to Fish Abundance[1] agreed that standardization across hydroacoustics platforms and software methods is a top priority for hydroacoustics applications in the Great Lakes region. A first step to standardization is to quantify the differences and similarities that exist between different hydroacoustics hardware configurations. Our objective was to compare the various acoustic systems that are in use in the Great Lakes region. To do this we brought together individuals from around the Great Lakes region to participate in an inter-calibration. Specifically, our objective was to determine if differences exist in the acoustic estimate of relative density, size (target strength- TS), and absolute density as a function of echosounder models, beam configurations and frequencies. A secondary objective was to determine the effects of analysis software and threshold effects on target strength and fish density estimates.

Methods

Site Selection and Description

Originally, we attempted to do the field exercise in Lake Ontario in September 1999, but we were unable to get on the lake due to severe weather. After this experience, we searched for a lake that would be protected from severe weather, has a simple pelagic fish community, is accessible to all participants, and has a research vessel available which is capability of housing and deploying several hydroacoustics systems and transducers at a time. Lake Champlain proved to be the ideal candidate. It is oriented on a north-south axis, making it less susceptible to prevailing westerly winds (Fig. 1), its pelagic community is highly dominated by rainbow smelt, and a research vessel RV Melosira (13.7m) was available from the University of Vermont (Fig. 2). We performed the study during the nights of October 25-26, 2000. Weather for the duration of the exercise was calm, providing an excellent opportunity to compare acoustic systems.

General Methodology

To accomplish our objectives we collected mobile hydroacoustics data from as many different hydroacoustics configurations as we were able to assemble. From the list of all hydroacoustic systems used in the Great Lakes (Table 1), we selected seven systems representing 3 manufactures, 4 frequencies and two beam pattern configurations +(Table 2). This provided us with two very important comparisons:

1. Same frequency across different models and manufacturers. Since 120 kHz appears to be the closest to a standard in the Great Lakes, our first priority was to collect data from 4 different systems operating at 120 kHz encompassing 3 manufacturers and 4 different models (Table 3). All four systems used split-beam transducers.

[1] Cornell University Biological Station, February 11-12, 1999. Sponsored by the Great Lakes Fishery Commission.

2. Different frequencies across different models providing us with comparisons between 70 kHz, 120 kHz and 200 kHz and 420 kHz systems. We had a limited data set for comparisons between frequencies within manufacture (Table 3).

We were unable to involve hydroacoustics systems within the same frequency but different beam-pattern configurations. However, we attempted to compare single beam to split beam results with different frequencies. Specifications for each hydroacoustics system used in this exercise can be found in Table 4.

Data Collection

Construction of a tow body. We modified an existing tow body to house 6 transducers (Fig. 3). The remaining transducers were towed in a second tow body.

Testing of system and frequency compatibilities. A daylight trial run was done to test deployment and towing capability of the modified tow body, to test acoustic instrumentation, and to determine which systems could be operated simultaneously. To determine compatibility between acoustic systems, we did paired comparisons between acoustics systems in active mode. Systems were considered incompatible to be run simultaneously if one or both imparted noise on the other hydroacoustics system as determined from observation of the echogram and oscilloscope (Table 4).

Two groups were established for simultaneous data collection based on the paired compatibility test. Group 1 contained the Simrad EY500 70kHz and 120kHZ split-beam systems, and the Biosonics DT4000 420kHz single-beam system. Group 2 contained the Simrad EY120kHz split-beam system, Biosonics DT6000 120kHz system, Biosonics DE6000 120kHz split-beam system, HTI model 241 120kHz split-beam system, and the Simrad EY500 200kHZ single-beam system. The Simrad EY500 120kHZ split-beam system was the reference system and used in both groups. Within group 2, common frequencies (120 kHz) where not operated simultaneously, but rather were rotated.

Standardization and Data acquisition. Data collection parameters were all standardized such that pulse width was set at 0.2 and 0.6 ms for Simrad EY500 70 kHz and 0.3 ms for all other systems, ping rate was 3 pings per second (pps) and the data acquisition threshold was set at –80dB and –70 dB. Simrad EY500 has limited choice of pulse width settings so two pulse widths, which bound 0.3 ms setting of the other systems, were used.

Data were collected at night. A single transect, about 2 km long, was established at the mouth of Shelburne Bay near Burlington, Vermont (Fig. 1). The transect was repeatedly traversed back and forth at 8 km hr^{-1} (2.2 m s^{-1}) the duration of each leg was approximately 15 minutes. In group 1 all three systems were deployed simultaneously during an entire leg. Within group 2, the three 120 kHz systems where not operated simultaneously, but rather were rotated at 2 or 2.5 minute intervals, with the 200 kHz sounder simultaneously deployed for the entire leg. Raw detected voltages were digitized, stored on hard disk, and later processed in the laboratory.

Ground Truthing. During the second night, two boats used trawling gear to identify acoustics targets. From the RV Melosira (University of Vermont), a midwater trawl was used to capture larger pelagic targets. We made one horizontal tow at each of three depths (10, 20, and 30 metres). The midwater trawl had a 5m square opening, a cod-end of ½ inch mesh (#63 knotless ace netting) and was towed at 4 km.hr^{-1} (1.1 m s^{-1}) for approximately 30 minutes. Catch was identified and measured. In addition, the RV Monitor (Lake Champlain Research Institute, Plattsburg University) made oblique (30m to surface, N=4) and horizontal (n=3 at 10m, n=1 at 20m, n=1 at 30m) tows using 1m^2 tucker trawl (1 mm mesh size) to identify small midwater targets.

Processing procedures. In the laboratory, raw acoustics data were processed using two approaches: (1) two mutually agreed upon standardized procedures and (2) 'best' procedure based on participants' experience. For the standardized procedures, threshold settings for both Echo Squared Integration (**S**$_v$) and TS ($\bar{s}_{bs}$) analysis were set at either -80dB or-70dB to produce two separate estimates. For the 'best' procedure, participants were free to select their own processing parameters.

The thresholds for the two standardized estimates were established by looking at the frequency distribution of TS estimates using the DT6000 120 kHz split-beam system and the Simrad EY5000 200 kHz single-beam system in the field. It was noted that on the 120 kHz that the TS frequency distribution decreased rapidly to –65 dB. The 200 kHz system showed another slight peak and then decline to –70 dB. The interpretation was that individual targets larger than –70dB were fish. Integration interval was set at 2.5 minutes horizontal (except for those occasions where files are only 2 minutes in duration, then use 2 minutes) and two-meter vertical resolution.

We did not control for the single target criteria in any of the predefined procedures, because the algorithms for detecting single targets vary between systems. Each participant used their best judgment for determining single targets. However, participants tended to use the more restrictive setting, and thus decreased the probability of multiple targets interpreted as single targets.

For each system and procedure, the participants provided estimates of s_v, mean TS and volume density for each 2.5 min (horizontal) x 2 m (vertical) cell. In addition, we calculated volume densities using target strengths based on mean lengths from trawl catches using Love’s (1971) equation:

$$\bar{s}_{bs} = 10^{\,19.1 \times \mathrm{LOG}(L) - 0.9 \times \mathrm{LOG}(f) - 62.0}$$

where $\bar{s}_{bs}$ is the linear equivalent of target strength, L is length in cm and f is frequency of transmitted sound in kHz.

Echosounder and frequency-specific estimates of TS (dB units of $\bar{s}_{bs}$), S_v (dB), and logarithmic transformed density where compared using ANOVA and Tukey’s multiple comparison test (significance level of 0.05).

Results and Discussion

<u>Midwater trawl</u>

Numerically, trawl catches were dominated by rainbow smelt with 98% of the catch at 10m tow, and 100% of the catch 20 and 30m being rainbow smelt. The other 2% of the catch at 10m was lake herring, all of which had lengths greater than 200mm. Prominent modes in the length frequency distribution (Fig.4) appeared at 50-60mm, and a much weaker mode appeared at 65 mm. Mean fish length was 71mm at 10m, 56mm at 20m and 61mm at 30m.

Depth dependence of acoustic measures

Variance. The estimates of S_v, TS, and density, all showed a common depth-dependent pattern of variability. The variances within systems (between individual segment estimates from the same system) were the greatest near surface, and decreased to a low and steady level beyond approximately 15 meters (Figures 5, 6). This pattern is consistent with the fact that all acoustic systems sampled a cone shaped volume, where high variability is associated with low ensonified volumes near the transducer. Higher within-system variances lessen the significance of the generally high between-system differences observed in the upper layers (Figures 7,8). Beyond 15 meters, where within-system variabilities tended to be low, we also found that the estimates of acoustic measures from different systems tended to converge. Near bottom beyond approximately 30 meters, however, the variability of all acoustic measures increased again, which can be attributed to variation in sampled volume caused by non-uniform bottom depth.

S_v (Relative density). Relative density initially increased with depth, and then leveled off at 20-25 meters (Fig. 5A, 7A). The greatest differences between systems occurred in the upper 15 meters, and the estimates converged below this depth. An exception to this pattern of convergence was observed for the 420 kHz single beam system, where relative density estimates remained less then the other systems across all depths, and possibly the Simrad 120 kHz system which yielded somewhat higher estimates. Threshold setting had little or no effect on the depth-dependent relative density estimates, with the exception of the highest frequency, 420 kHz (Fig. 5A, 7A), where relative density was notably higher for –80 dB threshold at depths less than 15 meters. Differences between frequencies existed. Lowest values for relative density occurred for the highest frequency (420 kHz) while the highest variances was associated with the 120 kHz systems for depths less than 10m and at both thresholds (Fig. 7A, 8A).

Summary: Greatest differences in relatively density and associated variances occurred at short ranges from transducer (< 15m). However, estimates of relative density and the associated variances converged and were similar (amongst frequencies and manufactures) at depths greater than 15m. An exception to this was the 420 kHz with estimates of relative density less than the estimates from the other acoustics system.

TS (Acoustic size). At the –80dB processing threshold there was a general trend of increasing target strength with increasing depth (Fig. 7B). This pattern was especially apparent at depths beyond 10-15m, and less clear near surface, where it may have been obstructed by higher variances. At –80 dB the pattern was evident in all systems with the exception of the DE6000-120kHz. At –70 dB the pattern of increase was seen in only three of the seven systems, while the other systems showed no discernable trend with depth (Fig. 8B). Overall, near surface the target strengths obtained with –80dB threshold were substantially lower than those obtained with –70dB threshold by about 8 dB. The –80dB target strengths increased in deeper water, and beyond 20 meters, they were comparable to the –70dB target strengths.

Mean differences between minimum and maximum mean TS was 17.8dB at the –70 dB threshold and 23.6 dB at the –80 dB threshold; approximately a 2 orders of magnitude difference in intensity. Unlike estimates of relative density, values for mean TS did not converge with depth, but remained different between acoustic systems. The 420 kHz system consistently had the lowest estimates of mean TS, with a 13dB average deviation from the other systems at –70dB, and 17dB at –80dB.

Summary: Estimates of TS varied by system and threshold setting. Differences also existed for estimates of mean TS within a frequency (120 kHz). Range of mean TS estimates spanned approximately 2 orders of magnitude.

Density (# m^{-3}). Density was estimated using *in situ* estimates of TS, and using TS estimates based on net catches. In general, density tended to increase with depth, but this pattern was method (*in situ* vs. net), frequency, and threshold dependent (Fig. 7C, 7D, 8C, 8D).

Density estimates using *in situ* target strength measurements increased with depth using the -70 dB threshold (Fig. 8C), but no apparent pattern was evident using the –80 dB threshold setting (Fig. 7C). Density estimates tended to converge at depths greater than 15m, but the estimates amongst acoustic system still ranged by 6.6 dB and 10.6 dB for the -70 and –80 db thresholds respectively. Threshold effects occurred with the highest frequencies showing the greatest disparity in density estimates.

Differences between density estimates from the various acoustic systems were reduced when we based the estimates on common mean TS values derived from trawl catches, although the highest frequency (420 kHz) still tended to be much different (less in this case) than the other frequencies (Fig. 7D, 8D). The use of data reduced all estimates of density, with the greatest reduction occurring for the 420 kHz data. The estimates were similar for both the –80dB and –70dB thresholds.

Summary: Density estimates using *in situ* TS estimates differed greatly between systems. The use of trawl-derived TS estimates reduced the variability between systems.

Summary: Depth-dependence of relative density (S_v) was similar between acoustic systems, whereas *in situ* estimates of TS varied widely between acoustic systems. Between-system differences in the *in situ* mean TS values were primarily responsible for the observed differences in density estimates. Highest frequencies (420 and 200 kHz) yielded the lowest mean TS estimates, resulting in highest density estimates. Use of TS trawl-derived estimates appeared to be more robust creating density estimates more similar between acoustic systems, reduced variances at depths and with reduced differences in variances between systems.

Target strength (TS)

Target strength estimates (Fig. 9) varied between frequencies, between models within frequencies (120 kHz), and between frequencies within specific models ($P<0.001$), with the lowest TS estimates occurring at the highest frequency (420 kHz). Net-derived TS estimates where similar between frequencies ($P>0.10$).

Differences between frequencies were dependent upon threshold settings with the greatest number of different paired comparisons occurring at the –80 dB threshold (Fig. 10). There were only a few consistent patterns observed between density estimates: (1) mean TS for the 420 kHz was always different ($P<0.05$) from estimates for the other models and frequencies, and (2) mean densities were similar within manufacturer (Biosonics) and frequency (120 kHz) but between models (DT6000 vs DE6000).

Target strength estimates were sensitive to the threshold setting used (Fig. 9). Within a model, mean TS differed between threshold settings ($P<0.05$). There were two notable differences-Simrad 70 kHz system and HTI 120 kHz system.

The frequency and threshold dependent differences in target strength estimates may be explained by the physics of sound. Backscattering from a target is a function of the wavelength (λ), which in turn is a function of the speed of sound in water (c) and operating frequency (f), such that $c = \lambda f$. If the target is very small relative to the wavelength than the intensity of the backscatterer is small and the ability to detect the target is reduced. For targets that are relatively large when compared to the wavelength, the intensity of the returning echo is large and the ability to detect the target is assured. For intermediate targets roughly the same size as the wavelength, backscattering depends on the geometric structure and material properties of the target and it is difficult to predict the backscattering (TS) of a target. Thus, backscattering by a small target increases rapidly with frequency.

In agreement with expectations based on physics of sound, the highest frequency system in our study (420kHz) consistently yielded the lowest mean TS values at all depths, and with both processing thresholds (Figures 7,8,9). The second highest frequency also yielded low TS values in the upper half of the water column, especially at the –80dB threshold. The degree of change in TS estimates resulting from change in processing threshold varied directly with the acoustic frequency (Fig. 11), indicating that the lower frequency, the less sensitive the systems were to targets in the –80dB to –70dB range. Among the 120kHz systems, the HTI showed the lowest sensitivity to the change in threshold, behaving similar to the 70kHz system.

Differences ($P<0.05$) in TS where also observed between pulse duration setting for the Simrad 70 kHz system (Fig. 9). This may reflect the higher densities of fish observed at depths greater than 20m. Shorter pulse lengths (0.2 ms) have higher resolution to detect individual fish at higher fish densities than longer pulse lengths. Thus, one would expect to have smaller targets incorporated in to mean TS estimates for the shorter pulse duration than the longer pulse duration. The differences in TS estimates between pulse width settings are consistent with this expectation (Fig. 9).

Summary: Estimates of TS varied between acoustic system, frequency and threshold settings. Frequency dependence and threshold-dependence of TS can explain much of the differences between operating frequencies. However, causes of differences between TS within frequencies and threshold settings are unknown, but may be a result of the manufacturer-specific processing software. Evidence for this occurs for the one situation in which we had two different models operating at 120 kHz from the same manufacturer, and this two system had similar TS estimates. In addition, we found that TS estimates from the lowest frequency is less sensitive to then changes in threshold densities applied in this study.

<u>Absolute density (# m^{-2}) estimates</u>

Density estimates differed between ($P<0.001$ ANOVA) and within ($P<0.001$, ANOVA) acoustics systems (Fig. 12). Highest density estimates occurred using the lowest threshold (-80 dB) and with the highest frequencies, 420 kHz and 200 kHz. Greatest range of estimates also occurred with the highest frequency (420 kHz), with less variation and most robust estimates from the lowest frequency (70 kHz).

Differences between systems and frequencies were least pronounced when using in situ TS with –70dB threshold (Fig. 13). For the within frequency comparison, the 120kHz systems were similar, with the exception of the Simrad120 which deferred somewhat at the –80 dB setting and entirely when using trawl-derived estimates of TS. The 70kHz system tended to be similar to the 120kHz systems (other than the Simrad 120), except when using in situ TS with –80dB threshold. The 200kHz system had a tendency to be different from other systems, especially with the –80dB threshold. The 420kHz system differed from all other systems under all circumstances. There was no obvious logical pattern in the similarities and differences between estimates based on users' experience.

Density estimates within frequencies, using the –70 dB threshold and *in situ* TS standardized procedure, where aggregated to further test for differences between frequencies. Estimates from the 70 kHz and 120 kHz were not statistically different ($P > 0.05$) (Fig. 14). However, estimates from the 200 kHz were different from estimates from the 70 and 120 kHz, and the 420 kHz ($P>0.05$). Density estimates using the 420 kHz was also different from estimates from the 70 and 120 kHz systems. Variation in density estimates, as measured by the coefficient of variation, was a function of operating frequency (Fig. 15). The general relationship was of increasing CV with increasing operating frequency indicating greater variation with higher frequency

The effect of threshold setting differed between systems (Fig. 16). When using trawl-based mean TS, in three of the four 120 kHz systems, as well as in the 200 kHz and 420 kHz systems, a decrease in threshold setting from –70 to –80 dB resulted in a corresponding significant increase is density estimates ($P<0.05$). In the remaining two systems (Simrad 120 kHz and 70 kHz), threshold did not appear to have an effect on the density estimate. As above with estimates of TS, we would expect less of a difference or no difference at all with the lowest frequency. However, the cause for deviation of the Simrad 120 kHz from that pattern observed for the other 120 kHz system is unknown.

Summary: In general, density estimates using 70 kHz and 120 kHz were similar at the highest threshold settings (-70 dB) for the *in situ* standardized approach, and for all of the densities from net-derived estimates of average target strength. However, within frequency, density estimates differed with respect to threshold settings, with the greatest densities associated with the lowest threshold settings. Variances of the mean density were minimized using net-derived estimates of acoustic backscatter. Highest estimates of density and variance occurred using the highest frequency (420 kHz).

Recommendation

The primary conclusion from this study is that density estimates from 120 kHz systems are comparable between models and manufacturers of acoustic equipment. In addition, density estimates using the 120 kHz systems are comparable to other operating frequencies- 70 kHz and 200 kHz, but differences can occur depending upon instrument settings for data acquisition, and parameter settings in the post-processing software. The 420 kHz system, did not compare favorably to any other system, and should not be used for comparative studies. The results of our study also highlight the need to develop a standard protocol for the collection and processing of acoustic data within the Great Lakes basin. We recommend that a committee be formed to develop a Standard Operating Procedures for Acoustic Surveys in the Great Lakes. Lastly, differences in TS estimates were different within frequencies and between systems. Between frequency differences are explainable, however, causes for the differences observed within frequencies are unknown. We suspect that there may be differences between software packages in the single target algorithms. This issue should be explored in more detail at a later date.

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APPENDIX. Definitions of Acoustical Terms

Acoustics axis: The center of the transmitted acoustic beam. Sound intensity is highest along the acoustic axis.

Acoustic target (or scatterer): Objects that reflect sound in water. When sound encounters an object in the water with density different from that of water, a portion of the sound will be reflected back to the transducer as an echo.

Backscattering cross section (σ_{bs}): A measure of the reflectivity of an acoustic target; the ratio of the sound intensity reflected (I_r) from an acoustic target to sound intensity incident (I_i) to the target at a distance R from the target; $\sigma_{bs} = R^2(I_r/I_i)$. Linear equivalent of target strength (TS) where $\sigma_{bs} = 10^{TS/10}$ (unit: m^2)

Beam angle: The full angle (in degrees) from the acoustic axis of the transducer at which the sound intensity is one-half (-3 dB) that on the acoustic axis.

Decibel (dB): A dimensionless unit used for expressions of rations of sound intensities. Decibel is defined as 10 times the logarithm of the ration of a measured sound intensity (I_M) to a reference sound intensity (I_R), $10\ LOG_{10}(I_M/I_R)$.

Dual-beam transducer: A transducer that has both a narrow beam and a wide beam. Sound is transmitted on the narrow beam and received on both the narrow and wide beams. The ratio of the intensity of the of the two returning echoes (narrow:wide), allows for the determination of the radial location of the target in the acoustic beam (i.e., angle of off the acoustic axis).

Echo: Sound reflected from an acoustic scatterer.

Frequency: The number of sinusoidal sound waves per unit time expressed in Kilohertz (KHz), or 1,000 cycles per second.

Pulse duration: Duration in time from start to end of an acoustic pulse (unit: sec).

Pulse length: Length of an acoustic pulse (unit: m).

Source level (SL):

Single-beam transducer: A transducer with one beam. Unlike dual-beam and split-beam transducers, information from single-beam transducers cannot be used to determine the location of acoustic targets in the beam.

Split-beam transducer: A four-quadrant transducer that measures the differential arrival times of echoes in order to define the location of an acoustic target in the acoustic beam.

Standard target: A target of known target strength that is used to calibrate acoustic hardware.

s_v: Linearized form of the volume scattering coefficient (S_v) where $sv = 10^{Sv/10}$

S_v: Volume scattering coefficient. Logarithmic form of s_v where $S_v = 10\ LOG_{10}(s_v)$.

Target strength (TS): A measure of the proportion of sound that is reflected from an acoustic scatterer back to the transducer. It is expressed in decibels and is equivalent to $10\ LOG_{10}(\sigma_{bs})$, where σ_{bs} is the backscattering cross section.

Transducer: A pressure sensitive device that converts electrical energy into sound energy for sound transmission and sound energy into electrical energy during sound reception.

TABLES

TABLE 1: Scientific echosounders in the Great Lakes Region

Manufacturers	Configuration	38 kHz	70 kHz	120 kHz	200 kHz	420 kHz
BioSonics	Dual-beam (model 102, 105)	x		xx		xx
	Single-beam (model 105)					x
	Split-beam (DT6000)			x		
	Split-beam (DE6000)			x		
	Single-beam (DT4000)				x	x
Simrad	Spilt-beam (EY500)		x	xxxxx		
	Single-beam (EY500)				x	
	Single-beam (EYM)		xx			
HTI	Split-beam (model 241)			x		

Table 2: Participants and echosounders in October 2000 workshop.

Participant	Hydroacoustic System (kHz)	Affiliation
Tom Hrabik	HTI Model 241, split-beam (120)	University of Wisconsin
Doran Mason	Biosonics DT6000, split-beam (120)	NOAA/GLERL &
Brian Nagy		Michigan State University
Donna Parrish	Simrad EY500, single-beam (200)	University of Vermont &
Bernie Pientka		Illinois Natural History Survey
Lars Rudstam	Biosonics DT4000, single-beam (420)	Cornell University
Sandra Parker	Simrad EY500, split-beam (70)	
Dave Warner	Biosonics DE6000, split-beam (120)	
Ted Schaner	Simrad EY500, split-beam (120)*	Ont. Ministry Nat. Resources
Clif Tipton	Simrad EY500, split-beam (120)	West Virginia University

* Not used in exercise

Table 3. Scientific echosounders used in October 2000 cross-comparison exercise

Manufacturer	**Configuration**	70 kHz	120 kHz	200 kHz	420 kHz
Biosonics	Split-beam (DT6000)		×		
	Single-beam (DT4000)				×
	Split-beam (DE6000)		×		
Simrad	Spilt-beam (EY500)	×	×		
	Single-beam (EY500)			×	
HTI	Split-beam (model 241)		×		

Table 4. Matrix of paired compatibility comparisons for simultaneous pinging.

	S70SP	S120SP	S200S	DT120SP	DT420S	DE120SP	HTI120SP
S70SP	1						
S120SP	**C**	1					
S200S	C	**C**	1				
DT120SP	C	NC	**C**	1			
DT420S	C	**C**	NC	C	1		
DE120SP	NC	NC	**C**	NC	**C**	1	
HTI120SP	**C**	NC	**C**	NC	C	NC	1

C- Compatible pair
NC- Non-compatible pair

S70SP- Simrad EY500 70kHz split-beam
S120SP- Simrad EY500 120kHz split-beam
S200S- Simrad EY500 200 kHz single-beam
DT120SP- Biosonics DT6000 120kHz split-beam
DT420S- Biosonics DT4000 420kHz single-beam
DE120SP- Biosonics DE6000 120kHz split-beam
HTI120SP- HTI model 241 120kHz split-beam

TABLE 5. System specifications for hydroacoustics systems used in comparison exercise.

Manufacturer	Model	Frequency (kHz)	Beam Type	Beam angle	Source Level dB//uPa @1m
Biosonics	DT6000	120	Split-beam	6.2	225.0
	DE6000	120	Split-beam	7.6	221.8
	DE4000	420	Single-beam	7.0	220.5
Simard	EY500	70	Split-beam	11.1	
	EY500	120	Split-beam	7.0	
	EY500	200	Single-beam	7.4	213.7
HTI	241	120	Split-beam	13.4	200.8

FIGURES

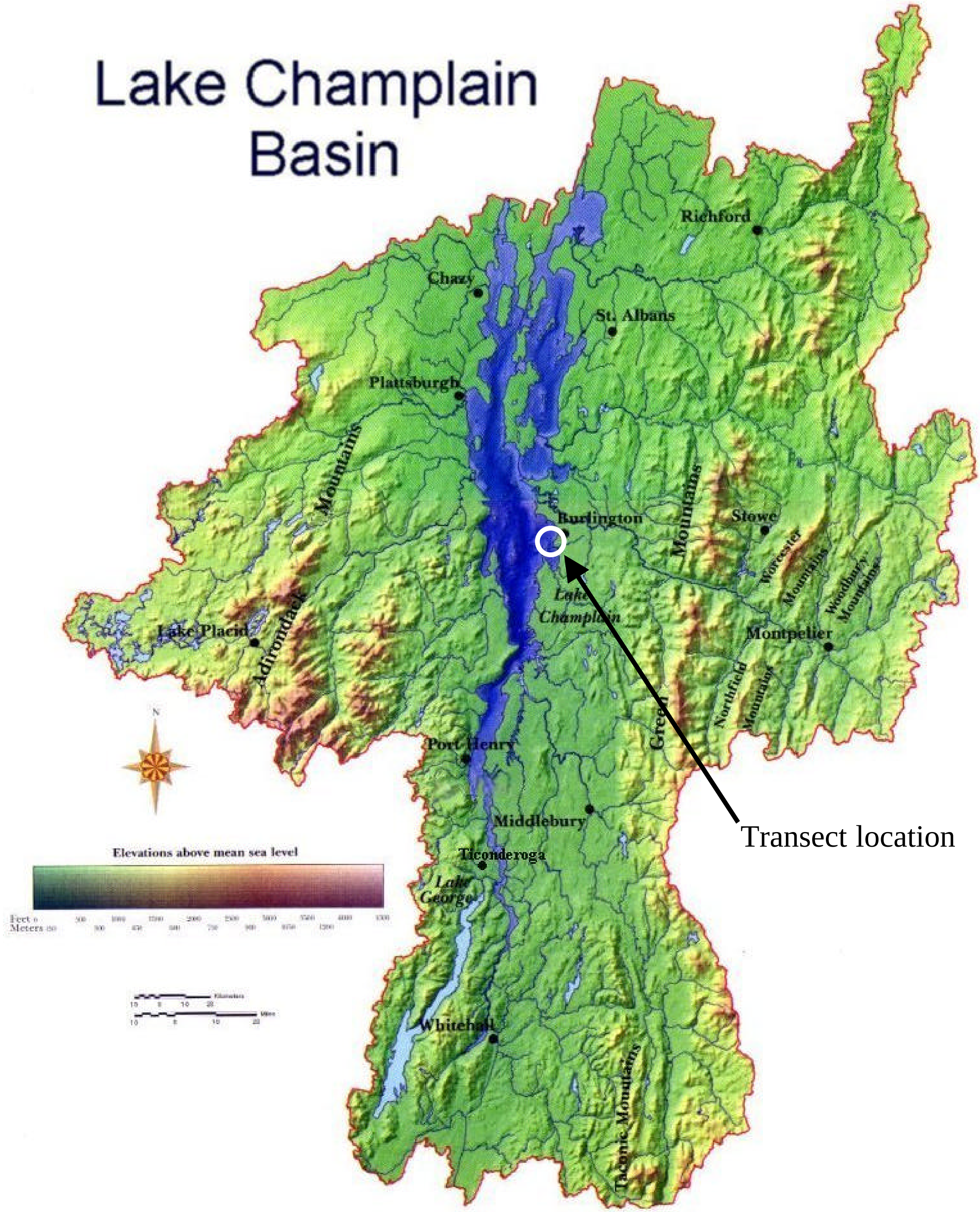

Figure 1. Map of Lake Champlain and location of acoustic transect

Figure 2. RV Melosira

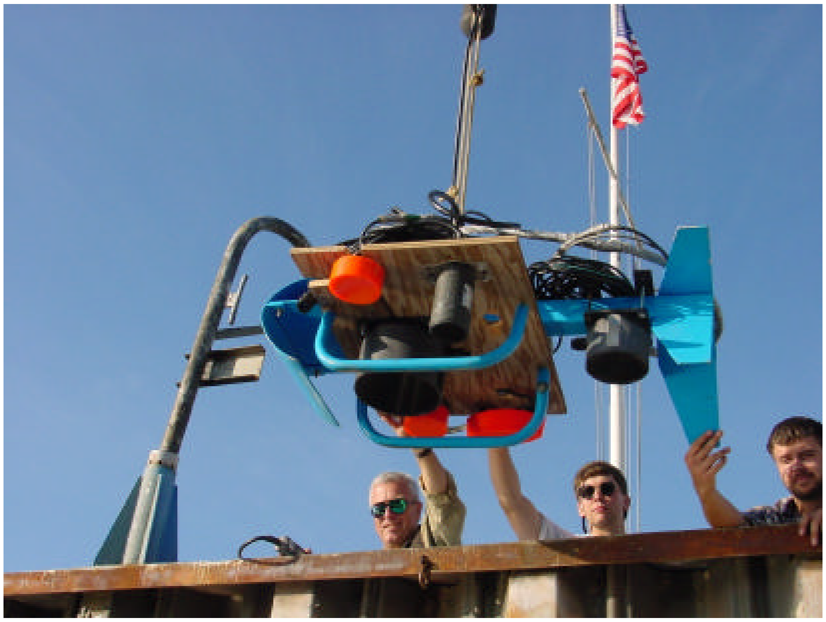

Figure 3. Modified tow body to house transducers

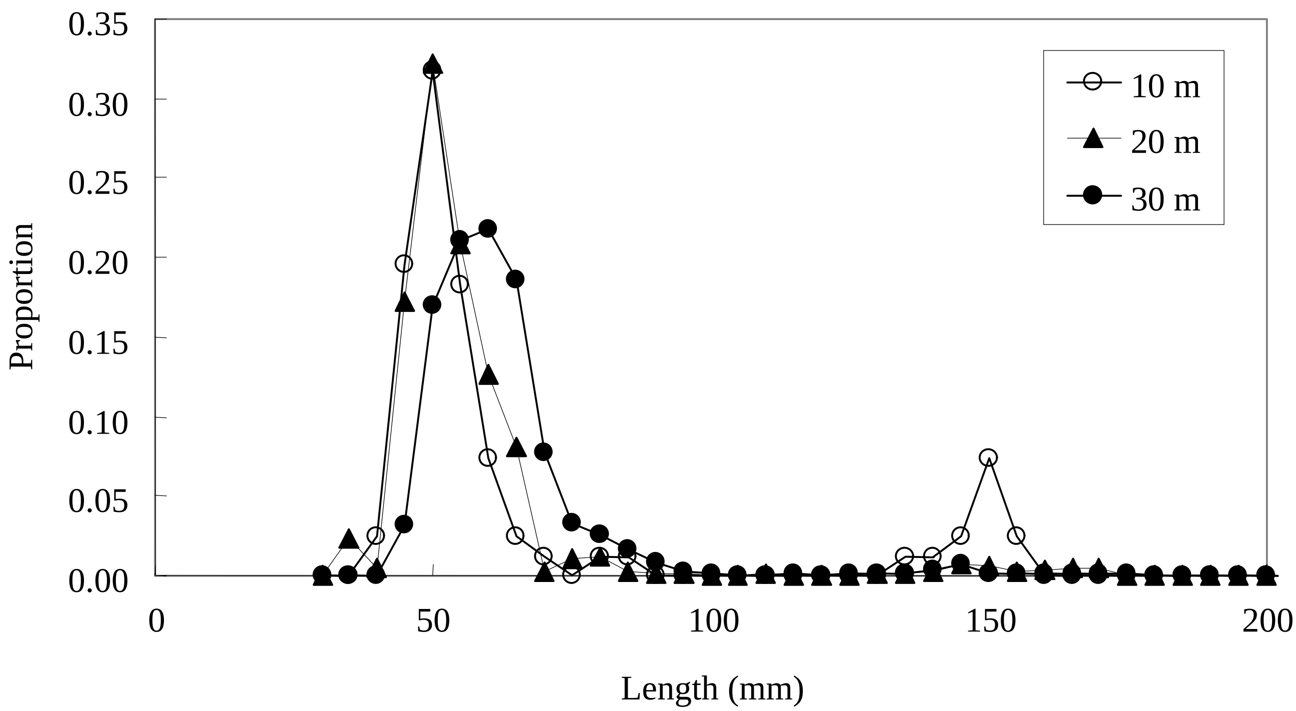

Figure 4. Length frequency distribution of fish catch from midwater trawls at 10m, 20m and 30m. Trawls were dominated by rainbow smelt.

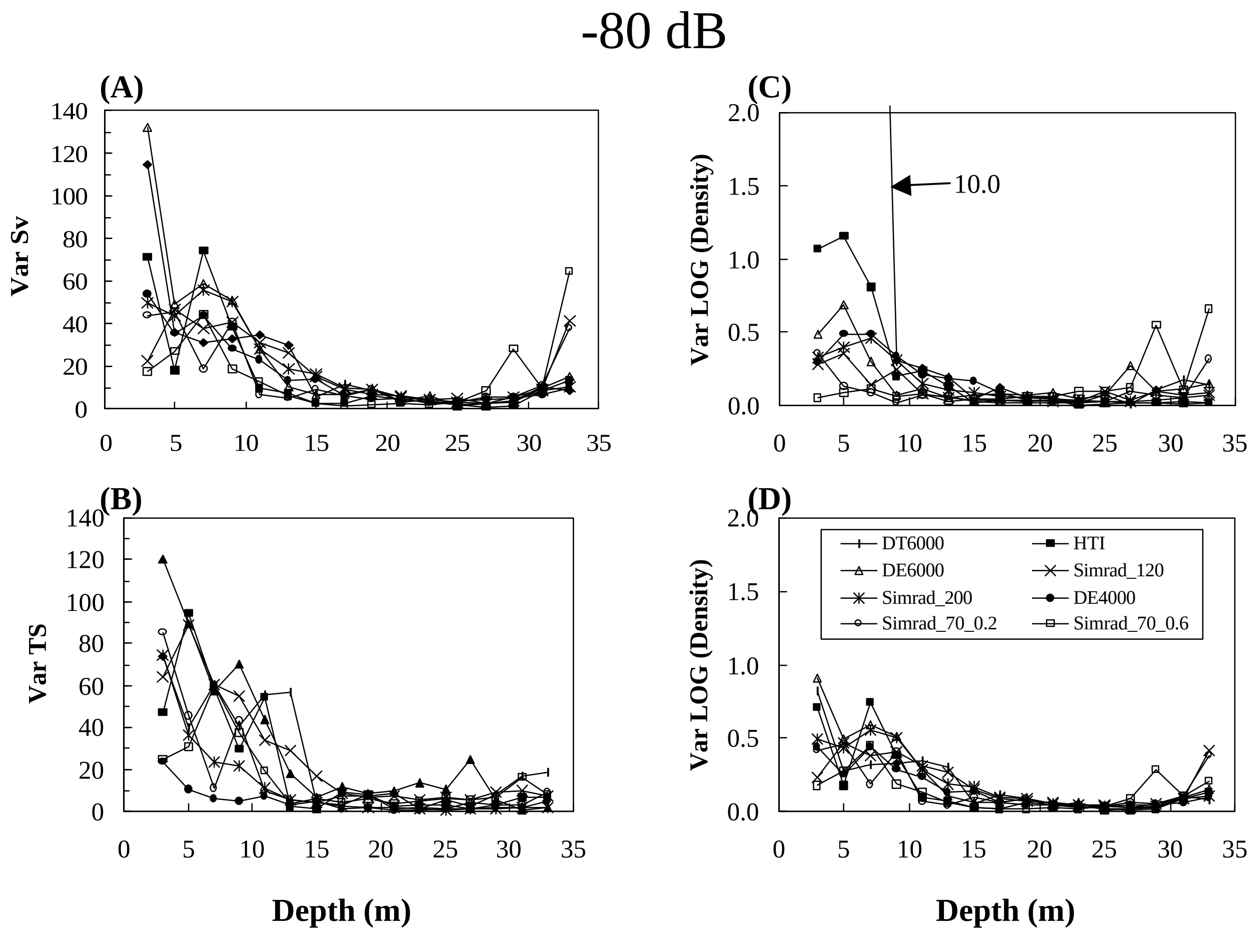

Figure 5. Echosounder specific depth-distribution using –80 dB processing threshold for (A) variance of S_v, (B) variance of TS, (C) variance of density (# m^{-3}) using in situ estimates of TS- graph B, and (D) variance of density (# m^{-3}) using net-derived estimates of TS. Frequencies: DT6000- 120 kHz, DE6000- 120 kHz, HTI- 120 kHz, Simrad_120- 120 kHz, Simrad_200- 200 kHz, DE4000- 420 kHz, Simrad_70_0.2- 70 kHz collected at 0.2 ms pulse duration, Simrad_70_0.6- 70 kHz collected at 0.6 ms pulse duration. Refer to legend in (D)

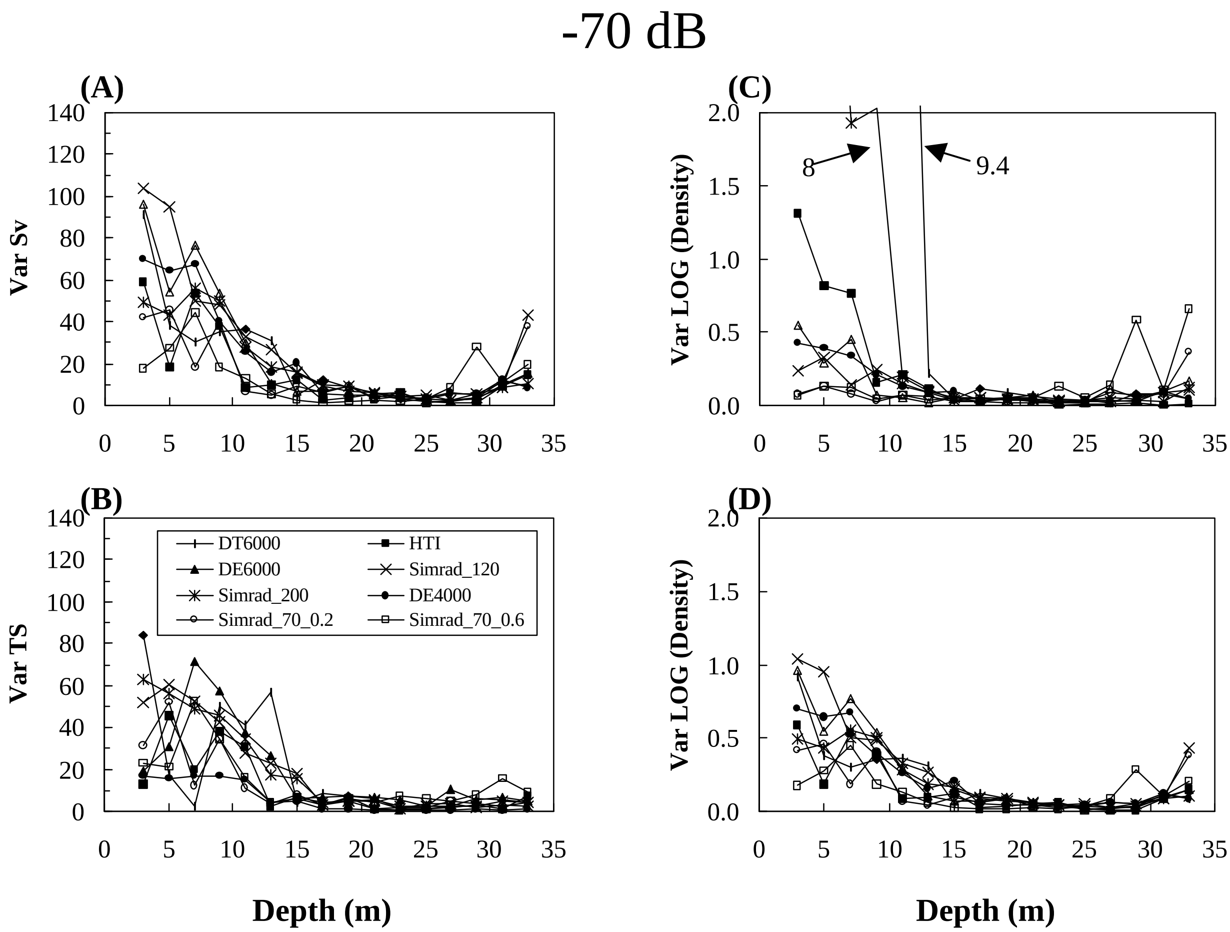

Figure 6. Echosounder specific depth-distribution using –70 dB processing threshold for (A) variance of S_v, (B) variance of TS, (C) variance of density (# m^{-3}) using in situ estimates of TS- graph B, and (D) variance of density (# m^{-3}) using net-derived estimates of TS. Frequencies: DT6000- 120 kHz, DE6000- 120 kHz, HTI- 120 kHz, Simrad_120- 120 kHz, Simrad_200- 200 kHz, DE4000- 420 kHz, Simrad_70_0.2- 70 kHz collected at 0.2 ms pulse duration, Simrad_70_0.6- 70 kHz collected at 0.6 ms pulse duration. Refer to legend in (B)

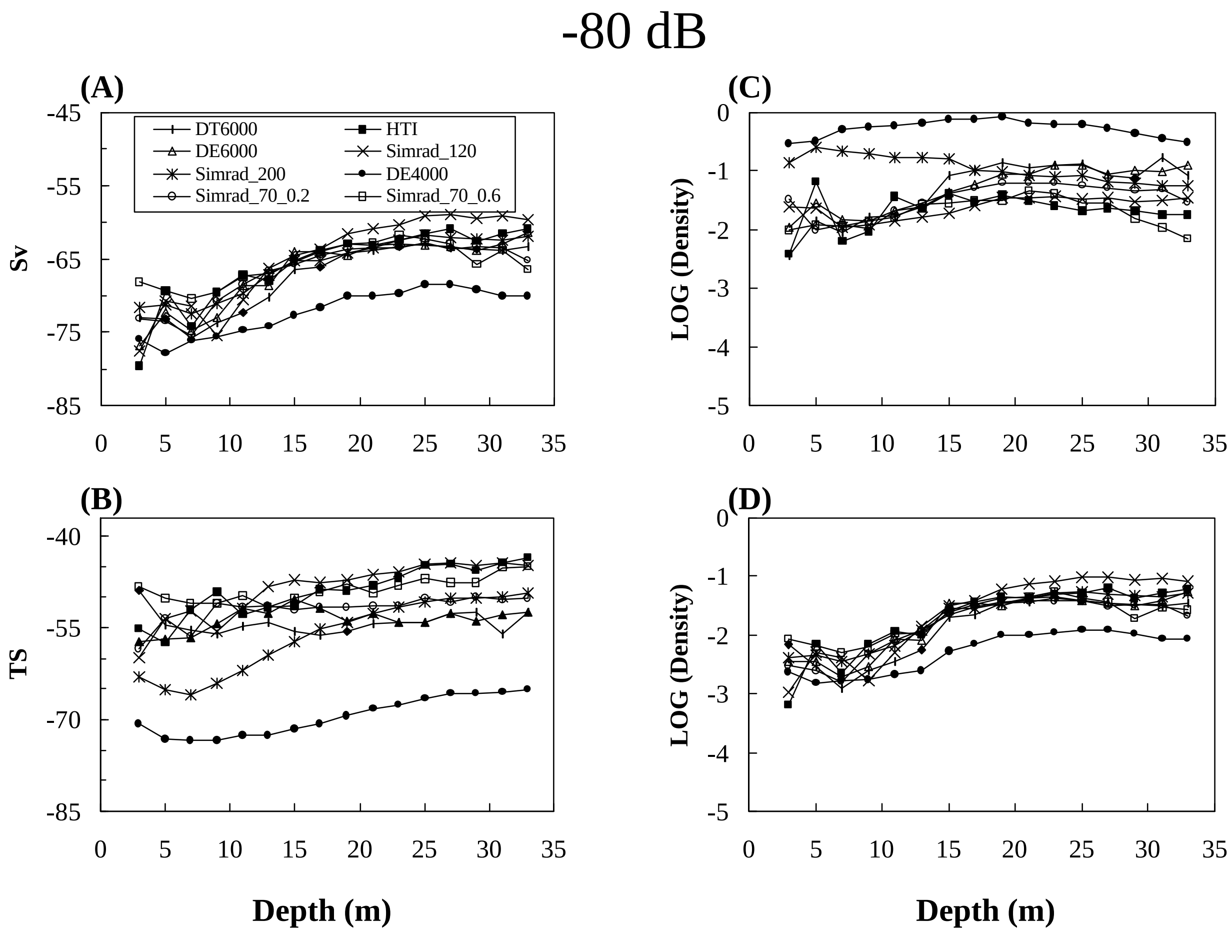

Figure 7. Echosounder specific depth-distribution using –80 dB processing threshold for (A) S_v, (B) TS, (C) Density (# m^{-3}) using in situ estimates of TS- graph B, and (D) Density (# m^{-3}) using net-derived estimates of TS. Frequencies: DT6000- 120 kHz, DE6000- 120 kHz HTI- 120 kHz, Simrad_120- 120 kHz, Simrad_200- 200 kHz, DE4000- 420 kHz, Simrad_70_0.2- 70 kHz collected at 0.2 ms pulse duration, Simrad_70_0.6- 70 kHz collected at 0.6 ms pulse duration. Refer to legend in (A)

-70 dB

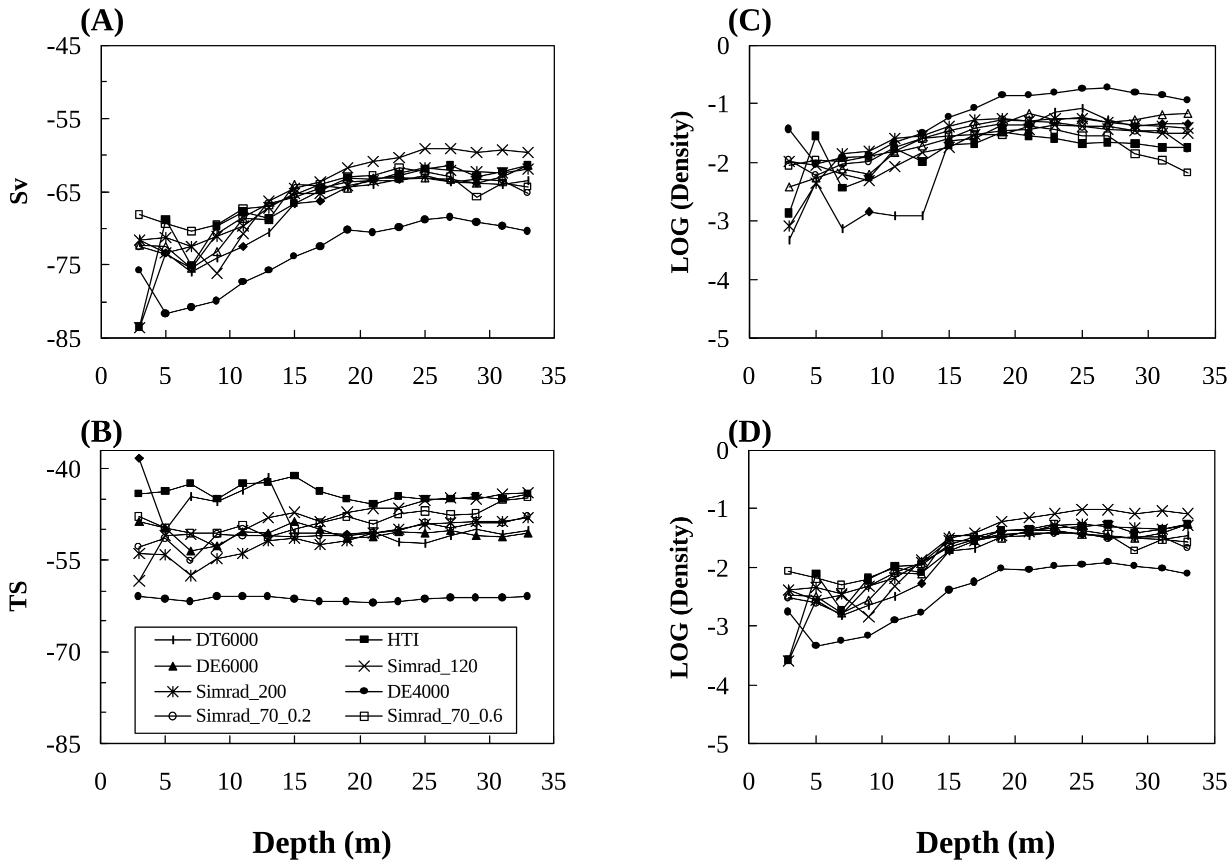

Figure 8. Echosounder specific depth-distribution using –70 dB processing threshold for (A) S_v, (B) TS, (C) Density (# m^{-3}) using in situ estimates of TS- graph B, and (D) Density (# m^{-3}) using net-derived estimates of TS. Frequencies: DT6000- 120 kHz, DE6000- 120 kHz HTI- 120 kHz, Simrad_120- 120 kHz, Simrad_200- 200 kHz, DE4000- 420 kHz, Simrad_70_0.2- 70 kHz collected at 0.2 ms pulse duration, Simrad_70_0.6- 70 kHz collected at 0.6 ms pulse duration. Refer to legend in (B)

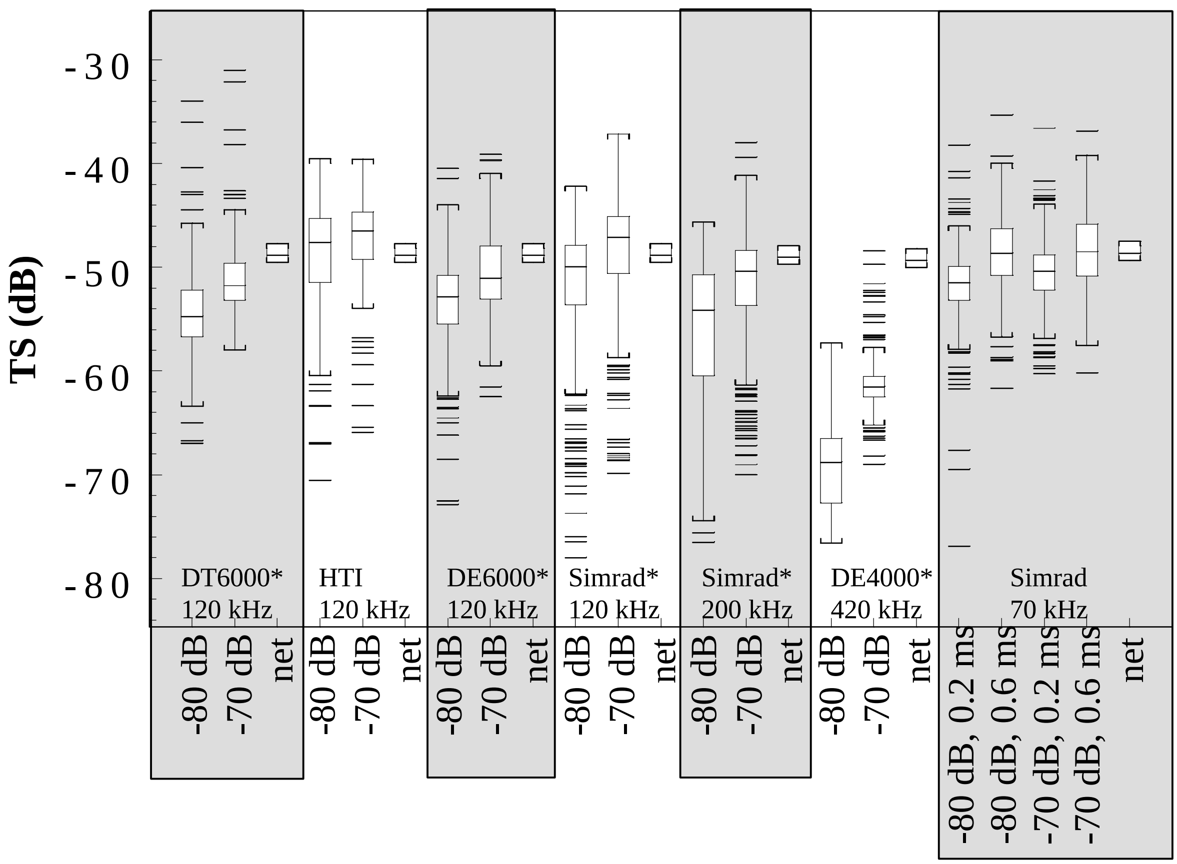

Figure 9. Box and whisker plot of the estimated target strengths for each acoustics system and for each threshold setting. Net refers to the net-derived target strength estimates. For the Simrad 70 kHz system, the different pulse durations are shown as 0.2 ms and 0.6 ms. Asterisks denote differences ($P<0.001$) in TS estimates between the –80db and –70 dB processing processing thresholds.

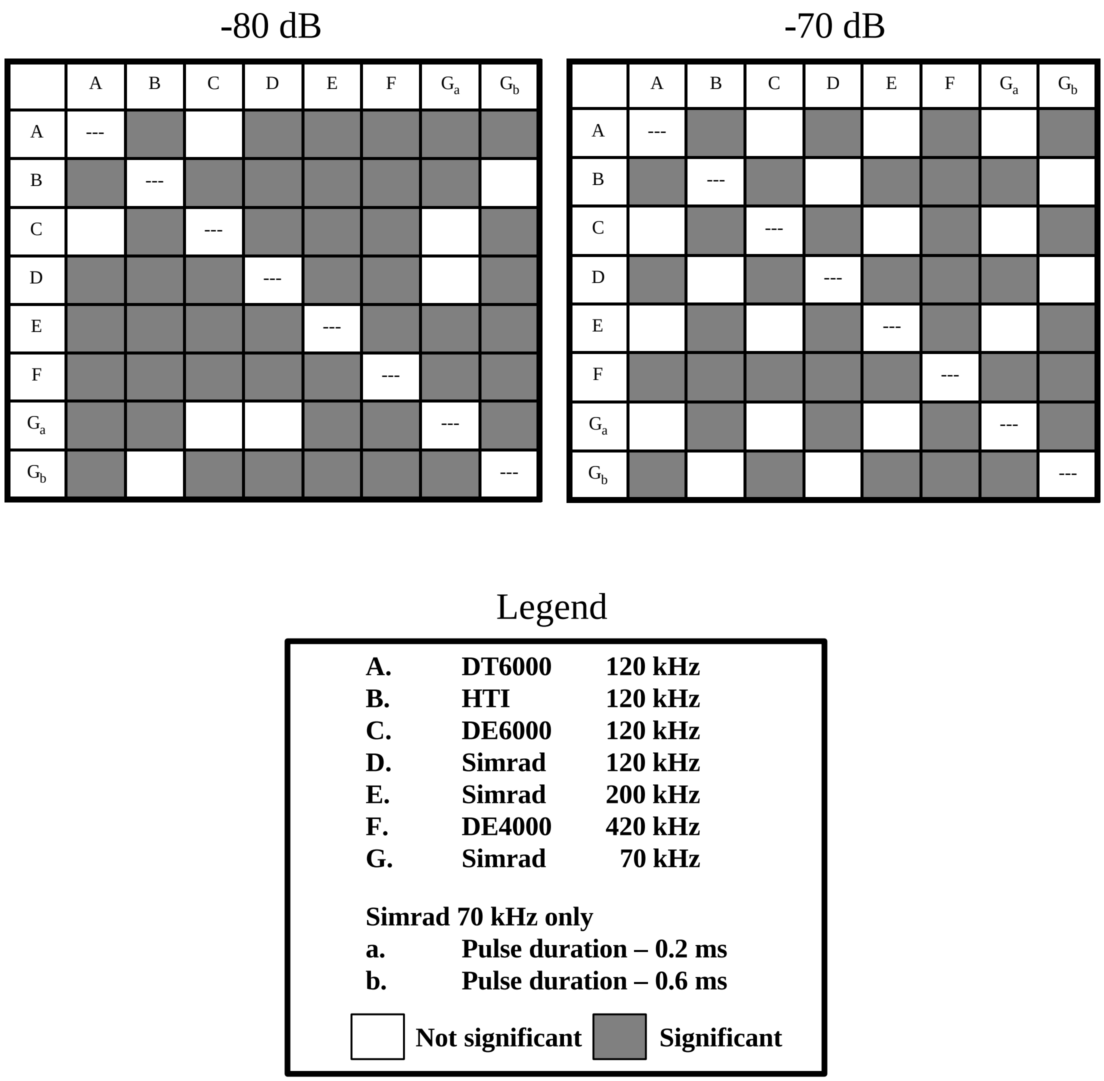

Figure 10. Comparison of acoustical target strength (TS, dB) between acoustic frequencies as a function of processing thresholds. Significance is at the 0.05 level.

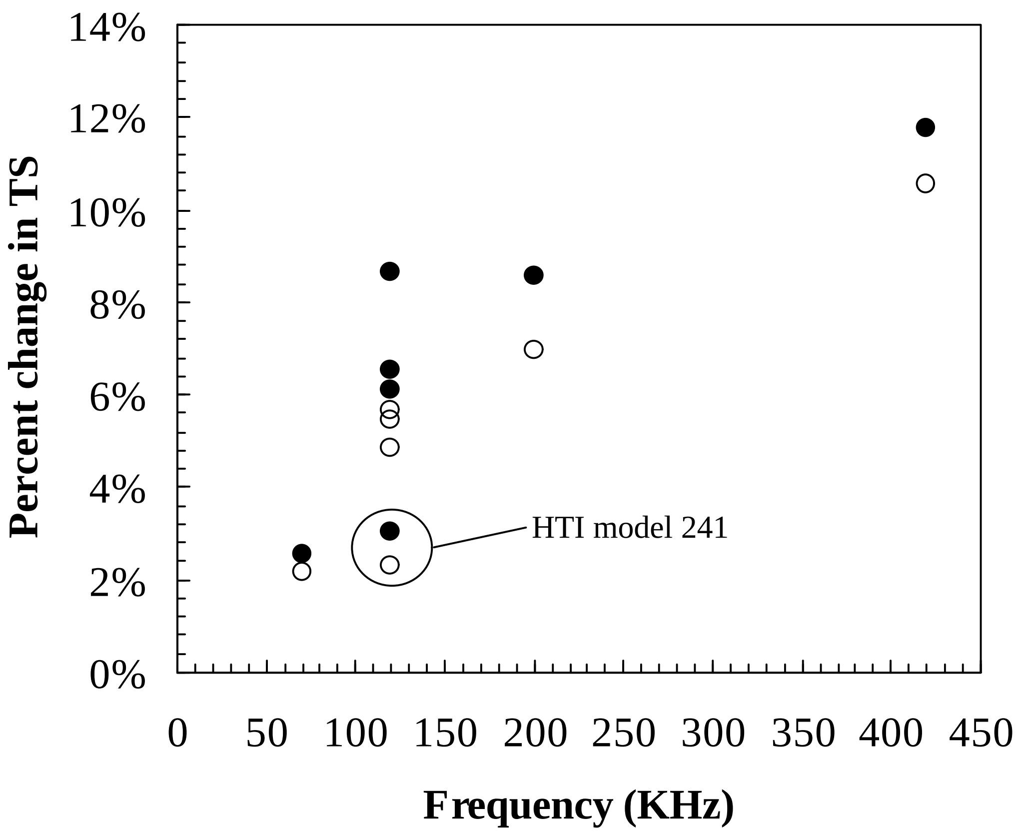

Figure 11. Percent relative change in mean and median TS estimates as determined using the –80 dB and –70 dB processing thresholds. Solid circle is mean TS and open circle is median TS. Outliers appear for the HTI 120 kHz split beam system.

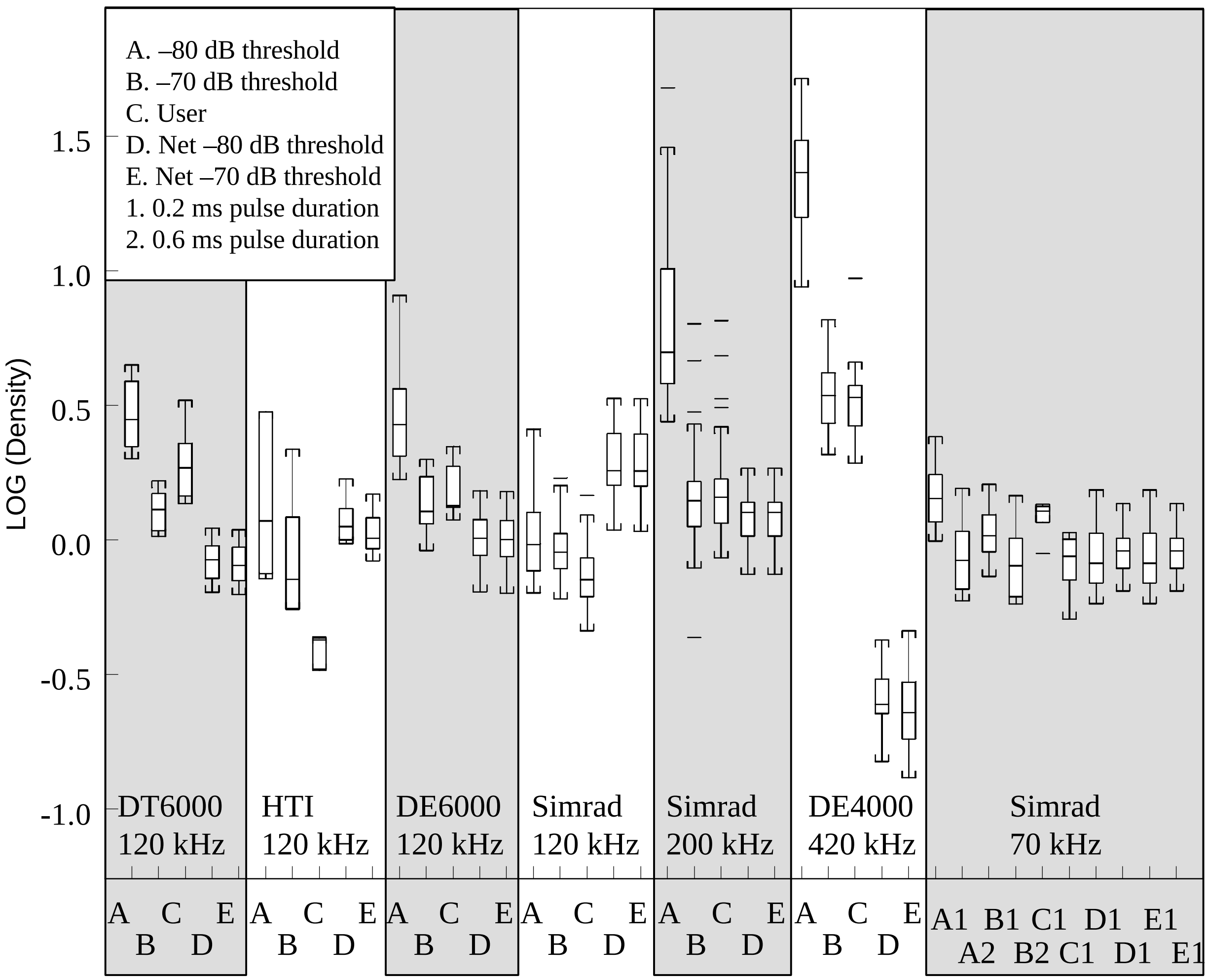

Figure 12. Box and whisker plot of aerial Log (density, # m^{-2}) for all acoustic systems and settings. Key for codes found on the horizontal axis are in the figure legend: threshold refers to the threshold setting used in post-processing, net refers to the use of net-derived TS estimates for abundance, and numbers (1 and 2) refer to the pulse duration used in acquiring raw data from the Simrad 70 kHz system only. See text for details.

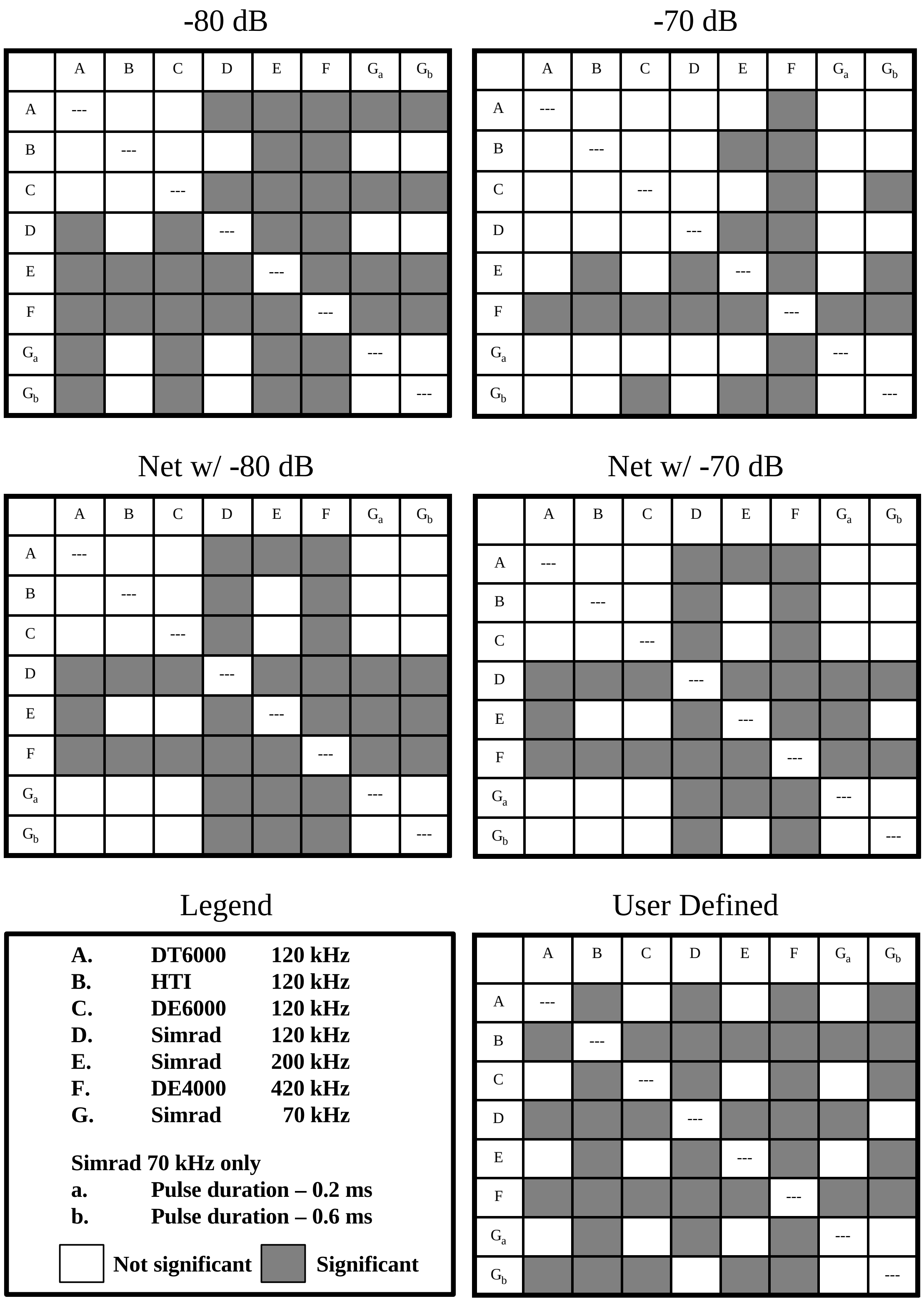

Figure 13. Comparison of density (# m^{-2}) between acoustic frequencies as a function of processing thresholds. Top row represents standardized processing procedures using in situ estimates of acoustic size. Middle row uses standardized processing procedure but calculates density using acoustic size as estimated from trawl data. User defined comparison is based on experience of the person doing the processing- non-standardized approach. Significance is at the 0.05 level.

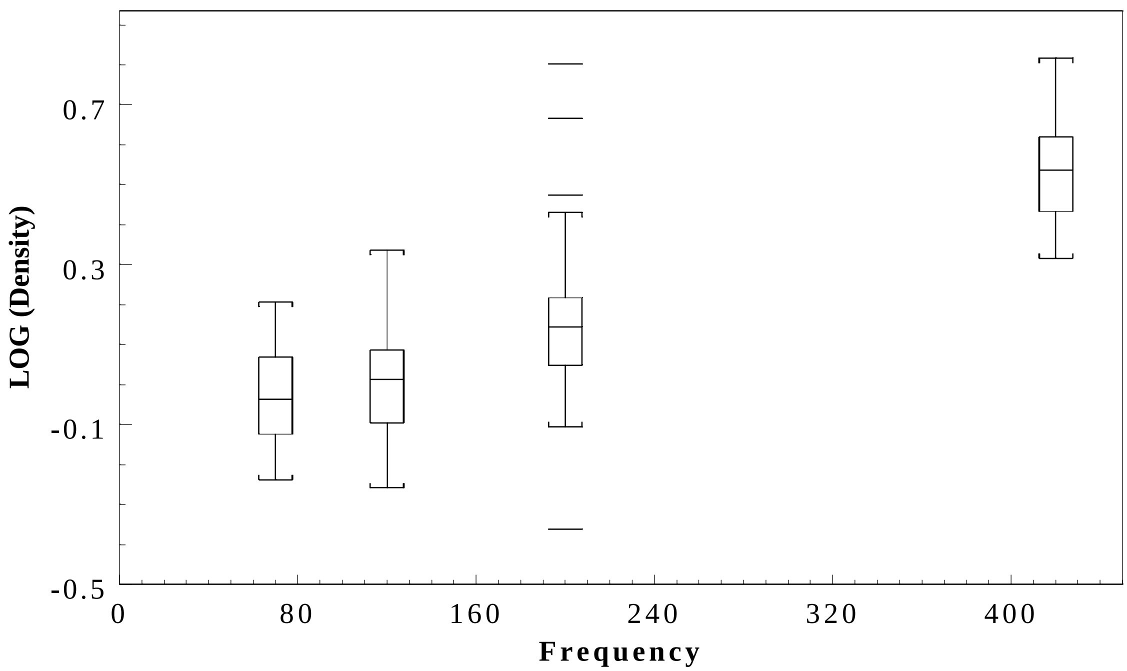

Figure 14. Box and whisker plot of the logarithmic transformed density (# m^{-2}) as a function of frequency. Comparison is for data processed using the –70 dB threshold and density estimated using in situ TS estimates.

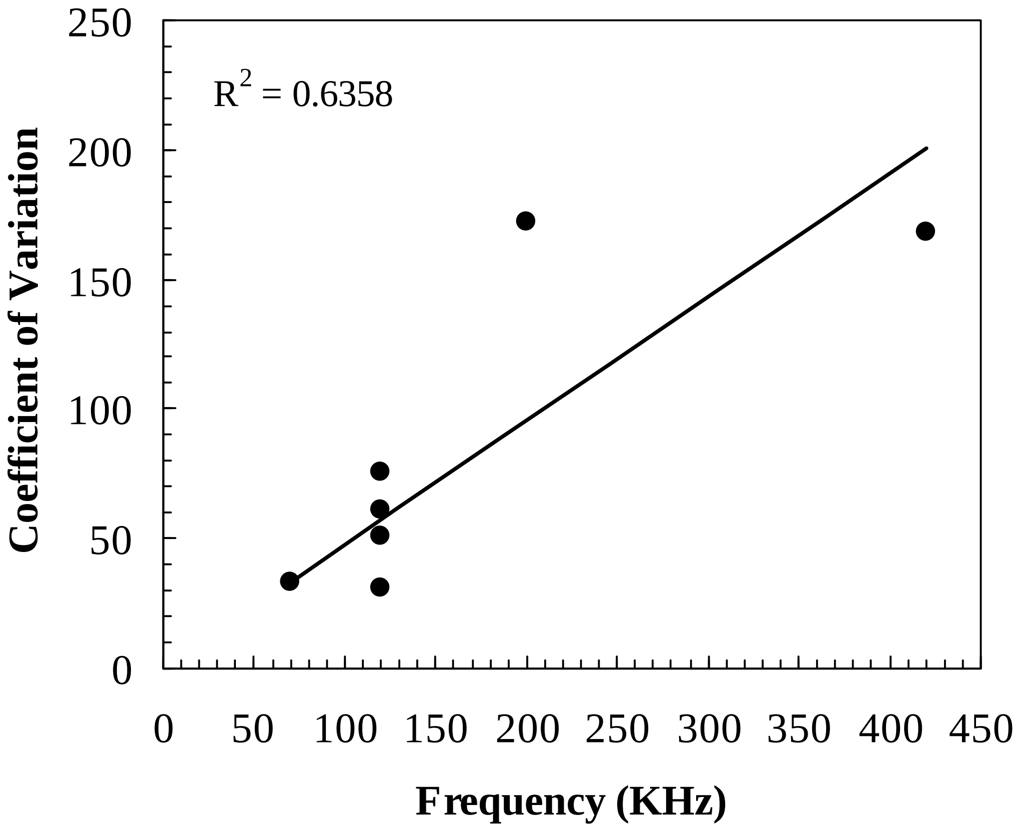

Figure 15. Relationship between coefficient of variation of the untransformed density and frequency.

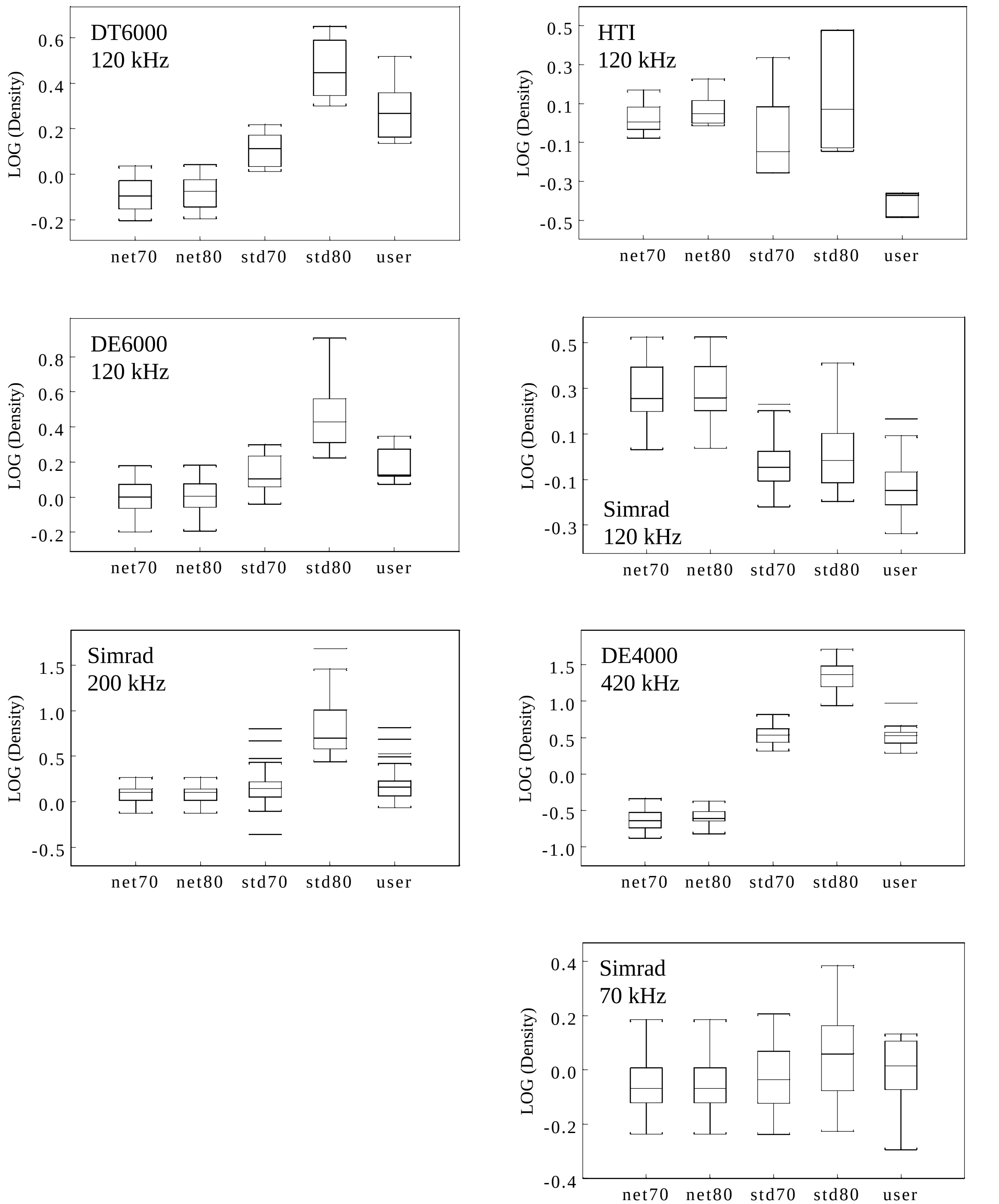

Figure 16. Box and whisker plot of logarithmic transformed density (# m^{-2}) for each of the acoustic systems by processing threshold. Thresholds include net 70 (-70 dB threshold using net-derived TS), net80 (-80 dB threshold using net-derived TS), std70 (-70 dB threshold with in situ estimates of TS), std 80 (-70 dB threshold with in situ estimates of TS), and user (user defined setting, non standardized).