Hydroacoustics: Lakes and Reservoirs

J. Christopher Taylor and Suzanne L. Maxwell

Background

Fisheries hydroacoustics uses transmitted sound to detect fish. Sound is transmitted as a pulse and travels quickly and efficiently through water. As the sound pulse travels through water it encounters objects that are of different density than the surrounding medium, such as fish, that reflect sound back toward the sound source. These echoes provide information on fish size, location, and abundance. The basic components of the acoustic hardware and software function to transmit the sound, receive, filter and amplify, record, and characterize the echoes. While there are many manufacturers of commercially available "fish-finders," quantitative hydroacoustic analyses require that measurements are made with scientific-quality echo sounders that have high signal-to-noise ratios and are easily calibrated.

Over the past three decades, vertical or down-looking hydroacoustics has become increasingly important to the assessment of anadromous and land-locked salmonids (Thorne 1971, 1979; Burczynski and Johnson 1986; Mulligan and Kieser 1986; Levy et al. 1991; Yule 1992; Parkinson et al. 1994; Beauchamp et al. 1997; Wanzenbock et al. 2003), and lake and reservoir fishes (Thorne 1983; Brandt et al. 1991; Degan and Wilson 1995; Schael et al. 1995; Vondracek and Degan 1995; Cyterski et al. 2003; Taylor et al. 2005). Hydroacoustics provide a repeatable, noninvasive method of collecting high-resolution (submeter scale), continuous data along transects in three dimensions (MacLennan and Simmonds 1992). MacLennan and Simmonds (1992) as well as Brandt (1996) give a thorough introduction in the use of hydroacoustics for measuring fish abundances and distributions.

The density and distribution of lake, reservoir and lowland river fishes varies by season and time of day and is influenced by a range of abiotic, biotic and behavioral factors such as temperature, oxygen concentration, and vertical distribution of predators and prey (Lucas et al. 2002). Schools of sockeye salmon *Oncorhynchus nerka* occurring in lakes and reservoirs disperse in midwater at night (Johnson and Burczynski 1985; Clark and Levy 1988; Parkinson et al. 1994; Beauchamp et al. 1997). Likewise, forage fishes occur in patches, typically aggregated during the day and more dispersed at night (Appenzeller and Leggett 1992; Schael et al. 1995). Under these dispersed or disaggregated distribution patterns, densities can be acoustically estimated using vertically oriented transducers as long as the fishes are a sufficient distance from the surface to permit detection.

In earlier studies, surveys were conducted with a single downward-oriented transducer. Unfortunately, acoustic estimates of surface-oriented fish gathered by down-looking transducers can be biased and lack precision because of limited sample volume near the apex of the cone (Burczynski and Johnson 1986). This limitation is problematic when assessing species known to be surface-oriented, such as rainbow trout *O. mykiss* (Wurtsbaugh et al. 1975; Stables and Thomas 1992; Warner and Quinn 1995) and cutthroat trout *O. clarkii* (Nilsson and Northcote 1981; Beauchamp et al. 1997; Knudsen and Saegrov 2002; Baldwin et al., in press). Several studies have demonstrated that this limitation can be overcome by sampling with a horizontally aimed (side-looking) transducer (Johnston 1981; Kubecka et al. 1992; Kubecka and Duncan 1994; Tarbox and Thorne 1996; Hughes 1998; Kubecka and Wittingerova 1998; Lyons 1998); however, other factors can limit the effectiveness of side-looking transducers.

Acoustic technology has become increasingly sophisticated, making synoptic down- and side-looking hydroacoustic assessments viable. The development of narrow-beam transducers with negligible side lobes allows depths between 1.5 and 5.0 m to be sampled with horizontal sonar (Kubecka 1996). The ability of split-beam transducers to measure angular locations of echoes in the ensonified volume has also improved measurements of in situ target strengths (Foote et al. 1986; Traynor and Ehrenberg 1990). Target tracking, or the assemblage of multiple echoes from a single scatter into an ensemble, has led to lower variance estimates of target strength and improved ability to resolve returns from single and multiple targets (Ehrenberg and Torkelson 1995). Finally, the advent of fast multiplexing, or alternating ping transmission between two or more transducers controlled by a single Echosounder, now allows near simultaneous data collection with multiple transducers (Thorne et al. 1992).

General equations relating target strength (measured in decibels [dB]) to total length have been developed for fish in dorsal aspect (Love 1971, 1977; McCartney and Stubbs 1971; MacLennan and Simmonds 1992; Brandt 1996). These equations are often used to convert mean target strengths to mean fish lengths, assuming that most fish are oriented dorsal-ventrally when sampled. Horizontal acoustic measurements of target strength in limnetic environments are less useful because there is no way to determine the orientation of the fish relative to the axis of the acoustic beam. The relationship between target strength and horizontal aspect has been studied under laboratory conditions, and equations relating fish lengths to target strengths in side aspect (Dahl and Mathisen 1983) and random orientation (Love 1977; Kubecka 1994; Kubecka and Duncan 1998) have been developed. Although these equations exist, few researchers have applied these algorithms to compare in situ measurements of fish length from horizontal beaming to measurements collected with an active sampling gear such as a purse seine.

For hydroacoustic assessments to gain wider acceptance from decision makers, it is important to show that sonar data can be corroborated with density, biomass or relative abundance data collected with an active sampling gear, such as purse seines (Yule 2000; Taylor et al. 2005) or a midwater trawl (Burczynski and Johnson 1986), electrofishing (e.g. Kubecka et al. 2000), or angler surveys (Frear 2002). Used in conjunction with hydroacoustics, these gears verify the species composition and sizes of fish in lake and reservoirs. Purse seining is effective at determining open-water species composition, developing length–frequency distributions, and measuring relative abundance of populations (Whitworth 1986). But seines and trawls only sample a small portion of the total surface area, and spatial heterogeneity in fish distributions can lead to high variation in catches.

Rationale

The ability to "see" and count what is under the surface of the water without disturbing the habitat or the fish is a key advantage of hydroacoustics. Hydroacoustics can sample the entire water column quickly, and detailed maps of fish densities and mean sizes can be obtained over large bodies of water. As more area is encompassed by a sample, many of the sampling problems created by the spatial patchiness of fish distribution are alleviated. Thus, there tends to be less variation in density estimates across acoustic transects compared to purse-seine hauls or other gear types. Also, the frequency band used in scientific sonars (typically 38 to 200 kHz) is not detectable by most fishes (except see Mann et al. 2001; Gregory and Clabburn 2003). There remain limitations in the type of data that can be collected using hydroacoustics. Currently, single frequency hydroacoustics cannot identify the target species, though broadband and multifrequency sonar systems are showing promise in discerning species in low-diversity systems (Fernandes et al. 2003). Side-looking mobile hydroacoustics cannot discern modes in length–frequency distributions unless large differences in length classes exist. When these limitations are recognized, hydroacoustic sampling efforts are cost effective, as estimates from creel surveys are expensive and labor intensive, and the estimates developed from catch-per-unit-effort (CPEU) measures are not necessarily directly proportional to fish density (Hubert 1996:158–159; Yule 2000). When used in concert with purse seining or other active sampling gears, hydroacoustics can provide a comprehensive survey method capable of providing valuable information on target size, population densities, and spatial distribution. Additional aspects of the strengths and limitations of acoustic surveys can be found in MacLennan and Simmonds (1992) and Brandt (1996).

Objectives

There are several levels of information that can be obtained from a mobile hydroacoustic survey in lakes, inland reservoirs, or lowland rivers. These levels range from simple species or object detection (presence/absence) to spatial (or temporal) distribution of individuals or groups (densities) to systemwide biomass estimates for the target species or guild. Care should be taken to clearly identify the objectives of the study to optimize a sample design in terms of timing of sample, staff hours of effort and data, and analytical methods that will be required to address the objectives. Below are examples of objectives for mobile hydroacoustic surveys, followed by examples of prior studies that have addressed similar objectives using mobile hydroacoustic surveys (see pages 159–60)

1. to determine spatial and temporal fish distribution in a water body;
2. to obtain density estimates for either adult or juvenile fish in lakes, reservoirs, or lowland rivers using down-looking or a combination of down- and side-looking hydroacoustic methods; and
3. to estimate systemwide fish biomass (e.g., forage fish) when hydroacoustics are combined with other sampling techniques

Events Sequence

Given the objectives of the study, a sequence of events is followed in order to optimize the sampling program:

1. Select a lake or river, for example, where fish estimates are needed;
2. Determine the level of information required for the study (e.g., presence/absence or biomass estimation);
3. Create or obtain a shoreline and bathymetric map of the lake or rivers;
4. Establish a spatial sampling design based on prior knowledge of target species distribution or statistical considerations;

5. Determine the best timing for the sampling based on diurnal or seasonal behavior of the species;
6. Determine the best down- and side-looking transducers deployment on either a boat mount or towed platform based on prior knowledge of vertical distribution of the species;
7. Determine the optimal acoustic parameters for sampling based on water conditions, target size, or other acoustical properties;
8. Perform an in situ calibration of the acoustic system using an object of known target strength and known location;
9. Perform the hydroacoustic survey;
10. Select software processing tools and analytical methods dictated by the objectives final output;
11. Perform quality checks on the data; and
12. Process data.

Sampling Design

Site Selection and Timing

Selection criteria for hydroacoustic sampling of lakes or reservoirs include sufficient water depth and known species composition. If the lake contains predominately one species, or if the target species can be distinguished from other species by depth or other spatial properties (e.g., littoral versus limnetic), a hydroacoustic survey can stand alone. If mixed species are present, an alternate method is needed to apportion the hydroacoustic estimates into individual density estimates for each species. Possible apportionment methods include purse seines, towed nets, and gill nets (Cyterski et al. 2003).

Transect sampling designs can include single paths following the main channel of a lake or reservoir, a single transect that zigzags from shore to shore, or several parallel transects that run perpendicular to the axis of the water body (see Figure 1; Yule 2000; Jolly and Hampton 1990). Using any of these transect designs results in hydroacoustic data that are typically auto-correlated (Schael et al. 1995; Vondracek and Degan 1995; Taylor et al. 2005). Abundance estimates are calculated from these data by extrapolating from blocked averages of depth-integrated (two-dimensional) data (Vondracek and Degan 1995) or are modeled using spatially explicit techniques such as geostatistics (e.g., Taylor et al. 2005). Typically, the transect design will dictate the analytical methods (or vice versa) that are used to assess the distribution pattern of fish populations.

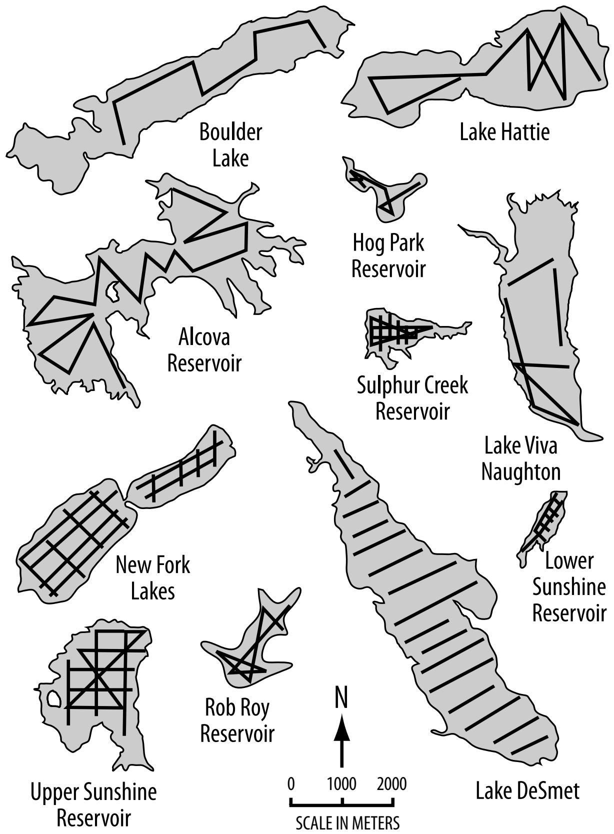

FIGURE 1. — Map of 11 study waters showing various hydroacoustic transect designs (from Yule 2000).

Objective 1: Characterizing spatial distribution

Schael et al. (1995) provide a description of evaluating patchiness in the distribution of shad in a reservoir. They used a patch recognition algorithm (Nero and Magnuson 1989) to analyze echo-integrated hydroacoustic data to define patches and patch characteristics (e.g., numbers, density, area, mean depth) for shad in Lake Norman, North Carolina. Their transects were 2.5 km long and 0.2 km apart, and extended across the lower main basins of the reservoir. During most surveys, they observed 12–16 patches/km with fish densities exceeding twice the average background density, and 1–2 patches/km with fish densities 50 times the average background density.

Objective 2: Obtaining density estimates of a fish population

Vondracek and Degan (1995) provide a thorough evaluation of among- and within-transect variability in estimates for shad populations in Lake Texoma, Texas–Oklahoma. They found that the within-transect variation was significantly higher during the day than at night. Coefficient of variation values decreased nonlinearly with increasing blocking intervals for day and night surveys; estimated values of 20% were achievable at interval lengths of about 150 m at night, whereas during the day, the minimum interval was greater than 210 m. They suggest the best approach in surveys of forage fishes in temperate reservoirs is a nighttime, stratified-random design of transects that incorporate large-scale gradients of fish density. Nighttime surveys were recommended since the shad species both tended towards disaggregated distribution patterns during the evening and night (see also Schael et al. 1995). They also recommend block averages of transects of 150–200 m in length to minimize complications of spatial correlation and reduce within-transect variance. Gangl and Whaley (2004) used target tracking to locate individual targets. Transect subunits between 300 and 500 m in length produced densities that were statistically independent. Assuming statistical independence to employ arithmetic methods of density calculations will require analysis of the data to determine the spatial scale or distance of serial correlation. Subsampling distance or transect length will depend upon the spatial structure and distribution of the selected species. A method is presented below that does not require assumptions of statistical independence in subsamples and considers the spatial correlation implicitly in the estimates of density or abundance.

Objective 3: Estimating systemwide abundance and biomass

Taylor et al. (2005) compared both longitudinal and cross-channel sampling designs in Badin Lake (reservoir) in North Carolina in July 2000 and December 2001 and characterized both large- and small-scale spatial patterns in forage fish density. They found that sampling along longitudinal transects was a more efficient means to characterize spatial patterns of forage fish distribution and to estimate systemwide abundance and biomass, relative to data collected using both longitudinal and cross-channel sampling designs. They used geostatistics, and specifically kriging in their approach to estimate mean density and lakewide abundance. As previously mentioned, the sampling design must take into account the spatial distribution of the species as it may relate to other correlates such as water column depth or distance from shore.

Field/Office Methods

Setup and Measurement Details

To set up transects for the survey, bathymetry maps are helpful, but at minimum, an outline of the lake region is required. The sampling transects need to be contained within regions deep enough for the sonar and should include more intensive sampling in regions where fish are more concentrated (Jolly and Hampton 1990; Taylor et al. 2005). Adequate coverage of a water body is important to take advantage of the continuous nature of the data collection that occurs as part of hydroacoustic surveys. Several texts provide details on establishing optimal sampling programs to maximize system coverage with transects while not overextending staff (Cochran 1977; MacLennan and Simmonds 1992). The design of transects should take into account all these factors in addition to other logistical considerations such as navigability of the water bodies and workers' safety.

It is important to address both seasonal and diurnal movements and behavior of fish species prior to setting up the survey. Preliminary acoustic surveys or prior knowledge of a species' behavior and ecology can be utilized to obtain this information prior to setting up the survey to assess abundance (Lucas et al. 2002). Both time of day and light level have been found to alter fish behavior (MacLennan and Simmons 1992), and should be taken into consideration when planning a hydroacoustic survey. Yule (2000) sampled during the day and night and then chose to forego the daytime estimates because target species (rainbow and cutthroat trout) were either few in number or in schools, making density estimates difficult. Vondracek and Degan (1995) sampled both day and night, but the data was divided into two groups to account for the behavioral differences in their primary target species (threadfin shad *Dorosoma petense*). Shad displayed schooling behavior during the day and were mostly dispersed at night. Following advice from Vondracek and Degan (1995) and Schael et al. (1995), Taylor et al. (2005) sampled for forage fish at night, when local shad species were more disaggregated.

Appenzeller and Leggett (1992) reported on pelagic fish community abundance estimates obtained by acoustic methods for pelagic fish in Lake Memphremagog, Quebec. Reflecting diel light conditions, the fish were either in aggregated schools during the day or dispersed schools at night. Due to acoustic shadowing, densities were underestimated when fish were aggregated, with data suggesting that this bias could have been as large as 50%. When sampling juvenile sockeye salmon in lakes, surveys are traditionally done at night because the juveniles are more dispersed. In addition to considerations of time of day, seasonal patterns of distribution as well as other logistical considerations will likely influence the timing of a hydroacoustic survey. When sampling in temperate climates, surveys should be planned to avoid leaf-fall, wind, or rain that could affect surface interference, and boat traffic on navigable waterways can also affect the amount of noise that can disrupt the detection of target species in the water column.

Equipment Deployment

Recent developments in hydroacoustic technology have resulted in equipment that is generally portable and readily mobilized to even the most remote study site (see Figure 2). Echosounder placement on the survey vessel is usually determined by the user and likely includes such concerns as engine noise (both acoustic and electrical), comfort of operator, and location of power sources. Most commercially available scientific echo sounders are powered by 12-V power that is readily available on most boats. The power supply should be separate or otherwise isolated from that used by the vessel engine, as electrical interference can cause noise on the acoustic signal. Operators can use either deep-cycle 12-V batteries or gas-powered generators.

FIGURE 2. — Portable split–beam hydroacoustic systems from the major manufacturers: (a) Biosonics Inc., (b) Hydroacoustic Technology, Inc. (HTI), and (c) Simrad. Systems include an echo sounder contained in a rugged container or rack-mountable unit that has waterproof ports for attaching transducer cables, global positioning system cables, and network cables. Systems are controlled via wired or wireless LAN communication by a laptop computer.

Transducer deployment is specific to the survey and vessel design in addition to mounting requirements of the specific manufacturer. The transducer can be mounted under the hull of the boat, attached to the side of the boat (when a side-looking transducer is used), mounted in a towed body, or mounted on a rotator forward of vessel (see Figure 3). For horizontal work, it is important that the side-looking beam is on a stable platform and the beam direction and angle can be adjusted to account for interference caused by reflection of sound on the water–air interface. Sea-state or surface conditions usually dictate the best approach for deploying the horizontal-aimed transducer beam or whether a survey can be conducted (Gangl and Whaley 2004).

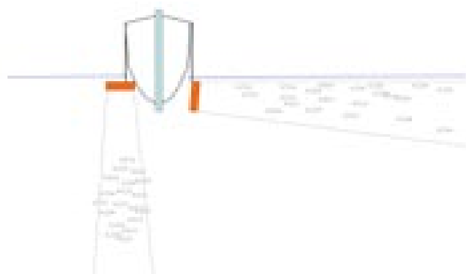

FIGURE 3.—Two transducers for simultaneous down-looking and side-looking deployments to sample fish targets throughout the water column.

Hardware settings and software controls

Most scientific grade echo sounders are controlled by a laptop computer connected via serial cable, wired, or wireless network connection. Echo sounder settings are selected through the user interface of data acquisition software provided by the manufacturer or third-party vendor. Setting the sonar parameters is site- and survey-specific and also depends on the manufacturer (see Table 1). General parameters would include speed of sound and sound loss or absorption, which is primarily determined by salinity/conductivity and water temperature. Thresholds are also set to accept returns from echoes that are above a given level or target strength. Thresholds need to be set low enough so that the echo returns from the target species can be observed on the edge of the nominal beam width. Target strengths of the surveyed species should be researched or calculated based on fish length (e.g., Love 1977). Ideally, the threshold should be set as low as possible; however, a signal to noise ratio of 12 dB or higher is desired and is usually the limiting factor when reducing the threshold for small species (e.g., 20 mm) (MacLennan and Simmonds 1992). Other environmental conditions also need to be considered for both setting threshold parameters. High conductivity can greatly attenuate the acoustic signal. Extremely high turbidity can scatter the signal, weakening the returning echoes. Under either condition, the power and gain settings may be increased effectively lowering the thresholds. Detection at the deeper levels can be greatly compromised in very deep lakes with high conductivity or turbidity due to signal spreading and attenuation.

Global positioning systems (GPS) are typically an integral part of mobile hydroacoustic surveys. Handheld to boat-mounted navigational systems can be integrated into the data acquisition system. The method of data transfer between the GPS and hydroacoustic system is dependent upon manufacturer specification, but usually involves latitude, longitude, speed, and directional information transfer in real time or as a separate time-stamped data file to be linked to hydroacoustic data.

TABLE 1. — Examples of recently published mobile hydroacoustic studies including specification of equipment settings and data processing procedures used

System	Family	Day/night	System	Freq (kHz)	Transducers	Mount	Vert./horiz.	Pulse rate (s–1)	Pulse width (ms)	Processing method
Reservoir[a]	Clupeid	Night	Biosonics, DB	200	1	Towed–side	Vertical	5	0.4	Integration
Lake[b]	Salmonid	Night	Biosonics, DB	420	1	Towed–bow	Vertical	2	0.4	Both
Lowland River[c]	Various	Day	Simrad, SB	120	1	Fixed–bow	Horizontal	Unknown	Unknown	Integration
Lakes and Reservoirs[d]	Salmonid	Night	HTI, SB	200	2	Fixed–side	Both	5	0.20	Tracking
Lake[e]	Salmonid	Day	Simrad, SB	200	1	Towed–side	Vertical	Unknown	0.4–1	Tracking
Lake[f]	Salmonid	Both	Simrad, SB	70	1	Unknown	Vertical	Unknown	Unknown	Tracking
Lake[g]	Coregonid	Night	Simrad, SB	120	1	Fixed–side	Vertical	2–10	0.1	Tracking
Lake[h]	Various	Day	HTI, SB	200	2	Fixed–side	Both	10	0.2	Tracking
Reservoir[i]	Clupeid	Night	HTI SB	200	2	Fixed–side	Both	10	0.18	Integration

[a]Vondracek and Degan 1995. [b]Beauchamp et al. 1997. [c]Kubecka et al. 2000. [d]Yule 2000. [e]Elliot and Fletcher 2001. [f]Mehner and Schulz 2002. [g]Encina and Rodriguez–Ruiz 2003. [h]Gangl and Whaley 2004. [i]Taylor et al. 2005.

Laboratory and field calibration

Setting threshold levels and determining target strength values of fish are dependent on a calibrated acoustic system. Without good calibration information, the results are invalid. Many project leaders send their sonar systems in for yearly laboratory calibrations. The advantage of yearly calibrations is that the vendor or specialist performing the calibration has the opportunity to verify that the electronics of the system and make sure all is working correctly. Finding out that something has gone wrong after the system is in the field can be very frustrating.

Regardless of whether a preseason laboratory calibration is performed, a field calibration is essential. Site-specific environmental conditions can determine the calibration technique. Two calibration methods are presented below. (Note: Many spherical objects can be used as targets for in situ system calibration; however, manufacturers suggest a standard calibration target of known target strength constructed of copper or tungsten carbide [Foote and MacLennan 1983].)

Yule 2000

The receiving sensitivity of the echo sounder was calibrated in the field periodically using a Dunlop long-life Ping-Pong ball (target strength of –39.5 dB). Results of field tests indicated agreement with laboratory calibration and consistent sensitivity between surveys. The pole mount was designed to adjust the vertical aiming angle of the six-degree transducer by worm gear. The initial metering of the worm gear was accomplished by sampling five Ping-Pong balls placed at known depths and set along a straight line. With knowledge of target depth, range, and angle of target passage through the beam, the orientation of the transducer axis was calibrated using trigonometry. Under slight chop, the vertical aiming angle was set to 7° below the surface, and this change was noted on field sheets.

Vondracek and Degan 1995

The hydroacoustic system was calibrated with U.S. Navy standards at the Biosonics laboratory in Seattle, Washington. Once in the field, the system was again calibrated before and after sampling with standard tungsten carbide reference calibration spheres (Foote and MacLennan 1983). If system calibrations were different than the expected target strength of the standard calibration sphere, the systems source level voltage was adjusted before analyses.

Data Handling, Analysis, and Reporting

Data handling and data management

Data collected using hydroacoustic equipment is stored in proprietary formats specific to the manufacturer on a computer hard drive, and for some systems as raw sound on digital audiotapes. File formats, file types, and the specific information included in each file are specific to the manufacturer. Users should consult manuals and be familiar with the structure of the data that is being collected. Regardless of the data format, accurate labeling of files and tapes is critical to reconstruct surveys during analysis and archive data for future analysis. These hydroacoustic systems and computer controllers are frequently exposed to less-than-ideal conditions, which can risk data loss due to damage. After completing a survey (or a leg of a survey), data should be archived in raw format to external or removable media such as a CD or DVD.

Data accumulation can be significant depending upon the aquatic systems being surveyed, temporal and spatial resolution of the data, and the specific configurations of the hydroacoustic system. It is not unusual to collect data on the order of hundreds of megabytes per survey day. In addition, it is very common for data to be collected in several files per survey, corresponding to a temporal duration based on sampling strategies (hourly, daily, etc.) or per transect, region, or system; therefore, consistent and logical file naming should be maintained throughout the survey. Many systems automatically assign a time stamp as part of the file names during each survey. This file name should be recorded on a field data sheet along with pertinent attributes such as more detailed descriptions of hydroacoustic system settings, regions being surveyed, time duration, personnel involved in data collection, and potential system errors, or other notes related to data quality during the survey. Copies of these field data sheets can then be stored with archived versions of the raw data files for future analysis. Where surveys require the use of many hydroacoustic systems, people, and complex sampling strategies, the nature of associating files with surveys may require additional data handling in the form of databases to maintain accurate records to link field notes with raw data and for data analysis and project report preparation. This can be accomplished in a simple spreadsheet or something as complex as a relational database or even a geographic information system (GIS).

Data processing

Data processing can incorporate any or all of the following three analysis components:

a. Echo counting
b. Target tracking or track counting
c. Echo integration

Data analysis (as per study objectives) follows and is dependent on the question addressed with the mobile hydroacoustic surveys:

d. Characterizing spatial pattern
e. Estimating and mapping densities
f. Estimating systemwide biomass

Once the data files are collected, the next step is to process the files. The first step in file processing is to remove unwanted signals from bottom reverberation, boat engine noise, or other sources from the data. Most sonar systems come with editing software programs designed for this task.

Echo counting

Echo counting is the technique of counting individual echoes that pass through the acoustic beam during a mobile survey. This technique is used when fish densities are very low and echoes from individual fish do not overlap (due to close proximity of fish at the same distance from the transducer). Echo counting is based on user-determined criteria such as target strength threshold, which is equivalent to restricting to an expected size range of fish targets.

Echo/target tracking

This procedure accumulates individual echoes into tracks or traces corresponding to individual fish moving through the acoustic beam (see Figure 4). Additional characteristics such as average target strength and direction of movement (relative to the moving survey vessel) can be gleaned from this technique. This accumulation method can be done manually or automatically using manufacturer's software or third-party software described in detail on pages 164–165. For both echo counting and target tracking, corrections need to be made to account for the changes in detection of fish as the beam width increases and more water is sampled at great depth or distance from the transducer.

Echo Integration

When fish density is high and fish targets overlap, it can become difficult-to-impossible to isolate individual fishes or tracks (see Figure 4). In this case, it is no longer appropriate to use echo counting or target tracking. Instead, a process called echo integration is used. The procedure is based on the principle that the total acoustic energy returned from a sampled water volume is proportional to the number of fish in that volume. That is the total energy is equal to the sum of the acoustic energy from the individual targets. Knowledge of the acoustic size (target strength) of the individual targets is still needed as this information is used to scale the total acoustic energy returned to an estimate of fish density. Therefore, some form of target strength analysis or target tracking is typically performed on a subset of the data, where the targets are non-overlapping, or by using supplemental information from biological sampling to get an estimate of the average size of fish present.

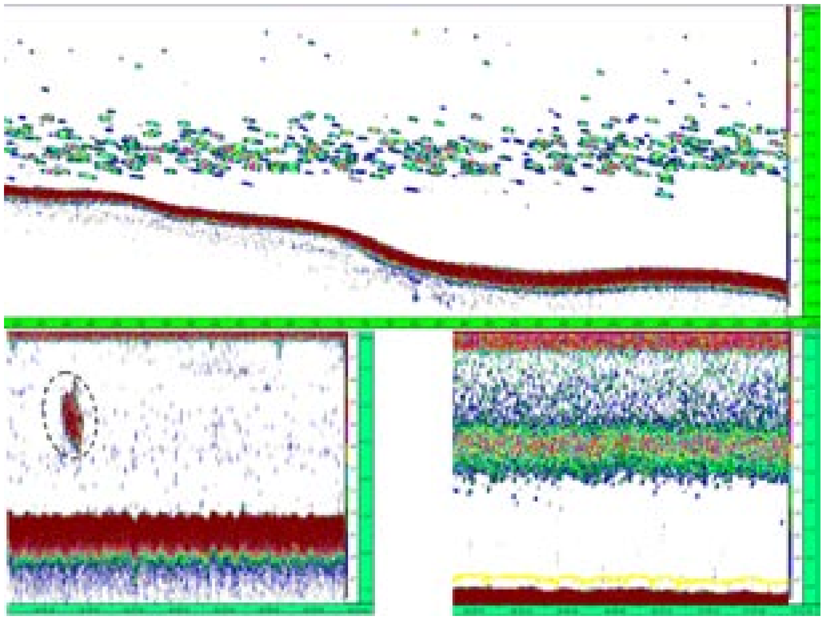

FIGURE 4. — Example of hydroacoustic echogram for individual fish targets when target tracking would be appropriate (top). Two examples of hydroacoustic echograms when target tracking would not be possible and when echo integration would be used: aggregated fish distributed in a school (bottom left) and layer (bottom right).

Available Software for Data Processing and Analysis

SonarData's Echoview (<www.SonarData.com>) now supports all the main scientific sonar system vendors. This software is expensive but very good for working with this type of data. The files are first imported into the editing software, calibration information is added, and then the echograms are ready for editing. All unwanted data is selected and labeled "bad data." The remaining data is then echo integrated using traditional integration methods (Ehrenberg and Kanemori 1978). The data is output both as a linear summed voltage and as 20-log of the summed voltage (dB). Additional progress is being made in hydroacoustic processing software. Packages such as Sonar 4 and Sonar 5 (<http://folk.uio.no/hbalk>) are showing great promise in handling data from numerous manufacturers and providing a wide range of analytical techniques.

Following the echo integration process, the single-target data is output based on user-set criteria. The output is in the form of average target strength values (average back-scattered cross section from individual fish) per cell. The target strength measures should be plotted both in range and time increments to determine how much variation exists. If fish differing in size are vertically stratified, then target strength values will vary according to range. If diel patterns exist in fish of different sizes, target strength will vary according to time. A possible averaged target strength matrix might be divided into 1 m depth bins and day/night temporal segments. The scaling of the integration data will be based on the matrix determined from the variability in the target strength values.

Taylor et al. (2005) processed their data for echo-integration and split-beam target tracking using Echoscape (v. 2.10, Hydroacoustic Technology, Inc., Seattle, Washington). Split–beam analysis was used to determine the acoustic size (target strength) of individual fish targets in decibels. Using equations for clupeiform species, target strengths from the down-looking (dorsal aspect) were converted to approximate fish size (Love 1977) and to wet weight. Volumetric densities were integrated throughout the water column to produce densities in two dimensions having units of fish/m^2. The database was incorporated into a GIS for data visualization and analyzed using S-PLUS (ver. 6.1, Insightful Corp.) for spatial structure and determination of abundance and biomass. Two statistical procedures were used to calculate densities and estimate systemwide abundance and biomass. First, an arithmetic mean and variance of densities assuming identical and independent data were determined for the entire survey and then for each survey design. These summary statistics were extrapolated across the surface area of the reservoir and summed to produce systemwide abundance and variance of this estimate. The second procedure involved empirically modeling the spatial structure of the data using geostatistics. This technique involved three steps: spatial detrending, variogram analysis, and kriging. This latter technique of using geostatistics resulted in similar average densities and improvements in the precision of abundance estimates based on approximated variance when compared to arithmetic averaging and extrapolation. Model-based density and abundance estimations are beneficial as they also provide information on the spatial structure and distribution of the species of interest in the aquatic system. These spatially explicit approaches have the added benefit of not requiring a prescribed randomized sampling plan as it implicitly models both large- and small-scale spatial variability (Rivoirard et al. 2000). Precision of abundance estimates still require adequate coverage of the water body as undersampling regions of high fish density can result in poor estimates and reduced precision (Taylor et al. 2005).

To obtain an abundance estimate for the lake or reservoir, the cell densities are expanded based on a ratio of the volume sampled to the volume of the water body. Further analyses can address issues such as among-transect variation (Vondracek and Degan 1995), diel patterns, depth distributions, and seasonal patterns. In the excerpt below, Yule (2000) describes the process used to obtain density estimates from target tracking.

Yule 2000

Side-looking fish density estimates by transect were calculated by dividing the numbers of detected fish by the volume of water sampled. Sample volume (m^3) was calculated by multiplying travel distance (m) by the average side-looking range (m) by the average height of the cone (m). Sample volume was corrected for the inability to detect fish within 10 m of the transducer. Side-looking population estimates for each reservoir or lake were calculated by multiplying the mean density estimate (averaged across all transects) by the volume of water between the surface and a depth of 8 m.

With the down-looking transducer, sampling volume expands with increasing range. To standardize fish density estimates for increasing sample volume, detected fish were weighted back to a 1-m wide swath at the surface using the following formula:

$$F = 5\ 1/[2 \cdot R \cdot \tan(7.58)], w \qquad \text{(eq 1)}$$

Where *Fw* equals weighted fish, *R* equals range, and 7.5° equals one-half the nominal transducer beam width.

For example, at 3.8 m below the 15° transducer, the cone diameter 2· *R* [tan (7.5°)] is 1.0 m. It follows that a fish tracked at 3.8 m of range equaled one weighted fish at the surface (all fish were normalized to a 1-m transect width). At 20 m below the transducer, the cone diameter is 5.3 m, and a fish tracked at this range equaled 0.19 weighted fish. I derived estimates of fish densities (fish/m^3) by summing weighted fish by transect and dividing that by transect length. Fish detected by the down-looking transducer in the top 8 m of the water column were not processed to avoid overlap with side-looking density estimates (i.e., double counting). Down-looking population estimates for each reservoir and lake were calculated by multiplying the mean density (averaged across all transects) by the surface area.

Confidence intervals surrounding mean density estimates were calculated for both side-looking and down-looking acoustics. Each transect, regardless of length, was treated as a sample unit in the calculation of variability. Horizontal acoustic estimates of fish tracked during daylight surveys were partitioned to salmonids and nonsalmonids based on proportions captured by purse seining. Nighttime acoustic estimates of pelagic fish at Boulder Lake, New Fork Lakes, and Lake Viva Naughton were partitioned to salmonids and nonsalmonids based on overnight gill-net catches.

Exploratory data analysis should be conducted on preliminary surveys to determine the best approach for data analysis depending upon the chosen objective (as outlined above). If there is no indication of spatial autocorrelation in the transect survey data sets, a more simple arithmetic approach can be employed to calculated systemwide densities or total biomass or abundance. If data are spatially correlated, spatially explicit methods like geostatistics or spatial subsampling will be required. Further improvements in these spatially explicit, model-based estimation techniques are still the topic of much research and advances are continuously being made in statistical theory and software development.

Personnel Requirements and Training

Responsibilities

Project leader

1. Purchase and assemble needed sonar and ancillary equipment
2. Mount the sonar
3. Calculate thresholds and determe optimal sampling parameters
4. Set up the transect coordinates
5. Ensure that the boat operator is able to stay on the designated transects
6. Check weather conditions prior to setting up sampling dates
7. Perform all pre-season tasks needed for the project
8. Train technicians
9. Process final data; perform Quality Assurance and Quality Control of data; write report

Technicians

1. Acquire/develop detailed maps (including depth contours) of the lake or reservoir
2. Assist with data collection
3. Edit data
4. Export data for further processing
5. Operate the vessel

Qualifications

The project leader should have some background in basic acoustic principles and experience in operating the type of acoustic system selected for the study. In addition, the project leader should have experience in all aspects of operating a project, including budgeting, writing operational plans, coordinating the study, and operating boats. Technicians should be experienced in the operation of boats and have basic computer skills. The project leader and/or technicians should be familiar with the seasonal and diel behavior and ecology of the target fish species.

Training

Specialized training is required to use hydroacoustic techniques. Project leaders (at least) will need to be knowledgeable in how to use the equipment, understand the basic concepts, determine that applicability of this technology to their project, and be able to undertake the data survey design, analyses, and interpretation. Training on how to operate hydroacoustic systems is usually available from the vendor from which the system was purchased. The vendor should be contacted directly to obtain the location and timing of training schedules.

Operational Requirements

Workload and Field Schedule

The workload and field schedule are dependent on the study parameters. The size of the lake or reservoir and the number of transects required will determine the level of effort needed to complete the study.

Equipment Needs

1. Split beam echo sounder with one or two transducers (beam dimension should be considered based on sampling volume and expected water depth).
2. Mount or towable platform to attach transducers to boat.
3. Power to operate the echo sounder (battery or small generator).
4. Calibration equipment (calibration spheres/Ping-Pong balls).
5. Editing software programs.
6. Rotating device (optional).
7. Attitude sensor to record pitch of the side-looking transducer (optional).

8. Global Positioning System (GPS) linked to boat/echo sounder array.
9. Laptop computer and back-up hard-drives.
10. Deep-cycle 12-V batteries or gas-powered generator for power supply.

Budget Considerations

Purse-seine and horizontal acoustic assessments are rapid, and with good weather, a crew of six people can estimate salmonid numbers in a small impoundment (500–1,500 ha) in 1–2 d (Yule 2000). Similarly, a forage fish assessment in a 2,100-ha reservoir, using both horizontal and vertical acoustics, along with a purse seine, was accomplished during 2 nights (Taylor et al. 2005).

Fisheries hydroacoustic systems with one transducer cost approximately US$40,000 (as of 2005). Costs for all accessory equipment such as GPS, mounts, or tow-fish and laptops will need to be researched as prices for these technologies are becoming more cost effective.

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