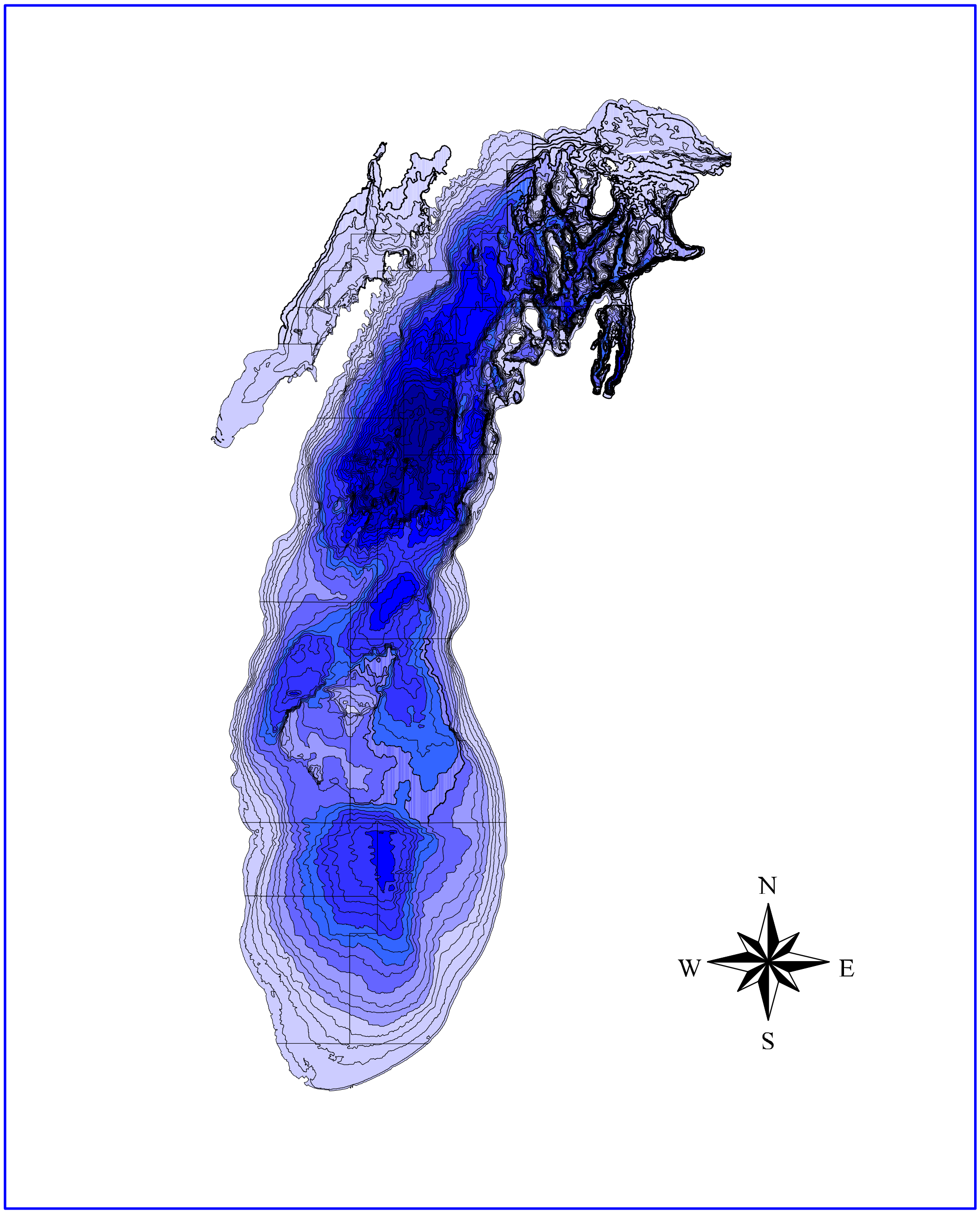
An Integrated Acoustic and Trawl Based Prey Fish Assessment Strategy for Lake Michigan



U.S. Geological Survey - Biological Resources Division
Great Lakes Science Center

An Integrated Acoustic and Trawl Based Prey Fish Assessment Strategy for Lake Michigan

By Ray L. Argyle, Guy W. Fleischer, Gary L. Curtis, Jean V. Adams, and Richard G. Stickel

A Report To

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Indiana Department of Natural Resources
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Wisconsin Department of Natural Resources

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An Integrated Acoustic and Trawl Based Prey Fish Assessment Strategy for Lake Michigan

Introduction

> *"If you thought counting people was difficult — try counting fish". A report issued in November 1997 by the National Research Council attested to the difficulty of estimating the size and status of the ocean fisheries. The report further warned that government scientists and researchers need to find better ways to assess populations if overfishing and population crashes are to be averted in the future.*

Although the focus of the National Research Council report referred to ocean fisheries, the difficulties, problems, and needs of Great Lakes fisheries managers are similar. In the Great Lakes, changes in the attitudes and expectations of the fishing public along with changes in fish stocks during the past four decades have underscored the need for fishery managers to have more effective ways to address the problems that confront their agencies. In order to address these problems they need better tools for measuring fish stocks and developing predictive capabilities. This need has not been met with conventional assessment programs (Christie et al. 1987). Lewis et al. (1987) observed that short-term forecasting capabilities were critically needed by fisheries managers in the Great Lakes region. Although single species models are available for predicting fish yield, those models are not satisfactory for many Great Lakes situations (Lewis et al. 1987). The changing status of the alewife *Alosa pseudoharengus* is a good example. In less than two decades the alewife changed from a nuisance species to a valued prey species needed to sustain the high value salmonine sport fisheries created since 1965. Demands for more sophisticated information on the biology and dynamics of alewives have increased accordingly. Without the appropriate information for understanding the dynamics of the Lake Michigan predator-prey system, of which the alewife has been an important part, fishery managers have often been unable to respond effectively to the demands of competing user groups.

Before this information could be provided, the methods in place for assessing fish stocks in Lake Michigan had to be examined and the best of old methodologies and technologies retained and new methods and technologies adapted or developed. Progress in that direction has been admittedly slow however, partly because it is easier and safer to maintain programs already in place than to reallocate resources to unproven new methodology or programs that may or may not yield better results (Lewis et al. 1987). Nevertheless, the limitations of conventional survey methods are obvious when the size and complexity of the aquatic system and its fish communities are contrasted with the available and affordable sampling effort. These limitations should insure at least the gradual adoption of more advanced technologies that are now available.

The trawling gear and the sampling strategy in use by the Great Lakes Science Center (GLSC) for prey fish assessments in the Great Lakes were selected by design to match the constraints imposed by the size and diversity of the system, along with logistic, weather, and practical constraints. For example, the maximum-size catch that can be adequately processed and recorded, have dictated the final gear and design criteria. In addition, there is the question of how the fishing power of the trawling gear changes as the number of fish in the trawl increases. These constraints or unknowns have certainly influenced the robustness of the data; however, the validity of the trends portrayed by the trawling data have been demonstrated repeatedly. Even the single transect surveys conducted off Saugatuck, Michigan in 1962-1967 clearly mirrored the actual buildup and crash of alewives in Lake Michigan. These dramatic changes in the alewife population were also evident from the commercial catch data collected off Saugatuck and from Two Rivers south to Kenosha, Wisconsin (Brown 1972). Of course, these changes were very large which begs the question of how small a change in stock size can be reliably detected.

State, Federal, and tribal resource agencies need accurate and timely information on the status and structure of prey fish populations in Lake Michigan. Fishery managers from the various agencies have established populations of Pacific and Atlantic salmon, splake, lake trout and other salmonids in Lake Michigan as part of intensive programs designed to rehabilitate (or develop new) game-fish populations. These valuable predator species sustain an increasingly demanding multi-million dollar sport fishery. In turn, these predators are sustained by forage-fish populations comprising largely three pelagic planktivores: rainbow smelt, bloaters, alewife. In addition, the bloater is also directly important to the commercial fishing industry. Therefore, it is very important, based on (1) present levels of salmonid abundance, (2) stocking projections, (3) lake trout restoration goals, and (4) commercial fishing interests, that the carrying capacity of the prey populations be better understood. The fish community objectives for Lake Michigan specify that in order to restore an ecologically balanced fish community, managers must maintain a diversity of prey species at population levels matched to primary production and predator demands (Eshenroder et al. 1995). As such, fishery managers have begun to quantify the trophic supply and demand with use of sophisticated models (e.g. Koonce and Jones 1994; Jones et al. 1993; Stewart et al. 1981). The successful application of these models require accurate measures of absolute prey fish abundance.

The aim of this study was to examine technologies and sampling designs to improve the methodology and accuracy of the prey fish assessments on Lake Michigan. It was implicit that the best of the old technologies would be used and interruptions in the collection of data from the standard bottom trawl assessments would not occur. Since 1972, the Great Lakes Science Center has conducted a continuous series of annual bottom trawl assessments of the prey fish populations in Lake Michigan. The original intent of these surveys was to obtain biological information on important species of fish and an develop an index for detecting changes in the major populations. Demands on these data to provide the additional information needed by resource agencies for evaluating their stocking strategies prompted researchers at the GLSC to examine alternate methods for estimating biomass and measuring fluctuations in abundance a alewives (Hatch et al. 1981).

The Hatch et al.(1981) publication is the most recent published account of applying a statistical approach to using the Lake Michigan bottom trawl catch data more effectively. This study examined analytical methods for stratifying the catch data and statistically estimating alewife biomass and fluctuations in the population. The objectives were to estimate alewife biomass with confidence intervals for the period 1967 through 1978 and examine potential biases. Hatch et al. (19810 considered the biomass estimates to be conservative because coefficients of fish availability and catchability were not incorporated in the calculations. However, the biomass indices were believed to be preferable to simple catch per unit effort for indicating trends because they provide a correction for spatial distribution by areal weighting. Since then advances in technology have improved our understanding of how the bottom trawls fish under various depth and gear configurations and more exact data on the bottom topography and depth strata of Lake Michigan have become available.

Fabrizio et al. (1996) used the 1977 through 1994 Lake Michigan bottom trawl catch data set for alewives, rainbow smelt *Osmerus mordax*, and bloaters *Coregonus hoyi* to examine what effect a reduction in the spatial sampling would have on the precision and accuracy of the assessment data. They concluded that reducing the number of ports surveyed from seven to six or five yielded similar estimates of relative accuracy, precision, and long term trends, but the level of precision was low even for the seven port survey and may or may not be acceptable to meet some objectives.   Clearly, the objectives of the survey must be considered in any sampling design and if the objective is to estimate biomass, even the full seven port assessment currently used may not be adequate for population estimation. This, of course begs the question — what is needed in order to obtain an accurate estimate of stock size?

Physical considerations of Lake Michigan

The size of Lake Michigan, a shoreline in excess of 2500 km and a surface area of more than 52,000 km^2 in the main basin, combine to make the logistics of rapidly moving the sampling platforms and equipment around the lake a formidable problem. The differences in bottom topography between the north and south basins of the lake add further complexity to the sampling design. The northern basin has more pronounced relief than the southern basin and fish distribution patterns and densities vary between the two basins. About 16 % of the surface area in the main basin is over water deeper than 150 m and although the deeper depths are not entirely devoid of fish, most of the fish associated with the deeper depths are neither pelagic nor contribute significantly to the pelagic biomass.

There is no question that temperature profoundly affects fish distributions. In Lake Michigan the annual warming cycle begins in mid to late March and extends into mid to late August (Figure 1.1). In northern Lake Michigan the surface water temperature stays a little cooler than in the southern part of the lake. Thermal stratification develops after mid May but it does not stabilize until late June (Wells and McLain 1972). Thermal conditions continue to be rather stable through mid September although this varies from south to north since the lake covers nearly four degrees of latitude (Carr et al. 1973).

Historical and contemporary fish communities

There is a considerable body of information on the historical fish communities in Lake Michigan and Wells and McLain (1972, 1973), as well as other authors, provide detailed descriptions. By the 1950s the fish community changed dramatically and by the 1960s most of the fish biomass in Lake Michigan was concentrated in alewives Eshenroder et al. (1995). The alewife population crashed in 1967–68 (Brown 1972) and he estimated the alewife population at 1.1 million metric tons at it's peak in spring 1967; this estimate was about 10 times larger than the largest biomass estimates from the bottom trawls from 1973 – 1997 (Figure 1.2). Because so much of the biomass was tied up in alewives in the late 1960s the contrast between the 1967 biomass estimates and the more contemporary trawl based estimates must be tempered by the changes in abundance of other species, particularly bloaters. But, even if we factor bloaters into the equation when bloater abundance was greatest in the early 1990s and add another 100,000 metric tons of miscellaneous species, the total biomass is little more than one-half the estimated biomass of fish flesh attributed to alewives in spring 1967. Whether or not this represents a loss of primary productivity or partitioning of nutrients between species that were introduced after the peak of alewife abundance is arguable. However, one irrefutable fact remains, and that is the aquatic populations in Lake Michigan have undergone substantial changes in the short 30 years since alewives reached their peak abundance.

Long-term fish population data sets — The long-term data sets for Lake Michigan populations provide the only estimates of prey fish abundance trends available. The value of such long-term data sets for use in constructing predictive models of the populations should not be underestimated. Furthermore, field studies at the scale of the environmental problem are essential for successful management (Carpenter 1996). For example, the SIMPLE model of the Lake Michigan pelagic fish community used these long-term data and results and the model suggested that reversal of the alewife decline was unlikely without rather large reductions in predator stocking rates (Koonce and Jones 1994). Although new technology promises to provide alternatives to the bottom trawl surveys, it is prudent to maintain the long term data base until the capabilities of alternative methods are proven.

It is unclear how changes in densities or species affect the long term data sets. The tendency is to view the long term data sets as being constrained by constants such as gear type, size of gear, length of tow or set and as long as these constants remain fixed the integrity of the data set is validated. In truth we know little about what affect strong year classes or weather patterns have on the catches and instead rely on the assumption that variations balance out over years and remain secure in the belief that as long as we don't change the gear and the design the data sets are comparable between years.

In order to depart from this mind set requires either substantiated proof of better methodology yielding more robust data or clear evidence that the gear can not or will not function as it did originally. Two examples serve to illustrate these points. Our experience in Lake Huron during the 1980s with two sizes of trawls prompted us to change to the larger trawl for the fall prey fish assessments in1992. The transition to the larger trawl was based on data showing the larger gear captured a more representative range of fish sizes. In Lake Ontario, the large numbers of zebra mussels in the catches were affecting the fishing power of the gear, which in turn dictated a modification in that trawling gear.

The Lake Michigan bottom trawl assessments — The standard trawl used for the Lake Michigan assessments has been variously described as a semi-balloon bottom trawl, a Yankee Standard number 35 trawl, and a North Atlantic whiting trawl (Hatch et al. 1981; Argyle 1982). Regardless of the name this trawl had a 12-m headrope, 15.5-m footrope, and 13-mm mesh in the cod end. Its effective width when fishing was 6.5 m, with a maximum height of 2.4 m and a mean height of 1.7 m, based on measurements made by divers. Its frontal area, based on the same measurements was 10.8 m^2, and a 10-min tow covered 0.5 ha (Hatch et al. 1981). Tows with the standard trawl at the original transect off Saugatuck were made at depths of 5, 9, 13, 18, 22, 27, 31, 37, 46, 55, 64, 73, 82, and 91 meters along the contour during daylight hours. The 12-m bottom trawl used on Lake Michigan has also been the standard trawl of the Great Lakes Science Center for prey fish assessments on Lake Huron until recently, and of the Center's field stations on the other Great Lakes in general.

In 1964, Wells (1968) used the Saugatuck transect for a comprehensive study of the seasonal depth distribution of prey fish with reference to water temperature. Three additional transects were established in 1967, off Waukegan, Illinois and St. Joseph (adjacent to Benton Harbor) and Ludington, Michigan (Hatch 1981). In 1973, four additional transects were added off Port Washington and Sturgeon Bay, Wisconsin and Manistique and Frankfort, Michigan. With the addition of these transects, deeper trawling contours or fishing stations of 82 and 91 m were added to all transects, lakewide, and fishing stations of 110 and 128 m were added at several of the transects. To compensate for the time required to cover these greater depths, trawling at 5, 13, 22, and 31 m was discontinued. Although the St. Joseph transect was dropped in 1990 so that transects could be added near Charlevoix, Michigan and Two Rivers, Wisconsin, seven of the original eight locations have formed the core transects for the bottom trawl surveys. The data set was strengthened in 1973 and subsequent years with the addition of the four port locations identified earlier and the inclusion of some deeper sites. In addition to trend or index data, the trawl surveys provide the data needed to determine year class strength, age structure, mortality, growth, and other attributes.

Lake Michigan acoustic assessments

Although the use of acoustics to assess prey fish in Lake Michigan date back into the early 1970s, the first attempt at using acoustics to estimate the lake-wide biomass of pelagic alewives was by Brandt (1978). A cooperative research study *Acoustic assessment of pelagic fish abundances in Lake Michigan* provided some of the background data for planning this research initiative (Brandt 1989). In addition, we drew heavily on published literature for the cooperative research (Brandt et al. 1991; Argyle 1992). These studies generated considerable ancillary information in addition to the compelling evidence that acoustic technology has an important role to play in the management of Great Lakes fisheries. They also demonstrated that closely related technologies such as mensuration equipment for determining gear parameters and remotely operated vehicles play a key role in the assessment methodology. A major shortcoming of these studies was that species composition and average size were based on the bottom trawl catch data which, are unlikely not completely representative of the average size and species composition in the pelagic zone.

The multi-species prey stocks in Lake Michigan exhibit considerable spatial overlap, and since acoustic gear cannot distinguish between individual species, supplemental trawl sampling had to be integrated into the assessment strategy for the present study. Other factors we considered included seasonal differences in nearshore vs. offshore distributions, depth distributions, and seasonal changes in target size. Key areas needing research included target strength, trawl development, and sampling design. An extensive database was essential for planning and optimizing sampling designs.

Target strength is a critical parameter for acoustic assessment, and includes quantification of the relation between echo and fish sizes. Estimation of target strength is simplified in single species surveys where the size range is relatively small. Estimates of target strength can be obtained from literature values (virtually non-existent for Great Lakes species), tank and cage studies, tethered live, dead, or moribund fish, or *in situ* with trawls, which provide species composition and size distributions. Although some progress was made in obtaining data on target strength during previous Lake Michigan assessments, it remained a major area that needed to be investigated. Because of the large number of variables influencing target strength, the research involved a multi variate approach based on temperature, bottom depth, target depth, and mean target strength as primary data inputs.

Organization and format

This report was divided into several sections due of the volume and complexity of the material. Some of the material was better presented as a complete study because of it's importance to the objectives. An example is the target strength section, which was essential for estimating biomass. It would be redundant to repeat methodology throughout the report since some of the methods were specific for particular sections. General methods are presented so continuity is not lost, whereas specific, detailed methods covering specific aspects are relegated to the individual sections. In addition, some of the material was published in the literature or as reports for our internal or supportive use. In some cases these have been paraphrased as discreet sections. In other cases the publication or report was topically related to the study because some or most of the data were collected coincident to the research but were not directly related to the original objectives. Written reports and oral presentations at scientific meetings are cited.

Objectives

The objective of the study was to develop the strategy and sampling protocols for an integrated survey system that will define the relations important to the prey fish communities. Such a system would provide the basic biological data needed to project, using mathematical models, the effects that changes in abundance would have on predator stocks, within various limits of mathematical certainty.

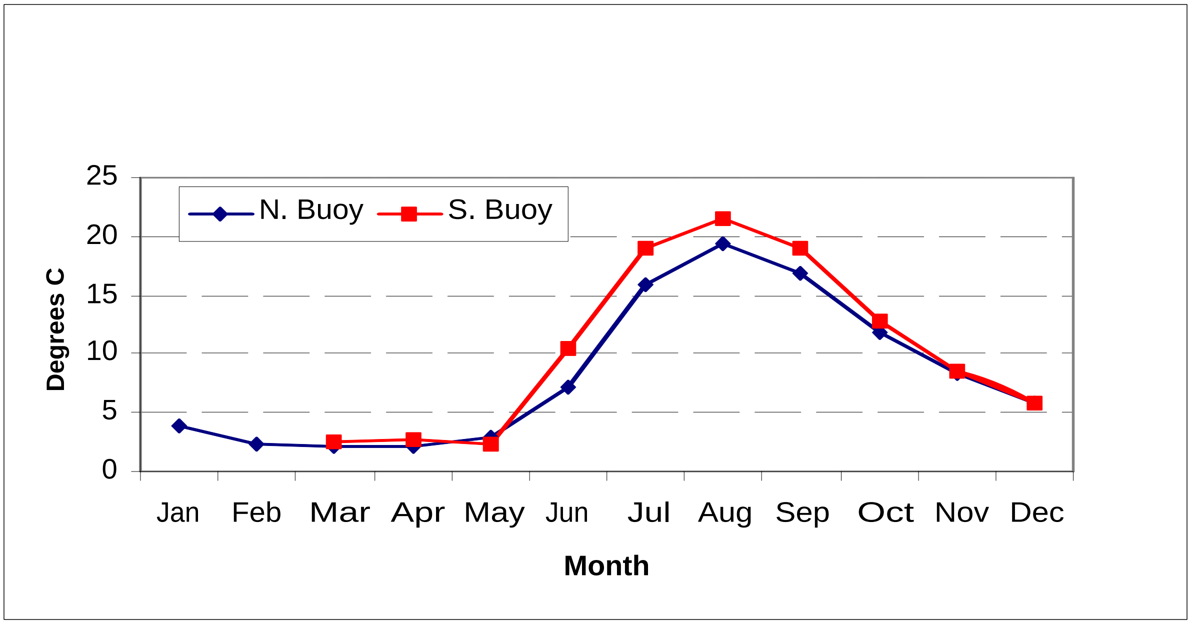


Figure 1.1 Mean monthly surface water temperature (C ^{0}) in northern (N. Buoy) and southern (S. Buoy) Lake Michigan from 1980 — 1993.

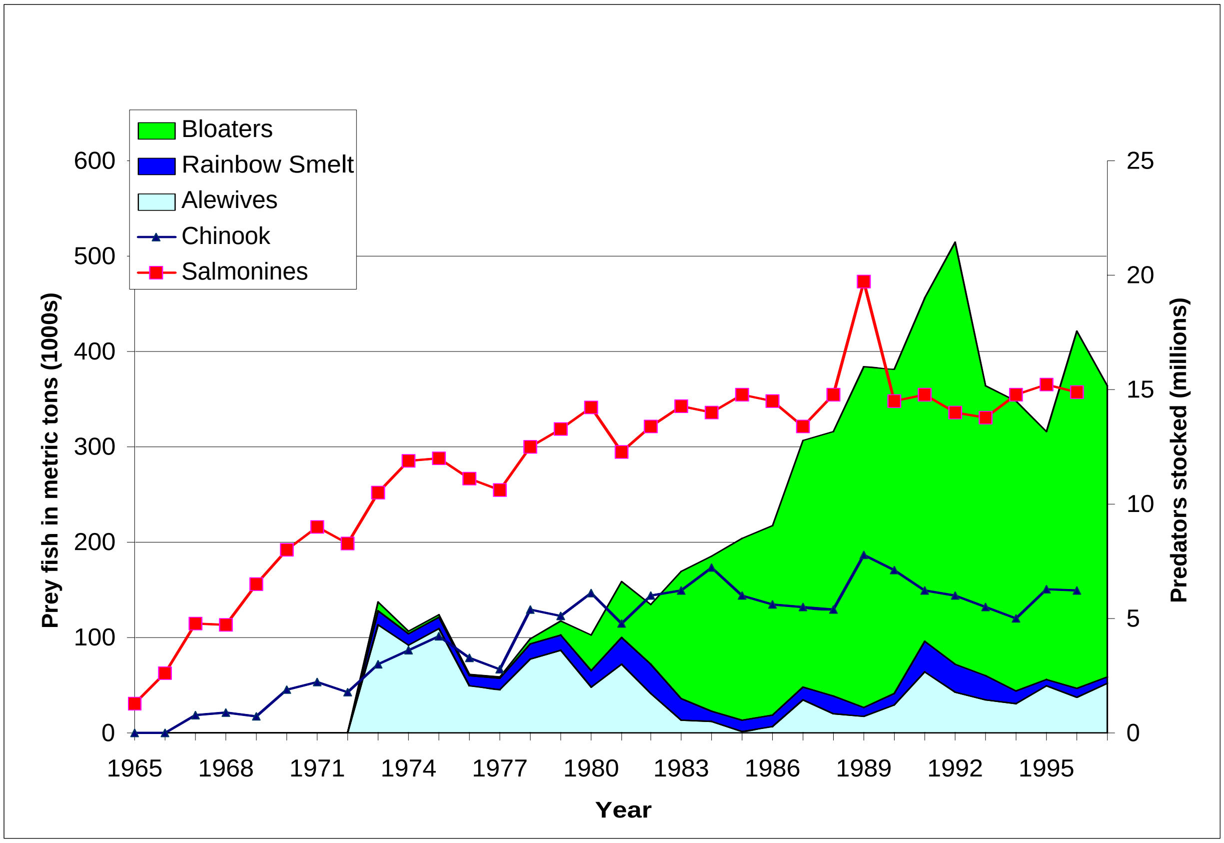


Figure 1.2. Chinook and salmonine stocking (millions stocked) in Lake Michigan beginning in 1965 and prey abundance (1000s of metric tons) as estimated from bottom trawl surveys beginning in 1972.

Section 2.

Acoustic Technology and Theory

Like the other Great Lakes, fish populations in Lake Michigan have changed greatly during the past century (Wells and McLain 1972, Brown 1972, Brown et al. 1987). The pelagic planktivores perhaps best illustrate the continual change that has characterized the fish community in Lake Michigan. Due to their trophic position – as consumers of zooplankton and the principal prey for top predators – these fish are very important components of the aquatic ecosystem. To date, our understanding of the status of prey fish in Lake Michigan has been based on bottom trawl surveys conducted by the Great Lakes Science Center. These trawl surveys were designed to provide an index of abundance of the fish stocks. Due to limitations of bottom bathymetry and gear biases, bottom trawls may not be the best tool to provide estimates of absolute fish abundance (Hatch 1981b). Whereas, use of acoustics for fishery surveys is appealing since this technique is not limited by bathymetry, it allows greater areal coverage, and is sensitive to a wide range of fish sizes. Because of these features, the application of acoustic technology for fish stock assessment is the most promising method to accurately estimate abundance of the major prey fish species (Ney 1993). Argyle's (1982) comparison of bottom trawl and acoustic-based estimates of prey fish abundance in Lake Huron indicated that between 20% and 30% of the total biomass was in midwater. He concluded that a survey approach that includes acoustics provides a better understanding of the status of both benthic and pelagic components of the prey base.

Acoustics technology has been developed into scientific-grade systems with capabilities that allow accurate measurements of acoustic signals to quantitatively assess fish stocks (MacLennan and Simmonds. 1992). This technology is established as a standard tool in quantitative fish stock assessment and had found application to the pelagic planktivores in the Great Lakes (Argyle 1992; Brandt et al. 1991). An assessment scheme designed to achieve realistic approaches to Great Lakes fishery problems and reach solutions will need to employ all available tools, which will undoubtedly integrate acoustics technology with traditional techniques for fisheries assessment.

Although it is not the intent in this report to include much of the theory behind the operation of the acoustic system, a general overview of the dual-beam technique is necessary for a basic understanding of the terminology used throughout the report and for conceptualizing how fish size (weight) and the biomass estimates are derived. The overall concept is relatively straight-forward. The acoustic system (a transmitter/receiver, associated circuitry, and transducer) transmits a short burst of electrical energy to a ceramic transducer in the water. The electrical pulse, causes the transducer ceramic to vibrate at a set frequency and a pressure wave traveling at a nominal speed of 1500 m sec^{-1} is transferred to the water. Objects (usually fish and the bottom) within the wave path reflect a portion of the pressure wave which returns to the face of the ceramic transducer. The pressure wave causes the transducer ceramic to vibrate, which in turn is converted to an electrical signal. The signal is amplified by the receiver, corrected for loss, and displayed or processed.

The reflecting power of the fish, or any other target, is termed the target strength (TS) and is technically a measure of the target's backscattering cross section expressed as the decibel (dB) equivalent. In general, the target strengths for the common sizes fish range from between -25 and -65 dB. The strength of the returning echo is dependent upon the location of the fish in the conical beam, with those directly in the center of the beam (on the acoustic axis) reflecting the strongest echo. Therefore, in a single beam system, fish of the same species and identical size would vary in apparent target strengths depending on their location in the beam.

By adding a second beam (the dual-beam system) that is either wider or narrower than the first, the location of the fish in the beam can be calculated based on the difference between the voltage returns from the target detected, at the same distance from the transducer, in the two beams and the target shifted mathematically to the acoustic axis. In operation, the signal is transmitted on the narrow beam and the target returns received simultaneously by both the narrow and wide beams. The dual-beam processor identifies single echoes and classifies them for computer program analysis. For any population of echoes, the dual beam technique provides mean target strength and average backscattering cross section values. The average backscattering cross section values are used to determine the biomass scaling factor of the common echo integration technique.

Concurrent with the dual-beam data collection, the signal from the narrow beam is also processed by the echo integrator. The echo integrator estimates the target densities in discrete depth layers by summing and averaging the squared voltage output of the receiver. Without the average target strength data the echo integrator data are only qualitatively accurate as a relative estimate of density. By scaling the echo integrator output with the equipment parameters and the average target strength (fish size) the density estimate can be quantified. The target strength is essential for scaling the echo integrator data and it has a profound effect on the density (biomass) estimate; a 3 dB difference in the target strength estimate affects the biomass estimate by a factor of two. For further information on the dual-beam technique and echo integration refer to

Burczynski, (1979), Traynor and Ehrenberg (1979), Ehrenberg (1982, 1984). The use of an integrated target strength and echo integration approach allows for the most accurate and efficient measurement of fish stocks and is widely used in a variety of marine and freshwater environments (Maclennan and Simmonds 1992).

The acoustic equipment used throughout our investigation changed radically and rapidly, largely due to the dynamic changes that were occurring in the electronic and computer industries. For example, at the onset of the study, 80286 computers running at 16 MHZ were state of the art. By current standards these are obsolete and are incapable of acquiring and processing data at the rates we use to capture the data streams from the transducers. The increases in computing power and faster acquisition rates and processing speeds were beneficial, however the increased volumes of data did necessitate changes in how we could effectively handle the increase. Eventually, the huge volume of data necessitated writing new-adaptive software routines for data processing and analysis.

Many of the changes in acoustic gear were unanticipated at the onset of the study. Consequently, the acoustic units changed during the course of the study. The original system consisted of separate units for dual-beam processing and echo integration; this system was used in fall 1991 and spring 1992. Two additional ESP (Echo Signal Processing) units, acquired for this study, consisted of two circuit boards that handled the echo integration and dual beam processing functions. Both circuit boards were housed in a micro computer and operated in the windows domain. The first ESP system was used for the fall 1992, spring 1993, and summer 1993 surveys. The second ESP system was acquired in late summer of 1993 and both ESP systems were were used for the fall 1993 and fall 1994 surveys. The second ESP unit was used for the fall 1995 and 1996 surveys.

The technology continues to change rapidly and positive attributes of these changes are simplification of operation and software routines that automatically read all operating parameters. This effectively reduces the possibility of operator error by minimizing data collection decisions. In addition the newer technology operates with lower system noise due to the placement of most of the electronics in the transducer housing and using digitized signals. Other features of the newer systems are wider dynamic ranges, and split beam technology which has some advantages over the dual beam systems. The processing algorithms have also improved allowing for better sea-bed tracking and higher resolution nearer the bottom.

Section 3.

Target Strength – Fish Size Relation

Background

Because the acoustic reflectivity of fish is related to their physical size (Ehrenberg 1972; Foote 1979), accurate measures of target strength are required to scale echo-squared integration values for density estimates (see Section 7) and are used to estimate size composition of fish. The establishment of a reliable relation between target strength and fish size allows prediction of the sizes of fish throughout the water column from the measured levels of acoustic backscattering.

Love's empirically-determined equations (Love 1971; 1977), which represent some of the first comprehensive attempts to quantify the dependence of backscattering on fish size, have been widely used in many acoustics applications. The relation of target strength to fish length from these and other studies (e.g. Nakken and Olsen 1977; Dahl and Mathisen 1981) were developed from measurements on immobile fish under controlled conditions. However, differences between the predicted sizes of fish from target strength with these relations did not fully correspond with observed sizes of active fish in the wild. These differences are attributed to effects of fish behavior on target strength not present in controlled experiments (Nakken and Olsen 1977; Dickie et al. 1983; Rose and Leggett 1988). The variations observed in the target strength of active fish have been attributed to a variety of behaviors such as aspect (tilt angle), depth changes associated with vertical migrations, and characteristics of fish physiology that affects the volume and shape of the swim bladder (Blaxter and Batty 1990; Dawson and Karp 1990; MacLennan et al. 1990; Ona 1990). Therefore, relations between fish size and acoustic backscattering determined *in situ* are desirable for predictive purposes since they consider natural variations to target strength.

In bony fishes, the swim bladder reflects 90-95% of the acoustic energy (Foote 1980; Foote 1985). Larger fish have predictably larger swim bladders (Ona 1990), hence greater target strength values. Although the size of the swim bladder is related to fish mass (Saenger 1989), target strength is usually associated with fish length (MacLennan and Simmonds 1992), which is reasonable because weight and length are closely related. If the goal of the acoustic survey is to estimate fish biomass, the lengths of fish predicted from target strength require the additional conversion to weights (Bjerkeng et al. l991). This additional step may not be necessary with the establishment of a relation between target strength and fish weight that would allow direct estimation of fish mass.

To develop target strength-fish size relations, we conducted extensive midwater trawls and acoustic measurements in a variety of depth strata. We used 119 simultaneous *in situ* acoustic and midwater trawl collections, made during the lake-wide surveys conducted on Lake Michigan in 1990-1993, in our analysis. All acoustics signals were collected and processed as described in Section 7. All fish caught were individually measured to the nearest millimeter (total length) and weighed by species in aggregate. Mean weight was determined for the entire catch, however, infrequently-caught large predators such as lake trout *Salvelinus namycush* or chinook salmon *Oncorhynchus tshawytscha* would greatly skew the weight distribution so were not included in the calculation of mean weight. Mean back- scattering cross section ($\overline{\sigma}_{bs}$) expressed as dB was calculated for single echoes in the stratum defined by the trawl path. Only single echoes within a beam pattern threshold of 3 dB (approximately one-half the nominal beam width) were used for calculation of mean target strength to minimize the systematic bias towards larger echoes on the edge of the beams (Traynor and Ehrenberg 1979) or the inclusion of multiple echoes at similar ranges (Foote 1996).

Acoustic and midwater trawl data — The midwater trawl catches were dominated by various combinations of rainbow smelt, bloaters, alewives, ninespine sticklebacks *Pungitius pungitius*, and threespine sticklebacks *Gasterosteus aculeatus* (Table 3.1). Other fishes were relatively infrequent in the catches. Rainbow smelt were numerically most prevalent in the trawls, but bloaters dominated the catches by mass. Ninespine sticklebacks, threespine sticklebacks, and small alewives were frequently caught in the trawls but contributed less to the total catch than rainbow smelt or bloaters. Mean length of fish in the trawls ranged from 6.1 to 20.3 cm and their mean weight ranged from 2 to 71 g. In Lake Michigan, size of fish in the water column was positively related to depth ($r = 0.66$) (Figure 3.1). Mean target strength, which ranged from -54.9 to -38.0 dB, reflected this size-depth dependence and also increased with depth (Figure 3.1).

Target strength-fish size relation — To develop a predictive equation, we fit a general linear regression model that related log-transformed mean weight of catch to the mean target strength. However, *in situ* target strength studies rely on composite collections of fish and echo data. With error in both the fish size and target strength terms, measures of association between these variables rely on bivariate statistics. The merits of using linear regression for bivariate data have been debated (Ricker 1973, 1975; Jolicouer 1975). However, application of linear regression to bivariate data is useful for predictive relations (Sokal and Rohlf 1995). Further, examination of the bivariate density distribution of mean target strength and log-transformed mean weight revealed the potential presence of subgroups (Figure 3.2). To test for differences between linear relations for the groups, both classification and target strength-classification interaction terms were included in the regression analysis. This regression model simultaneously fits linear regression functions to the classification groups (Neter et al. 1990). We also developed equations to predict mean length from mean target strength by the same techniques.

Log-transformed mean weight was linearly related to mean target strength ($r = 0.81$) (Figure 3.2). However, the subgroups we identified by the examination of bivariate density suggested heterogeneity in the data. The catches of smaller-sized fishes were primarily combinations of rainbow smelt, alewives, and sticklebacks, whereas, the catches with larger-sized planktivores were predominantly bloaters. Mean weight of catch was positively correlated with proportion of bloaters ($r = 0.84$) which was expected since bloaters reach larger sizes than do the other pelagic species. Therefore, we concluded that the different size groups reflected differences in species composition and we used the classification variable in the general linear regression model to represent these species groups. Since the proportion of bloaters in the catches was typically very high or very low ("**U** -shaped" bimodal distribution), we classified those catches that contained a majority of bloaters (more than 50% of this species) as 1 and classified the others as 0. Addition of the species classification variable improved the linear correlation of log-transformed mean weight to mean target strength ($R = 0.86$).

With the full general linear regression model, the coefficient for the target strength-classification interaction term was not significant ($P > 0.04$), so we fit the model without the interaction term which gave:

$$(1) \quad \log_{10}\overline{WT} = 3.976 + 0.066\ \overline{TS} + 0.350\ I$$

where $\overline{WT}$ is mean weight in grams, $\overline{TS}$ is mean target strength in decibels, and I is the classification variable ($R^2 = 0.73$). All terms were highly significant ($P < 0.001$), including the classification variable coefficient which indicated a difference in the intercept between the groups and provided a measure of the differential effect of species composition on the weight-target strength relation. With this model, the functional response of weight and target strength for bloaters was:

$$(2) \quad \log_{10}\overline{WT} = 4.326 + 0.066\ \overline{TS}$$

and for the other species was:

$$(3) \quad \log_{10}\overline{WT} = 3.976 + 0.066\ \overline{TS}$$

(Figure 3.3). These functional response equations indicate that per unit body mass, bloaters are less acoustically reflective than the other species.

We applied the same general linear model to mean target strength and the mean length (log-transformed) of fish which gave:

$$(4) \quad \log_{10}\overline{L} = 1.904 + 0.019\ \overline{TS} + 0.119\ I$$

where $\overline{L}$ is mean length in cm ($R^2 = 0.65$). All terms in this model were highly significant (P <0.001), however the fit of mean length with mean target strength was not as good as the fit of mean weight with mean target strength.

Reliability of relation — The potential sources of error inherent in *in situ* target strength studies demand these sources be identified and addressed (Rose 1992). One obvious source of potential bias is due to an assumed equal catch efficiency among fish species and sizes; the validity of classifying the targets based on trawl catches may be compromised due to catchability differences. Wardle (1986) concluded that the avoidance reaction of fish to trawls is primarily visual, and is highly reduced in the low-light conditions of night. He further observed that the ultimate capture of fish in the cod end, once within the trawl, is dependant on swimming ability. Fish swimming performance is related in large degree to size, where larger fish can swim faster (Wardle and Videler 1980). Given the size range of fish, the tow speed and size of the midwater trawl, and that we conducted the tows during night, violations of our assumption of equal catchability for the planktivores was most likely minimal. Bias against larger fishes undoubtedly existed to the degree these fish influenced the target strength measure without a proportional representation in the catches. However, with a difference in relative abundance on the order of magnitude of 10^4 between planktivores and piscivores in Lake Michigan (Sprules et al. 1991), the exclusion of the few large individuals in developing the regression relations was justified for predictive purposes.

Target strength error due to heterogeneity of fish behavior and physiology also needs to be considered. Pooling target strength measures across inappropriate temporal and spatial scales can introduce bias (Rose 1992). Temporal patterns in depth distribution and body condition need to be considered for their effects on swim bladder volume, hence target strength (Ona 1990). The consolidation of acoustic measurements made throughout different times of night when fish are in various stages of active migration and over the entire four-year period may have contributed to the error in our predictive relations, and our application of these predictive relations should take into consideration possible changes in fish behavior or physiology within both time frames. But, given all the possible technical shortcomings, as well as the expected natural variation of *in situ* studies, we were able to explain 73% of the variation in mean weight of fish by mean target strength for the pelagic species in Lake Michigan. Identification of specific fish behaviors and physiological factors that have the most effect on the backscattering properties of the swim bladder would be helpful for improving our predictive relation.

Species differences — The significant difference we detected in the backscattering levels between bloaters and the other pelagic species indicates some fundamental difference in morphology or behavior between these species groups. The most obvious distinction is depth distribution. During thermal stratification, bloaters are found in greatest abundance at deeper depths compared to the other pelagic species (Argyle 1992). In collections made for this study, the median depth for catches that were predominantly bloaters was 60 m compared to a median depth of 25 m for catches of the other species. Changes in target strength of physostomous fishes is highly dependent on depth changes (Mukai and Iida 1996), and the differences in backscattering we detected may reflect the different depth distributions associated with vertical migration patterns. We observed that during night bloaters are scattered throughout a wide range of depths in the hypolimnetic strata whereas the other species are concentrated in association with the shallower metalimnetic and epilimnetic strata. A reduction in the volume of the swim bladder, hence in the level of backscattering, with implications of negative buoyancy would be expected in bloaters while suspended in the deeper portions of their vertical range. Bloater target strength could also be affected by lipid content. Ona (1990) found that most of the variation in swim bladder size for herring *Clupea harengus* at neutral buoyancy was attributed to differences in fat content and accounted for variability in target strength. The fat content of bloaters, especially for larger individuals (Rudstam et al. 1994), is much greater than for alewives or rainbow smelt (Rottiers and Tucker 1982; Hesselberg et al. 1990). The greater fat content could diminish the size of the swim bladder needed for neutral buoyancy and be a contributing factor in the reduced target strength in bloaters. Understanding the buoyancy characteristics of the pelagic planktivores would provide evidence of whether the differential backscattering we detected was a function of patterns of vertical migration.

Conclusions

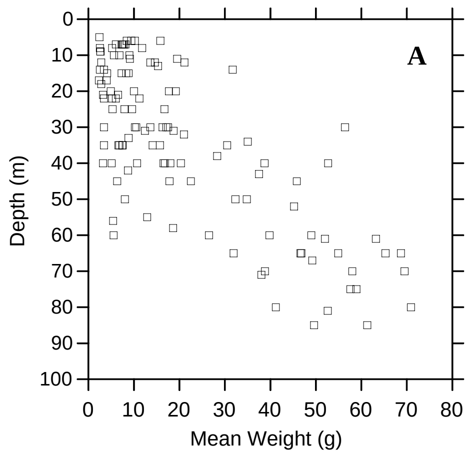
We found mean target strength to be closely related to *in situ* fish size. Moreover, our analysis showed that target strength was related to fish weight more closely than to fish length (the latter is the most commonly used measure of fish size in acoustic surveys). Acoustic backscattering is considered to be proportional to fish area or to fish volume (Love 1977; MacLennan and Simmonds 1992), and based on a structural relation model, Saenger (1989) concluded that swim bladder wall area is proportional to fish volume or mass. Therefore, target strength should be expected to be less variant to changes in weight than to length. Our fish mass-target strength relation is advantageous compared to the fish length target strength relation because we can directly and with improved precision estimate biomass density of fish throughout the water column.

Our results support the conclusion by Foote (1979) and McClatchie et al. (1996) that relations for prediction of fish size from target strength should consider species differences. The inference of fish size from acoustic size for multi-species fish populations must take into account the possibility of different backscattering populations, and if evident, they must be treated as separate populations to avoid bias in the estimates of biomass. Gerlotto (1993) relied on various acoustic-based characteristics to discriminate different acoustic populations and applied biological and hydrological information in order to develop biomass estimates for numerous tropical fish species. Barange et al. (1994) were able to differentiate multiple species by differences in target strength distribution, but these species showed distinct vertical distributions. The pelagic species in Lake Michigan demonstrate some spatial discreetness related to thermal preferences (Brandt et al. 1980; Section 8, this report). Our midwater catches show the greatest spatial overlap between species and size groups in the epilimnetic and metalimnetic zones, which indicates that these areas will always need some measure of species composition, whether by traditional trawls or by newly developed echo discrimination techniques (Zackaria 1990). In practice, we apply the bloater target strength-weight relation to echoes in the deeper, hypolimnetic strata that are predominated by adult bloaters. We recognize the need to gather behavioral information and additional backscattering data on other major pelagic species such as alewife. Unfortunately, catches dominated by species other than bloaters and rainbow smelt were too few to allow a reliable comparison of target strength in this study.

Our results also demonstrate the parochial nature of fish backscattering and use of target strength-fish size relations developed beyond the immediate application should be done with caution. Recent bioenergetics model applications in the Great Lakes (Brandt et al. 1991; Goyke and Brandt 1993) relied on acoustic-based fish abundance estimates and on the use of Love's equation (Love 1971) to estimate fish sizes. However, we found that the observed target strength values for the smaller sizes of fish were substantially smaller than predicted by Love's equation (Figure 3.4). This apparent underestimate of smaller fish by Love's equation, also noted for rainbow smelt by Burczynski et al. (1987), would result in an underestimate of fish biomass. Brandt et al. (1991) recognized that the application of a single relation for a mixed-species assemblage may result in biased estimates of fish size and fish biomass. But our results do not support Goyke and Brandt's (1993) contention that Love's equation is applicable to Great Lakes fishes. Differences in backscattering is not only expected between taxa, but the target strength relation also differs between marine and freshwater forms of the same species (McClatchie et al. 1996). With the number of target strength-fish size equations available (MacLennan and Simmons 1992), local conditions must also be taken into account in the application of a published relation for purposes of prediction. Acoustic assessment is the most promising method for accurately estimating prey fish biomass (Ney 1993), but the backscattering properties of each species should be carefully considered in any such assessment.

Table 1. — Species composition as percent occurrence and mean number and weight for fishes collected by midwater trawling in Lake Michigan. Ninespine and threespine stickelbacks were combined and reported as Gasterosteidae.

		Mean Proportion in Catches (%)	
Species	Occurrence (%)	Number	Weight
Rainbow Smelt	96	45	37
Bloater	76	32	45
Alewife	64	11	9
Gasterosteidae	25	11	7
Others	< 1	< 1	< 1



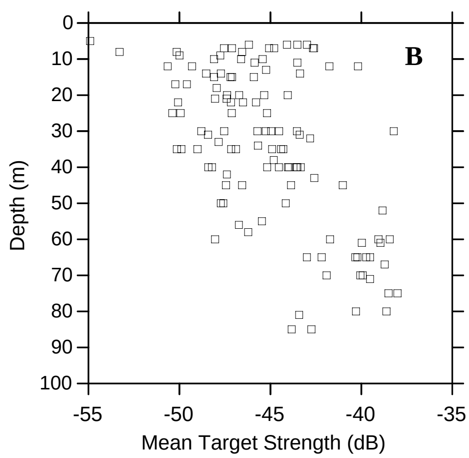


Figure 3.1. – Plots of mean weight by depth (**A**) and mean target strength by depth (**B**) for simultaneous acoustic and midwater trawl collections in Lake Michigan.

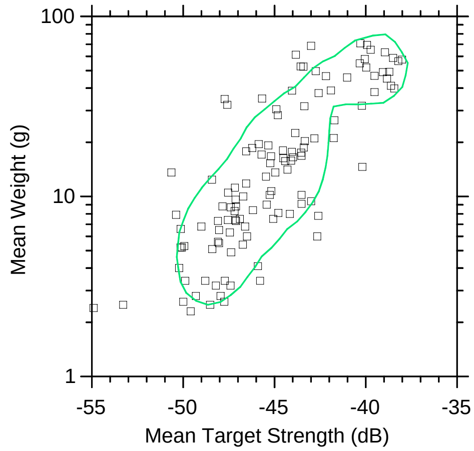


Figure 3.2. – Scatter and kernel density plot of mean target strength (dB) and mean weight (g) for fish from simultaneous acoustic and midwater trawl collections in Lake Michigan. The contour shows the bivariate confidence interval (relative concentration of data points) on the X-Y plane.

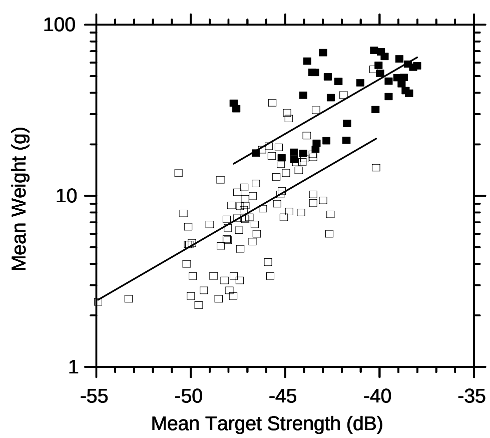


Figure 3.3. — Comparison of the distributions of mean target strength (dB) and mean weight (g) for fish from simultaneous acoustic and midwater trawl collections in Lake Michigan. The least-squares regression lines shown are for catches that were predominantly bloaters (filled symbols) and catches of all other species (empty symbols).

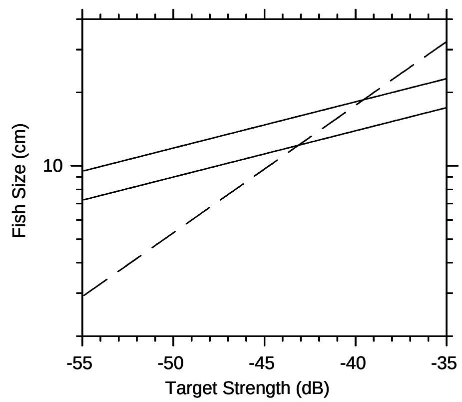


Figure 3.4. — Comparison of fish lengths predicted from target strength for in situ relations from Lake Michigan (upper for solid line for bloaters, lower solid line for other species) and Love's (1971) equation (broken line). Love's relation based on 120 kHz.

Section 4.

Frequency Comparison

Background

During 1993 and 1994 we used two frequencies for all the acoustic measurements and the frequencies were multiplexed. All samples were collected along individual line transects, stratified into depth and strata groups as described in Section 7 under Methods, with multiplexed (alternating transmission) 120 kHz and 420 kHz transducers. These simultaneous collections allowed paired comparisons of acoustic backscattering (target strength), relative density (volts squared), and derived acoustic estimates of fish densities and standing stocks at identical locations throughout the water column for the two frequencies. By providing minor corrections for the frequency used the two frequencies should yield identical target strength and echo integration values. However, during preliminary analysis of the 1993 and 1994 fall acoustic survey data, we began to notice discrepancies between the target strength estimates and echo integrator values derived from the two frequencies and investigated the reason for the discrepancies.

Target strength

Comparisons of mean backscattering (expressed in dB) indicate little agreement between values of target strengths measured by the two frequencies (Figure 4.1). Correlation of mean backscattering cross section comparing the two frequencies were low in both 1993 ($r = 0.24$) and 1994 ($r = 0.26$). Differences in mean target strength are expected between two frequencies for any given size of fish, based on the backscattering-fish size dependence to wavelength (Love 1971, 1977). Assuming that acoustic backscattering is proportional to the square of fish length, where the wavelength normalized fish length (length/λ) equals wavelength normalized acoustic cross-section (σ/λ^2), a target strength difference of up to -5 dB could be expected between 120 kHz and 420 kHz for the sizes common for prey fishes in Lake Michigan. However, other factors apart from the assumed geometry complicate this relation. Empirical studies (e.g. McCartney and Stubbs 1971; Love 1971) indicate an expected -1 to -2 dB difference in measured target strength between fish ensonified at 420 kHz compared to the same fish at 120 kHz. As a constant function, this fish size-frequency dependence should not effect the linear correlation of target strength between frequencies. Apparently, some other mechanism was responsible for the inconsistency in measured acoustic backscattering between the two frequencies.

One acoustic property that may be responsible for the poor agreement of target strengths between the two frequencies is a range effect due to differences in signal attenuation. Higher frequencies allow better target resolution, however higher frequencies also have greater absorption that limits the maximum range of observation (MacLennon and Simmonds 1992). Comparison of mean backscattering by depth shows a general trend of increased mean target strength with increased depth for 120 kHz but a decrease in mean target strength with depth for 420 kHz (Figure 4.2). Our midwater trawl catches showed a positive relation of fish size with depth ($r = 0.66$), and mean target strength should also reflect this size-depth dependence. Since this pattern was observed with 120 kHz and not with 420 kHz, the target strength values for the deeper strata at 420 kHz are suspect (we assume correct time-varied gain functions for all systems). A further indication of a potential range effect is demonstrated by the trend in decreasing correlation of mean backscattering for the two frequencies with depth, which was especially evident in 1994 (Fiure 4.3). A reduction in the backscattering levels for the deeper fish would be expected with a greater degree of attenuation in the 420 kHz signals.

To examine whether signal attenuation is the source of the differences in mean target strength between frequencies, we compared individual echo data in over a range of depths. These data were collected off Ludington, Michigan along two transects completed during the surveys in fall 1994. Individual echo data were comparable since source level and through-system signal loss differences between the 120 kHz and 420 kHz systems were compensated for at time of collection by adjustment of gain settings. Pulse-width criteria used for single echo discrimination were identical for each frequency. We examined the distribution of peak amplitudes for single echoes from fish that were suspended in midwater over deeper (bottom depths from 60 to 90 m) strata greater than 40 m and not closer than 5 m to bottom. Midwater trawl catches indicated these fish were adult bloaters. These fish, relatively uniform in size, ranged from 143 to 256 mm and averaged 194 mm (total length). In order to discriminate the larger fish echoes from smaller echoes (most likely *Mysis relicta*), only detected echoes of target strength greater than –52 dB were considered for analysis. Plots of narrow beam amplitudes for these fish show distinct differences in distribution between frequencies (Figure 4.4). The peak narrow beam voltages are of a much narrower range and lower modal value for 420 kHz than for 120 kHz. The lack of larger narrow beam values recorded at 420 kHz compared to 120 kHz explains the lower mean target strength for the higher frequency. The truncation of the larger values implicates signal attenuation at 420 kHz, where only the larger backscatterers would contribute sufficient signal strength to be detectable, albeit at diminished values. It is evident from both the individual and collective patterns that mean backscattering at 420 kHz is consistently of lesser amplitude for the deepwater fish than at 120 kHz.

Signal attenuation effectively increases the signal threshold, which results in an increased bias against smaller echoes. If signal attenuation is persistent with the higher frequency, then a discernable absence of smaller echoes should characterize the echoes detected at 420 kHz compared to 120 kHz. However, the relative proportion of large and small targets detected by the two frequencies in the hypolimnetic strata does not indicate any such pattern (Figure 4.5). The detection of the smaller echoes was similar in relation to the larger echoes for both 420 kHz and 120 kHz in the deeper strata. This result does not support the contention of greater signal attenuation effecting the higher frequency. Therefore, some other acoustic feature other than signal attenuation must be a cause of the observed differences in target strength.

Reduction in backscattering amplitude, especially at higher frequencies, can also be the result of fish orientation. Due to fish shape, concentration of the reflected signal is greater at higher frequencies, such that fish movements (changes in orientation from dorsal aspect) have greater effects on backscattering amplitude at higher frequencies than at lower frequencies (Nakken and Olsen 1977). As example, Jech et al. (1995) reported an unexpected variation in dorsal-aspect backscattering amplitude at 420 kHz compared to 120 kHz for individually tethered threadfin shad. They attributed this difference to a more sensitive response of the higher frequency to small changes in fish horizontal orientation. In Lake Michigan, bloaters, the principal deepwater species, are neutrally buoyant at depths that correspond to the upper level of their midwater distribution during diel vertical movements at night (Fleischer and TeWinkel 1997). Bloaters are not synchronous in their nocturnal vertical movements and many are suspended throughout the lower hypolimnion. Bloaters at these depths would be negatively buoyant and would likely have to employ swimming-generated hydrodynamic lift by altering attitude and using the pectoral fins as hydrofoils to maintain position (Alexander 1972; Harden Jones & Scholes 1985; Ona 1990). Eckmann (1991) reported that pelagic whitefish (*Coregonus lavaratus*), exposed to increased pressure in a hyperbaric chamber to simulate conditions in the deeper range of their vertical movement, responded by swimming with a positive tilt in an apparent attempt to produce hydrodynamic lift. If bloaters exhibit similar behavior during vertical movements, a greater attenuation of target strength at the higher frequency is consistent with known effects of fish aspect on backscattering (Buerkle 1987; Foote 1980; McClatchie et al. 1998) in relation to sonar frequency (Jech et al. 1995). Fish orientation provides a plausible explanation for the differences in target strength values we detected between frequencies.

Relative density

The plot of volts squared (log-transformed) for values measured with the two frequencies shows a significant linear relation (Figure 4.6). The non-parametric (Spearman) correlation of volts squared (r = 0.84 in 1993 and r = 0.67 in 1994) indicated better agreement for echo-squared integrator values for the two frequencies than for measured target strength. However, the scatter plot of log-transformed volts squared indicated a better linear relation at higher densities then at lower densities. As example, for measured volts squared values above 0.1 in 1994, the two frequencies were better correlated (r = 0.73) than for values of volts squared below 0.1 (r = 0.45). The reduced degree of agreement in echo integrator values at lower fish density levels may not elicit great differences in fish abundance estimates between frequencies since the absolute difference would be small. This pattern of correlation in echo integrator values does not appear to follow the range differences observed in backscattering between frequencies. The occurrence of values greater than 0.1 volts squared for either frequency were uniformly distributed across all depths, whereas density values less than 0.1 volts squared were most frequent in the shallow strata. Further, the correlation of the volts squared between frequencies were the largest in the deeper strata, where r values approached 0.8 to 0.9 (Figure 4.7). Our assertion that fish orientation accounts for the differences in target strength between frequencies must also then effect the echo-squared values. However, biases in target strength, which is time-varied gain adjusted for 2-way spreading loss (40 log R), are greater than those applicable to echo integration time-varied gain (20 log R). This gain difference accounts for the better correlation of echo integration values between the frequencies, where signal attenuation due to orientation would not be amplified to the same level.

Estimates of Fish Abundance and Biomass

Estimates of fish density and biomass were calculated for both 120 kHz and 420 kHz as detailed in Section 7 of the Methods. The plot of estimated fish densities (fish/m^3) by frequency shows some degree of linear correlation between the two frequencies for both years (Figure 4.8). The non-parametric (Spearman) correlation of absolute fish density (r = 0.76 in 1993 and r = 0.55 in 1994) was worse than for the relative density (echo-squared) values. This result should be expected, since the estimated fish densities are derived by scaling volts squared with the mean acoustic backscattering and include the error associated with the target strength values. Estimates of fish density for 420 kHz tended to be greater than for 120 kHz, especially in 1994, as indicated by the distribution of points above the diagonal line (Figure 4.8). Given the similarity in relative density estimates between the two frequencies, these trends of greater estimates of absolute density (fish/m^3) for 420 kHz would be attributed to the degree of difference in mean acoustic backscattering values for this frequency. As shown previously (Figure 4.2), the measured acoustic backscattering differed between the two frequencies in relation to range, with mean target strength increasingly smaller with depth for 420 kHz compared to 120 kHz. Comparison of mean density estimates for fish by depth suggests that differences appear to exist principally in the deeper strata, where the estimates were typically larger for 420 kHz (Figures 4.9 and 11). These differences in density estimates were statistically different in 1994, but not in 1993. Analysis with Wilcoxon signed-rank tests found significantly greater density estimates ($P < 0.0005$, two sided) measured at 420 kHz than at 120 kHz for 1994 in all but the shallowest and deepest strata (Table 4.1). The greater agreement between estimates of both frequencies in the deeper strata in 1994 is strictly coincidental, based on the distribution of mean target strengths in the deeper strata (Figure 4.2). Smaller targets that were detected at 120 kHz resulted in a subsequent reduction in mean backscattering. An apparent underestimation of the backscattering of the larger targets at 420 kHz resulted in similar values of mean backscattering for both frequencies. In 1993, the density estimates were also generally greater for 420 kHz (Table 4.1), but were not significant ($P < 0.0005$, two sided). The inability to detect statistical differences in 1993 is not unexpected given the higher degree of correlation in volts-square values and smaller sample size, where only 9 transects were completed in 1993 compared to 17 in 1994.

Biomass estimates (kg/ha), the product of the predicted mass and standing stock estimates (number/ha), on average appear greater for 420 kHz than for 120 kHz in many strata in 1994 but not 1993 (Figures 4.10 and 4.12). The predicted fish size (mass) for 420 kHz assumed a +2 dB correction before application the 120-kHz target strength to fish weight relation detailed in Section 7. As expected from the density estimates, analysis with Wilcoxon signed-rank tests also found significantly greater biomass estimates ($P < 0.0005$, two sided) measured at 420 kHz than at 120 kHz for all but the shallowest and deepest strata in 1994 (Table 4.2). In contrast, biomass estimates at the various strata were actually greater at 120 kHz than at 420 kHz in 1993 (Table 4.2), but these differences were not significant ($P < 0.0005$, two sided). As stated above, this result is not unexpected given the combination of better correlation in relative density estimates and smaller sample size in 1993 compared to 1994.

Conclusions

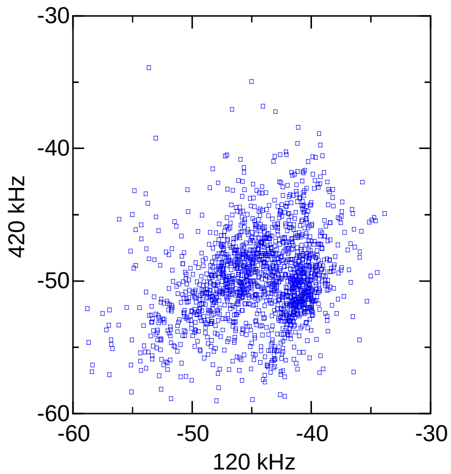
The acoustic measures of backscattering with 420 kHz, in contrast to 120 kHz, are not consistent with observed fish distributions in Lake Michigan. This result is important since an accurate measure of mean backscattering is required to scale echo-squared integration values for density estimates. In addition, acoustic-based estimates of fish size composition from target strength for 420 kHz would not be dependable. Based on our analyses, we infer that the inconsistencies in target strength measures are attributable to fish behavior. Further, the greater differences in estimates of fish abundance between frequencies in 1994 compared to 1993 undoubtedly reflect differences in fish behavior. Fish did not move far into the water column in 1993, especially those in deeper water, but were located nearer bottom possibly as a response to increased currents that would be associated with storm events. In contrast, fish were distributed throughout the water column in a more typical fashion during the survey in 1994. In the situation where fish are actively migrating, as is the case in 1994, it should be expected that changes in these patterns will show greater effects on acoustic-based abundance estimates at higher frequencies. This conclusion corroborates Foote's (1980) plea for more research on fish behavior affecting acoustic backscattering. Therefore, any improved resolution of a higher frequency must be weighed against a greater variability in backscattering amplitude from sensitivity to fish orientation.

Table 4.1. Results of Wilcoxon Signed-Rank tests to compare estimates of fish density and biomass by depth strata with paired 120 kHz and 420 kHz transducers during the 1993 acoustic survey in Lake Michigan. *P*= probability level of two-tailed tests; Z = sum of signed ranks/sum of squared ranks, which indicates magnitude of difference of ranks (positive value indicates greater mean rank of estimates with 420 kHz, negative value indicates greater mean rank of estimates with 120 kHz).

Depth Stratum	Density (number/ m^3)		Biomass (kg/ha)	
	P	Z	P	Z
2.5-5	0.000006	-4.53	0.058	-1.89
5-10	0.005	2.83	<0.000001	5.70
10-15	0.954	-0.06	0.043	2.02
15-20	0.589	0.54	0.267	1.11
20-25	0.123	-1.54	0.055	-1.92
25-30	0.730	-0.34	0.0002	-3.65
30-35	0.113	-1.58	0.00003	-4.16
35-40	0.791	-0.27	0.00018	-3.74
40-45	0.553	-0.59	0.0026	-3.01
45-50	0.084	1.73	0.147	-1.45
50-55	0.063	1.86	0.294	-1.05
55-60	0.014	2.46	0.389	-0.86
60-65	0.185	1.33	0.426	-0.79
65-70	0.137	1.48	0.039	-2.06
70-75	0.630	-0.48	0.027	-2.21
75-80	0.330	0.98	0.069	-1.82
80-85	0.645	-0.46	0.123	-1.54
85-90	0.600	0.52	0.599	-0.52
90-95	0.752	0.32	0.067	-1.83
95-100	0.936	0.08	0.029	-2.18
100-105	0.475	0.71	0.020	-2.32
105-110	0.322	0.99	0.004	-2.82
110-115	0.649	0.46	0.0003	-3.62
115-120	0.288	1.06	0.0003	-3.58
120-125	0.196	1.29	0.0015	-3.18
125-130	0.878	0.15	0.0015	-3.17
130-135	0.017	2.38	0.027	-2.19
135-140	0.173	1.36	0.0117	-2.52
140-145	0.460	0.73	0.068	-1.83
145-150	0.470	-0.73	0.179	-1.34

Table 4.2. Results of Wilcoxon Signed-Rank tests to compare estimates of fish density and biomass by depth strata with paired 120 kHz and 420 kHz transducers during the 1994 acoustic survey in Lake Michigan. *P*= probability level of two-tailed tests; Z = sum of signed ranks/sum of squared ranks, which indicates magnitude of difference of ranks (positive value indicates greater mean rank of estimates with 420 kHz, negative value indicates greater mean rank of estimates with 120 kHz).

Depth Stratum	Density (number/ m^3)		Biomass (kg/ha)	
	P	Z	P	Z
2.5-5	<0.000001	-6.6	<0.000001	-5.89
5-10	0.004	2.85	0.000006	4.52
10-15	0.00003	4.11	0.0015	3.17
15-20	0.0059	2.75	<0.000001	5.64
20-25	0.001	3.27	<0.000001	6.16
25-30	<0.000001	6.05	<0.000001	6.82
30-35	<0.000001	7.77	<0.000001	7.56
35-40	<0.000001	8.39	<0.000001	8.64
40-45	<0.000001	7.41	<0.000001	8.12
45-50	<0.000001	8.57	<0.000001	7.14
50-55	<0.000001	8.08	<0.000001	6.99
55-60	<0.000001	8.6	<0.000001	6.21
60-65	<0.000001	7.71	0.0000042	4.60
65-70	<0.000001	7.01	0.000001	4.87
70-75	<0.000001	6.40	0.000006	5.00
75-80	<0.000001	8.18	<0.000001	6.64
80-85	<0.000001	7.03	<0.000001	6.79
85-90	<0.000001	7.11	<0.000001	6.35
90-95	<0.000001	5.78	<0.000001	5.67
95-100	<0.000001	5.80	<0.000001	6.12
100-105	<0.000001	4.95	<0.000001	5.62
105-110	<0.000001	5.03	<0.000001	5.74
110-115	<0.000001	4.95	<0.000001	5.29
115-120	0.009	2.59	0.0006	3.34
120-125	0.014	2.44	0.001	3.29
125-130	0.000053	4.03	0.0002	3.74
130-135	0.339	0.96	0.004	2.86
135-140	0.199	128	0.09	1.69
140-145	0.310	-1.01	0.85	-0.18
145-150	0.767	0.29	0.40	0.84



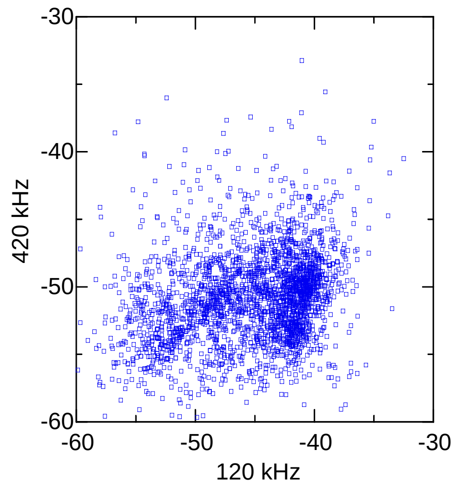


Figure 4.1 – Comparisons of mean backscattering cross section (dB) for paired target strength measurements made with 120 kHz and 420 kHz transducers in Lake Michigan. Results are from surveys conducted in fall 1993 (left) and 1994 (right).

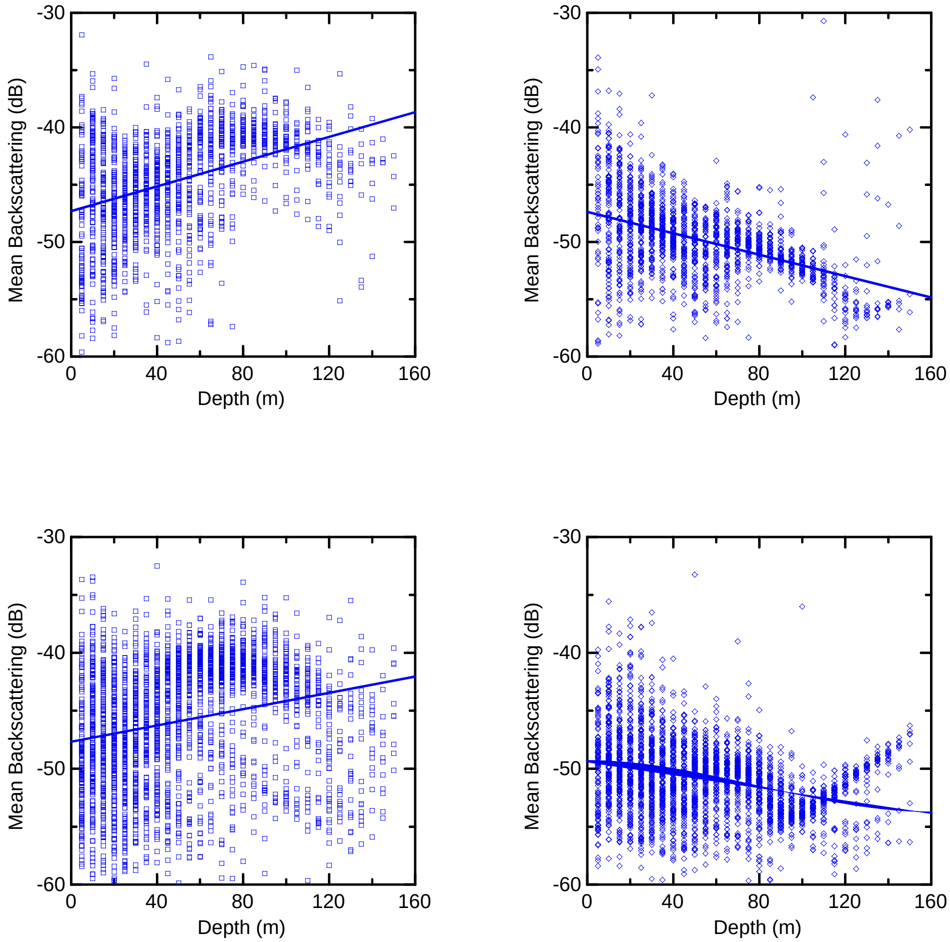


Figure 4.2 – Plots of mean backscattering cross section (dB) by depth (m) for paired 120 kHz (left) and 420 kHz (right) measurements in Lake Michigan from surveys conducted in fall 1993 (upper plots) and 1994 (lower plots). Lines show linear trends.

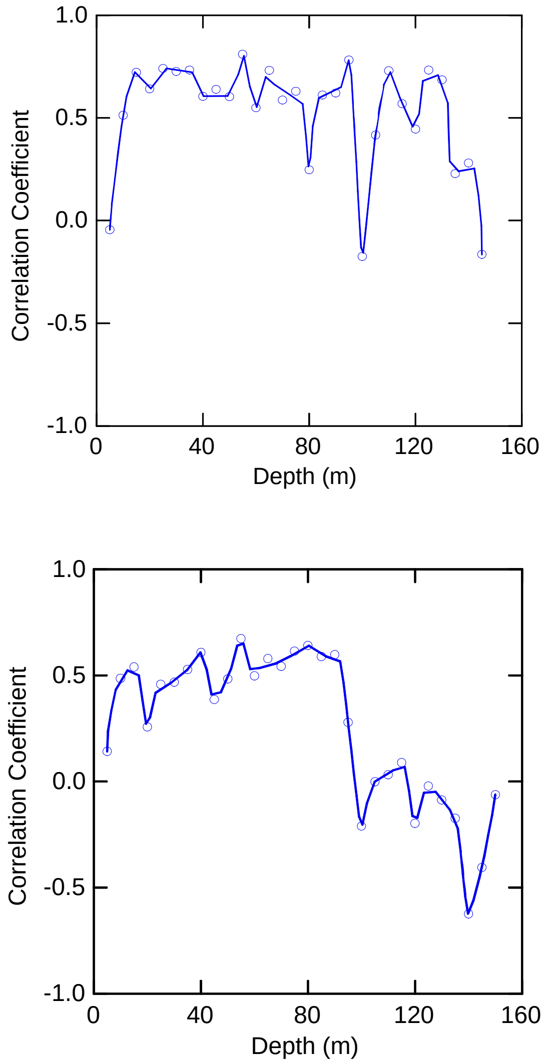


Figure 4.3 – Correlations of mean backscattering by depth for 420 kHz and 120 kHz transducers in Lake Michigan during fall 1993 (upper) and 1994 (lower).

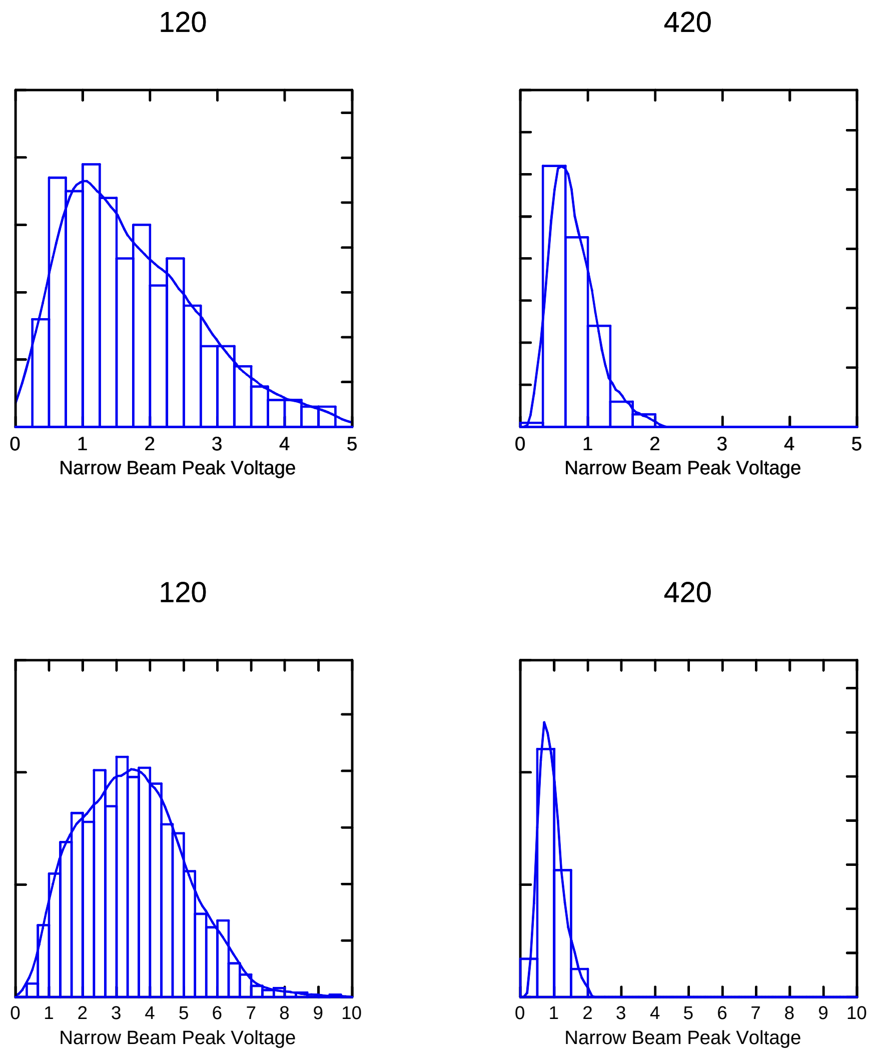


Figure 4.4 – Comparison of distributions of narrow beam peak amplitudes for single targets with 120 kHz (left) and 420 kHz (right) transducers. Echoes were from bloaters that were suspended in the deeper (bottom depths from 60 to 90 m), hypolimnetic areas (strata greater than 40 m and not closer than 5 m to bottom) in Lake Michigan off Ludington, Michigan. The upper and lower plots represent paired-comparisons of each frequency along two separate line transects surveyed in fall 1994.

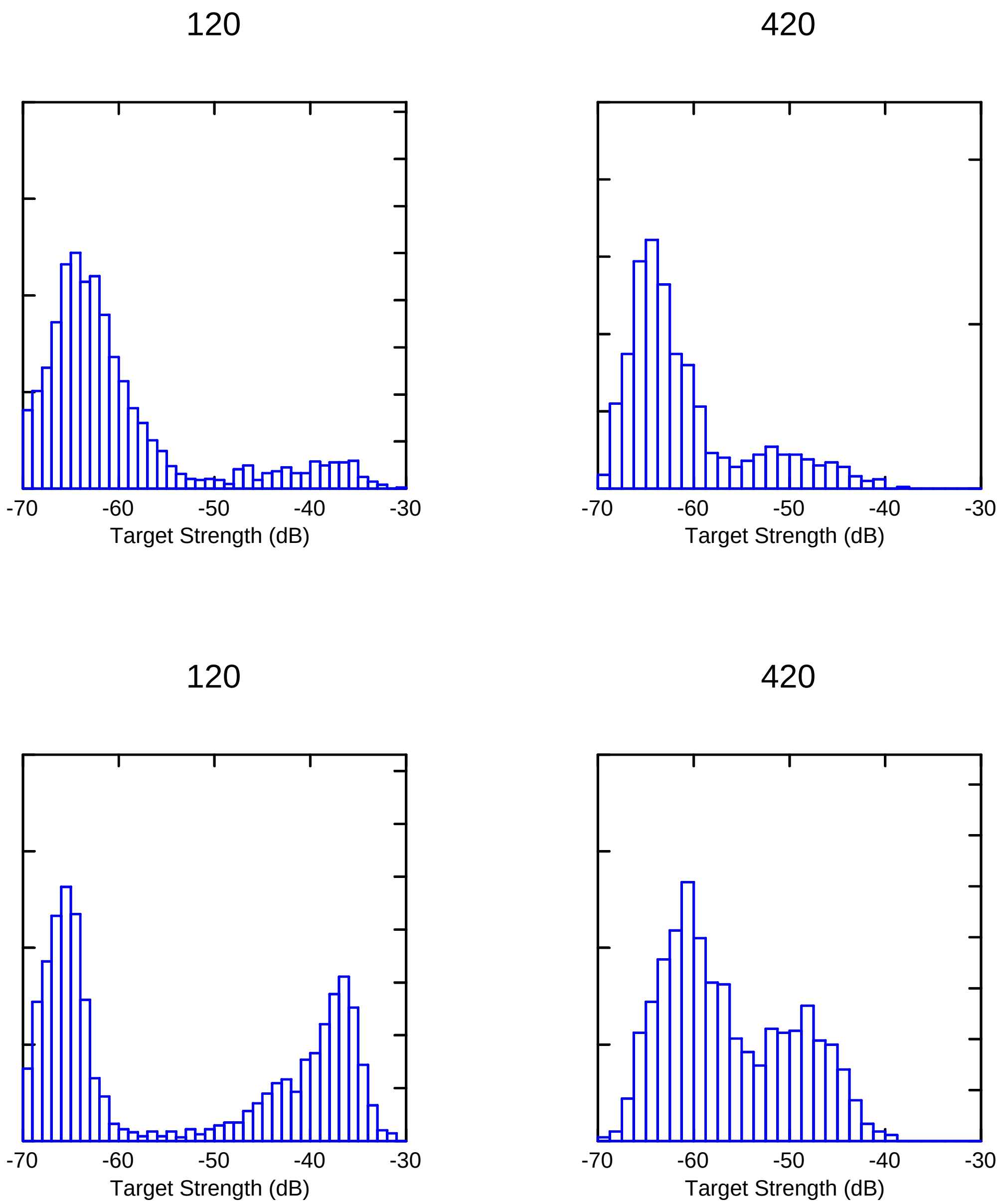


Figure 4.5 – Target strength distributions for single targets above –70 dB threshold with 120 kHz (left) and 420 kHz (right) transducers. Plots include all echoes in the deeper (bottom depths from 60 to 90 m), hypolimnetic areas (strata greater than 40 m and not closer than 5 m to bottom) in Lake Michigan off Ludington, Michigan. The upper and lower plots represent paired-comparisons of each frequency along two separate line transects surveyed in fall 1994.

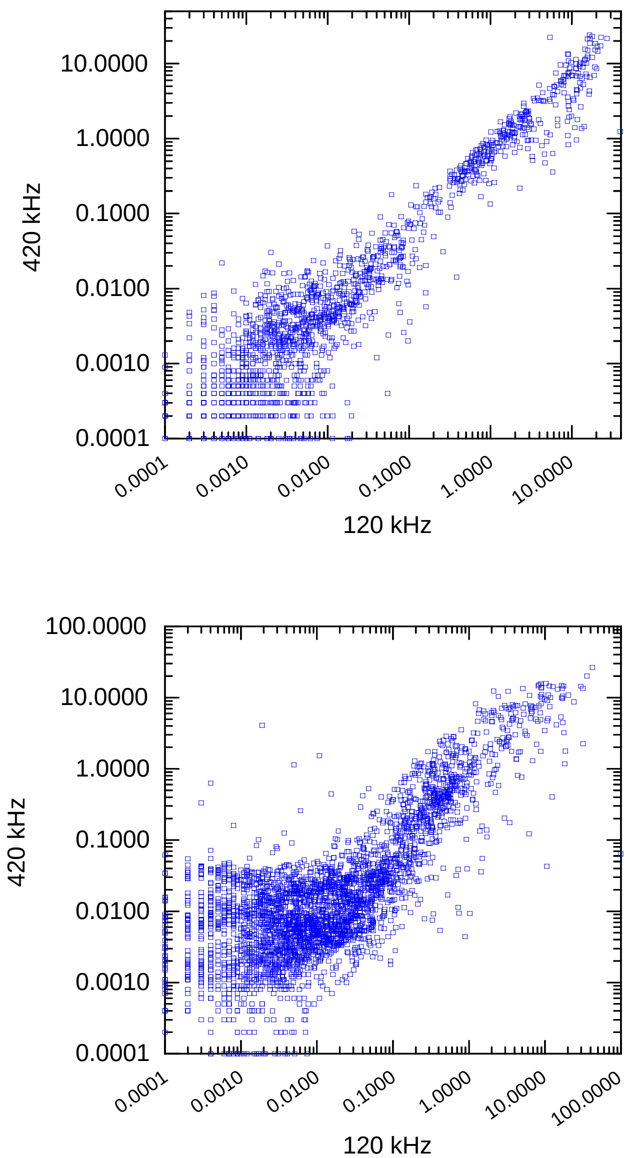


Figure 4.6 – Plots of relative density (volts squared) comparing paired measurements with 120 kHz and 420 kHz transducers in Lake Michigan during fall 1993 (upper) and 1994 (lower).

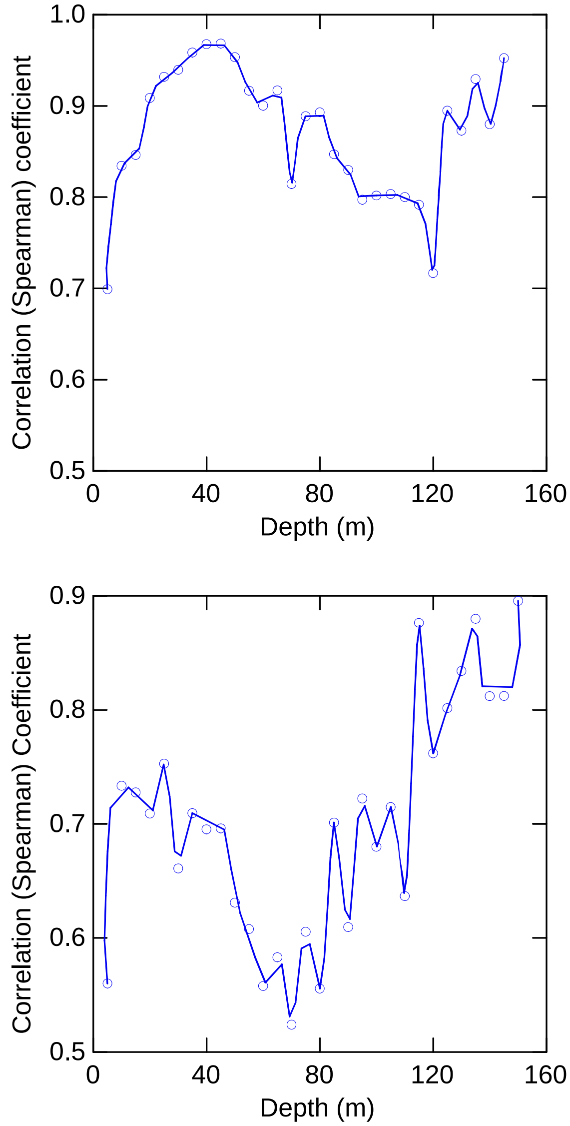


Figure 4.7 – Correlations (non-parametric) of volts squared values for 420 kHz and 120 kHz transducers by depth in Lake Michigan during surveys in fall 1993 (upper) and 1994 (lower).

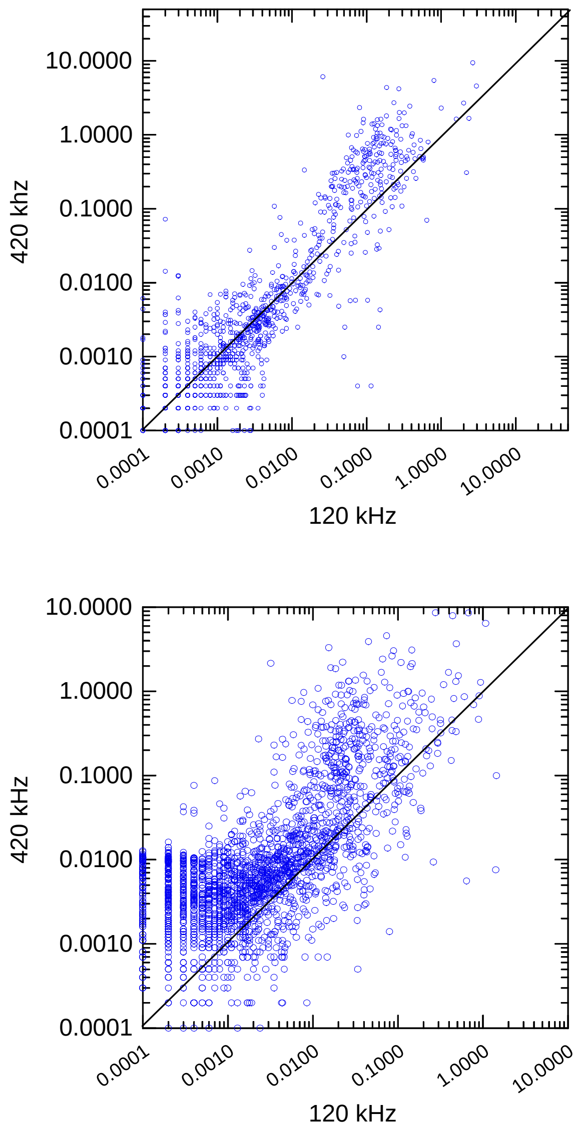


Figure 4.8 – Plot of estimated fish density (numbers/m^3) comparing paired measurements with 120 kHz and 420 kHz transducers in Lake Michigan during surveys in fall of 1993 (upper) and 1994 (lower). Diagonal represents equal values.

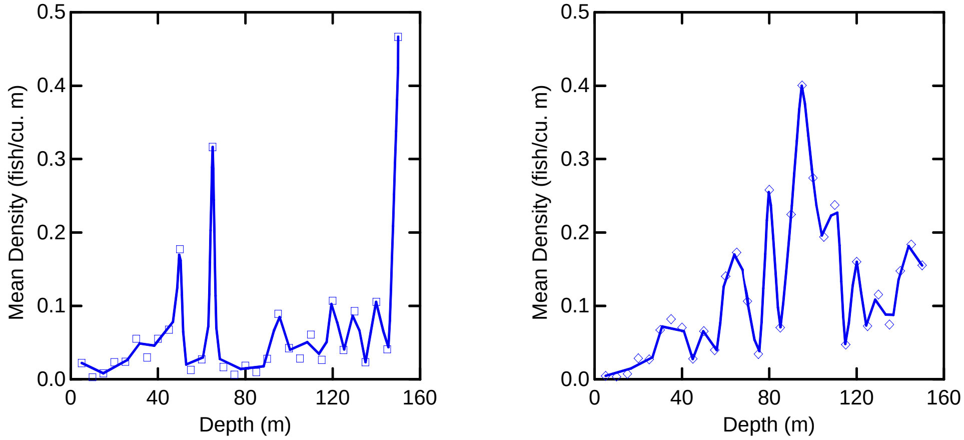


Figure 4.9 – Mean estimated fish densities by depth for paired 120 kHz (left) and 420 kHz (right) transducers for 1993.

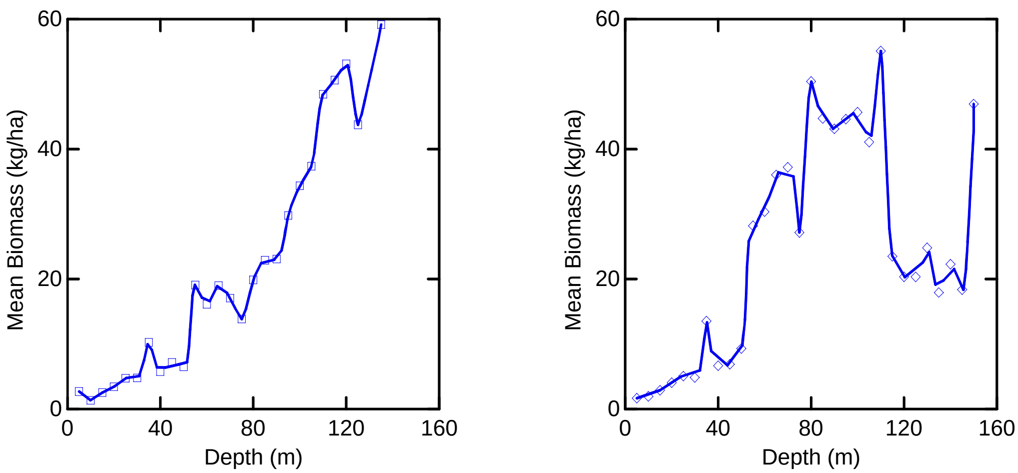


Figure 4.10 – Mean estimated fish biomass by depth for paired 120 kHz (left) and 420 kHz (right) transducers for 1993.

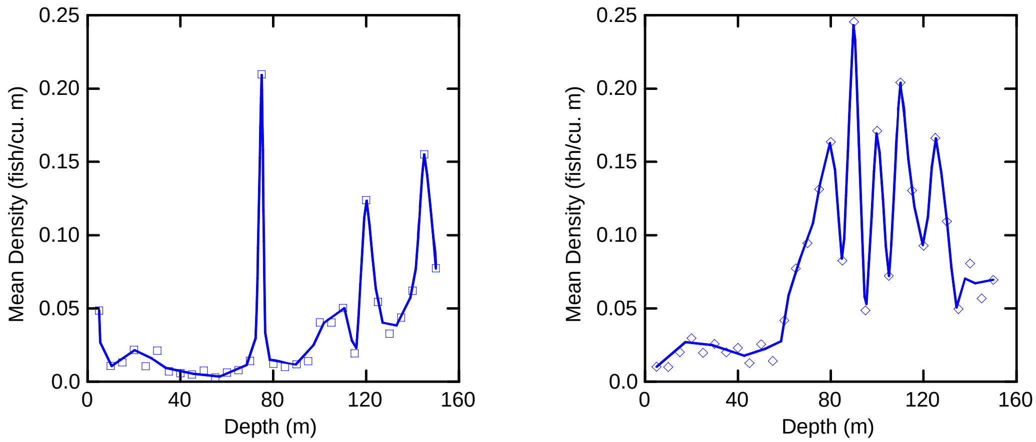


Figure 4.11 – Mean estimated fish densities by depth for paired 120 kHz (left) and 420 kHz (right) transducers for 1994.

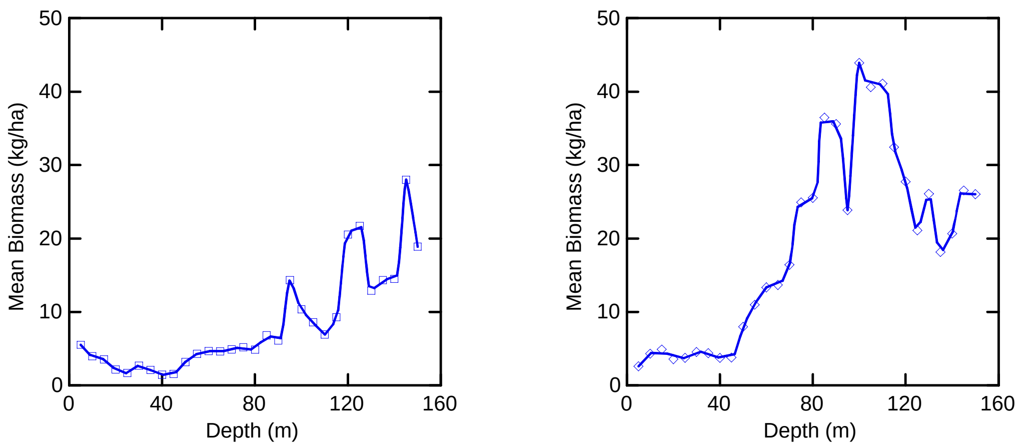


Figure 4.12 – Mean estimated fish biomass by depth for paired 120 kHz (left) and 420 kHz (right) transducers for 1994.

Section 5.

Evaluation of a Rubber-compound Window: Effects on Dual-beam Signal Intensity and Beam Pattens

Background

Echo sounder systems used in fisheries surveys generally use transducers that are either fixed to the hull of the survey vessel or deployed along side in a towed body. The cost of hull mounting and subsequent vessel haul-outs required for transducer maintenance or calibration make the use of tow bodies more attractive. Although use of tow bodies may be expected to provide a more stable platform in rough seas (MacLennen and Simmons 1992) , our experience found towed bodies to be highly affected by rough sea conditions, even with dampening systems designed to minimize the stresses exerted on the tow cable from vessel pitch and roll. In rough seas, we frequently experienced wave- and vessel-induced tow body motions that routinely resulted in the inability to successfully track the bottom signal, which limited our capability to complete some fisheries surveys.

Rubber compounds with density and sound transmission properties that closely match water have been developed by B.F. Goodrich[0] for use with sonar devices in military (principally for anti-submarine warfare) applications (B.F. Goodrich Engineered Products Group 1980). Other applications have included the use of this material in oceanographic vessels for general echo sounding, but echo sounding through rubber-compound windows have not been used with the scientific-grade systems used in fisheries acoustics. We saw the potential benefits of this product for through-hull echo sounding where acoustics surveys would be less affected by weather conditions but this configuration would also would allow access to the internally-mounted transducers for maintenance or system calibrations without vessel haul-out. The acoustic properties of these rubber compounds have not been extensively described due to commercial proprietary rights. However, the manufacturer judged that the acoustic properties of the rubber compounds were suitable for application to fisheries acoustics given our descriptions of the operating parameters. For installation, the rubber diaphragms are faired into the vessel as a flush, mated surface to the hull to avoid production of bubbles or turbulence near the face of the sound source. The manufacturer vulcanized a 5.1-cm thick rubber diaphragm (compound number

[0] [a]Mention of trade names or manufacturer does not imply U.S. government endorsement of commercial products

35080) into a 45.7-cm long and 30.5-cm wide steel frame. These dimensions were designed to accommodate the two transducers used for multiplex echo sounding. Suitable sites on a vessel for the placement of a rubber diaphragm are typically near the keel, as near to beneath the center of mass as possible to minimize changes in angular aspect due to pitch and roll (Stanton 1982). In our case, the mounting site on the hull that avoided external structures (other fixed transducers and keel coolers) and that allowed internal access through the bilge resulted in a 20E difference between the face of the transducers and the plane of the window (Figure 5.1). This angle of incidence was within the manufacturer's tolerance limits for acoustic performance of the rubber compound. However, since quantitative acoustic assessment of fish populations must rely on an accurate source level, receiver sensitivity, and beam pattern values, we were concerned that any sound absorption by the rubber compound may distort these system parameters which would compromise the accuracy of the fishery surveys. Therefore, to test the performance of the rubber compound for our application to fisheries surveys, we compared the source levels, receiver sensitivities, and beam patterns of dual-beam transducers in water to those through a rubber window situated at various angles in a controlled setting. In addition, system calibrations performed on the vessel before and after installation of the rubber window are compared.

Data Collection

Source levels and receiver sensitivities were determined for 120 kHz (10E narrow-beam and 25E wide-beam transducer) and 420 kHz (6E narrow-beam and 15E wide-beam transducer) dual-beam systems with calibration hydrophones off a barge in Union Lake near Seattle, Washington on 16February 1995. Source levels (dB 2Φ Pa at 1 m) and receiver sensitivity levels (dB 2 VΦ Pa at 1m) were first measured in water -- unfortunately, time and other logistical limitations prevented the collection of receiver sensitivity measurements in water for the 120 kHz transducer. To emulate the through-hull design (Figure 5.1), the transducers were housed in an aluminum container filled with U.S.P. grade castor oil and aimed horizontally through the side fitted with an identical rubber window. The transducers were attached to an articulating cam that was positioned to produce incidence angles of 0, 10 and 20 degrees between the face of the transducer and the rubber diaphragm. The entire container was attached to a cam that was rotated counter-clockwise from + 90E to - 90E off-axis to the hydrophone to measure beam directivity. Source levels and receiver sensitivities were measured at a 10 kHz sampling rate. The transducers were 6.1 m from the calibrated hydrophones in 4.6 m of water at 6.4E C.

The *in situ* performance of the acoustic systems were monitored before and after installation of the rubber window with the use of reference tungsten carbide spheres

1984; Foote et al. 1987). The spheres were centered from 10 m to 15 m beneath the transducers and ensonified. Mean target strength was calculated as the decibel equivalent of the measured mean backscattering cross section ($\overline{\sigma}_{bs}$). This procedure was completed in conjunction with several fisheries surveys in 1994 and 1995.

Data Analysis

The directivity relations of the near-axis portions of the main lobe were based on the non-linear fit (Quasi-Newton estimation method) of the power function

$$dB = \alpha\ \theta^{\beta}$$

where *dB* was the normalized sound pressure levels in decibels, θ was the absolute value of angle off-axis in degrees, and α and β are the estimated function parameters. Sound pressure levels up to a maximum off-axis value of 10° were used for both narrow and wide beam readings for the 120 kHz system and for the wide beam readings for the 420 kHz system; the presence of side lobes allowed a maximum off-axis value of 7° to be used for the narrow beam measurements for the 420 kHz system. The sound pressure values (dB) at 0.5-degree angle intervals, calculated from the power function equations, were used to calculate a directivity index with the Biosonics® program BSQUARE. This beam pattern index algorithm, a numerical approximation of the integral of the beam pattern power function, applied the extended Simpson's Rule for successive, non-overlapping pairs of intervals as

$$DI = h[\frac{1}{3}f_1 + \frac{4}{3}f_2 + \frac{2}{3}f_3 + \frac{4}{3}f_4 + \cdots + \frac{2}{3}f_{n-2} + \frac{4}{3}f_{n-1} + \frac{1}{3}f_n] + O(\frac{1}{N^4})$$

where *DI* is the directivity index, *h* is the angular interval of measurements (in radians), f_1 is the on-axis sound pressure value, and even and odd *f* values represent even and odd off-axis sound pressure measures (f_n is ignored since it is typically a very small value and the *O* term is an error estimate that was deemed insignificant due to the number of *n* values used)(Press et al. 1988). Effects of angle of incidence between the transducer and the rubber diaphragm on beam pattern was tested with the general linear model

$$logdB = \beta_0 + \beta_1 \cdot \log\theta + \beta_2 \cdot I$$

where *logdB* is the log-transformed absolute value of the normalized sound pressure in decibels, $\log\theta$ is the log-transformed absolute value of degrees off-axis, *I* is a classification variable to denote the control (water) and each treatment of incidence angle with the diaphragm, and β_n are with the diaphragm, and β_n are the estimated parameters (Neter, Wasserman, and Kutner 1990). A significant β_2 indicates a treatment effect. On-axis values (0 dB at 0 degrees) were not included in the logarithmic transformations used for the tests with the linear models.

Source Level and Receiver Sensitivity — Source levels and through-system receiver sensitivity levels are shown in Table I. For the 120 kHz transducer, the differences in source levels and receiver sensitivities between the control and those measured through the rubber-compound diaphragm were minimal and most were within expected measurement error. Source levels and receiver sensitivities with the diaphragm at a 20E angle of incidence were less than compared to water (Table 5.1). However, only the narrow-beam receiver sensitivity differences at this angle appeared to be great enough to suggest an effect by the rubber diaphragm.

Lower source levels and through-system receiver sensitivity values were evident in all measurements made through the rubber diaphragm at 420 kHz (Table 5.1). Source levels were 0.7 to 1.1 dB lower and receiver sensitivity values declined by 2.8 to 3.6 dB for measurements made through the rubber diaphragm. Lower source levels and reduced through-system receiver sensitivities indicated signal loss in both transmission and reception through the rubber diaphragm for this frequency. No effect of incidence angle was apparent. Based on these measurements, a 3-4 dB signal loss would be anticipated at 420 kHz.

The *in situ* target strengths of carbide reference spheres before and after installation of a rubber-compound diaphragm on the vessel are shown in Table 5.2. The mean target strength values at 120 kHz showed no discernable difference between those measurements made with and without the rubber diaphragm. The target strengths of the reference sphere were less consistent at 420 kHz, with through-diaphragm measurements up to 1.7 dB lower. The differences at 420 kHz were less than expected based on the calibration experiment and is likely due to the effects of ambient water temperature. The calibration experiment was performed at water temperatures of 6.4E C compared to the target strength measurements of the reference sphere at *in situ* water temperatures between 15E- 18EC. Sound velocities in water and in rubber are comparable at warmer temperatures and signal attenuation through the rubber increases with decreased temperature based on data provided by B. F. Goodrich showing signal loss as a function of frequency and temperature for rubber compound number 35080. In addition, the sound attenuation of this material increases with increased frequency and becomes appreciable at frequencies above 500 kHz . The frequency-temperature effects on the acoustic properties of the rubber compound explains the increased signal attenuation observed, especially at 420 kHz, in the calibration experiment.

Beam Patterns — Transmit (narrow) beam patterns for both frequencies in water and through the rubber diaphragm at each incidence angle are shown in Figure 5.2. These plots show that distortion of the beams were limited to the side lobes, and this distortion was more pronounced at increased angle of incidence of the rubber diaphragm. The observation that the main lobes at either frequency were not affected was confirmed by the general linear models which did not detect any angle effects on beam pattern ($P > 0.05$).

Through-diaphragm receive (narrow and wide) beam patterns for both frequencies are shown in Figure 5.3. Like the transmit beam patterns, the receive beam patterns only show distortion to the side lobes. Furthermore, the side lobes on the wide beams appear to be effected more than the narrow beam side lobes because of the increased asymmetry of the side lobes at increased angles of incidence (Figure 5.3).

The parameter estimates for the non-linear directivity relations for narrow and wide beams of both frequencies were characterized by a high degree of fit (Table 5.3), and appear similar at the different angles of incidence and based on the confidence intervals. This observation was verified by the linear models which showed that no significant incidence angle effect was detected ($P > 0.05$) for either the narrow and wide beams for either frequency. Directivity index values also show the similarity of the receive beam patterns between the control and at the various angles with the diaphragm (Table 5.4). These results agree with the transmit beam pattern tests indicating that the rubber diaphragm does not appear to have any effect on the directivity of the main lobe of the sound beam, even at the most severe angle of incidence tested.

Conclusions

The use of rubber-compound windows for fisheries acoustics must consider operating frequency and ambient water temperatures. Signal attenuation by the rubber become pronounced with increased frequency and decreased temperature. Based on our results, a 420 kHz system could be expected to lose up to 3-4 dB in colder water through a 5.1-cm thick rubber diaphragm. At 120 kHz, signal loss was negligible.

For both frequencies, the effects on beam pattern by the rubber diaphragm were limited to the side lobes and the different incident angles had no detectable effect on directivity of the main lobes. This is not a substantial effect since only targets within a beam pattern threshold of 3 dB, or approximately one-half the nominal beam width, should be used for calculations of mean target strength with dual-beam systems (Traynor and Ehrenberg 1979).

Table 5.1. Comparison of source levels (dB 2Φ Pa at 1 m) and through-system narrow beam (NB) and wide beam (WB) receiver sensitivity levels (dB 2 VΦ Pa at 1 m) for 120 kHz and 420 kHz dual-beam echo sounders in water and through a rubber-compound diaphragm at three angles of incidence. Parentheses indicate difference in values between water and diaphragm.

		Water	Rubber-Compound Diaphragm		
			0 Degrees	10 Degrees	20 Degrees
120 kHz	Source Level	213.99	214.12 (0.13)	213.91 (-0.08)	213.63 (-0.36)
	Receiver Sensitivity (NB)	-162.95	-162.67 (0.28)	-162.88 (0.07)	-163.88 (-0.93)
	Receiver Sensitivity (WB)	-156.24	-155.93 (0.31)	-156.03 (0.21)	-156.60 (-0.36)
420 kHz	Source Level	219.20	218.52 (-0.68)	217.91 (-1.29)	218.11 (-1.09)
	Receiver Sensitivity (NB)	-169.97	-172.81 (-2.84)	-173.56 (-3.59)	-173.23 (-3.26)
	Receiver Sensitivity (WB)	-171.15	-174.17 (-3.02)	-174.07 (-2.92)	-174.55 (-3.40)

Table 5.2. Comparison of mean backscattering cross section (expressed in dB) of reference tungsten carbide spheres with 120 kHz and 420 kHz dual-beam echo sounders before and after installation of a rubber diaphragm. Measurements were made *in situ* aboard a research vessel during 1994-1995. Target strength values shown for the 120 kHz system are for a 33-mm diameter reference sphere and for the 420 kHz system for a 17-mm diameter reference sphere.

	No Diaphragm	With Rubber Diaphragm		
120 kHz	-41.7	-41.7	-41.3	-41.7
420 kHz	-53.4	-55.1	-53.7	-[b]
Date	July 1994	July 1994	September 1994	September 1995

[b]Measurements not made.

Table 5.3. Parameter estimates, 95% confidence intervals (C.I.), and corrected R^2 values for directivity relations of narrow and wide beam patterns measured through a rubber diaphragm at three angles of incidence. Equations based on fit of power function $dB = \alpha\theta^{\beta}$, where dB is normalized sound pressure in decibels and θ is degrees off axis.

Angle of Incidence		Narrow Beam		Wide Beam	
		β	α	β	α
		120 kHz			
0 degrees	Estimate	2.318	-0.070	1.956	-0.046
	Upper 95% C.I.	2.614	-0.118	2.296	-0.081
	Lower 95% C.I.	2.021	-0.220	1.617	-0.010
	R^2 (corrected)	0.97		0.94	
10 degrees	Estimate	2.386	-0.065	1.706	-0.081
	Upper 95% C.I.	2.529	-0.044	1.912	-0.045
	Lower 95% C.I.	2.241	-0.086	1.500	-0.117
	R^2 (corrected)	0.99		0.97	
20 degrees	Estimate	2.453	-0.056	1.580	-0.108
	Upper 95% C.I.	2.733	-0.021	1.772	-0.064
	Lower 95% C.I.	2.173	-0.090	1.388	-0.153
	R^2 (corrected)	0.98		0.97	
		420 kHz			
0 degrees	Estimate	3.015	-0.064	2.201	-0.029
	Upper 95% C.I.	3.347	-0.022	2.587	-0.006
	Lower 95% C.I.	2.683	-0.105	1.815	-0.052
	R^2 (corrected)	0.98		0.97	
10 degrees	Estimate	2.671	-0.111	2.065	-0.041
	Upper 95% C.I.	2.994	-0.038	2.769	0.020
	Lower 95% C.I.	2.348	-0.184	1.361	-0.103
	R^2 (corrected)	0.99		0.89	
20 degrees	Estimate	2.888	-0.072	1.956	-0.054
	Upper 95% C.I.	3.160	-0.036	2.501	0.011
	Lower 95% C.I.	2.616	-0.107	1.351	-0.119
	R^2 (corrected)	0.99		0.93	

Table 5.4. Comparison of directivity index values calculated for narrow and wide (receive) beams of 120 kHz and 420 kHz dual-beam echo sounders in water and through a rubber diaphragm at three angles of incidence.

			Rubber-Compound Diaphragm		
		Water	0E	10E	20E
120 kHz	Narrow Beam	-	26.05	26.21	26.13
	Wide Beam	-	24.76	24.95	24.95
420 kHz	Narrow Beam	29.54	29.48	29.81	29.30
	Wide Beam	27.96	27.82	27.82	29.79

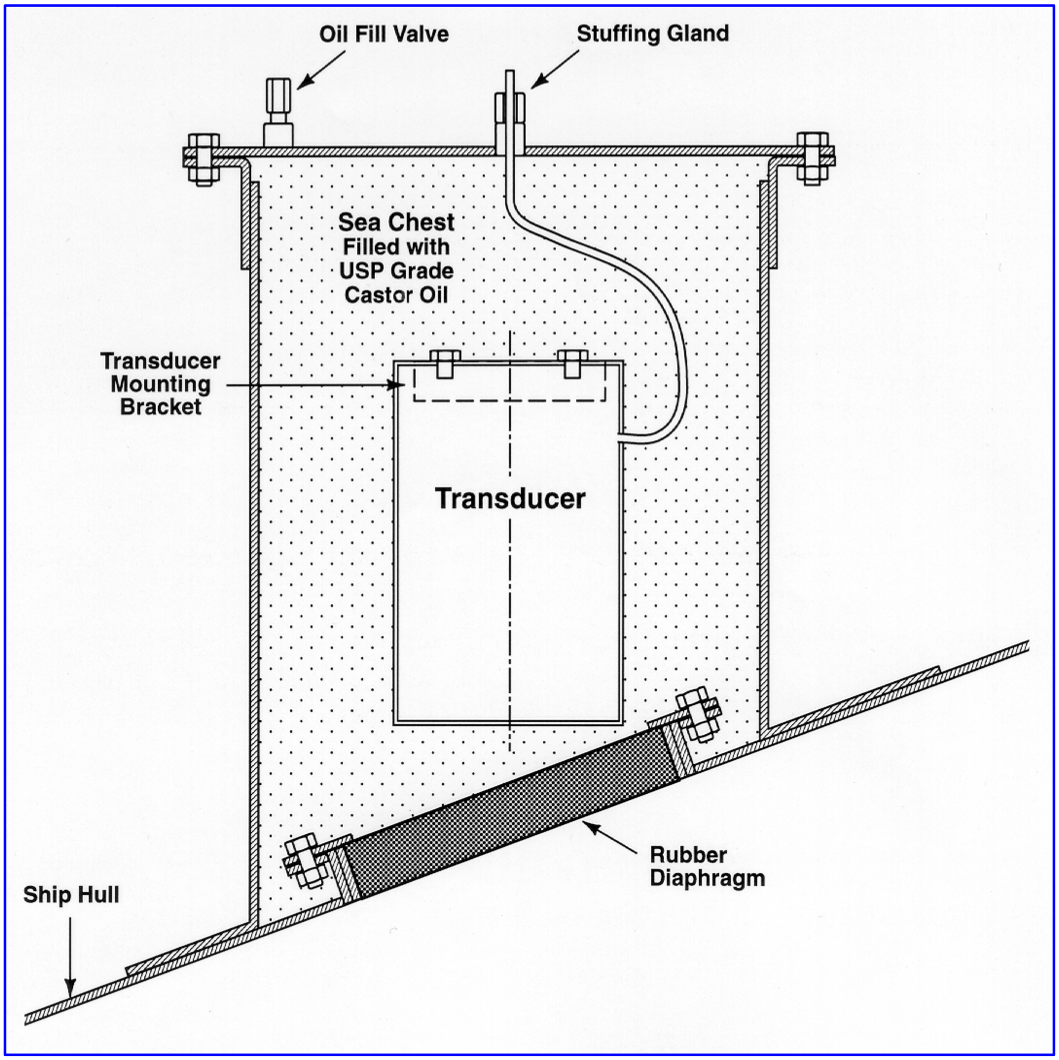


Figure 5.1 – Cross-section schematic of the hull-mounted rubber diaphragm. Transducer is housed in oil-filled sea chest. Hull aspect and downward orientation of transducer results in 20E angle difference between face of transducer and rubber diaphragm.

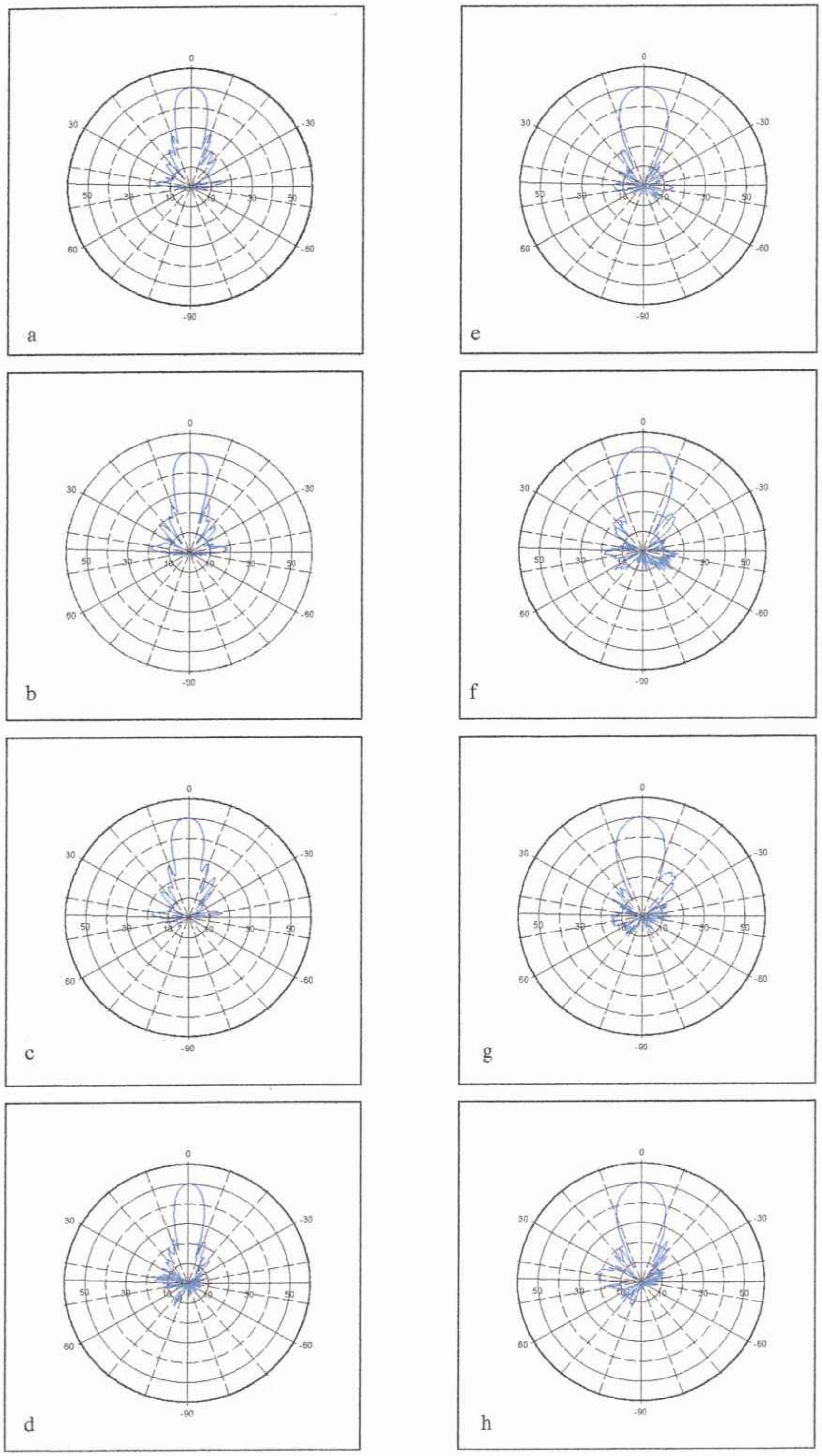


Figure 5.2 – Polar plots of transmit (narrow) beam patterns for 420 kHz (a-d) and 120 kHz (e-h) dual-beam transducers measured in calibration experiment. Beam patterns are for control in water (a and e) and through rubber diaphragm at angles of 0° (b and f), 10° (c and g) , and 20° (d and h). Radial measures are in decibels and angular measures range from +90° to -90° off axis to the hydrophone.

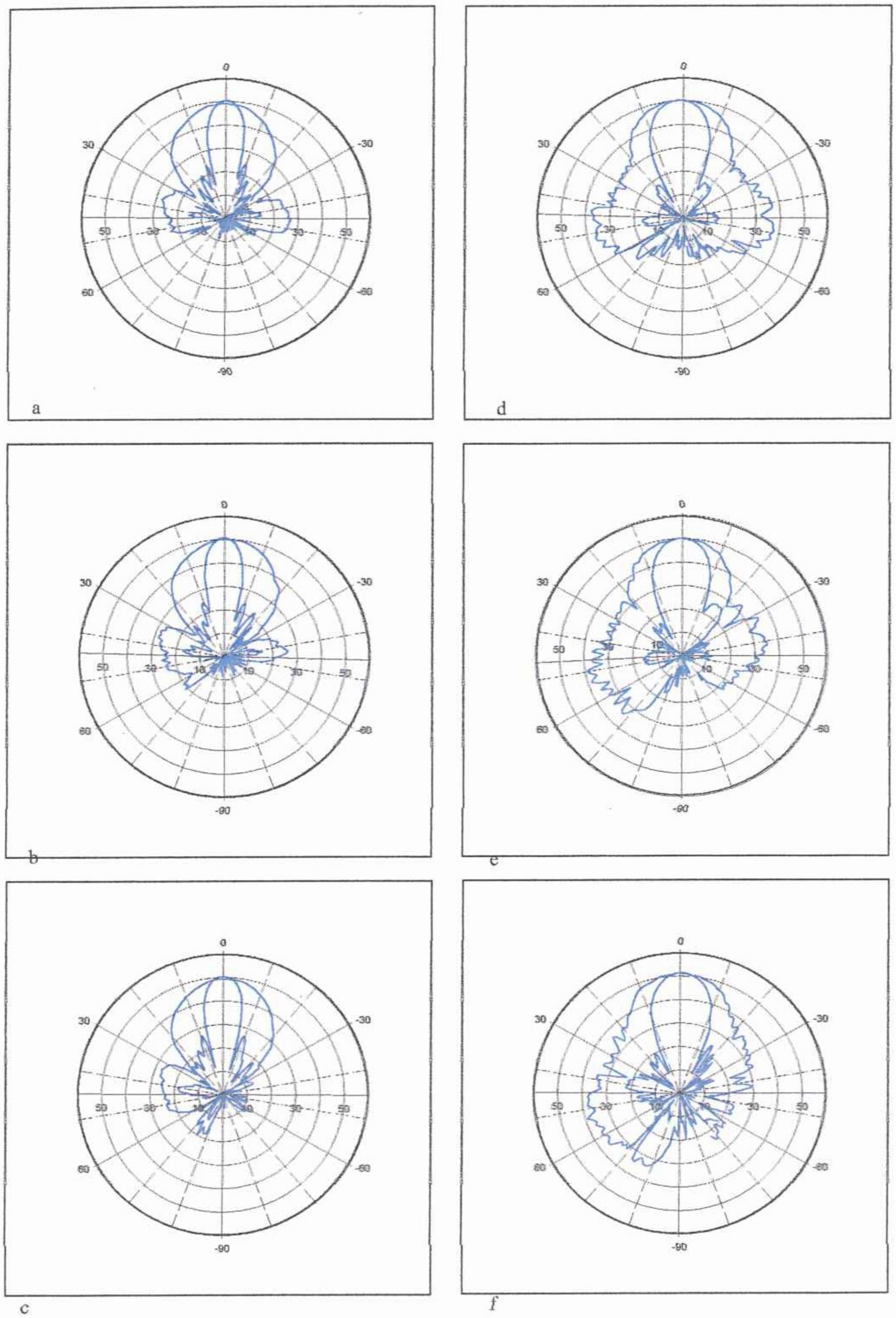


Figure 5.3 – Polar plots of receive (narrow and wide) beam patterns for 420 kHz (a-c) and 120 kHz (d-f) dual-beam transducers measured in the calibration experiment. Beam patterns were measured through the rubber diaphragm at angles of 0° (a and d), 10° (b and e), and 20° (c and f). Radial measures are in decibels and angular measures range from +90° to -90° off axis to the hydrophone.

Section 6.

Lake Michigan Geographic Information System

Reliable lake-wide estimates of fish biomass require accurate measures of the surface areas that represent the ranges of depths sampled, in addition to accurate measures of fish abundance. Acoustic estimates of fish standing stock (kg/ha) for each species were expanded by the total geographic area (ha) that represented a particular survey (see Procedures and Methods in Section 7 - Acoustic Estimates of Abundance). Further, stratification schemes of the measured fish densities, both in terms of bathymetric areas and geographic areas, rely on a depth profile database of sufficient resolution to afford the flexibility necessary to determine an optimal survey design.

Geographical Information System Development

A complete Geographical Information System (GIS) database for Lake Michigan was not available at the initiation of this study. At that time, the only geographic data that were available were surface area measurements that related to the established bottom trawl locations on Lake Michigan, and these were coarse measures that did not span the depth ranges nor the depth stratification scheme needed for the acoustic surveys. Without an appropriate GIS database, we were unable to determine lake-wide biomass estimates easily nor reliably from the acoustics surveys.

Depth profile data, soundings made at 2 km intervals in Lake Michigan, were available from National Oceanic and Atmospheric Administration (NOAA). We acquired these data and began the process of developing the GIS database with the ARC/INFO software product. Initial review of the spatial coverage of these data reveled large tracts of missing depth measurements in both off-shore and near-shore areas. To remedy this discontinuous coverage, we relied on the depths shown on the appropriate NOAA navigation charts and we were able to follow the 2-km latitudinal and longitudinal coordinates of these soundings by means of a grid superimposed on a Mylar overlay. These depth and spatial coordinate readings were added to the ARC/INFO database.

At the 2-km resolution, the database size was sufficiently large to tax the micro-computer processing and storage media capabilities at that time. We divided the database into more manageable sub-units, based on the established fishery statistical districts (Smith et al. 1961). We modified these district boundaries slightly to conform to the 10-degree grids that are the convention for sub-statistical district geographical references in the

Great Lakes. These management units form 12 districts within the main basin, excluding Green Bay and Grand Traverse Bay (Figure 6.1). The ARC/INFO GIS database for Lake Michigan was completed in 1993.

Surface Area Features of Lake Michigan

Based on our GIS database, the surface area in hectares was determined for 10-m depth contours in each statistical district (Table 6.1). These values were used in the expansion of measured fish densities to produce the lakewide estimates. The surface area of the main basin, not including Green Bay or Grand Traverse Bay, is 5,274,653 ha. The area of interest in this study, from 10 m to 150 m, totals 4,125,619 ha, or 78% of the total surface area of the main basin (Table 6.1). It should be noted that the area between the 10-m and 150-m contours are a greater proportion of the total area in the southern regions of the lake as compared to the northern regions (Figure 6.1).

Table 6.1 – Surface areas in hectares by 10-m depth contours for statistical districts on Lake Michigan, generated from GIS depth profile database.

	Statistical District															
Depth Contour (m)	MM-1	MM-2	MM-3	MM-4	MM-5	MM-6	MM-7	MM-8	WM-1	WM-2	WM-3	WM-4	WM-5	WM-6	Illinois	Indiana
0-10	73190.2	18236.2	98807.7	11795.5	18414.6	12156.6	9952.9	12411.8	66172.6	11593.6	21301.9	20787.3	16565.9	7798.4	27487.6	34178.6
10-20	59006.8	19482.9	122746.6	7019.2	21797.1	19412.2	17419.8	40018.7	30666.5	17609.9	16727.4	17941.1	22461.2	18535.7	48328.1	70283.1
20-30	48700.5	17373.8	106221.9	5789.1	16708.3	11744.4	13623.7	47272.3	15828.7	55245.4	14055.5	15519.9	21488.0	9433.5	34479.7	26016.5
30-40	16923.5	18393.4	61971.8	5488.4	1328.6	10600.1	14364.0	47693.3	696.9	40149.1	13823.7	14986.3	18313.5	6681.1	39956.2	2201.5
40-50	179.4	17737.6	59819.3	5704.8	12993.8	10169.4	15486.7	50714.4		8854.6	11738.4	15178.5	20862.5	9284.7	31493.2	
50-60		16793.6	52971.9	5148.0	11778.3	13865.0	18342.6	49399.3		679.0	28931.9	20385.1	27466.1	8541.2	22853.3	
60-70		12460.5	42826.5	3980.0	10566.3	12212.0	25083.3	52119.3			14369.8	18495.7	31567.7	7480.3	25084.0	
70-80		8179.9	33533.3	3335.6	10292.4	9388.7	48235.1	81622.7			12942.3	29188.6	67424.4	12411.3	32296.0	
80-90		7099.3	31495.8	3195.0	14301.2	6862.9	94991.2	76701.8			12289.6	37789.9	91426.7	12186.5	27205.5	
90-100		7326.4	33050.0	3285.6	11680.9	7553.5	110634.0	42939.3			10580.3	26534.3	102536.2	13020.8	18251.7	
100-110		8451.2	32940.2	2801.1	10402.8	9092.2	95473.9	34999.9			10921.7	19320.4	44476.9	18358.1	16425.8	
110-120		8318.9	24935.4	2732.3	10277.0	15872.2	57319.3	26858.2			9637.0	18924.4	32531.7	15595.7	16661.6	
120-130		9547.8	22580.2	759.6	9399.3	22937.8	50665.8	19266.0			10276.4	22456.4	33999.8	16002.5	17051.7	
130-140		9518.2	28618.9	779.9	11297.1	28776.7	22211.3	17560.7			11526.9	19607.1	40081.8	16832.5	11920.1	
140-150		8490.0	26678.7	714.5	14308.5	31192.6	12023.1	14711.5			12775.1	16683.2	19660.6	33717.3	4998.7	
150-160		4189.3	21555.9	793.6	12740.8	41762.0	2425.6	20015.3			13253.1	15325.4	1123.9	31230.3	42.3	
160-170		3148.1	18681.4	1074.9	11934.4	42671.2		22017.7			17030.9	16497.0	435.0	5336.2		
170-180		1703.3	7995.6	1244.8	14520.2	31135.8		147.0			18324.6	12797.1				
180-190			4073.9	240.6	19824.3	6287.3					25777.9	10844.5				
190-200					28918.0	5595.9					18598.6	12980.4				
200-210					19926.5	7723.7					12405.6	16585.3				
210-220					11933.1	7067.0					8206.1	18353.3				
220-230					9081.1	15498.6					4038.9	23565.3				
230-240					11456.2	25076.9					1764.9	23734.3				
240-250					17292.6	10202.9					1805.1	18584.9				
250-260					28568.2	6300.2					1305.7	7531.9				
260-270					17822.4	1579.8					515.2	1247.8				
270-280					546.5	169.3										
280-290						89.7										
290-300						15.6										
Total Area (ha)	198000.4	196450.4	831505.1	65882.4	390110.4	423012.2	608252.4	656469.2	113364.6	134131.6	334924.6	491845.7	592421.9	242446.3	374535.7	132679.7
Proportion 10-150	-	0.86	0.82	-	0.43	0.50	0.98	0.92	-	-	0.57	0.60	0.97	0.82	0.93	0.74

- indicates not considered for areal expansions as part of the acoustic study

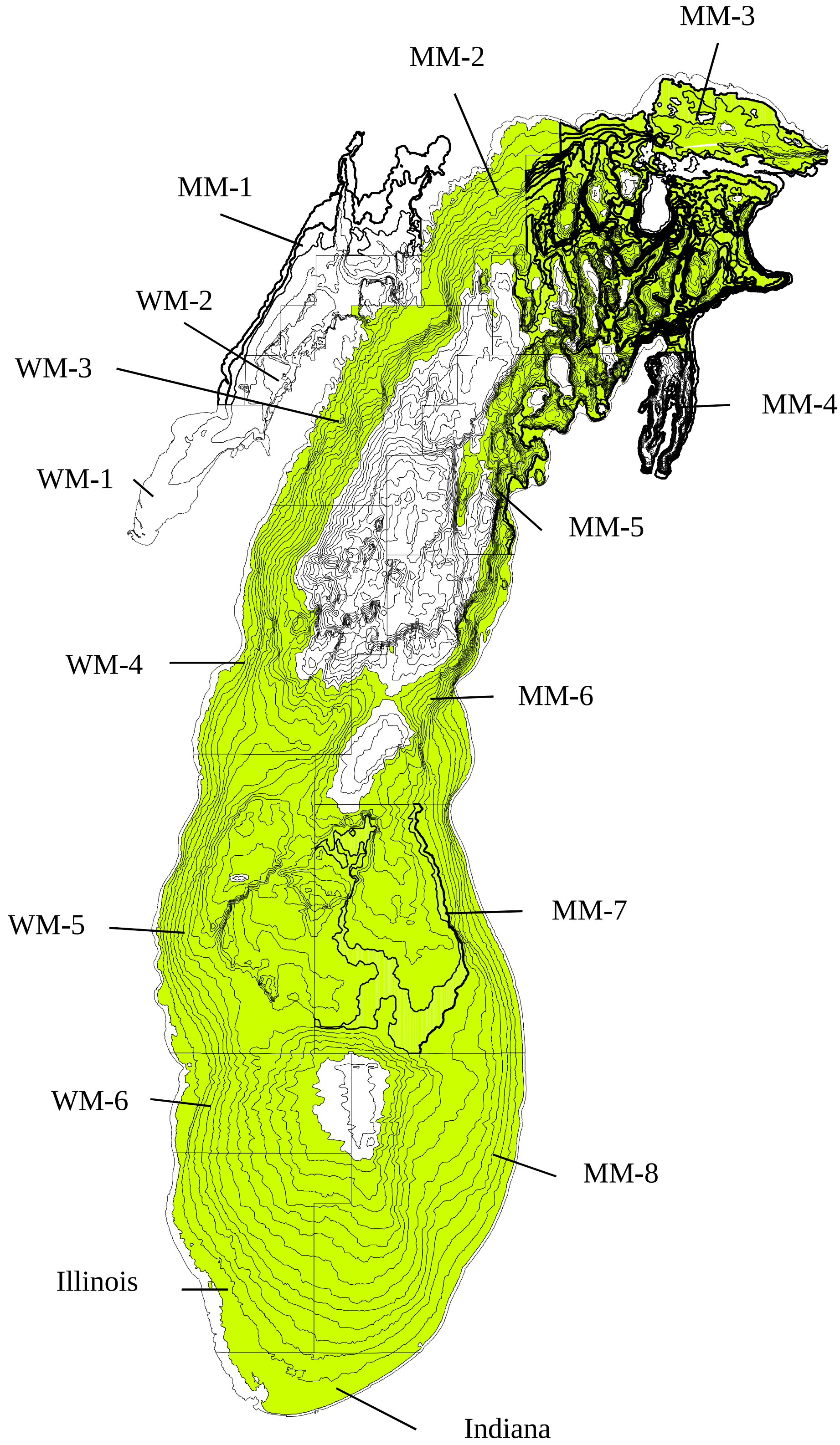


Figure 6.1 – Bathymetric relief map of Lake Michigan showing 10-m contour intervals and statistical districts. Area of lake between the 10-m and 150-m contours, highlighted in yellow (excluding Green Bay and Grand Traverse Bay), indicates area considered for the acoustic biomass estimates.

Section 7.

Acoustic Estimates of Abundance

Objective

The principal objective of this study was to acoustically estimate abundance (biomass) and to determine the stock structure of the pelagic fish community in Lake Michigan. However, this study was also designed to analyze seasonal, geographical and midwater distributions of the various pelagic fish species throughout Lake Michigan. Our recommendations for future integration of acoustics techniques as part of fish population assessment in Lake Michigan will be based on this full suite of findings.

Procedures and Methods

Since the various species of fish cannot be easily discriminated solely by their echoes, we investigated the integration of acoustic and midwater trawl survey techniques as part of this study. The coordination of acoustic and midwater trawl sampling required the development and application of a multi-vessel survey technique. Two vessels equipped with acoustic and midwater trawling gear – the *S/V* Steelhead (Michigan DNR) and the *R/V* Grayling (USGS/BRD) – were used to conduct the surveys (Figure 7.1). Acoustic measurements and midwater trawls were made during night along line transects by the two vessels in tandem: one vessel principally responsible for the acoustics followed by the second vessel conducting the midwater trawl collections.

For each survey, transects were located at various locations throughout Lake Michigan, excluding Green Bay and Grand Traverse Bay. The distribution of transect locations was not random. Our principal sampling strategy was to maximize the geographic coverage of Lake Michigan – within the constraints of vessel logistics and time – in order to encompass as wide a range as possible of potential fish densities. A distribution of sample locations that considers the full diversity of the population is desirable because the samples, being more representative, will allow for more precise estimates of the population mean or total (Thompson 1992). The number and selection of general locations was determined *a priori* based on this strategy. The specific site and position of each transect at a location, however, was determined at the time of the survey. Several local factors influenced the completed line transect location including bathymetric characteristics, vessel logistics, and avoidance of navigation hazards (e.g. fishing nets). This site selection method introduced an arbitrary feature that helped to ensure objectivity in the sample design, however we also considered the potential for site selection bias due to local spatial variability and any influence of geographic scales on fish density estimation (see Section 10 – Geographic Sampling Scale and Variability in Pelagic Fish Distributions).

Each line transect was oriented cross-contour and ranged in depth from 10 m to a maximum of 150 m (the exception was in fall 1991, where transects at the first sites were oriented along-contour in association with established bottom trawl stations – as this first survey progressed, the advantages of cross-contour design became apparent and the cross-contour technique was adopted). Acoustic density estimates were calculated for 5-m or 10-m vertical depth strata and by 10-m bottom contour depth zones (Figure 7.2). Along each transect, midwater trawl tows targeted fish aggregations at depths and locations as indicated by the acoustics. We employed netsondes (Figure 7.3) during each tow to accurately position the midwater trawl to the desired depth and to monitor the trawl's fishing performance. The trawl catches were used to determine the midwater species composition, and to provide biological information and samples for target strength analyses. Fish collected in the midwater trawls were identified, measured, and weighed in species-aggregate. In addition, water temperature profiles were measured along each transect at 20-m depth intervals, beginning at 10 m with an electronic CTD recorder.

Different sizes of midwater trawling gear were used aboard the research vessels. Since the trawl catches were used for species composition and not for quantitative comparisons of catch per unit effort, the use of different sized gear was acceptable. Trawl size was dictated by gear handling capabilities on the vessels: smaller trawling gear was fished from the *S/V Steelhead* and larger trawls were fished off the *R/V* Grayling. The midwater trawl used by the *S/V Steelhead* had a 8-m headrope and opened vertically about 3 m. The effective fishing area was about 25 m^2. The *R/V* Grayling used two midwater trawls. The original trawl deployed off the *R/V* Grayling had a 17-m headrope, a 6-m opening and an effective fishing area of about 60 m^2 (this net was also used for collections made during summer 1993 off the *R/V Cisco*). A second net, developed and custom built for this study, had a 28-m headrope, opened vertically 6-7 m, to provide an effective fishing area of about 100 m^2. Tows were made at 2-3 $m \cong sec^{-1}$ for 15- 20 minutes in duration at target depth.

The successful implementation of coordinated, multi-vessel sampling was dependant on both vessels being equipped with acoustic and midwater trawl gear, as well as Global Positioning System (GPS) navigation equipment. With this complimentary configuration, we had considerable flexibility in using either vessel to collect acoustic or midwater trawl data. Smaller trawling gear worked best in the shallower strata of the water column; the small trawl was easy to deploy and retrieve and more tows could be completed in a given time. The larger trawls were fished where fish were less concentrated or in the deeper strata; however, deployment of these nets required longer set and retrieve times. In practice, the vessel with the small trawl would typically follow the other vessel (conducting the acoustics) and carry out tows at locations communicated via radio. These fishing assignments included specific latitude-longitude coordinates and fishing depths. Where necessary, the acoustics vessel could complete a section of the transect and also begin to fish with the large trawl, and the second vessel could either continue to make fish collections or complete the acoustic measurements along the transect. In this fashion, we were able to sample efficiently due to our ability to respond to a variety of sampling conditions or our ability to continue to sample in the event of equipment failure (either acoustic or trawl malfunctions). In addition, each vessel was able to collect concurrent target strength measurements with each midwater tow in order to develop a relation between target strength and fish size, a critical relation for acoustic assessment (see Section 3 – Target Strength-Fish Size Relation).

The dual-beam, multi-frequency 120/420 kHz acoustic systems employed for the majority of the study were acquired and first used in fall 1992. These systems had 120-kHz, 7E narrow-beam and 18E wide-beam transducers and 420-kHz, 6E narrow-beam and 15E wide-beam transducers (Table 7.1). Acoustic sampling prior to this date was conducted with a previous generation dual-beam, single frequency 120 kHz unit with a 10E narrow-beam and 25E wide-beam transducer (Table 7.1)(see Section 2 for a detailed description of dual-beam acoustic methodology). The transducers were originally deployed in tow bodies that were held 3-4 m abeam the vessel and suspended from heavy-duty rubber snubbers to dampen the effects of vessel motions, which helped maintain a consistent downward aspect in all sea conditions. In 1994, the transducers were mounted inside the vessels and aimed through acoustic windows flush-mounted on the hulls of the research vessels (see Section 5 – Evaluation of Rubber-Compound Window). Each system was calibrated to U.S. Navy standards by the manufacturer (Table 7.1). The acoustic signals were processed during collection with BioSonics® ESP hardware and software, which includes computer-housed signal processing boards interfaced with the echo sounders. To avoid bias against smaller fish, a threshold voltage equivalent to a target strength of at least -60 dB was used during signal acquisition. Echoes which exceed the threshold were filtered by pulse width criteria to remove non-single (multi-modal) targets (Table 7.1). All signals were digitized and recorded with reference voltages on digital audio tapes (the taped acoustic data collected before fall 1992 were re-processed with the BioSonics® ESP system).

Performance of each acoustic system was monitored with the use of reference tungsten carbide spheres (Foote et al. 1987). During the survey, a reference sphere was centered from 10 m to 20 m beneath the transducers and ensonified. The measured target strength values for the reference spheres were compared with established values.

Acoustic-based estimates of abundance were derived from the application of a combined dual-beam/echo integration technique (Burczynski and Johnson 1986), where the measured *in situ* mean backscattering cross section ($\overline{\sigma}_{bs}$) of individual fish for the sampled area is used to scale the mean squared voltages ($\overline{V}^2$). The theory of echo integration states that the density of fish in a given depth stratum is directly proportional to the average squared voltage at a time varied gain of 20 log (R) + 2αR, where R is range and α is the absorption coefficient (for a derivation and discussion of the theory of echo integration, see Burczynski 1982). For a defined stratum in the water, the relation between fish density and the integrator output is given by (assuming range dependancy at unity):

$$D_{\Delta R} = A\overline{V}^2$$

where $D_{\Delta R}$ is fish density in stratum (fish/m^3), A_i is integrator scaling factor (fish/m^3 V^2), and $\overline{V}^2$ = averaged squared voltage of echoes from stratum. The integrator scaling factor A is defined as:

$$(\pi\,\tau\,c\,\overline{\sigma}_{bs}\,p_o\,g_x^2\,b^2(\theta,\varphi))^{-1}$$

where π = 3.1416, τ is the pulse width, σ_{bs} is the mean backscattering cross section, p_o is the RMS transmitted pressure measured at one meter from transducer (μPa), g_x^2 is receiver gain, and b^2 (θ,φ) is the beam pattern factor. The echo reflecting power of a fish, commonly referred to as the target strength (TS), is the decibel equivalent of the target's backscattering cross section where:

$$TS = 10\ \log(\sigma_{bs})$$

Since the acoustic size of fish typically range greater than -60 dB, a threshold voltage equivalent to a TS of -60 dB was used to calculate $\overline{\sigma}_{bs}$ for estimation of fish abundance.

Computations of fish abundance were performed with NBS/ESP software. This software was specifically developed for use with the BioSonics® ESP system by scientists at the Great Lakes Science Center in cooperation with the manufacturer (see Appendix). NBS/ESP is a Windows® application that allows considerable flexibility in data processing and output. Development of this echo processing software was a major undertaking with the final product completed in 1996; all BioSonics® ESP-formatted acoustic data files we collected prior to this date were subsequently processed with the final version of NBS/ESP. Fish abundance estimates derived with NBS/ESP were formatted for direct loading into the Center's RVCAT relational database housed in the Oracle® database environment. The fish abundance and associated acoustic data were selected from RVCAT and imported into SAS® for statistical analyses and calculation of species-specific biomass.

Species-specific density estimates for the different areas in the water column were determined by application of species composition from the midwater trawls to the total estimate of fish abundance. Coverage by the midwater trawling was not systematic, but targeted fish aggregations as indicated by the acoustics (Figure 7.2). The species composition from a particular trawl was applied to the immediate area and was extended to include adjacent areas assumed to be represented by the area trawled based on fish distribution patterns, similarity of size distributions (as determined by measured target strength), as well as temperature and strata depth characteristics (see Section 8 – Midwater Distribution of Pelagic Fishes in Relation to Physical Characteristics). Instances occurred where individual fish caught during a tow obviously were not collected at the target depth. This by-catch of fish occurred principally where high concentrations of fish in a shallower strata than where fished were caught during net retrieval (e.g. young-of-year alewives were present in a net that had been fished in deeper, hypolimnetic strata), or benthic species (e.g. sculpins) and bottom debris indicted the net hit bottom. In these cases, the by-catch species were recorded but excluded from the application to the biomass estimate. Sufficiently long tow times (15 - 20 minutes) at depth minimized the by-catch of fishes not at the target depths.

In each area of the water column, fish standing stock (kg/ha) was determined as the product of the estimated fish density (number/ha) and their predicted average mass. Fish mass throughout the water column was predicted from the regression equations developed by Fleischer et al. (1997) (see Section 3), which relates measured *in situ* mean target strength to mean fish size as mass. Density estimates for each species were summed over all strata, as

$$M = \sum_i N_i \, \hat{m}_i Pw_i$$

where M is density in kg/ha, N is the acoustic-based density estimate in number/ha, $\hat{m}$ is the predicted mean weight, Pw is the trawl-catch proportion of a given species by weight,, and i is the depth stratum. Due to their distinct differences by size distribution, alewives were further divided by life stage and the abundance of each life stage was based on proportion by weight in the trawl samples (individual weights were estimated from application of a weight-length relation to individual lengths and summed for young-of-year, yearling, and adult sized alewives). The mean standing stock (kg/ha) of each species and appropriate life stage was expanded by the total area of interest for each 10-m depth zone as

$$(\tfrac{1}{n}\sum_j M_j) \cdot a \;/\; 1000$$

to estimate biomass in metric tons, where n is the number of density estimates made for depth zone j, and a is the total area in hectares for depth zone j. These values were summed for all 10-m depth zones to estimate biomass for the appropriate geographical area in metric tons (see Section 6 – Lake Michigan Geographic Information System). Lakewide biomass was based on summed estimates of biomass for three geographic areas in Lake Michigan; this geographic stratification scheme was found to improve precision with little change in the point estimates (see Section 9 – Geographic Patterns in Lake Michigan Fish Densities). Variance of a biomass estimate was calculated as

$$\sum_j \; (V_M \cdot a^2 \;/\; 1{,}000{,}000)_j$$

where V_M is the variance of the mean standing stock (kg/ha) estimates at each depth zone j, and a is the total area in hectares for depth zone j (Cochran 1977). The variance for the lakewide biomass estimate was calculated as the sum of the variances for the three geographical regions with an assumed negligible covariance. We used the arithmetic mean to estimate of the true population mean of each depth strata for expansion to total population size. This practice, common in stock assessment of fisheries, is appropriate for stratified random surveys based on sample survey theory and finite population theory (Smith 1990). Though distributions of fish abundance tend to be positively skewed, expectations can be taken without knowledge of distribution as the expected (arithmetic) mean will tend toward normality even with non-normal frequency distributions (Cochran 1977). This design-unbiased property also holds for the variance, and standard error estimates can be derived by assuming repeated sampling from the finite population.

For measures of precision of the biomass estimates, we relied on the coefficient of variation rather than the construction of confidence intervals. With small sample sizes and observed abundances that exhibit skewed frequency distributions, confidence intervals of fish abundance estimates based on assumptions of normality are typically not useful since they are very long and extend to negative lower limits. A number of statistical models have been suggested for such occasions (Taylor 1953, Pennington 1983, Smith 1988, McConnaughey and Conquest 1993). However, Smith (1990) found the application of statistical models to fisheries survey data can result in biased estimates of population means and variances – a situation not desirable for the estimation of total abundance based on the value of the mean. Bootstrap re-sampling methods (Efron and Tibshirani 1993) allow for modeling survey estimates to form the basis for estimation of population means and construction of confidence intervals that do not require a normal (symmetric) distribution assumption. This technique has been applied to various fisheries survey data (e.g. Kimura and Balsinger 1985, Sigler and Fujioka 1988, Stanley 1992, Smith 1997) including acoustics (Robotham and Castillo 1990). Smith (1997) showed that these methods are useful for the estimation of nonparametric variance and confidence intervals, if attention is paid to application of the proper bootstrap technique (with associated assumptions about distribution) to account for sample design complexities. Although bootstrapped confidence limits could be used to derive asymmetric error intervals, they are not necessary for understanding the error associated with the point estimates. The coefficient of variation better served our purpose of characterizing the precision of the estimates. As a relative measure, the coefficient of variation allows comparisons of precision that are independent of the magnitude of the estimates. Such comparisons lend themselves to both practical (inference of the reliability of the estimates) and ecological (inference of the relative dispersion of the populations) interpretations. Detection of trends between the various estimates, if desired, would rely on hypothesis testing techniques applied to data that were appropriately transformed.

Examination of the processed acoustic data revealed instances of exceedingly large echo integration values in the near-bottom strata along some transects. Though high fish concentrations were observed in many cases in the deeper strata, occasional unrealistic echo integration values indicated that “bottom intrusion” had amplified the echo integration measurements, which would inflate the fish biomass estimates by including bottom return energy into the integrator output. The problem of "bottom intrusion" stems from the acoustic system's inability to accurately track and exclude the bottom echo from fish echoes and can be exacerbated by rapid decreases in the distance between the transducer and the bottom due to severe bathymetry, by high fish concentrations near bottom, or a combination of these features. For example, the fall 1991 acoustic measurements were made with an earlier-generation acoustic unit already in possession (described earlier in Procedures and Methods) and were later re-processed from the recorded data using the BioSonics® ESP system. During re-processing, bottom tracking was difficult due to the near-bottom distribution of fish; the system was not entirely effective in differentiating bottom returns from fish echoes. Our options were either not include those samples (pings) where the bottom tracking failed, or to adjust or ignore the fish density estimates in the near-bottom strata. The first option was not desirable due to the resulting loss of data through out the entire water column. The values shown for fall 1991 are based on the exclusion of lower-most strata. During subsequent years, the instances of bottom intrusion were less frequent due to the more reliable bottom tracking algorithm with the ESP systems. However, where encountered, the inflated values were adjusted by applying a correction factor based on the fish density values of the next shallower stratum. The frequency of bottom intrusion appeared to be related not only to bathymetry but also to fish behavior. Most notable was fall 1993, where large echo integration values in the near-bottom strata were prevalent. During this survey fish did not move into the water column, but were located nearer bottom possibly as a response to currents associated with severe storm events. Instances of bottom intrusion were less frequent in subsequent years where fish were distributed through out the water column.

Spring Survey Results

Coverage – In 1992 we conducted the only lakewide spring acoustic survey. Transects were completed off seven ports, and included cross-lake transects that extended from Frankfort to Sturgeon Bay, from Manitowoc to Ludington, and two parallel transects spanning from Saugatuck to Waukegan. The surveys conducted in spring 1993 were limited to the multiple sites off Ludington and Manitowoc as part of the investigation of spatial distribution of the pelagic fishes and these results are reported in Section 10 – Geographic sampling scale and variability in pelagic fish distributions.

Midwater trawl collections – At the southern sites, fish were observed at all depths surveyed (10 to 150 m) in 1992 but were not very abundant in waters deeper than 130 m and were generally distributed near bottom – very few targets were found in the upper strata in most areas. The midwater trawls, conducted at selected depths, found rainbow smelt and alewives in the shallower, near-shore areas and bloaters were the prevalent species off-shore. Yearling-sized alewives, members of the 1991 year class that were observed in large numbers in the upper depth strata in fall 1991, contributed the majority of the catch of this species in the midwater trawls. In the northern sites of Lake Michigan, fish were present at all depths but few fish were found in water deeper than 130 m. At Frankfort, yearling alewives dominated the catches in the 10-20 m strata followed by bloaters and rainbow smelt. Bloaters were the most abundant species in the offshore, deeper strata. Near Manistique, concentrations of ninespine sticklebacks, rainbow smelt and threespine sticklebacks were caught in the near-surface strata in midwater trawls fished over 90 m of water. Rainbow smelt, bloaters, and yearling alewives were caught in the 35 m stratum.

Biomass – Biomass estimates were not calculated for the spring survey in 1992. The combination of near-bottom fish distributions and the small number of sample locations completed (only one vessel was available for this survey) were not ideal conditions. Owing to the fish distributions we observed, we abandoned further spring surveys – other than the multiple transect study that was conducted in 1993 – in favor of fall surveys.

Summer Survey Results

Coverage – The surveys conducted in summer 1993 were limited to the multiple sites off Ludington and Manitowoc as part of the investigation of spatial distribution of the pelagic fishes (see Section 10 – Geographic sampling scale and variability in pelagic fish distributions).

Fall Survey Results

Coverage – We conducted lakewide fall surveys annually on Lake Michigan in 1991-1996. The total number of transects completed during any single year ranged from as few as 8 in 1991 to a maximum of 21 in 1995 (Figure 7.2). The fewer transects completed in 1991 reflect the shorter time period (10 days) that was available for this initial survey (Table 7.2). With the exception of 1991, our cruises were performed over an approximate 30-day period (two 17-day cruises separated by a 4-day break) during fall, starting as early as September and extending into November some years. During fall 1992 and 1993, the surveys were conducted from mid-October to mid-November. Thirteen transects were completed in 1992, but consistently inclement weather in 1993 hampered the progress of the survey and only 9 transects were completed. After 1993, fall surveys were conducted earlier in the season, mid-September to mid-October (Table 7.2), to avoid the greater frequency of severe weather typical of late October and early November. The number of transects completed in 1994 and 1995 – 16 and 21 – reflect the level of lakewide coverage possible by the application of acoustics; the lesser number of transects completed in 1996 were due to a combination of weather constraints and vessel mechanical problems (Table 7.2). Our goal of lakewide coverage was met in most years. Completed transects were distributed throughout most geographic areas of the lake, except 1993 where we were unable to provide coverage in north-central Lake Michigan and in 1996 where transects were not made in central Wisconsin waters and northern Michigan waters of Lake Michigan (Figure 7.4). Biases in lakewide estimates may occur where large geographic regions of the lake are not represented in the samples (see Section 9 – Geographic Patterns in Lake Michigan Fish Densities).

Midwater Trawl Collections – From 1991 to 1996, we completed a total of 393 midwater trawls in conjunction with the fall acoustic surveys. The number of tows made in during a single fall survey ranged from 43 in 1996 to 90 in 1995, largely the result of the number of transects completed during a single season. Over all years, we averaged 5 tows per acoustic transect. The number of midwater trawls made per transect was greater in the earlier years, about 7 tows per transect, compared to surveys made in the later years. This decline in fishing effort in more recent years was due to the recognition of predictable species composition in the deeper, hypolimnetic strata (see Section 8 – Midwater Distribution of Pelagic Fishes in Relation to Physical Characteristics). The areas fished ranged from 5 to 90 m over bottom depths that spanned 12 to 150 m for all years combined. The distribution of these midwater tows shows a concentration of effort in the shallower strata and near-bottom depth zones (Figure 7.5). This pattern reflects the pelagic distribution fish during fall in Lake Michigan.

The midwater trawl catches were dominated by alewife, rainbow smelt, bloater, and to a lesser degree threespine and ninespine sticklebacks. Numerically, alewives and rainbow smelt typically accounted for most of the fish caught, but during some years, sticklebacks and bloaters also contributed substantial numbers to the total catch (Figure 7.6). Combined, these species accounted for over 99% of the fish we caught in midwater. By weight, bloaters dominated the catches most years – which was expected due to their relatively larger individual size – and alewives also contributed a large portion of the catch by weight in some years (Figure 7.6). Annual differences in species composition generally reflected differences in relative abundance, but these differences are confounded by variations in fishing patterns; the non-systematic sampling regimen does not permit accurate cross-year comparisons by the catches alone.

Biomass

As expected, bloaters, alewives and rainbow smelt constituted the majority of the pelagic fish biomass in Lake Michigan. Bloaters dominated the estimates and accounted for an average of 71%, ranging 69-83% per annum, of the total acoustic-based biomass for 1991-1996 (Table 7.3). Alewife (all life stages) and rainbow smelt estimates were at lower levels, with alewives contributing on average 18%, ranging 7-43% per annum, to the total annual biomass per and rainbow smelt contributing on average 10%, ranging 4-17% per annum, to the total annual biomass during 1991-1996 (Table 7.3) Sticklebacks – threespine and ninespine, combined – were present but only contributed an average of 1% to the total biomass during these years.

Comparison of the annual biomass estimates over the study period shows conspicuously larger values for bloaters, rainbow smelt, and adult alewives in 1991 than for the other years (Table 7.3, Figure 7.7). These values, adjusted to avoid bottom intrusion (see Procedures and Methods), still appear to be inflated and should not be considered an accurate representation of the dynamics of these fish species. In contrast, the 1991 estimates of biomass for young-of-the-year alewives are reliable. These fish are found almost entirely in the upper, epilimnetic strata and are not susceptible to the amplified echo integration measurements associated with the bottom.

In as much as the 1991 estimates were biased high, the 1992 estimates for bloaters, rainbow smelt, and probably adult alewives appear to be biased low (Table 7.3, Figure 7.7). At the time, we attributed the source of this error as a random effect due to fish contagion and insufficient sampling intensity. However, in retrospect, given the number of transects completed and their wide geographical distribution in 1992 compared to subsequent years (Figure 7.4), the likelihood of this random effect seems slim. Rather, the most likely cause of this error was due to incorrect gain settings on the acoustic unit (this survey was our first use of the new ESP unit). In off-shore waters, typically 110 m and greater, a higher receiver gain setting was needed to obtain sufficient echo strength of fish in the deeper strata. The recorded gain level may not reflect the actual gain level on the echo sounder used during data acquisition since this setting is made manually. Changes in these settings were made frequently, so it is feasible that the deeper portions of some transects may have been collected at lower gain settings than were intended. Since the measured backscattering levels are a function of both system settings and fish densities, this operator error would be difficult to identify and correct due to the lower fish densities in these off-shore areas. This error would mostly effect bloaters, which are found in the deeper strata of the off-shore areas, but include rainbow smelt and adult alewives, whose distributions extend into the off-shore areas. Like 1991, the estimates of biomass for bloaters, rainbow smelt and adult alewives in 1992 are unfortunately not an accurate representation of the absolute status of these fish species.

From 1993 through 1996, estimated bloater biomass ranged from a maximum of about 475,000 metric tons in 1993 to about 240,000 metric tons in 1995 (Table 7.3, Figure 7.7). This general decline in biomass is expected due to the consistent lack of bloater recruitment in recent years (Madenjian et al. 1997). During the same time period, rainbow smelt biomass estimates ranged from a maximum of about 84,000 metric tons in 1993 to around 15,000 metric tons in later years (Table 7.3, Figure 7.7), indicating rainbow smelt populations declined during this period. Young-of-the-year alewives were estimated at levels that fluctuated from about 8,500 metric tons to an extremely large 1995 year class estimated at about 148,000 metric tons (Table 7.3, Figure 7.7). The 1995 young-of-the-year alewives accounted for 33% of the lakewide biomass of pelagic fish in Lake Michigan. From 1993-1996, adult alewives increased from about 13,000 metric tons in 1993 to about 54,000 metric tons in 1996 (Table 7.3, Figure 7.7). The peak estimate of adult alewives in 1996 was largely due to the abundant yearling alewives (about 37,000 metric tons) from the 1995 year class.

The precision of the lakewide biomass estimates exhibited distinct levels for the various species and in some cases showed annual patterns related to changes in abundance. The coefficients of variation (CV) for bloater biomass estimates were lower compared to that for the other species, averaging about 23% during the study period (Figure 7.8). Rainbow smelt biomass CVs averaged around 29%, and showed a trend of increased variability with the decrease in biomass (Figure 7.8). Alewife biomass estimates showed the greatest degree of imprecision with CV values of about 31% for adults and 35% for young-of-the-year (Figure 7.8). Annual fluctuations in the biomass estimates were also greatest for alewives, especially young-of-the-year (Figure 7.8). Though at greater levels of abundance, bloaters exhibited lower and less variant CV values. This pattern corroborates their more homogenous distribution and stable population status, which is not unexpected given the absence of younger age classes for bloaters in recent years. In contrast, young-of-the-year alewife CVs were at higher levels and were more variant between years. One implication of these results is that bloater population densities were more similar and, on a lakewide basis, would require fewer sampling locations to achieve some minimum level of precision for biomass estimates compared to adult and young-of-the-year alewives. The higher level of imprecision exhibited by alewives would indicates they are more contagious, or more ‘patchy’ in their distribution. The notable exception to this is the high degree of uniformity associated with the biomass estimate for the 1995 alewife year class; these young-of-the-year alewives were found consistently in high abundance through out the entire lake.

Comparison to Bottom Trawl Collections – During the study period, the standard fall bottom trawl surveys were also conducted by the Great Lakes Science Center. These annual trawls were made at established transect sites and sampling depths along each transect (Hatch 1981b). Catch rates in numbers (or weight) over time are used as an index of relative abundance for the various species, and the catches are also used to develop lakewide estimates of biomass for the different life stages of the important prey fish species (Hatch 1979, 1981a). The fish collected in these systematic surveys provide another source of fish abundance and stock structure information that can be compared to the current study. It should be noted that the bottom trawls are performed during the day.

As stated previously, the midwater trawls were used to target aggregations of pelagic fish to determine species composition. Because the midwater tows were deployed in a non-systematic approach, we were concerned that these catches may not represent the full range of sizes of the various species, which could introduce a bias in the acoustic biomass estimates. Comparisons of the length-frequency distributions of alewives, rainbow smelt, and bloaters collected in the midwater trawls and in the bottom trawls the same year, however, revealed that the midwater trawl catches were reliable. The size distributions for bloaters in the midwater and bottom trawls were indistinguishable for all years (Figure 7.9). Rainbow smelt size distributions from the two gears were nearly identical in 1992-1994, but less so in 1995-1996 (Figure 7.9). Similarity in size distributions between gear, however, was not observed for alewives. A much greater proportion of smaller alewives were collected in midwater than on bottom for most years (Figure 7.9).

These similarities and differences in sizes of fish collected in both gear are indicative of the patterns of vertical distribution of the different species. Most of the Great Lakes planktivores exhibit diel vertical migrations, moving into the water column at night and returning to bottom during the day (Janssen and Brandt 1980, Brandt et al. 1991, Argyle 1992). Others, like young-of-the-year and yearling alewives (fish < 150 mm) are known to be pelagic and are not sampled effectively by the bottom trawls (Brown 1972, Eck and Brown 1985). This distributional characteristic was clearly demonstrated where the large 1995 alewife year class were observed as both young-of-the-year in 1995 and as yearlings in 1996 in the midwater trawls, but were scarcely detected in the bottom trawls the same years (Figure 7.9). It is apparent that midwater trawling is the better technique for sampling juvenile alewives. The similarity of alewife size distributions observed in both gear types in 1994, however, was related to the relative weakness of the 1994 year class. These young-of-the-year alewives were found in the near-shore areas and did not extend out into the more off-shore, epilimnetic areas as observed in other years – without

the extended, midwater distribution of the younger fish, both gear collected the young-of-the-year and adult alewives in similar proportions.
The under representation of smaller fishes in the bottom trawls also occurs for bloaters and rainbow smelt. The ineffectiveness in collection of younger members of these species indicate they either are located to a greater degree above the headrope (pelagic distribution) or below the headrope (benthic distribution) – assuming the codend is sufficiently fine to retain these smaller-sized fishes. As seen with the alewives, comparisons of midwater trawl and bottom trawl catches can indicate which distribution feature effects the catchability. The similarity in the size distributions for most years for rainbow smelt between bottom and midwater trawls would suggest that the younger fish are more benthic and not fully recruited to either gear. In this case, neither gear would have any advantage in assessment of the younger members of the population. However, the somewhat greater proportion of smaller rainbow smelt in the bottom trawls (Figure 7.9) indicates that the bottom trawls sampled juvenile rainbow smelt more effectively. Juvenile bloaters were not abundant enough during the study period to detect in either gear to any satisfactory degree. The nearly identical size distributions of larger bloaters collected by both gear indicate both gear sample the population with equal effectiveness. Other research has indicated that midwater trawls may not adequately sample the largest members of the bloater population (TeWinkel and Fleischer, manuscript in press), but this has not been conclusively demonstrated and was not apparent in the current study.

Traditionally, estimates of lakewide biomass from bottom trawl surveys were made by expansion of the catch in weight per area swept for each species and life stage for each tow on the basis of the total area represented by the tow and summed for all depths and transects. Because of this fixed design, measures of precision are normally not reported for these lakewide estimates. However, to allow a comparison of acoustic and bottom trawl estimates and their precision, we considered each bottom tow a representative sample of the fish populations from that particular depth stratum. In a similar fashion as with the acoustic biomass estimates, the mean density (catch per area swept) and variance for a given species and life stage for a particular depth contour was determined across each depth and expanded to the total lakewide area represented by the depth contour. These point estimates with their error terms were summed to produce lakewide biomass and variance estimates (see Procedures and Methods for more detail on this procedure). It should be noted that we determined the area swept by the net with predictive relations of net wingspread and actual time towed by the depth fished, standardized to a 10-minute tow. These trawl relations were determined by observations of the actual trawl configurations during tows at the range of depths with trawl netsondes – a more complete description is found in Adams et al. (1996).

For both bottom trawls and acoustics, bloaters dominated the biomass estimates for the pelagic planktivores, and the two techniques provided very similar point estimates of biomass. The bottom trawl-based estimated bloater biomass ranged from about 450,000 to 300,000 metric tons during 1991-1996 (Figure 7.10). Young-of-the-year bloaters were almost entirely absent from these figures. The bottom trawl estimates declined slightly to less than about 300,000 metric tons from 1993 to1995, but increased in 1996 to about 375,000 metric tons. The acoustic estimated biomass was greatest for bloaters in 1993 at about 450,000 metric tons and declined in subsequent years to less than 300,000 metric tons. Like the bottom trawl estimates, the acoustic estimated bloater biomass increased slightly from 1995 to 1996.

In contrast, alewife biomass estimates were very different for the two techniques. The bottom trawl estimates were generally smaller for the annual estimates of the younger life stages (Figure 7.10), which would be expected due to the demonstrated ineffectiveness of bottom trawls for sampling young-of-the-year and yearling alewives. However, the annual estimates for larger alewives were generally greater for bottom trawls than for the acoustic-based estimates (Figure 7.10). Bottom trawl-based adult alewife biomass ranged from a maximum of about 60,000 metric tons to a minimum of 16,000 metric tons, averaging 36,000 metric tons during 1991-1996 (Figure 7.10). In comparison, acoustic estimates of adult alewife biomass ranged from only 45,000 to 13,000 metric tons, averaging about 24,000 metric tons. This result suggests that the adult alewives were under represented in the midwater trawl catches. Adult and juvenile alewives were both found in the near-shore and epilemnetic strata (see Section 8 – Midwater Distribution of Pelagic Fishes in Relation to Physical Characteristics), but the adults may have been able to avoid the net or were associated closer to the bottom where they were more difficult to collect in the midwater trawls.

The annual estimates of rainbow smelt biomass from bottom trawls showed similar trends in both gear. However, the annual biomass estimates calculated from bottom trawls were lower compared to acoustic-based estimates. From 1993 to 1996, bottom trawl-based estimates of rainbow smelt biomass declined from a peak of about 24,000 to about 10,000 metric tons, and averaged about 19,000 metric tons (Figure 7.10). The acoustic-based biomass estimates ranged from a peak of about 84,000 metric tons in 1993 to about 16,000 metric tons in subsequent years, averaging 33,000 metric tons (Figure 7.10). Since these differences cannot be ascribed to differences in size selectivity between gear, it is apparent that rainbow smelt are more pelagic and are probably more abundant members of the fish community than measured in bottom trawls.

The precision of the bottom trawl biomass estimates exhibited similar patterns among species as in the acoustic estimates, but generally at greater levels. As seen in the acoustic estimates, the coefficients of variation (CV) for the annual bloater biomass estimates were lower compared to the other species (Figure 7.11) and averaged only 15%, compared to 23% in the acoustic estimates. Rainbow smelt biomass CVs averaged around 25% for the bottom trawl estimates, compared to 29% for the acoustic estimates, and both showed a trend of increased variability with the decrease in biomass in recent years (Figure 7.11). Adult alewife biomass CVs averaged only 20% for the bottom trawl estimates, compared to 31% for the acoustic estimates. However, CVs for young-of-the-year alewives were generally greater for the bottom trawl estimates, averaging nearly 50% (Figure 7.11), compared to 35% in the acoustic estimates. These comparisons may be interpreted as a greater precision associated with the bottom trawl catches, but they do not necessarily indicate more reliable estimates. The lower variability in the bottom trawls may be in fact due to the homogeneity of the along-contour design and the narrow depth range fished for each depth zone, and possibly due to the constraints imposed by access only to areas that are trawlable. Further, the potential range of measures of fish density is much greater for acoustics compared to bottom trawls. The bottom trawls can saturate easily in higher densities of fish, and this characteristic has been observed and is frequently compensated for by reductions in tow time. Given the greater potential for variability in the acoustic estimates compared to bottom trawl estimates, the levels of precision exhibited by the acoustic estimates were not excessive and are probably a better reflection of the variability of pelagic fish populations in Lake Michigan.

Conclusions

Seasonal features influenced the effectiveness of the acoustic surveys. The combination of a greater range in vertical distribution of the fish into the water column at night, the segregation of the various species in relation to the thermal stratification, and the availability of younger life stages to the sampling gear made late-summer or fall the optimal time to conduct acoustic surveys. Mid-summer was characterized by a sufficiently developed thermal structure and adequate vertical movements of the fish, but the shortness of the nighttime period confines the survey times. In addition, the effectiveness of sampling the emerging year classes of most species is limited. In spring, the fish do not move far off bottom, undoubtedly in response to the thermal conditions, and the distributions of the different species are much less distinct and may require more trawling effort.

The fall acoustic biomass estimates appear to be reasonable and provide reliable fish stock status and trend information. When compared to bottom trawl estimates, the acoustic estimates are very similar for certain species, and differences between the two gears can be attributed to known or deduced patterns in vertical distribution of these species. Mutual agreement in both trends and estimated biomass derived independently from bottom trawls and acoustics for bloaters lends credence to our ability to assess the status of this species accurately with either gear. The similarity in the trends, but greater magnitudes of the acoustic rainbow smelt biomass estimates suggests that this species is pelagic and can be assessed more accurately in terms of absolute numbers by acoustic techniques. Juvenile alewives are pelagic and are better assessed by acoustic techniques, which has implications for better understanding of stock-recruitment relations for this species. Adult alewife biomass estimates were greater for bottom trawl surveys and appear to be underestimated in the acoustic estimates. This difference may be related to their contagious distribution, which suggests a greater level of midwater trawling effort in areas found to be favorable for this species (see Section 8 – Midwater Distribution of Pelagic Fishes in Relation to Physical Characteristics) would be needed.

The precision of the lakewide biomass estimates exhibited similar patterns for both gear, where coefficients of variation (CV) were lowest for bloaters and rainbow smelt. Alewives, especially young-of-the-year, exhibited the greatest variability. These trends suggest a more contagious distribution for alewives with implications for increased levels of sample locations, or a different stratification scheme, to minimize the variance of the biomass estimates for this species.

Table 7.1 — Beam width (degrees) of dual-beam transducers, source level (SL) as dB 2μPa at 1 m, 40LogR through-system gain (R_G) as dB 2V μPa at 1 m, beam pattern ($b(\Phi,\varphi)$), sampling rates (pulses≅min^{-1}), pulse width (τ) in ms, and pulse-width measurement criteria in ms for single echo filtering at half amplitude (-6 dB) and quarter amplitude (-12 dB) for the acoustic systems. Beam width, source level, through-system gain, and beam pattern values were provided by manufacturer.

Beam Width			R_G					Pulse-width Criteria	
Narrow	Wide	SL	Narrow	Wide	$b(\Phi,\varphi)$	Sampling rate	τ	-6 dB	-12 dB
120 kHz Transducers									
10	25	215.3	-162.1	-162.1	.002400	120	0.5	0.350-0.750	<1.250
7	18	224.4	-181.8	-180.8	.001026	120-150	0.4	0.320-0.720	-- [a]
7	18	226.5	-176.8	.-176.7	.001112	120-150	0.4	0.320-0.720	-- [a]
420 kHz Transducers									
6	15	218.4	-179.2	-180.5	.000976	120-150	0.4	0.320-0.720	-- [a]
6	15	221.9	-177.9	-177.6	.001001	120-150	0.4	0.320-0.720	-- [a]

[a] Quarter-amplitude pulse-width values were measured but not used to filter echoes.

Table 7.2 – Survey dates and number of transects completed during fall acoustic surveys on Lake Michigan, 1991-1996.

Year	Start Date	End Date	Completed Transects
1991	5 September	15 September	8
1992	15 October	11 November	13
1993	12 October	10 November	9
1994	8 September	11 October	16
1995	14 September	18 September	21
1996	15 September	13 October	11

Table 7.3 – Total estimated biomass and proportion of biomass for pelagic fishes based on fall acoustic surveys on Lake Michigan, 1991-1996.

Year	Adult Alewife	YOY Alewife	Yearling Alewife	Alewife (Total)	Bloater	Rainbow Smelt	Sticklebacks
				Lakewide Estimated Biomass (Metric Tons)			
1991	112,732	31,444	- [a]	144,176	746,209	174,184	11,500
1992	26,766	6,010	- [a]	32,776	167,468	41,680	2,019
1993	13,384	31,027	- [a]	44,411	476,927	84,089	19,411
1994	21,695	13,984	- [a]	35,679	251,196	14,024	3,813
1995	45,049	148,394	- [a]	193,443	239,735	16,501	452
1996	54,212	8,407	37,121	62,619	275,387	16,834	5,442
				Proportion of Biomass			
1991	0.11	0.03	- [a]	0.14	0.71	0.17	0.01
1992	0.11	0.02	- [a]	0.13	0.69	0.17	0.01
1993	0.02	0.05	- [a]	0.07	0.76	0.13	0.03
1994	0.07	0.05	- [a]	0.12	0.82	0.05	0.01
1995	0.10	0.33	- [a]	0.43	0.53	0.04	0.00
1996	0.15	0.02	0.10	0.17	0.76	0.05	0.02
Average	0.09	0.08	0.10	0.18	0.71	0.10	0.01

[a] Yearling alewives not distinguished; included with adult alewife values

Figure 7.1 – The USGS-BRD *R/V Grayling* (left) and MDNR *S/V Steelhead* (right). Both vessels, equipped with complimentary acoustic and midwater trawling gear, were used to conduct the acoustic surveys on Lake Michigan, 1991-1996.

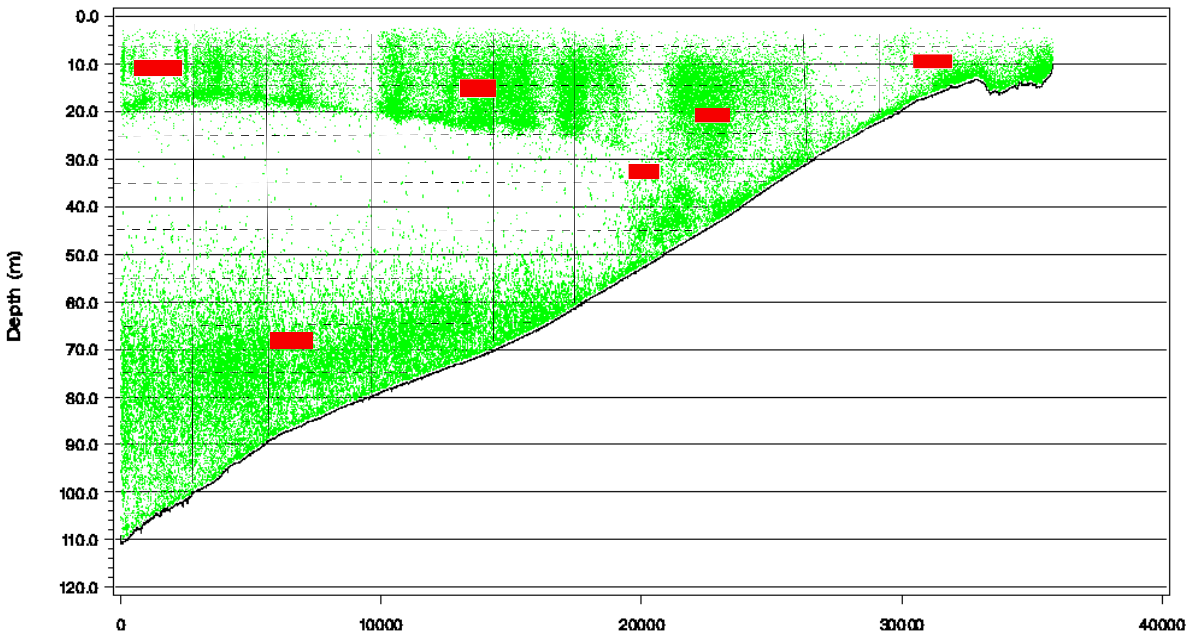


Figure 7.2 – Echogram showing an example of night-time fish distribution in Lake Michigan. Midwater trawls, indicated by the red markers, were used to target aggregations of fish to determine the midwater species composition.

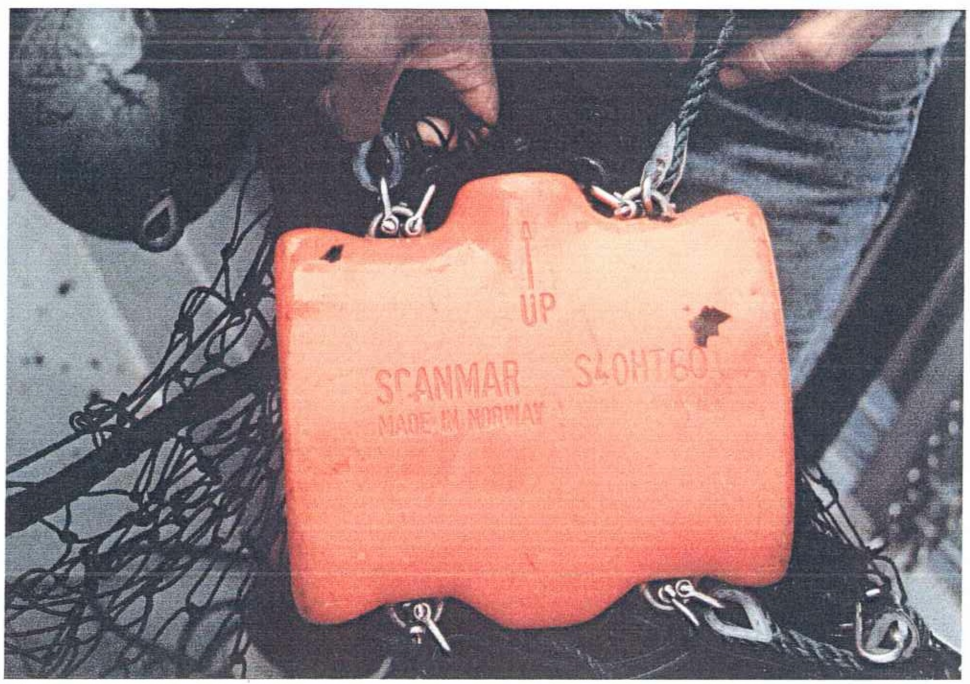


Figure 7.3 – Trawl sensors, or netsondes, used to monitor net configuration and allow accurate positioning of the trawl during acoustic surveys on Lake Michigan. The upper photograph shows the headrope sensor array: a depth sensor, a net opening and bottom clearance sensor, and a temperature sensor.

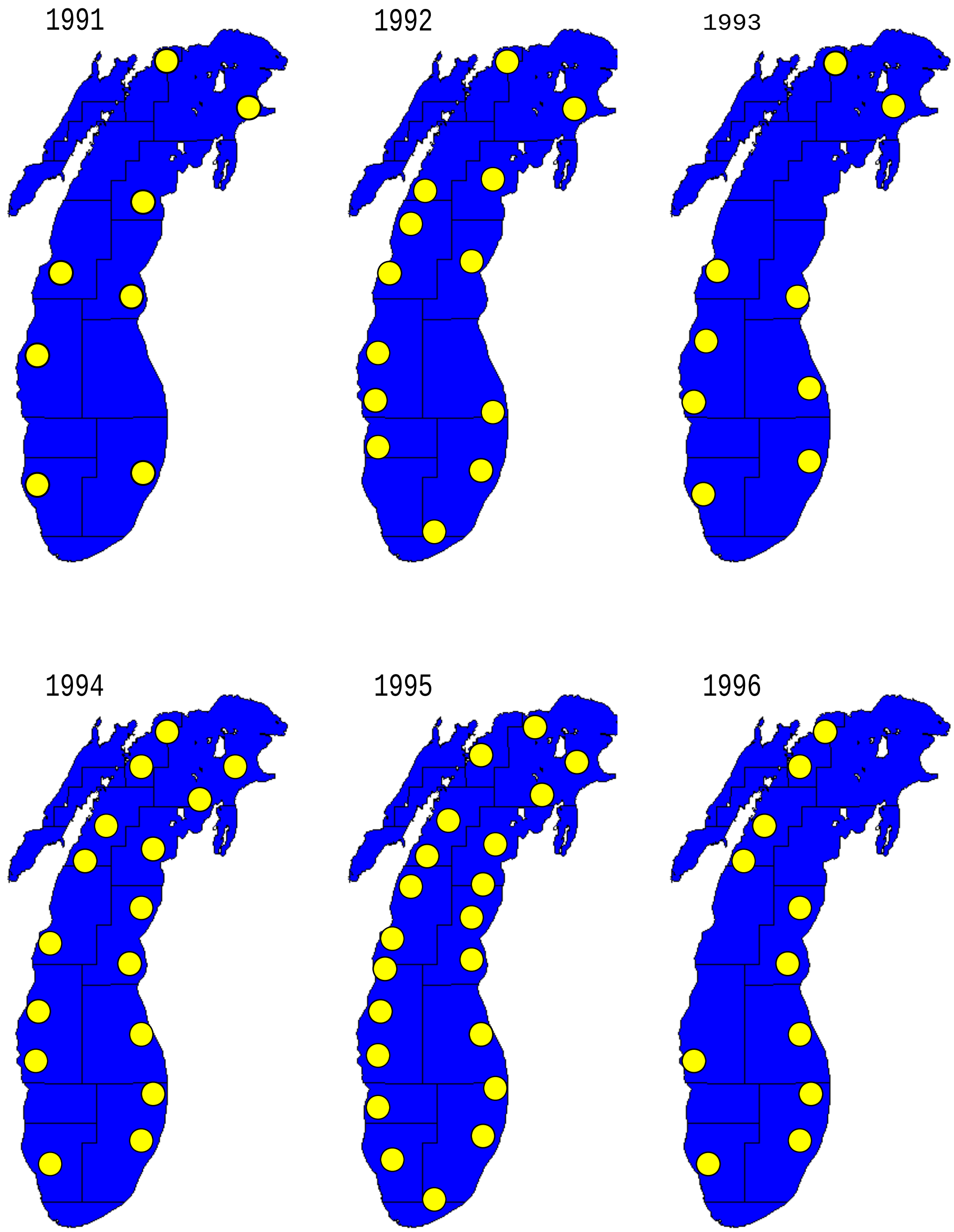


Figure 7.4 – Number and geographic distribution of transects (shown as yellow markers) during fall acoustic surveys in Lake Michigan, 1991-1996.

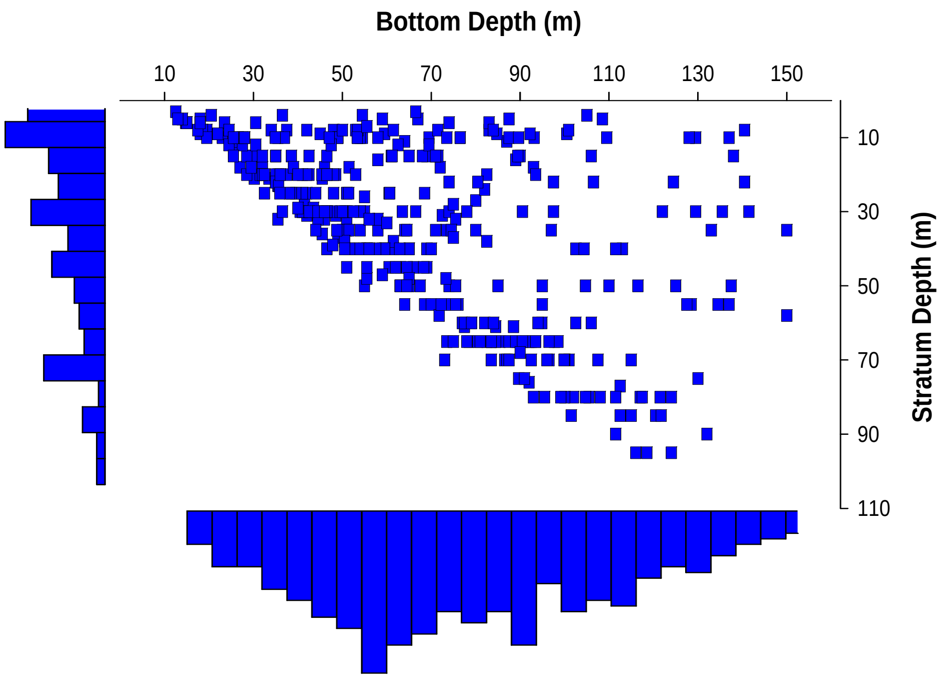
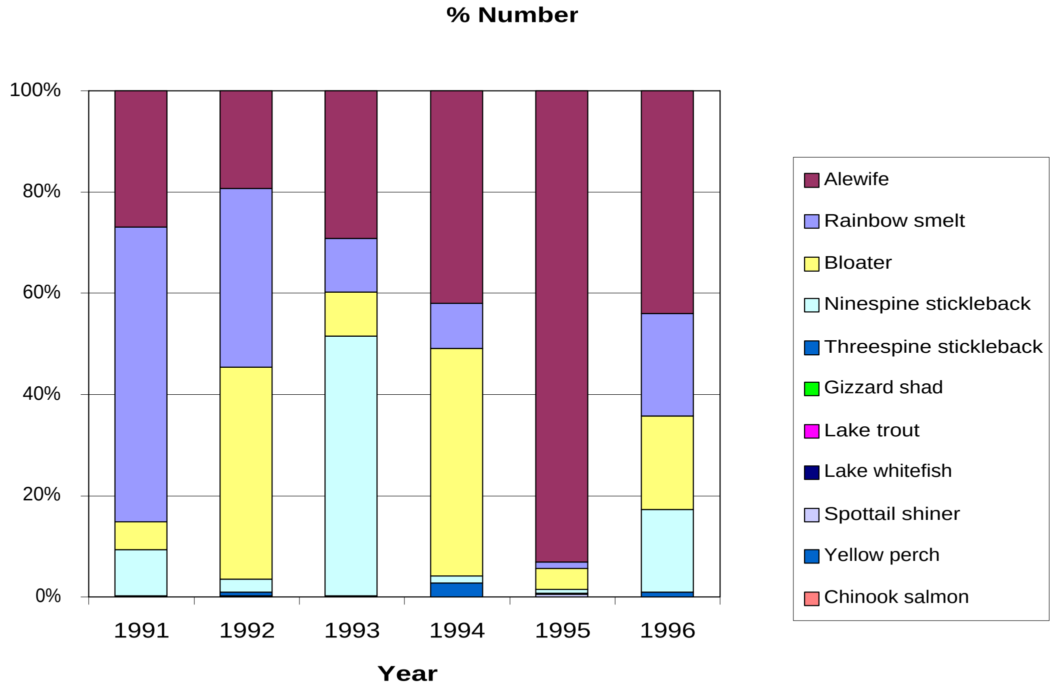


Figure 7.5 – Distribution of midwater trawls made during fall surveys in Lake Michigan, 1991-1996. Histograms indicate frequency of tows made by depth zone (bottom depth) and stratum depth.



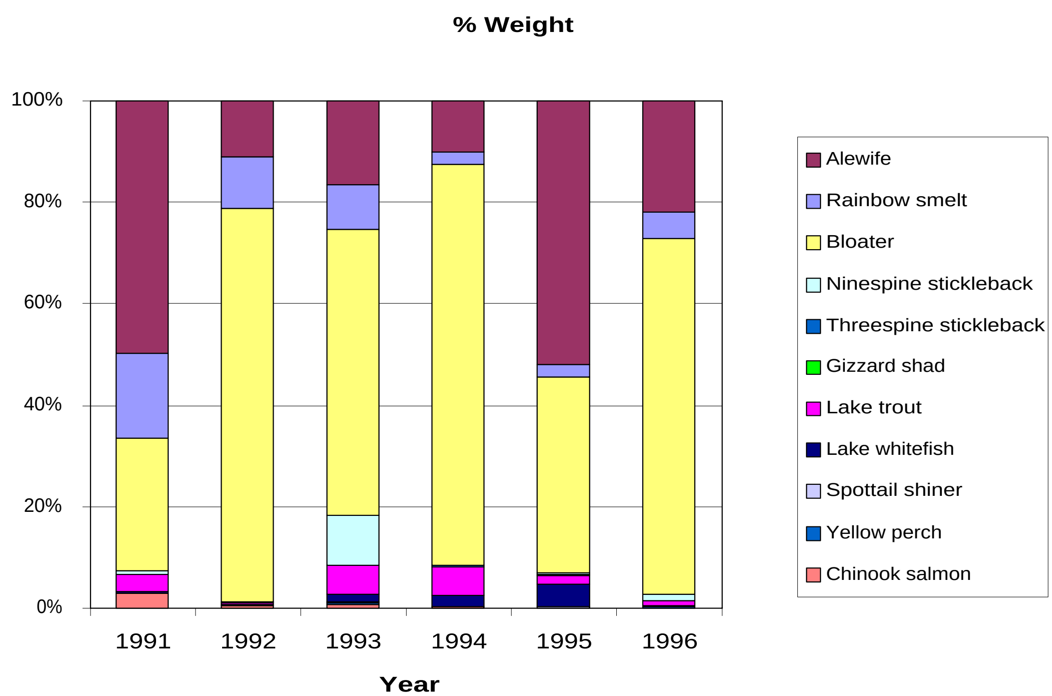
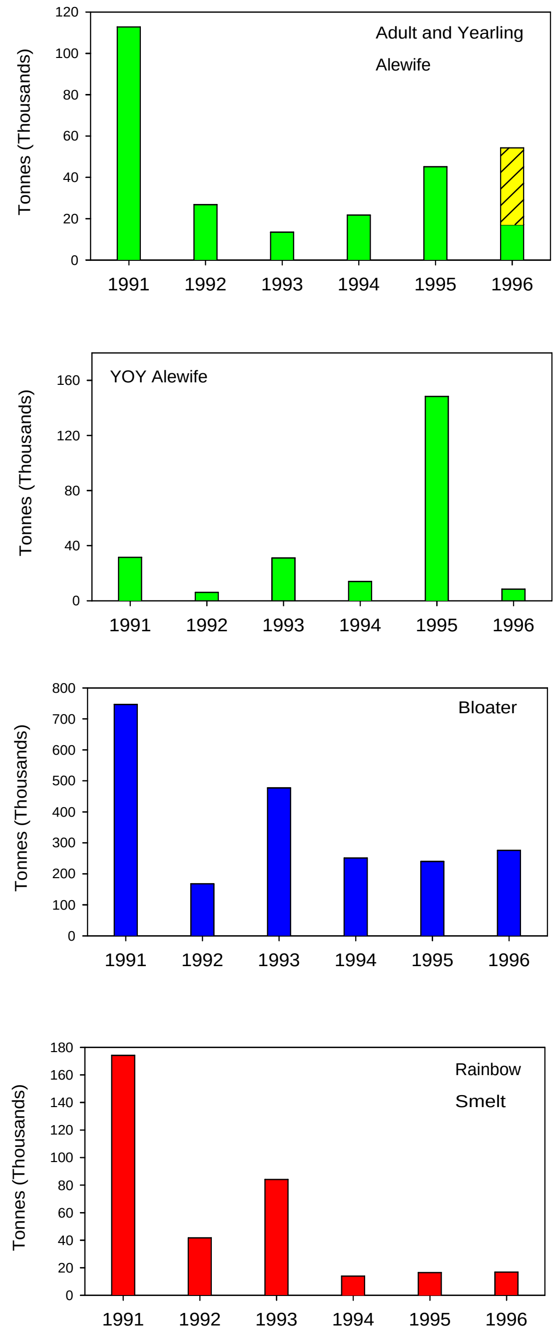


Figure 7.6 – Species composition (percent numbers and percent weight) by year for midwater tows made during fall surveys in Lake Michigan, 1991-1996.



1991 1992 1993 1994 1995 1996

Figure 7.7 – Annual acoustic-based biomass estimates for alewives (adult and young-of-the-year), bloaters, and rainbow smelt from fall surveys in Lake Michigan, 1991-1996. Contribution of large 1995 alewife year class as yearlings shown in yellow for 1996.

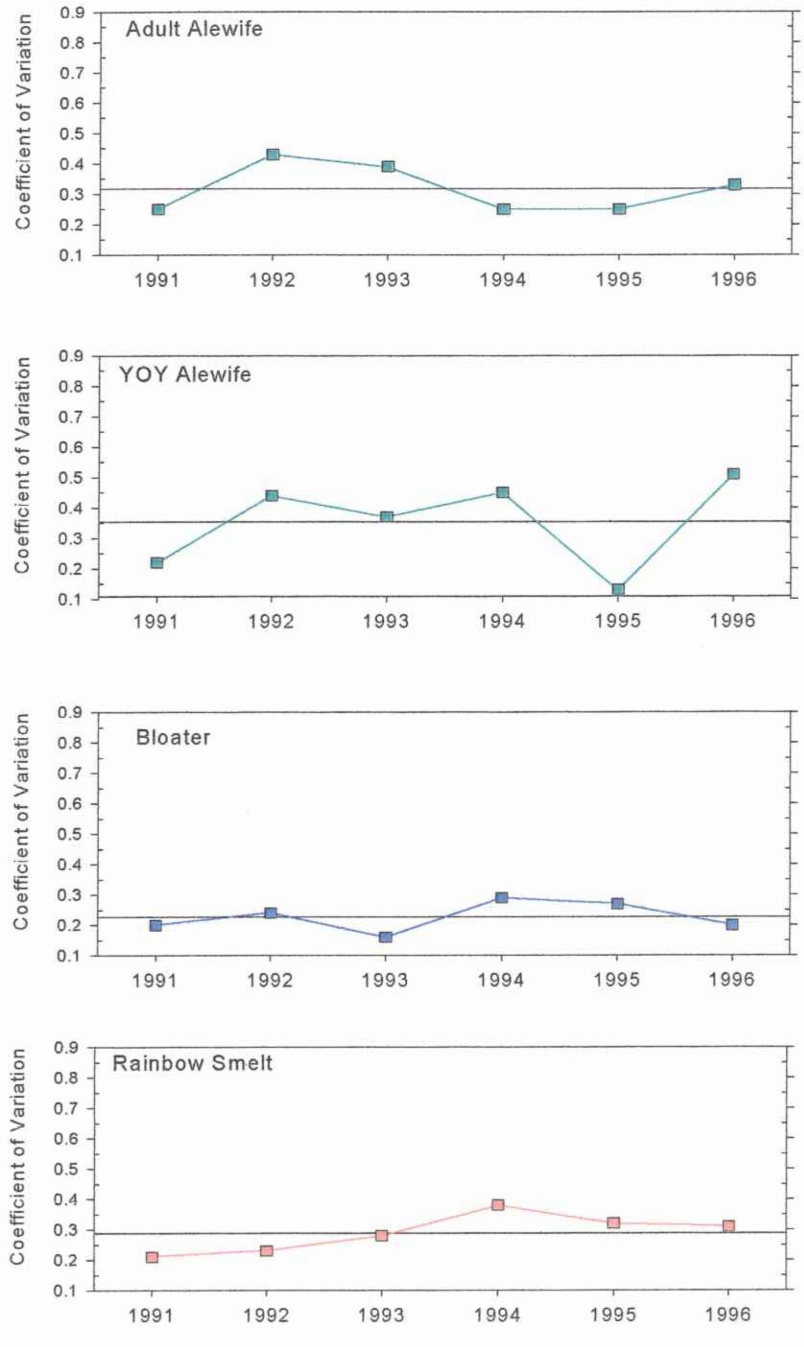


Figure 7.8 – Coefficients of variation for biomass estimates of alewives (adult and young-of-the-year), bloaters, and rainbow smelt from fall acoustic surveys in Lake Michigan, 1991-1996. Horizontal line indicates mean value for each series.

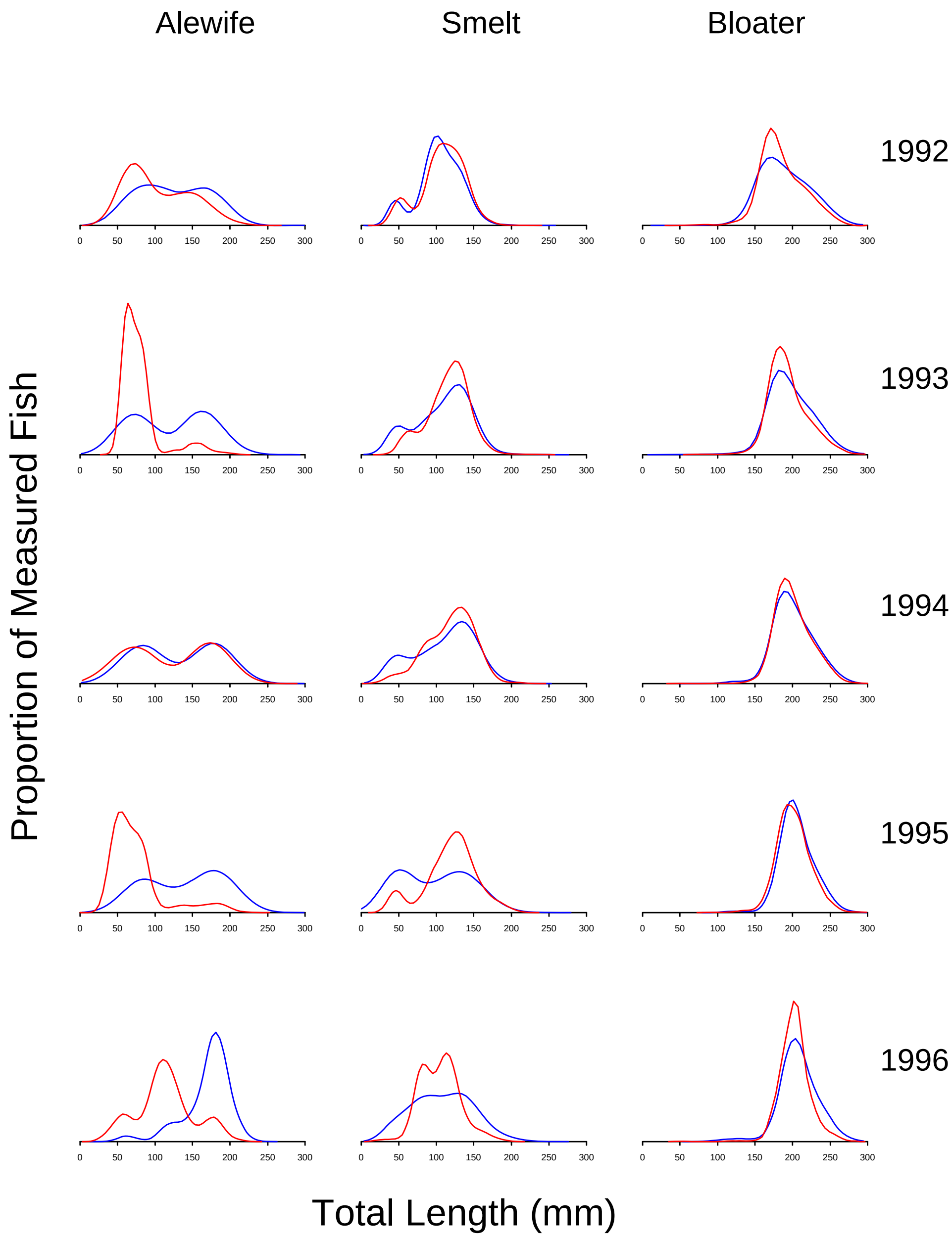


Figure 7.9 – Comparison of length-frequency distributions of alewives, rainbow smelt and bloaters collected in midwater (red line) and collected on bottom (blue line) during fall

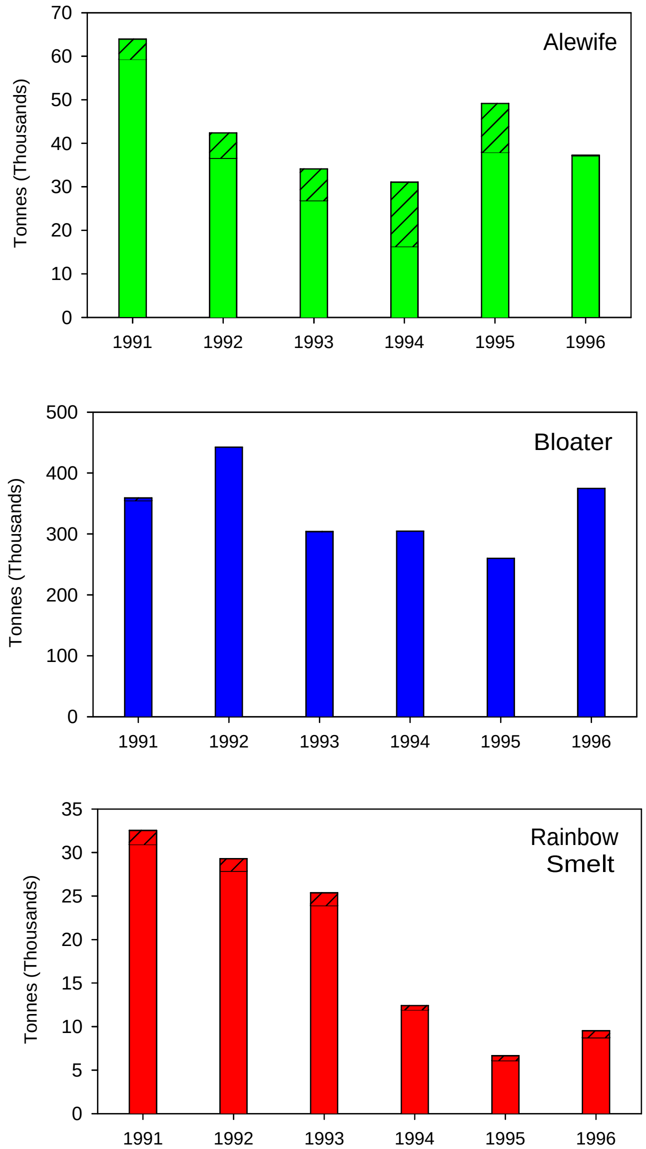


Figure 7.10 – Annual biomass estimates of alewives, bloaters, and rainbow smelt from fall bottom trawl surveys in Lake Michigan, 1991-1996. Hatched portions of bars indicate contribution of young-of-the-year for each species.

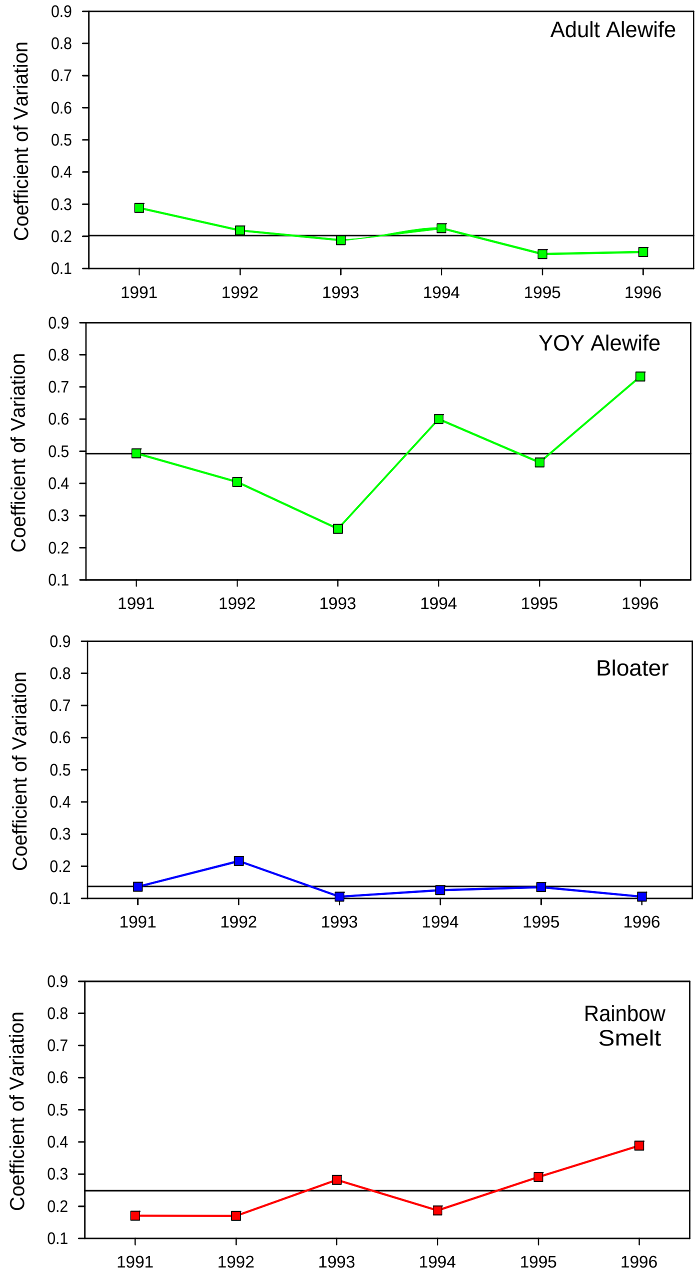


Figure 7.11 – Coefficients of variation for biomass estimates of alewives (adult and young-of-the-year), bloaters, and rainbow smelt from fall bottom trawl surveys in Lake Michigan, 1991-1996. Horizontal line indicates mean value for each series.

Section 8.

Midwater Distributions of Pelagic Fishes in Relation to Physical Characteristics

Introduction

Based on the integrated acoustic abundance estimates and midwater trawl sampling, estimates of species-specific abundance were made for the entire water column along each transect (see Section 7 – Acoustic Biomass Estimates). Comparison of the mean densities for fall 1994-1995 in each area of the water column revealed distinct patterns in the midwater distributions of the various species (Figure 8.1). Adult and young-of-the-year alewives were most abundant in the near-shore and upper strata. Bloaters were found in greatest abundance in the hypolimnetic and near-bottom areas of the water column. Rainbow smelt were in greatest abundances in the near-shore areas, but were also found throughout much of the upper strata associated with the metalimnion. Sticklebacks were also found widely distributed in the near-shore and upper strata. These plots show the overlap that occurs for the different species, however they also suggest predictable patterns.

Midwater trawl sampling is time consuming and is a constraining factor in the acoustic sampling design. If the relation between the species composition in a particular pelagic zone and some easily measurable habitat characteristics were quantified, it would be possible to predict species composition in that zone without conducting midwater trawling. This would allow for more efficient use of midwater trawls, by concentrating the trawling effort in those areas where the species composition is highly variable or unpredictable. Our objective in this analysis was to identify and quantify the relation of the midwater distributions of the major prey fishes to the physical habitat characteristics.

Methods

We used the midwater trawl samples that were taken as part of the acoustic sampling on Lake Michigan during fall 1994-1995 (a total of 157 tows). To characterize the midwater prey fish distributions in Lake Michigan in a general sense, a predictive model of species composition should be robust to annual variation and differences in trawl deployment. For this reason, we included fifteen predictors relating to the physical environment in the initial stage of model building (Table 8.1), and excluded the following sample-specific factors: year, sampling date, trawl area (equivalent to a vessel identifier), tow time, effort (trawl area × tow time), and longitude. Thus, we created models based on physical characteristics that might be expected to be useful predictors of pelagic species composition in Lake Michigan.

The analysis focused on the three major prey species: alewife, bloater, and rainbow smelt. These are the primary species for which the methodology for estimating biomass is being developed. In addition, principal components analysis indicated that these three species described most of the variability in the proportion (number of fish in the catch) of the midwater trawl catches made throughout the study.

In addition to predicting the proportion of the catch of individual species, we were also interested in developing a model to predict the catch composition of all three species simultaneously. Therefore, we defined species composition groups based on the proportional catch of alewives, bloaters, and rainbow smelt. The first group was defined as those catches with >50% of the catch (in number) composed of species other than alewife, bloater, and rainbow smelt. We performed a cluster analysis on the remaining tows based on their proportional catches (using an average linkage hierarchical clustering of a Manhattan dissimilarity matrix of the proportions). This analysis yielded an additional six species composition groups for use in the predictive model (Table 8.2).

We used tree-based models to predict species composition (Venables and Ripley 1994). Regression and classification trees are powerful nonparametric models that repeatedly split the data into two groups according to values of the predictors (see Figure 8.2 for an example of a regression tree). Trees are invariant to monotone transformations of predictors, are good at capturing non-additive behavior, and allow for general interactions between predictors. They offer a useful way to find prediction rules and to identify important predictors. These features are particularly important in our study because of the large number of predictors and their skewed distributions.

Re-sampling techniques were used to select the predictor variables. The resulting models would be more robust to possible inconsistencies in the survey sampling procedure. We used regression trees to model the percent in number of each of the three species in the catch, and classification trees to model the species composition groups. A random sample of about 50% of the data (78 of 157 observations) was selected, a tree was created (for each response separately), and the variables selected for tree building were recorded. This procedure was repeated on 100 random samples of half the data, keeping a tally of the variables used in the trees. We identified those variables that were included most frequently as important predictors in a robust sense. Trees were then built from these variables using all of the data and simplified by eliminating branches that did not markedly improve the model. If possible, less important variables of highly collinear pairs were eliminated. Residuals from the model were plotted against those variables initially excluded from the tree building. The excluded variables were also added to the trees to see if they improved the overall fit. For comparison, linear and logistic models were also built, but they rarely explained as much of the variability in the data as did the trees.

Results

<u>Individual species predictors for alewife</u> — The most important variables for predicting the percent of alewife in the midwater trawl catch were nearness to bottom, maximum available temperature, and percent maximum temperature (see Table 8.1 for descriptions of these variables). The regression tree explained 74% of the variability in the percent of alewife captured (Figure 8.2). In general, the percent of alewife in the catch increased off bottom, in warmer parts of the water column, and under cooler surface waters. Predictions were most precise for trawl catches near the surface (99% alewife), and least precise for those in deeper water. Examination of the residuals showed no relation to factors not included in the model. Their inclusion in the regression tree did not improve the fit.

<u>Individual species predictors for bloater</u> — The most important variables for predicting the percent of bloater in the catch were nearness to bottom, latitude, and fishing depth. In general, the percent of bloaters in the catch increased with deeper tows (both nearness to bottom and fishing depth) and more southern latitudes (Figure 8.3). Predictions from the regression tree ($R^2 = 0.73$) were most precise for trawl catches off bottom (3% bloater). The predictions were least precise for trawl catches near bottom. Examination of the residuals showed no relation to factors not included in the model. Their inclusion in the regression tree did not improve the fit.

<u>Individual species predictors for rainbow smelt</u> — The most important variables for predicting the percent of rainbow smelt in the catch were latitude and minimum and maximum bottom depths. In general, the percent of rainbow smelt in the catch decreased with bottom depth and increased with latitude. Predictions from the regression tree ($R^2 = 0.49$) were most precise for trawl catches over the shallowest (9% rainbow smelt) and deepest waters (2% rainbow smelt). Predictions were least precise over medium depth waters.

Examination of the residuals showed no relation to factors not included in the model.

However, when added to the regression tree, sampling date (number of days from August 31 regardless of year) and longitude increased the R^2 value to 0.68. The percent of rainbow smelt in the catch was higher earlier in the season and at more western longitudes.

Species composition groups — The most important variables for predicting the species composition group were nearness to bottom, percent maximum temperature, and latitude. The classification tree built on these three variables correctly predicted the species group for 75% of the tows (Table 8.3). Introduction of additional factors to the classification tree did not markedly improve the overall classification rate.

Alewife dominated the species composition in the upper half of the water column, except for a few tows in the north that were made near the middle of the water column, which were classified as alewife-smelt dominant (Figure 8.3). Bloater dominated the proportion of the catch in the coolest part of the water column, except for a few tows in the north classified as alewife-bloater dominant. In the lower half of the water column, but not in the coolest part of the water column, a mix of species groups were found: mostly alewife-bloater dominant catches, some rainbow smelt in the north, and bloater and bloater-smelt in the south, near bottom.

We have the most confidence in our predictions of the species group dominated by alewife (85% correct) and that dominated by bloater (80% correct). Other predictions were less precise (Table 8.3). Note that the classification tree made no predictions for the species composition group dominated by "other" species. The most important variables for predicting the species composition group were nearness to bottom, percent maximum temperature, and latitude.

As an example the application of the model, fish species composition was predicted with the classification tree to a “typical” situation ! along a transect at Point Aux Barques in northern Lake Michigan in the fall of 1996. These predictions, based on vertical location in the water column, latitude, and water temperature measured in a year not part of the model development, were then compared to the actual composition of the midwater trawl catches sampled. Although there was agreement between the predicted and observed species compositions for most tows, not all tows were predicted correctly (Figure 8.4). This result illustrates the potential for error with the model (3 out of 4 correct) and indicates that in certain areas, trawling will still need to be conducted.

Effects of sampling design

Samples were numerous in some regions of the design space and sparse in others. The entire volume of water, as described by the bottom and fishing depths, was not well sampled over bottom depths > 70 m where there were few midwater trawls at fishing depths from 40 to 70 m and > 90 m. Also, the two vessels used for sampling were confounded with net size and, hence, effort as well as year (76% of the 1994 tows were made by the *R/V Grayling* and 99% of the 1995 tows were made by the *R/V Steelhead*).

The bottom depths and fishing depths sampled varied with time of night. The mean bottom depths and fishing depths sampled tended to be shallow early in the evening, and gradually deepened with time until about 2200 h when the sampling became more scattered over all depths. Ninety percent of the sampling took place between 1925 and 2350 h, although tows were made as early as 1840 h and as late as 0250 h.

The transects (and latitudes) sampled varied with the date of sampling. The transects were sampled in the same general order both years, so that each transect was sampled within the same 10 day calendar period both years, except for Saugatuck and Ludington (within 20 days) and Leland (40 days). On average, sampling in 1995 occurred eight calendar days later than in 1994.

The same range of bottom depths was not sampled at each transect. Two transects had very small ranges with tows only at 40 and 50 m for Seul Choix Pt. and tows only at 60 and 80 m for Milwaukee Reef. One transect, Manitowoc, had a median bottom depth over 100 m and no sampling over shallow waters. Over 60% of the transects were not sampled over bottom depths of 20 m or less, and over 60% of the transects were not sampled over 120 m.

The data used in this analysis were not collected from a designed experiment. The selection of sampling sites was based on observed fish aggregations and was not random, therefore, any estimations of precision we make are biased. We view this analysis as an exploration of the midwater species composition on a spatial and thermal scale as well as an investigation into the analytical techniques used to build predictive models in Lake Michigan.

Discussion

Given all the shortcomings, the models provided some reliability in predicting the presence of alewife and bloater in the midwater trawl catches. However, they were less successful in predicting the percent of rainbow smelt in the catch. We have also built a model to predict the dominant species in the midwater trawl catch using seven species composition groups defined by the proportional catches of alewife, bloater, and rainbow smelt. Note that in our model of the species composition groups, we have the most confidence in our predictions of two groups, those dominated by alewife and bloater.

Our difficulty in predicting the proportion of rainbow smelt in the catch requires further investigation. Other physical features may have been overlooked with this model. As example, the importance of sampling date to the model indicates within-season changes in the distribution of rainbow smelt, which were not evident for alewife or bloater. This effect can be particularly important during surveys that span 30 or more days when seasonal changes are occurring. Longitude was also an important predictor of the composition of rainbow smelt and perhaps some indication of east-west location should be included in the model. Geographical differences in fish density distributions are know to exist (see Section 10 ! Geographic Sampling Scale and Variability in Fish Distributions).

Our models indicate that spatial and thermal characteristics appear to be good predictors of species composition. The most important predictors over all four models were nearness to the bottom and latitude (included as predictors in three of the models) and percent maximum temperature (included in two of the models). However, to be reliable, such models would need to be unbiased. Additionally, they must be continually updated and verified to take into account inter-annual changes in the abundance of individual species and changes in relative species composition.

The number of midwater trawl tows and their placement along a particular acoustic transect are critical factors in determining species composition. This investigation emphasizes the need for a better understanding of the factors affecting pelagic fish distributions. To build unbiased models for predicting species composition from habitat characteristics, we recommend conducting specific experiments designed to measure species composition in the water column. These experiments must consider the effects of time of sampling, gear variation and other factors, integrated with a more appropriate sampling design. In addition, biological factors such as feeding patterns and diet selectivity should be considered. Such models would provide valuable insight into the pelagic ecology and inter- and intra-species dynamics of the various prey fishes.

Table 8.1. Variables used as predictors of species composition of midwater trawls in Lake Michigan.

Variable	Unit	Description
latitude	E N	
adjusted time	hours	e.g., 6:00 p.m.= 18 and 2:00 a.m. = 26
minimum bottom depth	m	
maximum bottom depth	m	
bottom depth midpoint	m	(min. b. depth + max. b. depth) / 2
fishing depth	m	Head Rope depth + (mtr vert. spread) / 2
nearness to bottom	percent	100% (fishing depth / b. depth midpoint)
distance to bottom	m	bottom depth midpoint - fishing depth
minimum available temperature	EC	minimum temp. of entire vertical profile
maximum available temperature	EC	maximum temp. of entire vertical profile
available temperature midpoint	EC	(min. a. temp. + max. a. temp.) / 2
spread of fishing temperatures	EC/m	temperature range within mtr / vertical height of mtr (note: essentially an indication of thermocline)
fishing temperature	EC	temperature at fishing depth
percent maximum temperature	percent	100% (f. temp. - min. a. temp.) / (max. a. temp. - min. a. temp.)
degrees to bottom	EC	fishing temp. - minimum available temp.

Table 8.2. Species composition groups used in the classification tree analyses.

Group	Dominant Species
A	Alewife
B	Bloater
S	Rainbow Smelt
AB	Alewife, Bloater
AS	Alewife, Rainbow Smelt
BS	Bloater, Rainbow Smelt
O	Bloater, Rainbow Smelt

Table 8.3. Frequency of observed and predicted species composition groups from the classification tree.

Observed Group	Predicted Group A	B	S	AB	AS	BS	O	Total
A	**57**	0	1	2	0	1	0	61
B	2	**41**	0	4	0	0	0	47
S	4	1	**3**	2	1	0	0	11
AB	0	4	0	**11**	0	1	0	16
AS	1	0	3	0	**3**	0	0	7
BS	0	1	1	1	0	**3**	0	6
O	3	4	0	0	2	0	**0**	9
Total	67	51	8	20	6	5	0	157
% Correct	85	80	38	55	50	60	0	75

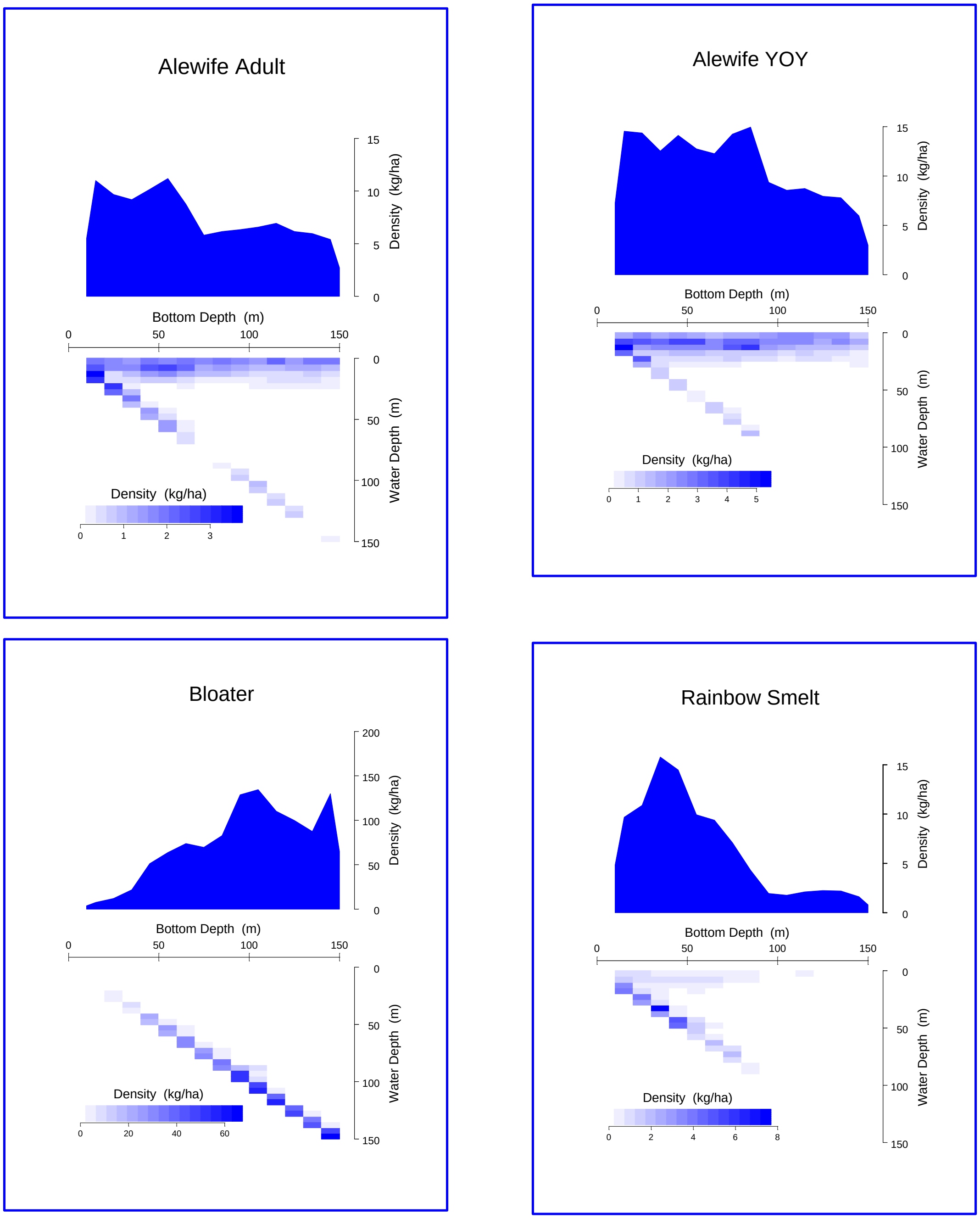


Figure 8.1 – Midwater densities (kg/ha) of alewives (young-of-the-year and adult), bloaters, and rainbow smelt based on fall acoustic surveys conducted on Lake Michigan, 1994-1995. Shown are mean densities for the entire water column by bottom depth (upper panel in each graph) and mean density throughout the water column (lower panel in each graph) for each species.

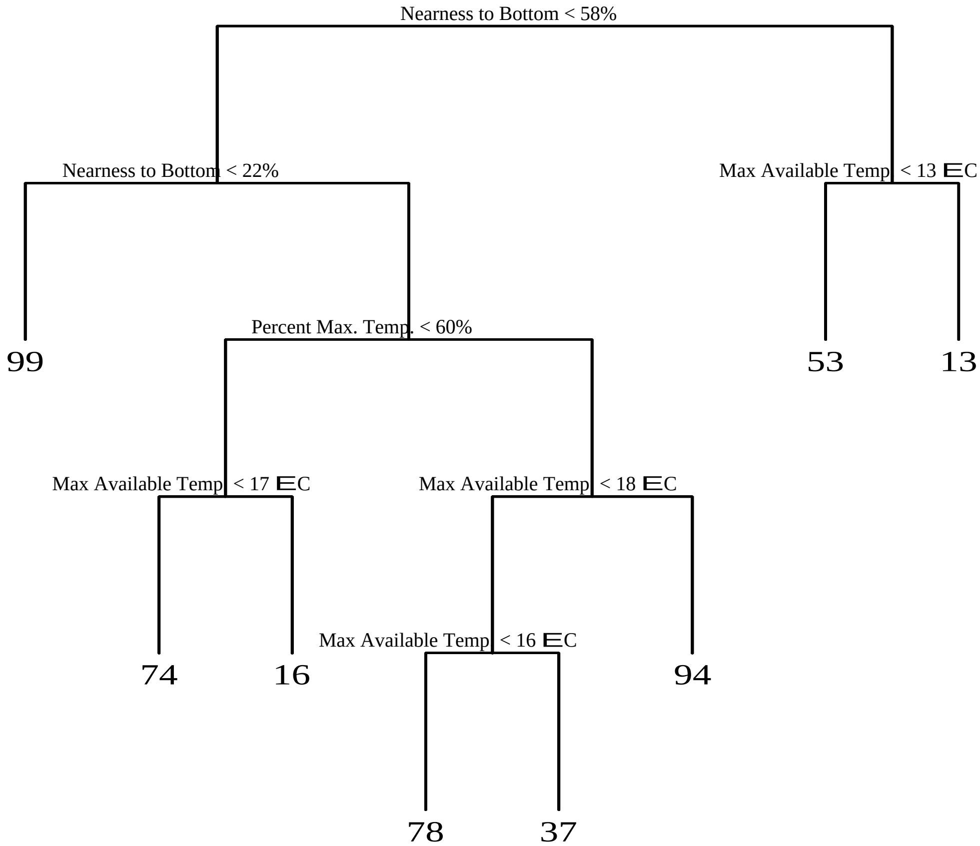


Figure 8.2 Regression tree predicting the percent of alewife in the midwater trawl catch using three selected variables. Each inequality describes the left branch of the split (<); the right branch is the opposite inequality (>). The number at the end of each branch is the predicted percent of alewife.

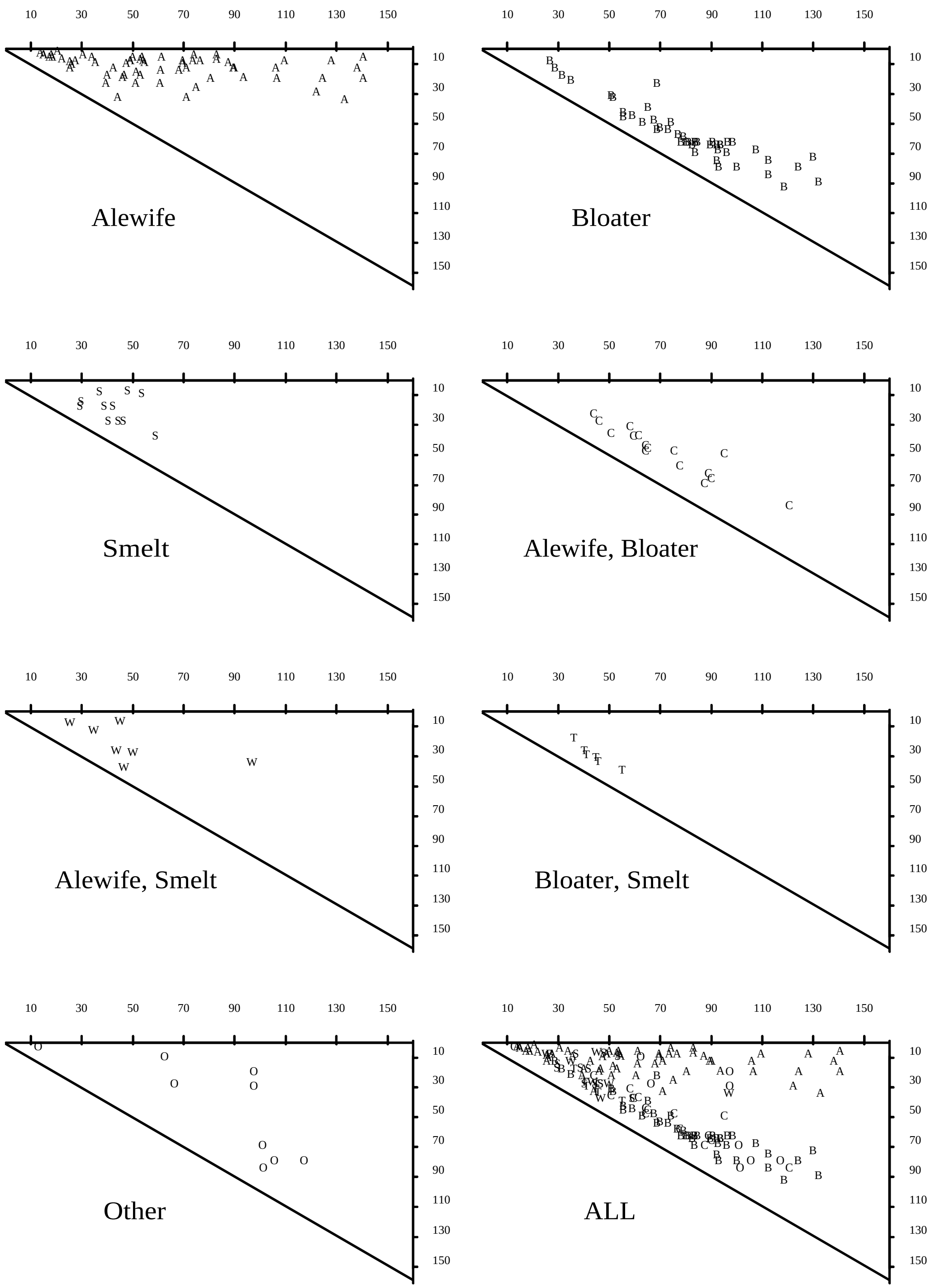


Figure 8.3 Location of midwater trawl tows in the water column by species composition group. The horizontal axis is bottom depth (m); the vertical axis is fishing depth (m).

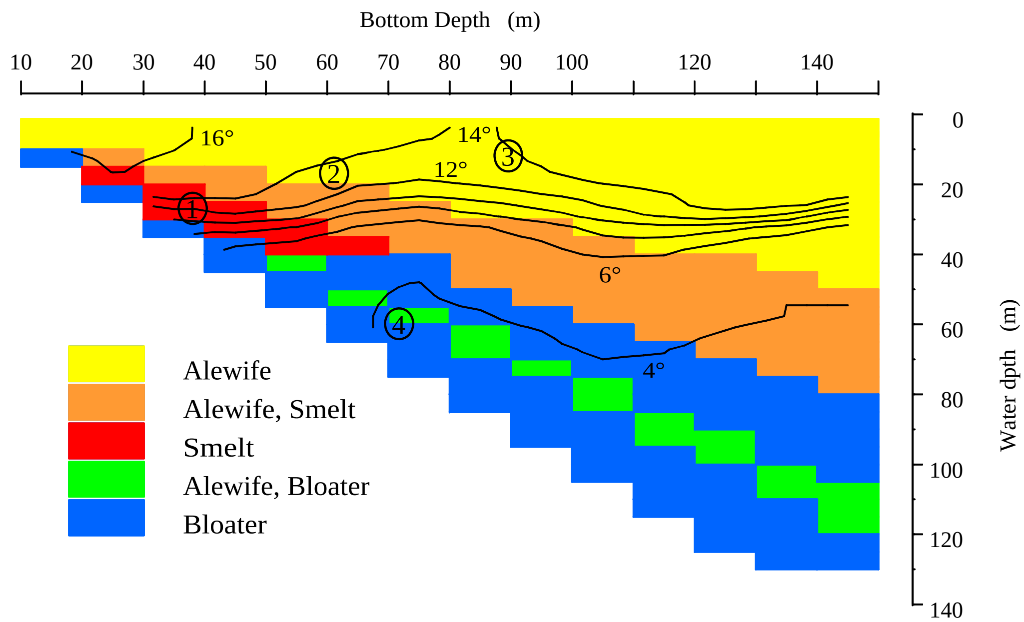


Figure 8.4 Comparison of predicted and observed species composition along a transect at Point Aux Barques, Lake Michigan, 1996. Colors indicate the predicted species composition group. Circled numbers identify the location of midwater trawls. The observed catch compositions for the trawls were (1) 79% rainbow smelt, (2) 50% rainbow smelt and 50% threespine stickleback, (3) 72% alewife, (4) 69% bloater. Contour lines reflect the temperature profile of the transect.

Section 9.

Geographic Patterns in Lake Michigan Fish Densities

Introduction

The accurate measurement of the abundance of prey fish populations in Lake Michigan is vital to managing the sport and commercial fisheries. Because of the large size of Lake Michigan, conducting surveys to estimate the biomass of prey fish on a lakewide basis is expensive and time consuming. It may be possible to make the surveys more efficient by optimizing the sampling design. One approach to survey improvement is to examine possible stratification schemes. If regions of the lake are characterized by different prey fish distributions, these regions may be useful as strata in future sampling plans. One way to examine this is through cluster analysis, which groups objects together based on similarities in their multivariate response. Our objective in this analysis was to investigate patterns in the distribution of Lake Michigan prey fish species with cluster analysis.

Methods

We focused our analysis on fall surveys conducted in 1994-1996, because of the greater coverage of the lake in these years (Figure 7.4). Observations consisted of the vertical acoustic densities (kg/ha) of three major prey fish species: alewife, rainbow smelt, and bloater (for a description of fish density calculations, see section 7 ! Acoustic Biomass Estimates). Because of the variable bathymetry of Lake Michigan, not every transect was sampled over the same range of bottom depths. We conducted two separate analyses, one for near-shore, 21 transects that extended from 10 to 90 m and one for off-shore, 13 transects that extended from 90 to 150 m (Table 9.1).

To define geographic regions for use as strata in future sampling designs and to reflect the general patterns in prey fish distributions in a manner that was robust to annual fluctuations in fish densities, we averaged the fish densities over all three years. Further, we scaled the data for each species, subtracting the species mean from the densities and then dividing by the species standard deviation. (The means and standard deviations used were based on weighted averages of the near and off shore values.) This procedure allowed each of the species to play an equally important role in the cluster groupings. In order to perform the cluster analysis on all the species and depth zones simultaneously, we created a matrix of scaled density estimates where each row represented a transect and each column represented a 10-m depth zone × species combination.

Thus, information on the relative densities of all the species over all the depth zones was used simultaneously to group the transects in the cluster analysis. Finally, we then created a dissimilarity matrix of Euclidean distances to which we applied complete linkage hierarchical clustering, in which groups were combined based on the largest distance between any two of their points. This type of clustering typically forms more compact clusters than other methods.

Results

<u>Near-shore analysis</u> — Most of the 21 transects with near shore data clustered into one of three groups (Figure 9.1). The transects off Manistique and Kewaunee were separated from the rest of the transects due to high smelt densities in both transects and high alewife densities off Kewaunee. Note that both of these transects were sampled in only one of the three years used in the analysis (Table 9.1). The cluster groupings suggested three geographic regions, north, south-central, and west (Figure 9.2; Table 9.1). Once the regions were defined (based on all species combined) we examined the patterns in the distributions of individual species within the regions. Transects in the western region were characterized by high alewife densities, and transects in the northern region were characterized by high rainbow smelt densities (Figure 9.3). The distributions of bloater densities were similar across all three regions, and the relative density of bloater was not an important factor in the formation of the cluster groups.

Under an optimal allocation scheme, the number of transects planned for a given region is proportional to the standard deviation of densities within a region. For each species and region, we calculated the variance among transects for each depth zone, and used the square root of the mean of these variances as the standard deviation within a region. From these standard deviations, we then calculated the proportion of total effort spent in each region that would optimize the lakewide biomass estimates of each species separately (Table 9.2). For alewife, the optimal allocation suggested that most of the sampling effort should be spent in the south-central region of Lake Michigan. For rainbow smelt and bloater, most of the effort should be spent in the northern region of Lake Michigan. However, the proportions in the table do not take into account the size of each of these regions in Lake Michigan. In order to examine the relative effort that should be spent on each area by species, we must take this difference in size into account. Figure 9.4 displays the concentration of effort suggested by the optimal allocation of 20 transects for Lake Michigan prey fish sampling. Twenty transects are used here simply as an example of what might be planned in future surveys. The optimal allocation for alewife is nearly proportional to the areas covered by the regions, so that the sampling intensity is essentially constant lakewide. For rainbow smelt most of the samples are concentrated in the northern region, where the smelt variability is higher. The allocation for bloater concentrates most of the sampling in the relatively smaller northern and western regions, where the bloater variability is higher.

<u>Off-shore analysis</u> — Most of the 13 transects clustered into one of two groups (Figure 9.5). The transects off Point Betsie and Manistee were separated from the rest of the transects due to high bloater densities. Eight of the 13 transects were grouped together in one large cluster group and had the greatest similarity. Yet, these transects are distributed all over the lake, from Baileys Harbor and Leland in the north to Kenosha and Saugatuck in the south. Thus, the cluster analysis did not yield any geographical regions based on the densities of these three prey fish in off shore waters of Lake Michigan.

<u>Regional stratification</u> — To investigate the potential benefits of the regions defined in the near shore analysis, we applied the geographical strata in the estimation of lakewide biomass from 1993 data that were not used in the cluster analysis (because no regions were defined in the off shore analysis, we let the regions determined by the near-shore analysis be used to stratify the whole lake). The calculated biomass estimates for each of the three species were similar with and without the regional stratification, however the precision of the estimates was much improved with the stratification (Figure 9.6). For alewife the coefficient of variation (CV) declined from 54% to 28% for alewife, declined from 49% to 28% for rainbow smelt, and dropped from 23 to 16% for bloater.

Conclusions

Cluster analysis was useful in defining regions of Lake Michigan based on prey fish distributions. By treating all species equally we were able to define major geographic regions that, when allocated the appropriate effort, should result in improved precision in the estimates of the total biomass of the major prey species. Use of these regions to stratify Lake Michigan, even without optimal allocation, improved the precision of 1993 lakewide biomass estimates for all three species. Thus, despite differences in the regional abundances of the individual prey species, the proposed geographic stratification provides an optimal design for measuring the abundance and biomass of all major species in a single survey. Within this overall stratification scheme, sampling effort can be adjusted to provide even more precise estimates for a particular species, while maintaining a high level of overall precision in the biomass estimates of other species. This design offers considerable flexibility in defining the major objectives of the survey while maintaining the integrity of the estimates of species other than the species of primary focus.

We recommend the consideration of these strata in future lakewide sample surveys, in which the number of transects in each region are determined by the optimal allocation suggested by the survey objectives, whether they are focused on a particular target species or the estimation of total prey biomass.

Table 9.1. Twenty-one transects used in the cluster analysis, identified by the name of the nearest port, number of years sampled, cluster grouping, and geographic region (N = north, SC = south-central, and W = west).

Transect	Years of Complete Data		Near Shore Results	
	Near Shore (10-90 m)	Off Shore (90-150 m)	Cluster Group	Region
Point Au Barque	3	2	1	N
Manistique	1	0	4	N
Beaver Island	2	0	1	N
Leland	2	2	1	N
Sturgeon Bay	3	3	3	SC
Baileys Harbor	3	3	3	SC
Point Betsie	2	2	3	SC
Frankfort	1	1	3	SC
Manistee	3	3	3	SC
Ludington	3	3	3	SC
Muskegon	3	0	3	SC
Port Sheldon	3	0	3	SC
Saugatuck	2	3	3	SC
Michigan City	1	0	1	SC
Waukegan	3	0	3	SC
Kenosha	1	1	1	SC
Milwaukee	3	0	3	SC
Port Washington	2	2	2	W
Sheboygan	1	0	2	W
Manitowoc	2	2	2	W
Kewaunee	1	1	5	W

Table 9.2. Proportion of effort that should be spent in near shore regions of Lake Michigan to optimize lakewide biomass estimates for each species. The relative proportion of lake surface area in the near shore zone is also displayed.

Region	Alewife	Smelt	Bloater	Area
North	0.2	0.5	0.5	0.3
South-Central	0.6	0.4	0.2	0.6
West	0.2	0.1	0.3	0.1

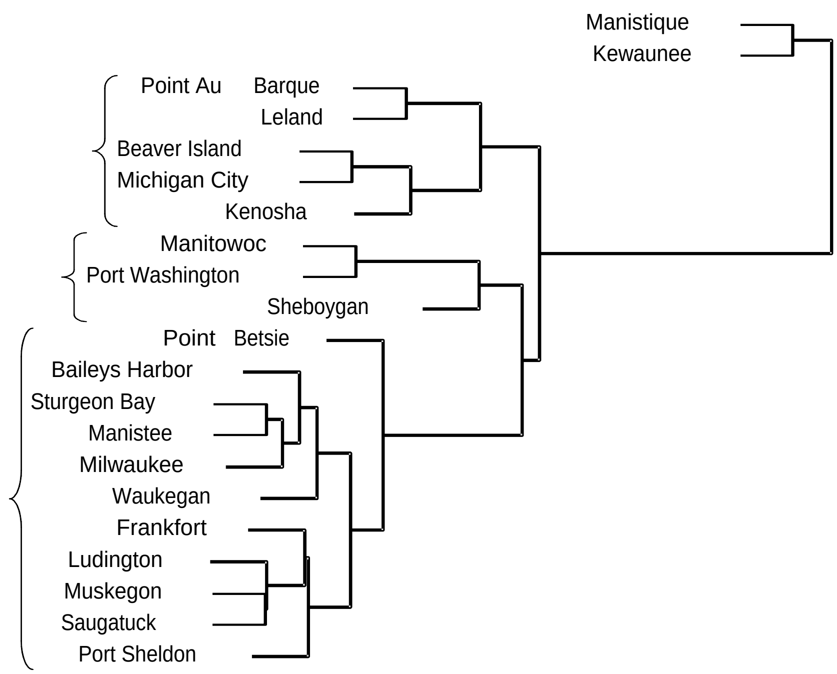


Figure 9.1. Tree diagram of cluster analysis on 21 transects based on near shore densities (10 - 90 m) for alewife, rainbow smelt, and bloater.

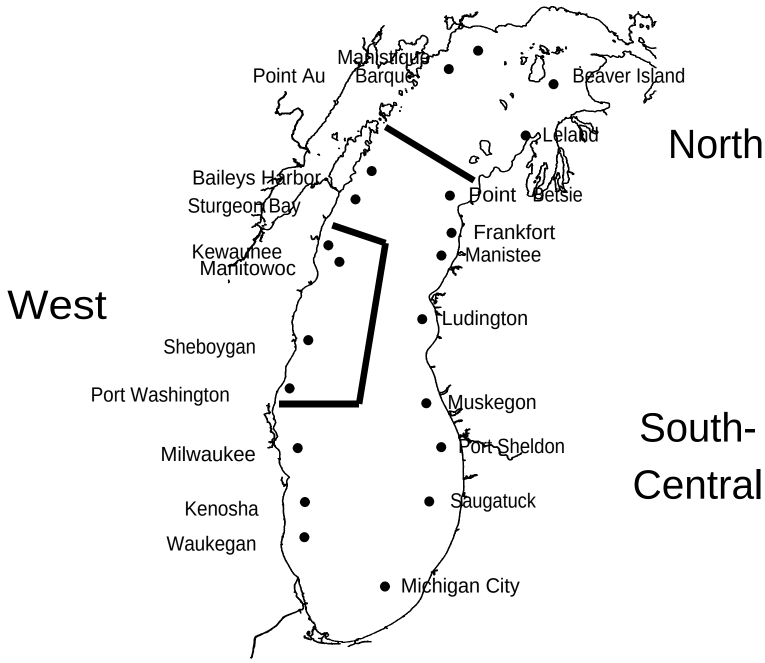


Figure 9.2. Geographic regions of Lake Michigan as suggested by the cluster analysis of near shore prey fish densities.

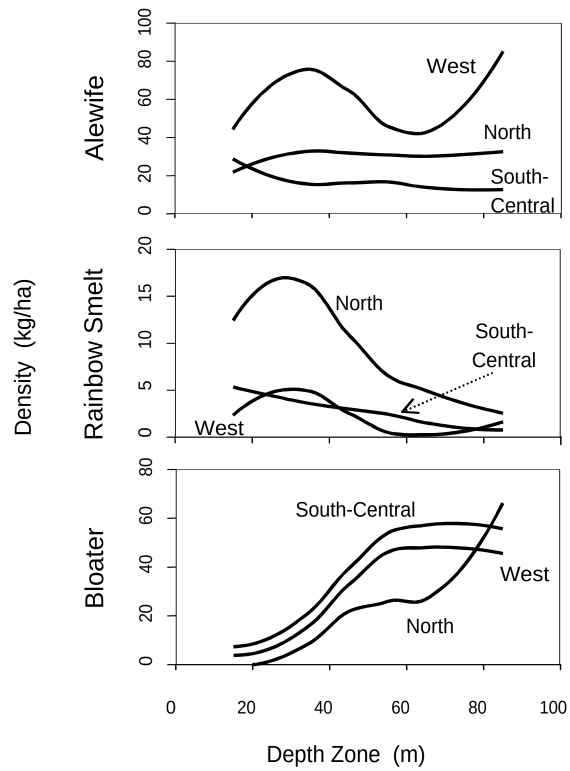


Figure 9.3. Distribution of prey fish in three geographic regions of Lake Michigan, smoothed with local regression lines.

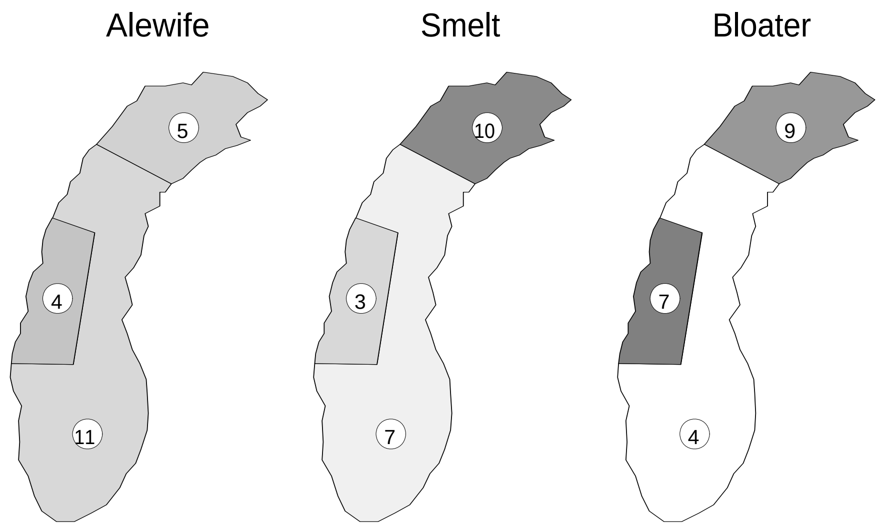


Figure 9.4. Optimal allocation of 20 transects to Lake Michigan for biomass estimation of three prey fish species. The shading in each region reflects the sampling intensity in terms of the number of transects per unit surface area.

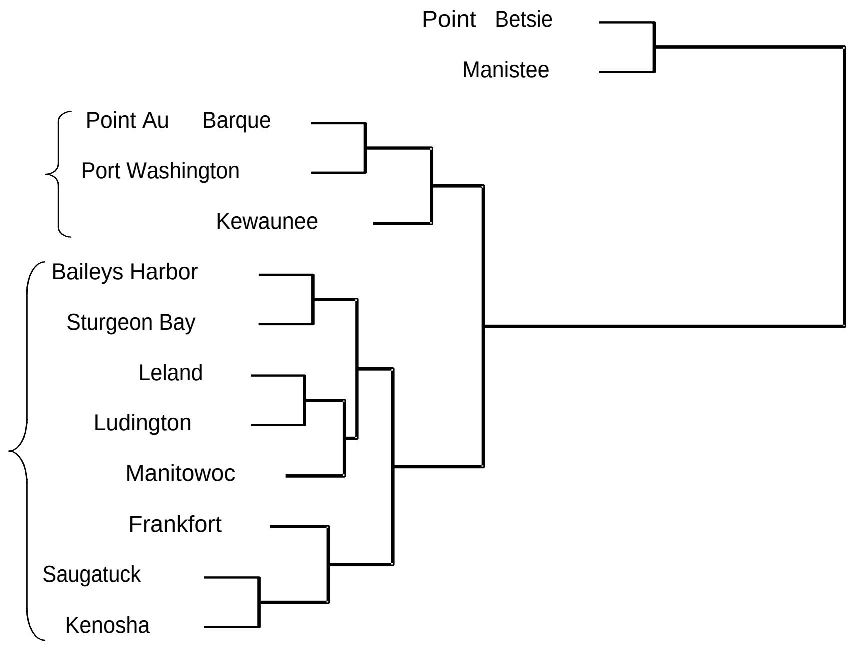


Figure 9.5. Tree diagram of cluster analysis on 13 transects based on offshore densities (90 - 150 m) for alewife, rainbow smelt, and bloater.

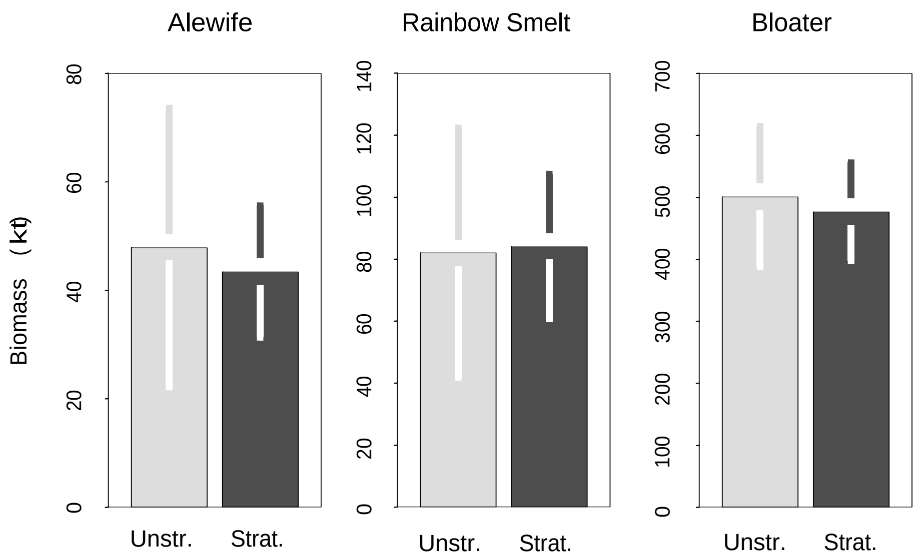


Figure 9.6. Lakewide biomass estimates for three prey fish species with stratification (Strat.) and without stratification (Unstr.) by region. Bars indicate plus or minus one standard deviation.

Section 10.

Geographic Sampling Scale and Variability in Pelagic Fish Distributions

Introduction

The use of acoustics to assess fish populations is enhanced by knowledge of the spatial distributions of the species being studied. In large systems such as Lake Michigan, an understanding of fish distributions is especially critical to the development of efficient sampling designs. Because long-term surveys with bottom trawls in Lake Michigan have shown high lakewide variability in pelagic fish abundance and species composition, knowledge of the geographic scales over which fish densities are sufficiently homogeneous is necessary to determine the appropriate scales for sampling. Even though acoustic sampling allows more efficient sampling over a much wider areas than bottom-trawl surveys, the size of Lake Michigan dictates that sampling transects must be widely spaced if the survey is to be completed within a reasonable time frame. Sampling sites are often located substantial distances apart (> 50 nm) and random selection of transect locations is logistically difficult. For example, lakewide sampling coverage to date has required a total of more than 60 vessel days per year.

In our initial acoustic sampling conducted on a lakewide basis, we observed high variability in fish densities in different parts of the lake. In the process of calculating areal biomass estimates during the initial part of this study we noticed a wide disparity in the estimates for a particular area depending on the transect(s) data selected for expansion. Other analyses indicated greater variability in fish densities in some areas throughout the lake (see Section 9 ! Geographic Patterns in Lake Michigan Fish Densities). This presented a practical problem in how much sampling was adequate for a particular area.

The objectives of this section were to examine variability in fish densities at a smaller geographic scale than that encompassed by our lakewide sampling, compare seasonal variability in fish density at a smaller scale, and compare these among sites located on east and west sides of the lake.

Methods

To determine the spatial variability of fish densities on a smaller scale we chose two areas in central Lake Michigan. Sampling was conducted at Manitowoc, WI and

Ludington, MI (Figure 10.1). These two locations were chosen to allow comparison of east-west distributions in addition to localized fish distributions. Sampling was done at night during April and July and October (referred to as spring, summer, and fall in the rest of this section) with dual-beam acoustics (to obtain fish density estimates) and midwater trawls (to determine species composition in the pelagic zone).

A maximum of five parallel transects, spaced three nautical miles apart, were sampled at each location. Individual transects extended from the 10 m to the 150 m depth contours, but because that depth was not attainable along all transects we limited the data analysis to 10 m to 90 m. In spring four transects were sampled at each location and in summer five transects were sampled. In fall inclement weather only allowed three transects to be sampled at Manitowoc and one at Ludington. Midwater trawling was conducted only along selected transects, and targeted at areas of high fish densities observed during the conduct of the transect. The total area of the grid sampled by the transects was 240 square nm; the farthest distance between two transects at a site was 12 nm, which is considerably less that the typical distance between locations sampled during the lakewide surveys.

Fish densities (number of fish per surface hectare) were calculated for each 5 m vertical strata within each 10 m depth contour. Because our primary interest was in the variability in overall fish densities, this analysis was limited to total fish densities rather than those of individual species. To compare density estimates among transects we developed a point estimate for each transect. This estimate was the average of the fish densities (number of fish per surface hectare) for each 10 m bottom contour. We compared average fish densities among transects within a site, among sites within a season, and among seasons by analysis of variance (ANOVA).

Results

The distribution of fish densities with depth varied among seasons. Fish density was highest in spring at depths <50 m, while in summer, density was highest in the near shore areas and consistently high at all depths (Figure 10.2). In the fall fish density was highest at depths < 40 m. The sharp demarcation in fish densities at this typically corresponded with the lower edge of the thermocline during the fall surveys (Figure 10.3), and the high abundance at the 30-40 m depth contour indicated that fish tended to concentrate in depths where the thermocline intersects the bottom..

The pelagic distribution of fish densities in spring, summer, and fall are shown in Figure 10.4. In spring fish densities are highest near the surface and at mid-depths. Fish are more evenly distributed through the water column during summer, and highest densities are at deeper depths. In fall densities were highest at intermediate depths, corresponding to the areas in and below where the thermocline would typically be. However, in 1993 severe prolonged storms during the sampling period resulted in a dissipation of the thermocline at both sites.

Fish density estimates used in this analysis were for all species combined. However, midwater trawl catches indicated species composition in the water column was most uniform in spring because water temperatures were isothermic (Figure 10.3). In summer 1993 there was typically good thermal structure, and species were more segregated. However, the youngest life stages of most of the species were not large enough to be seen in in the acoustic sampling or be caught in the midwater trawls. The most segration by species was observed when temperature differences between thermal strata were greatest and all life stages of the various species were present.

Seasonal comparisons — Mean fish densities for individual transects at Manitowoc and Ludington in spring and summer are shown in Figure 10.5. Mean fish densities were not significantly different among spring, summer and fall at the Manitowoc site ($P= 0.28$). There were also no significant differences in mean fish densities between spring at summer at Ludington ($P=0.18$); fall was not included because only one transect was completed at Ludington in the fall.

Within-season comparisons — Mean fish densities for the individual transects are shown by season for each location in Figure 10.6. There was no significant difference between mean fish densities at Manitowoc and Ludington during spring ($P= 0.17$). However, differences in mean densities for individual transects at Manitowoc were highly significant ($P= 0.0001$) indicating the fish distributions were patchy within the sampling grid. At Ludington, mean fish densities for the individual transects were not different ($P= 0.38$) indicating that fish densities were more evenly distributed within the sampling grid.

There was no significant difference between mean fish densities at Manitowoc and Ludington grids during spring ($P= 0.37$). Mean densities for individual transects at Manitowoc were different ($P= 0.001$) indicating that fish distributions were patchy. At Ludington there were no differences among individual transects ($P= 0.07$), although the degree of significance suggests that fish distributions may have been more patchy in this grid in summer than in spring.

Mean fish densities at the three transects sampled in fall at Manitowoc were not different ($P > 0.05$). A 3-d plot of interpolated fish densities for the Manitowoc and Ludington grids during summer are shown in Figure 10.7. The relative unevenness of the fish distributions can be seen in the figures, particularly at Manitowoc where mean density of individual transects were highly significantly different.

Summary

Based on the resolution of our study, the development of lakewide estimates of the abundance of the major prey species is not significantly affected by the large distances between sampling transects. Even though fish densities measured at individual transects were highly variable, estimates of fish densities within areas the size of our sampling grids suggest that widely-spaced transects, on average, provide reasonably good estimates of larger-scale densities. For example, we saw no evidence of differences in overall fish densities between the two areas in any season. This was probably the result of the greater variability in fish densities off Manitowoc where differences among the mean densities for individual transects were found in spring and summer. In contrast, no differences between transects were detected at Ludington. This finding corroborates the result of the cluster analysis that identified the area surrounding Manitowoc as separate region due to the greater variability in comparison to the other regions (Section 9 ! Geographic Patterns in Lake Michigan Fish Densities). Site selection is more critical in the area off Manitowoc and the greater variability demands more sampling effort in this region.

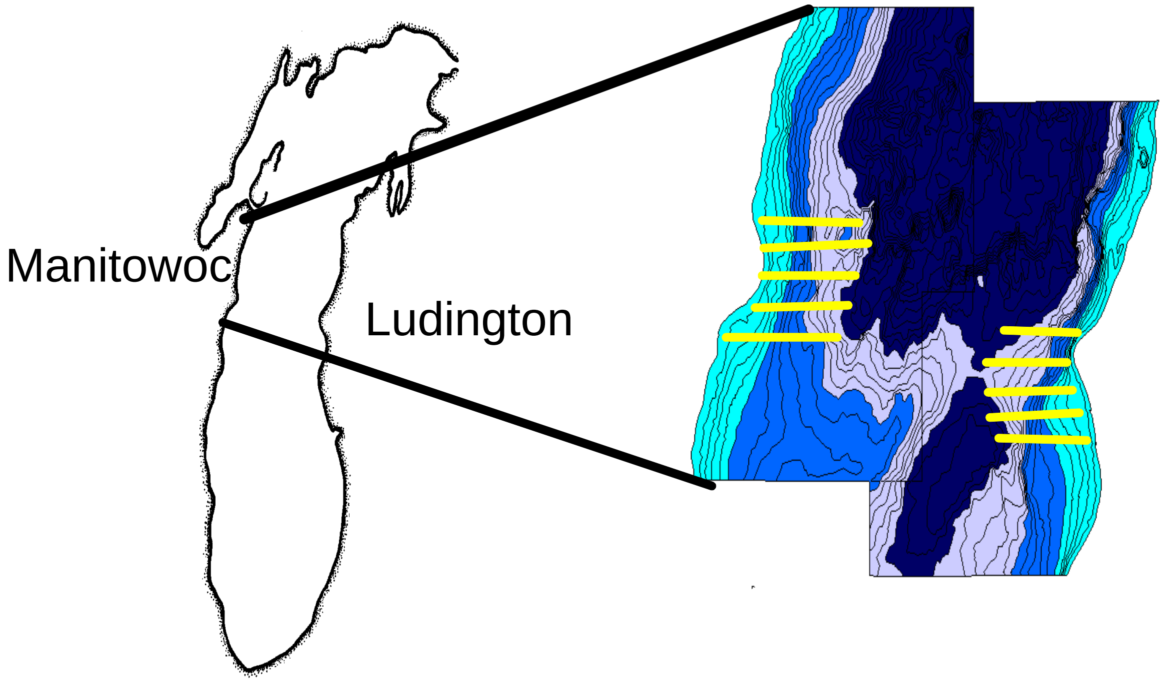


Figure 10.1. Location of the sampling sites at Ludington and Manitowoc and arrangement of the transects with the sampling grids.

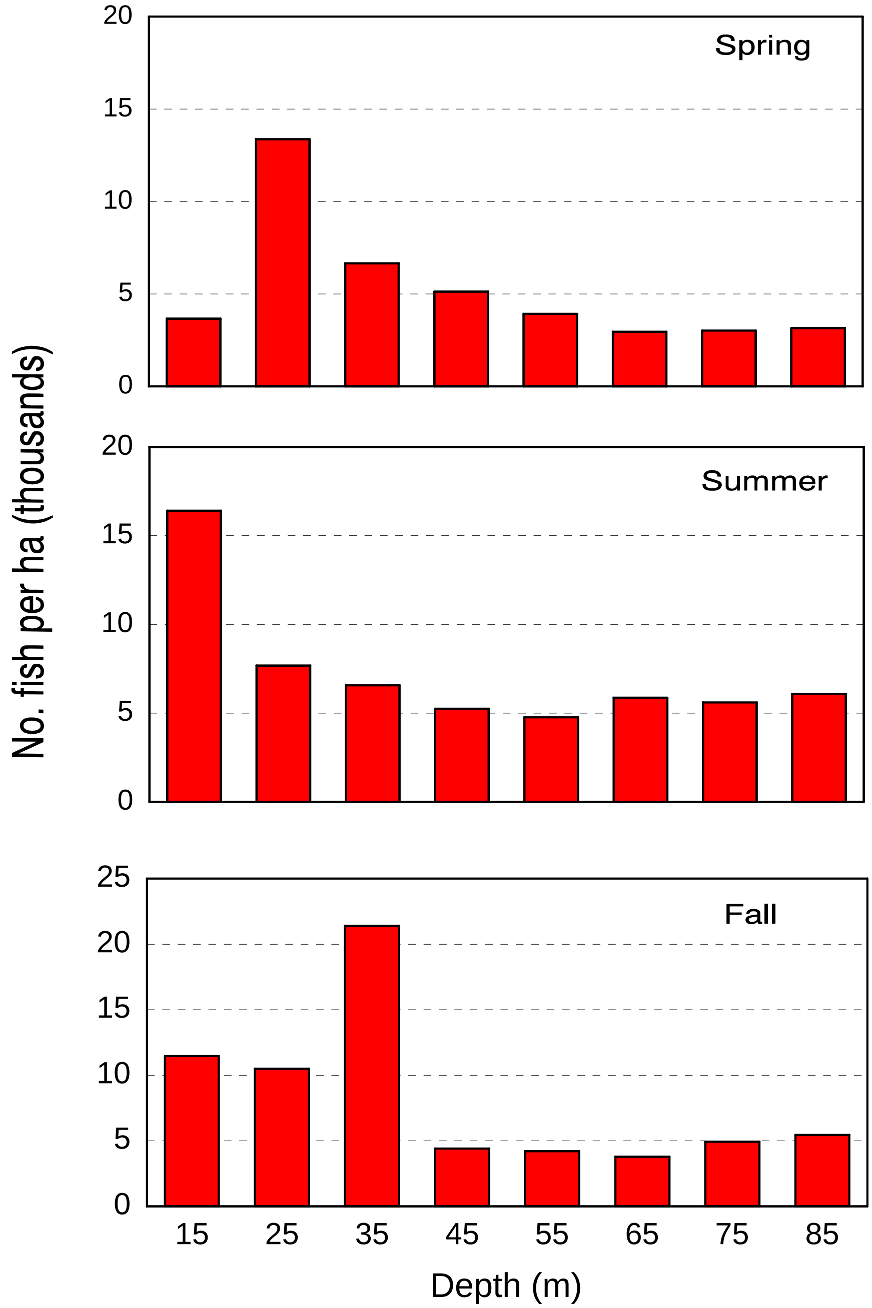


Figure 10.2. Seasonal distributions of mean fish densities (all species combined) by bottom depth contours in 1993.

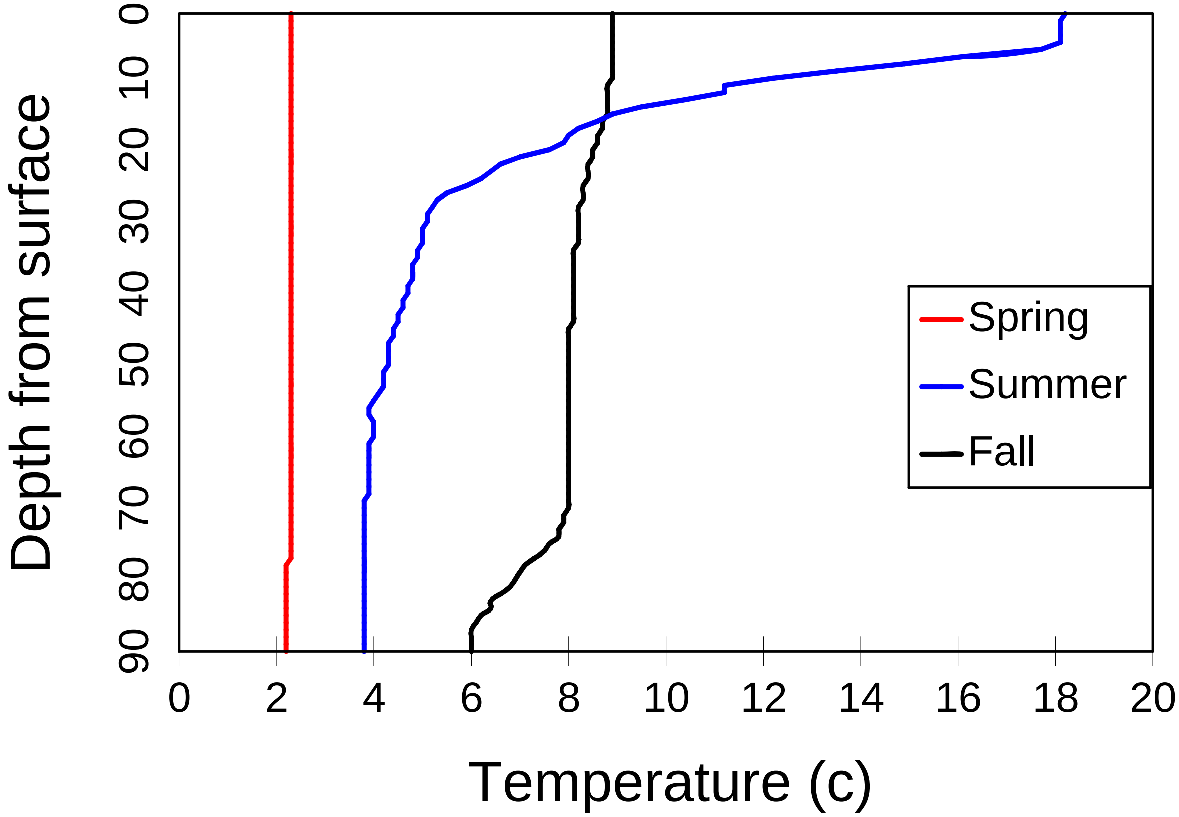


Figure 10.3. Examples of typical temperature profiles observed during spring, summer, and fall sampling in 1993.

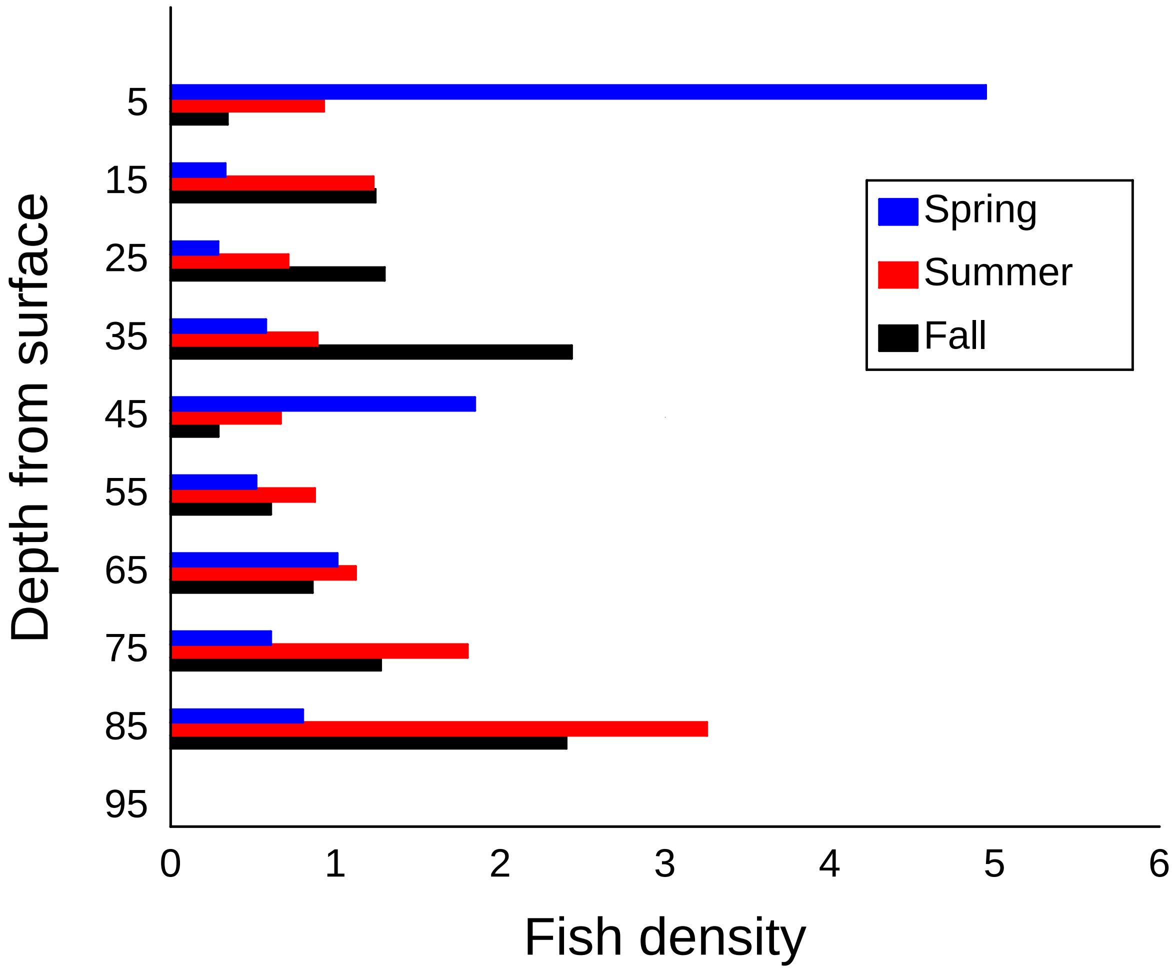


Figure 10.4. Pelagic distributions of fish densities (all species combined) in spring, summer, and fall in 1993.

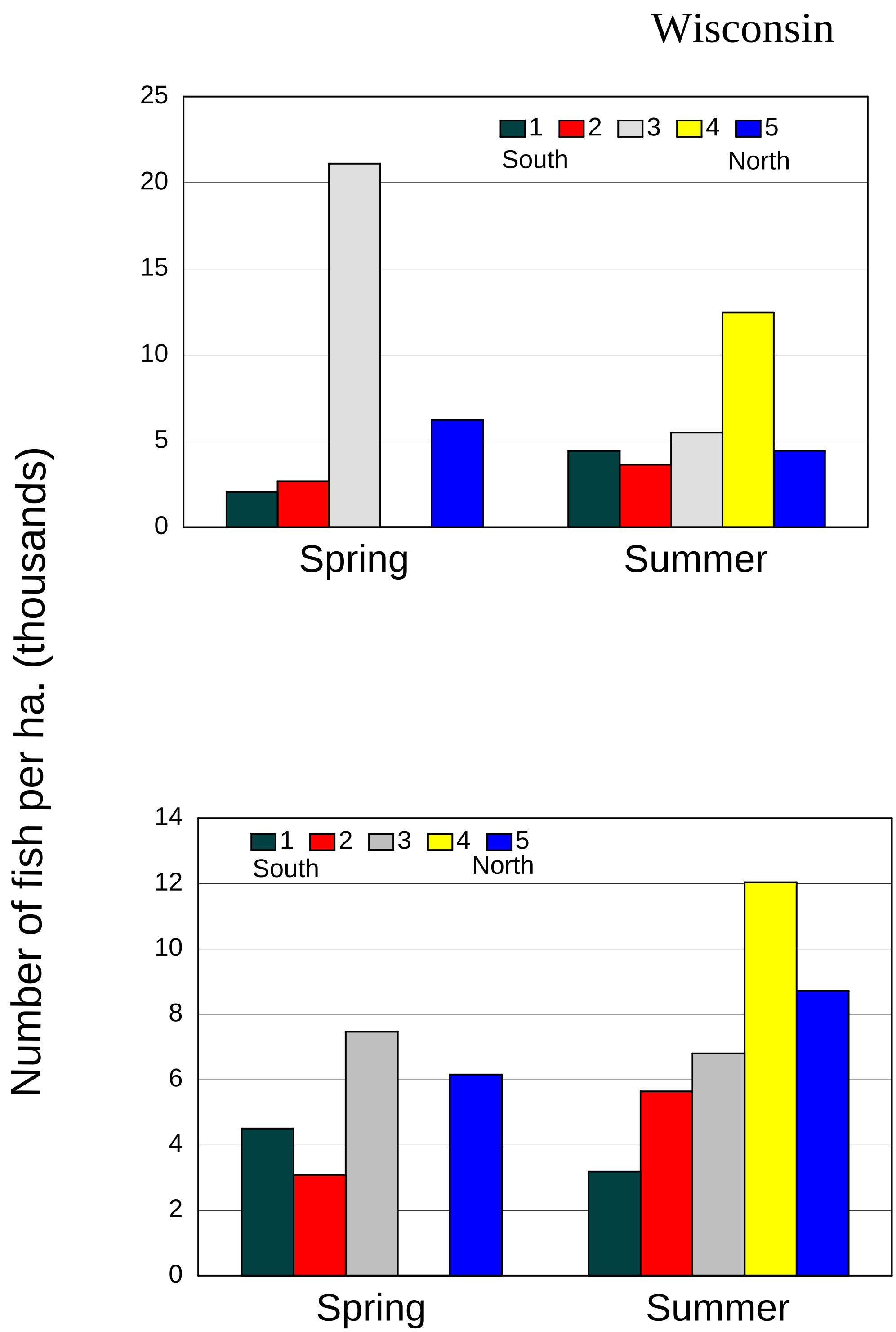


Figure 10.5. Mean densities at individual transects at Manitowoc and Ludington in spring and summer 1993, grouped by location.

Spring

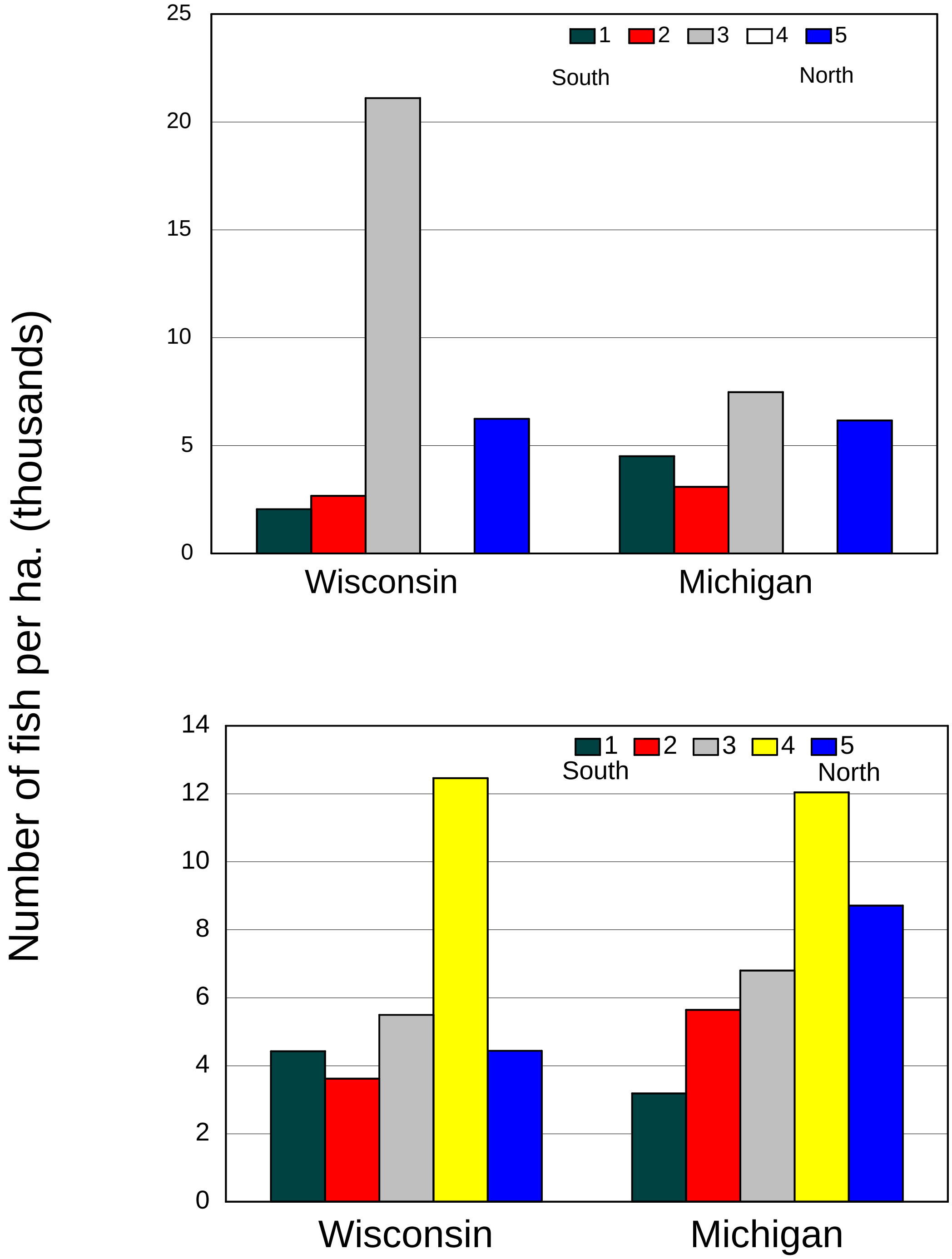
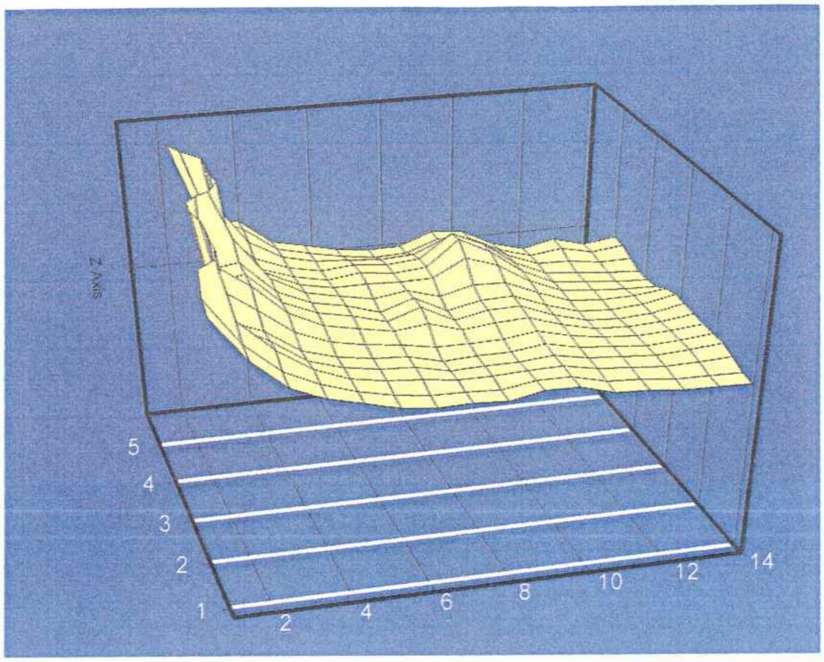


Figure 10.6. Mean densities at individual transects at Manitowoc and Ludington in spring and summer 1993, grouped by season.

Michigan summer



Wisconsin summer

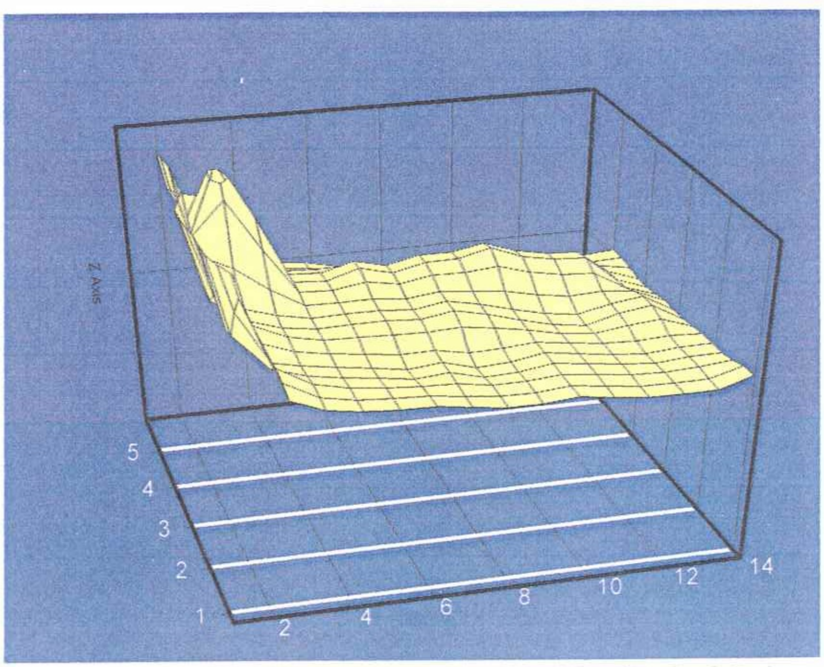


Figure 10.7. Plots of interpolated fish densities for the Manitowoc and Ludington grids during summer 1993.

Section 11.

Seasonal Food Habits and Prey Selectivity

Integral to the determination of the patterns of distribution and abundance of fish is an understanding of the factors affecting fish distributions. This is particularly important when using acoustics and midwater trawls as the primary sampling tools, because sampling designs are often based on knowledge of fish distribution patterns. Many of the prey fishes either migrate from the bottom into the water column during night or otherwise change their distributions diurnally; this pattern likely depends on a variety of factors such as time of the year, water temperature, and food availability. Little is currently known about the pelagic diets of the major planktivores in Lake Michigan and the role that food availability may play in determining how the various species are distributed in the pelagic zones. The objectives of this part of the study were to determine seasonal diet of alewives, rainbow smelt and bloaters, the dominant pelagic prey species, and determine if food availability influenced the pelagic distributions of these species. The lower-trophic food web interactions among the primary prey species were also examined.

Procedures and Methods

Prey fish and zooplankton were sampled concurrently along a series of transects located near Ludington, MI and Manitowoc, WI (Figure 10.1). These sampling sites provided an east-west gradient for comparison. Sampling was conducted in spring (April), summer (July), and a limited amount of sampling in fall (October) 1993 for seasonal comparisons of prey fish diets. However, bad weather limited the sample collections to one transect at Ludington in the fall. Fish were collected during midwater trawling done in conjunction with the acoustic survey. The trawl tows were made in areas of high acoustic densities or in areas where species identification was critical to the acoustic sampling. When the trawl catch was small, the entire catch was retained. When the catch was large it was randomly subsampled onboard. Each sample was placed in labeled plastic bags and frozen for later transport to the Great Lakes Science Center for analysis.

Zooplankton populations were sampled concurrently with the fish collections at the two sites during the three seasons. Samples were collected along three or four transects at each site over six different bottom depths (10, 30, 50, 70, 90, and 130 m). A Puget Sound style closing net with 160 Φ mesh and 50 cm diameter mouth was used in taking stratified vertical zooplankton tows. Sample collections were stratified by depth in two to three strata (two replicates per strata) – epilimnion, metalimnion, and hypolimnion -- depending on time of year and extent of the metalimnion.

The zooplankton samples were washed from the cod end of the net into the bucket of the net and an alka-seltzer tablet (narcotizing and buffering agent) added to the bucket. The sample was washed from the bucket with distilled water into a 1 quart sample jar. Buffered and sugared formalin (2 g Borax per100 ml and 4 g sucrose per100 ml with 8 mg Phloxine B dye/l formalin to enhance visibility of zooplankton) was added to each sample jar to achieve a 5% formalin concentration by volume.

At each site and season at least 20 fish were collected in the following categories: small bloater (< 160 mm), large bloater (> 160 mm), small alewife (60-120 mm), large alewife (> 120 mm), small rainbow smelt (< 100 mm), and large rainbow smelt (>100 mm). Because the age of the various species was not known in the field, a length cut-off based on sampling in recent years was used to obtain an approximate separation by age group. At least five fish were analyzed in each sample.

Prey fish collected for food habit studies were thawed, weighed to the nearest gram, measured to the nearest millimeter, and sexed if possible. Stomachs were removed and preserved in 10% formalin. For analysis the stomachs were opened and contents removed and teased apart to determine if the contents could be completely counted or needed to be subsampled. All large prey (such as *Mysis*, *Bythotrephes*, and amphipods) were counted. When subsampling the contents were diluted to a known volume (usually 100 ml), gently stirred, and a ten percent subsample removed. The contents were identified to the lowest taxon, counted, and measured with aid of a Ward counting wheel under a dissecting microscope fitted with an ocular micrometer. Up to ten individuals per taxon per fish were measured to the nearest micron. Length measurements were converted to biomass estimates based on regression equations.

Each zooplankton sample was strained and drained of formalin. If subsampled, the sample was diluted with water to a known volume, stirred to provide a consistent density of plankton, and then subsampled (4-ml). The subsample was returned to the original sample after processing and the procedure was repeated for a total of three subsamples. Certain taxa (such as *Mysis*, *Bythotrephes*, and amphipods) were considered too large to be subsampled; all were removed and processed in the same manner. The zooplankters were identified to lowest possible taxon, counted, and measured with aid of a Ward counting wheel under a dissecting microscope fitted with an ocular micrometer. Most mature specimens could be identified to genus and species;

most immature animals could be identified to family or genus. Specimens smaller than rotifers (<100 microns) were not counted. Up to ten individuals per species per station were measured to the nearest micron. Length measurements were converted to biomass estimates based on regression equations. The three subsample counts were averaged and the resulting mean was used to calculate number of organisms per cubic meter.

Results

A summary of the numbers and sizes of fish sampled from each location and season are given in Table 11.1. Bloaters were the dominant size group caught during all seasons and generally they were largest near Manitowoc. There were no discernable differences in sizes of the other species by port or season.

Bloater food habits — The diet of large bloaters consisted almost entirely of three taxonomic groups: microzooplankton, *Mysis*, and *Diporeia* (Figure 11.1). There were some clear differences in the diets of bloaters off Ludington and Manitowoc. In the spring, microzooplankton was the dominant food item at Ludington, whereas *Mysis* was the dominant food item at Manitowoc. In summer, *Mysis* was the dominant food item at Ludington and *Diporeia* was dominant at Manitowoc. In fall, *B. cederstroemi* was the dominant food item at Ludington and *Diporeia* was again dominant at Manitowoc. The dominant microzooplankters in the diet were *Limnocalanus macrurus* in the spring, *L. macrurus* and other assorted taxa in summer, and *Daphnia galeata mendotae* and *L. macrurus* in fall (Table 11.2). In the spring a total of 15 different taxonomic items were eaten by the fish sampled at Ludington and 13 at Manitowoc, whereas in the summer 25 items were eaten at Ludington and 23 were eaten at Manitowoc, and in the fall only 11 were eaten at Ludington and 10 at Manitowoc. Large bloater were consistently feeding since only 19 of 102 fish stomachs from Ludington and 30 of 103 from Manitowoc were empty (Table 11.1). Of the 49 empty stomachs, 26 were from the fall collections.

Small bloaters mainly ate microzooplankton, but *Mysis* and *Diporeia* also contributed to their diet (Figure 11.1). Microzooplankton dominated the diet at both ports in the spring. In summer *Mysis* was the dominant food item at Ludington, but was present in the stomachs from Manitowoc. In fall *Bythotrephes* was the dominant food item at both ports. The dominant microzooplankters in the diet were *L. macrurus*, although they were more important in the spring than the summer (Table 11.2). In the spring a total of 10 different taxonomic items were eaten by the fish sampled at both Ludington and Manitowoc, whereas in the summer 23 items were eaten at Ludington and 13 were eaten at Manitowoc, and in the fall only one item was eaten at

Ludington and five were eaten at Manitowoc. Only eight of 47 fish sampled were empty (Table 11.1), however, five of these were from the seven fish in the fall sample.

Alewife food habits — Large alewives ate mostly microzooplankton, *Diporeia*, and *Mysis* (Figure 11.1). Microzooplankton was the dominant food item in spring, summer, and fall at Manitowoc. However, at Ludington, *Diporeia* was the dominant food in spring and *Mysis* was dominant in summer. The dominant microzooplankters in the diet were *L. macrurus* (except in summer at Manitowoc), *Diacyclops thomasi,* and in the fall, *Leptodiaptomus sicilis* and *D. galeata mendotae* (Table 11.2). In the spring 11 different taxonomic items were eaten by the fish off Ludington and nine items off Manitowoc, whereas in the summer 30 items were eaten at Ludington and 26 at Manitowoc, and in fall 18 items were eaten at Manitowoc. Large alewife fed consistently since only 2 of 69 fish sampled had empty stomachs (Table 11.1).

Small alewives ate mostly microzooplankton, but *Mysis* were present in 60% of the fish at Ludington in summer (Figure 11.1). The dominant microzooplankters in the diet were *L. macrurus* in the spring, *D. thomasi* in the summer, and *D. galeata mendotae* and *Bosmina longirostris* in the fall (Table 11.2). In the spring eight different taxonomic items were eaten by the fish collected off Ludington and 10 for those off Manitowoc, whereas in the summer 20 items were eaten off Ludington and 25 off Manitowoc, and in the fall 22 items were eaten at Manitowoc. Small alewives were also feeding consistently since only four of 134 fish stomachs were empty (Table 11.1).

Rainbow smelt food habits — The diet of large rainbow smelt was mainly *Mysis* at Ludington in both spring and summer (Figure 11.1). At Manitowoc, *Diporeia* made up 70% of the diet in the summer, whereas *Mysis* was most important in the spring, and young fish were most important in the fall. *Limnocalanus macrurus* was the dominant microzooplankter in the spring diet, but it was only one of three items that dominated the summer diets, and *L. macrurus* was secondary to *D. galeata mendotae* in the fall (Table 11.2). In the spring a total of eight different taxonomic items were eaten by fish off Ludington and nine off Manitowoc, whereas in the summer 16 items were in the diet of rainbow smelt off Ludington and 27 items off Manitowoc, and in the fall 18 items were eaten off Manitowoc. Large rainbow smelt had a higher number of empty stomachs than other species. In spring 119 of the 338 the fish sampled had empty stomachs but only five were empty during the summer and 29 during the fall (Table 11.1).

Small rainbow smelt ate microzooplankton and *Mysis* almost exclusively (Figure 11.1). *Mysis* was dominant in the diet at Ludington but microzooplankton was dominant at Manitowoc, except in the fall. Similar to large rainbow smelt diet, *L. macrurus* was the dominant microzooplankter in the spring diet; however, it was not among the dominant items in summer or fall (Table 11.2). In spring seven different taxonomic items were in the diet of fish off Ludington and Manitowoc, whereas in the summer 24 items were eaten at Ludington and 21 at Manitowoc, and in the fall 19 items were eaten off Manitowoc. Small rainbow smelt also had a higher number of empty stomachs in the spring and fall with 51 of 168 fish sampled having empty stomachs, but only seven from the summer collections (Table 11.1).

Diet overlap — The amount of diet overlap among the various species varied seasonally and was generally lower when thermal stratification was present (Table 11.3). All diet overlap values were high (>50%) in the spring, and were usually much higher in the spring than in the summer at each location. Diet overlap also changed with site and it was higher off Manitowoc than off Ludington in eight of the 15 comparisons in the spring; in the summer, Manitowoc was higher in 11 of 15 comparisons. The diet overlap in all intraspecies comparisons between size groups was fairly high, with two exceptions (rainbow smelt at Ludington in summer, and bloater at Manitowoc in fall). Because of an almost exclusive diet of *Mysis*, large rainbow smelt had the lowest diet overlap in the summer at Ludington. However, the lowest overall values were between both large and small bloater and the other groups in the fall at Manitowoc. Conversely, overlap values remained relatively high among alewife and rainbow smelt at Manitowoc in the fall.

Composition and zooplankton density in the water column — Zooplankton densities differed with season, depth, and site. In the spring zooplankton densities decreased from near shore to offshore and densities off Ludington were consistently higher than off Manitowoc (Figure 11.2). In the summer zooplankton densities were highest off Manitowoc, particularly at the shallower stations and densities were low at the 30, 50, and 70 m stations at Ludington. In the fall, densities were again higher off Ludington with the exception of the 10 meter station off Manitowoc where the density was highest of either side. Calanoid copepods, particularly *Leptodiaptomus sicilis* and *L. ashlandi*, were the dominant zooplankton in terms of biomass at both ports in the spring. Summer zooplankton populations were more diverse. At Ludington in the summer *Bosmina longirostris* was the dominant nearshore zooplankter, but a variety of other taxa became more important offshore. At Manitowoc, *B. longirostris* was abundant only at the 10 m station and copepods were more dominant throughout the water column in which there was also a few *Daphnia galeata mendotae*. In the fall calanoid copepods were again the dominant zooplankter at both ports, however, *Mysis* were also important in terms of biomass. *Bosmina longirostris* was again abundant at the 10 m station at Manitowoc.

Discussion

This study was conducted to provide seasonal diet information on the major pelagic planktivores in Lake Michigan. Prior to this study, seasonal diet studies have typically been done by collecting fish in bottom trawls, usually during the day, rather than pelagic capture (Janssen and Brandt 1980; Crowder et al. 1981). In our study all species of fish examined were similar in that microzooplankton and *Mysis relicta* a large component of the diet by weight at sometime during the study. *Diporeia hoyi* was also important to all bloater, large alewife, and large rainbow smelt, but not to small alewife or small rainbow smelt. Small alewife and small bloater had similar diets at both sites in the spring. Rainbow smelt ate poorly in the spring as demonstrated with many empty stomachs. Timing of the spring sampling (April) likely coincided with the smelt spawning season. Diets of all fish were more diverse in the summer, reflecting use of a broader range of thermal habitats and a more diverse plankton population. *Limnocalanus macrurus* was the most important microzooplankter in the diet of all fish in the spring, but several taxa were important in the summer. Diet overlap was consistently higher in the spring, and was usually high when comparing size groups within a species. Density of zooplankton was higher at Ludington in the spring and fall but not in summer. The assemblage of zooplankton differed more between the two sites in the summer than in the spring or fall. Diets were usually different between sites for all species in the summer, and difference in feeding patterns among bloaters, alewives, and rainbow smelt between east-west sites were common, likely reflecting differences in zooplankton distribution patterns.

Crowder et al. (1981) found that alewives (adult and YOY) and rainbow smelt fed on *Daphnia* spp. and copepods at night and exhibited considerable diet overlap. Our results were generally consistent with these results. Adult alewives in our study consumed few *Mysis*. This is in contrast to Janssen and Brandt (1980) who reported extensive feeding on *Mysis* by adult alewives. Based on observations that alewives fed extensively on *Mysis* at night in summer and fall, they hypothesized that alewife vertical migration was strongly influenced by *Mysis* migration patterns. In our study large alewife typically fed more on *Diporeia* than *Mysis* in the spring, suggesting a more benthic-oriented feeding strategy. In summer large alewives fed mostly on *Mysis* at the site near Ludington, but fed primarily on zooplankton at the site near Manitowoc. It is not clear if this represented different feeding strategies or merely differences in plankton distributions at the two sites. Fall feeding by alewives was varied but they did not consume *Mysis.* In our fall acoustic surveys adult alewives were typically well dispersed throughout the water column, rather than concentrated at specific depths (see Section 8 – Midwater Distribution of Pelagic Fishes in Relation to Physical Characteristics). It should be noted that the Janssen and Brandt study was conducted in the mid-1970s, prior to the recovery of bloater populations throughout Lake Michigan in the 1980s (Eck and Wells 1987); abundant bloater populations may have affected alewife distribution patterns.

The diet of adult bloaters was the most diverse in fall, in contrast to summer when they fed mostly on *Mysis* and *Diporeia*. Adult rainbow smelt and adult bloaters exhibited similar feeding patterns in summer, but overall, *Mysis* was more important to rainbow smelt than to bloaters. There were strong east-west differences in bloater diets during all seasons. Rainbow smelt consumed mostly *Mysis* at both sites in the spring and small fish in the fall when fish larvae were available in the planktonic zones, whereas bloaters fed on *Mysis* to a lesser extent and consumed a variety of different prey in fall.

We saw little evidence of predation on fish eggs and larvae by any of the three prey species in our study, except that rainbow smelt did consume small fish in the fall. However, all three species are known to have preyed on the eggs and larvae of other species (Wells and Beeton 1963; Morsell and Norden 1968; Rasmussen 1973; O'Gorman 1974). Such predation, particularly by alewives, has been hypothesized to have caused the decline of several native species in Lake Michigan (Crowder 1980; Eck and Wells 1987). Whether declines in native species occurred as a result of direct predation or from competition for similar food resources is not known, although our study suggests that predation on eggs and larvae may be low. Crowder et al. (1981) reported little diet overlap between the exotic alewives and rainbow smelt with several native species but suggested that competition for food is an important factor in maintaining pelagic fish community structure in Lake Michigan.

The night-time pelagic distribution of prey species depended highly on thermal structure (see Section 8 ! Midwater Distribution of Pelagic Fishes in Relation to Physical Characteristics). In spring, when isothermic conditions typically exist, we saw much higher diet overlap among the three prey species. This is likely because the species were more uniformly distributed when no thermal structure was present, and the fact that plankton populations were smaller and comprised of fewer species. In summer, when thermal stratification was present, diet overlap among the prey species was considerably lower. Previous surveys of prey fish populations in Lake Michigan with bottom trawls and daytime acoustic sampling indicate that most fish, particularly adults, migrate to the bottom during the day (unpublished data, Great Lakes Science Center). Only juvenile fish remain pelagic during the day, usually small alewives and rainbow smelt that live in the epilimnion. In 1993, fall sampling was conducted in late October when the thermal structure had been severely eroded by severe storms that also limited the amount of sampling. It is likely that the observed increase in diet overlap in our fall samples was due to increased mixing of the pelagic species. After 1993 we conducted our fall acoustic surveys in September when thermal structure was typically good and the species were better segregated. It is likely that less diet overlap occurs during this time period and that feeding patterns play a more important role in the distribution of the pelagic planktivores when good thermal structure is present.

It is clear that night-time vertical migrations and the resulting pelagic distributions of the planktivores are influenced by a variety of factors, of which feeding is an important component. The role of water temperature, depth and other factors in determining the patterns of pelagic fish distributions in Lake Michigan were examined elsewhere in this report (see Section 8: Midwater Distribution of Pelagic Fishes in Relation to Physical Characteristics). At this point the relative importance of physical factors and prey availability and selectivity in the establishment of pelagic fish distribution patterns remains unclear. Further analyses integrating measures of diet composition and diet overlap with thermal and bathymetric data, plankton distribution data and observed fish distributions should allow us to better understand these night-time interactions and their role in determining pelagic community structure.

Table 11.1 Mean length (mm) (±SE), mean weight (g) (±SE), total number of fish and number empty at sites near Ludington, MI, and Manitowoc, WI in spring, summer, and fall 1993. The mean includes all fish analyzed from that sampling period (i.e., with or without food).

Species	Mean Length	Mean Weight	Total Number - Number empty
	Spring Ludington		
Large Bloater	176.8 (±2.82)	42.7 (±2.69)	44-7
Small Bloater	152.1 (±1.41)	26.8 (±0.87)	19-2
Large Alewife	157.6 (±6.93)	31.7 (±4.69)	8-0
Small Alewife	74.9 (±2.22)	2.9 (±0.22)	14-1
Large Rainbow Smelt	116.7 (±1.49)	9.9 (±0.48)	91-36
Small Rainbow Smelt	81.7 (±1.43)	3.4 (±0.22)	46-18
	Manitowoc Manitowoc		
Large Bloater	196.4 (±3.88)	62.6 (±4.48)	46-9
Small Bloater	131.8 (±12.00)	27.1 (±2.28)	8-1
Large Alewife	153.5 (±4.67)	27.6 (±2.83)	15-1
Small Alewife	79.7 (±1.81)	3.5 (±0.28)	41-2
Large Rainbow Smelt	124.4 (±1.85)	12.9 (±0.69)	82-49
Small Rainbow Smelt	94.5 (±1.10)	4.9 (±0.25)	8 -1
	Summer Ludington		
Large Bloater	169.2 (±1.36)	38.5 (±1.07)	20-0
Small Bloater	154.3 (±2.29)	29.2 (±1.05)	4-0
Large Alewife	143.4 (±4.62)	22.9 (±1.44)	16-1
Small Alewife	85.0 (±3.01)	4.5(±0.66)	13-0
Large Rainbow Smelt	129.2 (±2.49)	12.8 (±0.79)	36-3
Small Rainbow Smelt	79.8 (±2.00)	2.9 (±0.21)	28-6
	Manitowoc		
Large Bloater	197.6(±5.09)	68.4(±6.07)	27-7
Small Bloater	153.0(±1.61)	26.9(±1.18)	9-0
Large Alewife	159.9(±4.77)	30.6(±2.77)	19-0
Small Alewife	84.0(±2.71)	4.2(±0.53)	26-1
Large Rainbow Smelt	142.9(±3.40)	17.0(±1.32)	47-2
Small Rainbow Smelt	78.2(±2.47)	2.5(±0.19)	29-0
	Fall Ludington		
Large Bloater	178.3(±2.09)	49.2(±2.23)	38-12
Small Bloater	149.0(±3.11)	27.1(±3.05)	4-3
Large Alewife	0	0	0
Small Alewife	0	0	0
Large Rainbow Smelt	141	21.9	1-1
Small Rainbow Smelt	0	0	0
	Manitowoc		
Large Bloater	192.5(±3.32)	60.9(±4.43)	30-14
Small Bloater	155.7(±1.86)	30.5(±0.64)	3-2
Large Alewife	142.8(±6.35)	27.0(±3.43)	11-0
Small Alewife	75.9(±2.37)	3.8(±0.37)	40-0
Large Rainbow Smelt	126.0(±2.17)	12.11(±0.78)	81-28
Small Rainbow Smelt	84.8(±1.22)	3.2(±0.14)	57-26

Table 11.2 ! Zooplankton species making up the major portion of the diets of pelagic planktivores from sites near Ludington, MI, and Manitowoc, WI in spring, summer, and fall 1993.

	Spring		Summer		Fall	
	Ludington	Manitowoc	Ludington	Manitowoc	Ludington	Manitowoc
			Large Bloater			
Limnocalanus macrurus	89.08	96.29	65.96	80.82	32.74	72.08
Leptodiaptomus sicilis	-	-	12.80	-	-	13.54
Daphnia galeata mendotae	-	-	6.30	-	51.31	-
			Small Bloater			
Limnocalanus macrurus	88.82	99.50	65.45	75.78	-	-
Leptodiaptomus sicilis	-	-	12.25	-	-	-
Diacyclops thomasi	-	-	-	18.89	-	-
Senecella calanoides	-	-	7.25	-	-	-
Daphnia galeata mendotae	-	-	-	-	-	42.86
Bosmina longirostris	-	-	-	-	-	41.56
			Large Alewife			
Limnocalanus macrurus	65.86	88.56	35.89	-	-	52.11
Leptodiaptomus sicilis	29.76	-	9.48	-	-	-
Diacyclops thomasi	-	-	19.74	61.94	-	-
Bosmina longirostris	-	-	12.87	24.37	-	-
Bythotrephes cederstroemi	-	-	7.31	-	-	-
Daphnia galeata mendotae	-	-	-	-	-	28.27
			Small Alewife			
Limnocalanus macrurus	90.83	76.38	-	10.02	-	-
Leptodiaptomus sicilis	-	21.58	5.31	-	-	8.74
Diacyclops thomasi	-	-	39.80	63.33	-	7.70
Bosmina longirostris	-	-	25.24	10.03	-	16.88
Daphnia galeata mendotae	-	-	14.53	-	-	50.65
Polyphemus pediculus	-	-	5.45	-	-	-
			Large Rainbow Smelt			
Limnocalanus macrurus	94.86	87.61	24.82	51.25	-	27.66
Daphnia galeata mendotae	-	-	67.46	24.83	-	45.93
Diacyclops thomasi	-	-	-	19.60	-	-
Epischura lacustris	-	-	-	-	-	9.46
			Small Rainbow Smelt			
Limnocalanus macrurus	75.34	62.19	-	-	-	-
Leptodiaptomus sicilis	23.98	20.26	15.99	-	-	8.20
Diacyclops thomasi	-	-	22.14	50.31	-	-
Daphnia galeata mendotae	-	-	25.54	33.64	-	60.22
Polyphemus pediculus	-	-	9.99	-	-	-
Calanoid copepodite	-	-	7.01	-	-	-
Epischura lacustris	-	-	-	-	-	14.86

Table 11.3. Percent of diet overlap for fish sampled at sites near Ludington, MI, and Manitowoc, WI in spring, summer, and fall 1993. The ‘#’ denotes insufficient numbers of fish for comparison.

	Large Bloater	Small Bloater	Large Alewife	Small Alewife	Large Smelt	Small Smelt
Spring						
Ludington						
Large Bloater	-	97.9	78.1	80.9	75.5	93.8
Small Bloater	97.9	-	79.3	79.8	72.2	93.7
Large Alewife	78.1	79.3	-	62.8	53.9	82.5
Small Alewife	80.9	79.8	62.8	-	90.6	77.3
Large Smelt	75.5	72.2	53.9	90.6	-	71.2
Small Smelt	93.8	93.7	82.5	77.3	71.2	-
Manitowoc						
Large Bloater	-	62.2	81.4	78.6	84.9	79.9
Small Bloater	62.2	-	79.9	60.1	73.7	61.3
Large Alewife	81.4	79.9	-	79.0	92.0	80.0
Small Alewife	78.6	60.1	79.0	-	81.3	94.3
Large Smelt	84.9	73.7	92.0	81.3	-	81.8
Small Smelt	79.9	61.3	80.0	94.3	81.8	-
Summer						
Ludington						
Large Bloater	-	80.6	47.6	39.3	22.3	61.0
Small Bloater	80.6	-	39.3	31.1	24.3	48.0
Large Alewife	47.6	39.3	-	83.8	18.2	53.9
Small Alewife	39.3	31.1	83.8	-	13.8	55.3
Large Smelt	22.3	24.3	18.2	13.8	-	26.6
Small Smelt	61.0	48.0	53.9	55.3	26.6	-
Manitowoc						
Large Bloater	-	69.1	38.4	39.5	59.6	36.3
Small Bloater	69.1	-	58.2	67.7	69.6	68.5
Large Alewife	38.4	58.2	-	80.0	48.9	57.8
Small Alewife	39.5	67.7	80.0	-	49.0	71.8
Large Smelt	52.3	69.6	48.9	49.0	-	72.5
Small Smelt	36.3	68.5	57.8	71.8	72.5	-
Fall						
Ludington						
Large Bloater	-	83.2	#	#	#	#
Small Bloater	83.2	-	#	#	#	#
Large Alewife	#	#	-	#	#	#
Small Alewife	#	#	#	-	#	#
Large Smelt	#	#	#	#	-	#
Small Smelt	#	#	#	#	#	-
Manitowoc						
Large Bloater	-	27.3	10.0	8.8	20.2	13.1
Small Bloater	27.3	-	14.2	14.7	18.7	13.7
Large Alewife	10.0	14.2	-	69.1	75.2	70.2
Small Alewife	8.8	14.7	69.1	-	62.2	69.9
Large Smelt	20.2	18.7	75.2	62.2	-	83.9
Small Smelt	13.1	13.7	70.2	69.9	83.9	-

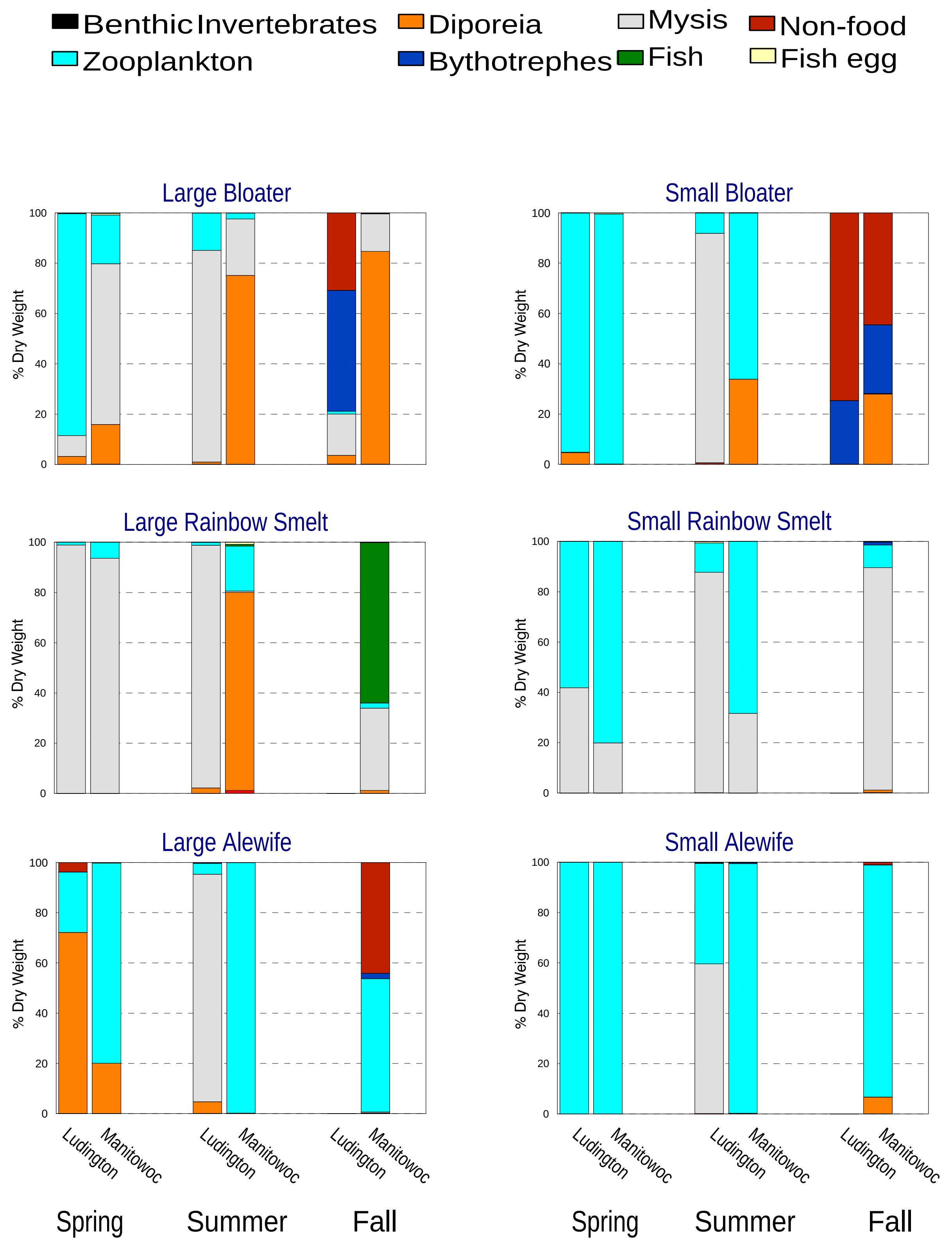


Figure 11.1. Diet by percent biomass of two size groups of bloater, rainbow smelt, and alewife in Lake Michigan at sites near Ludington, MI., and Manitowoc, WI. in 1993.

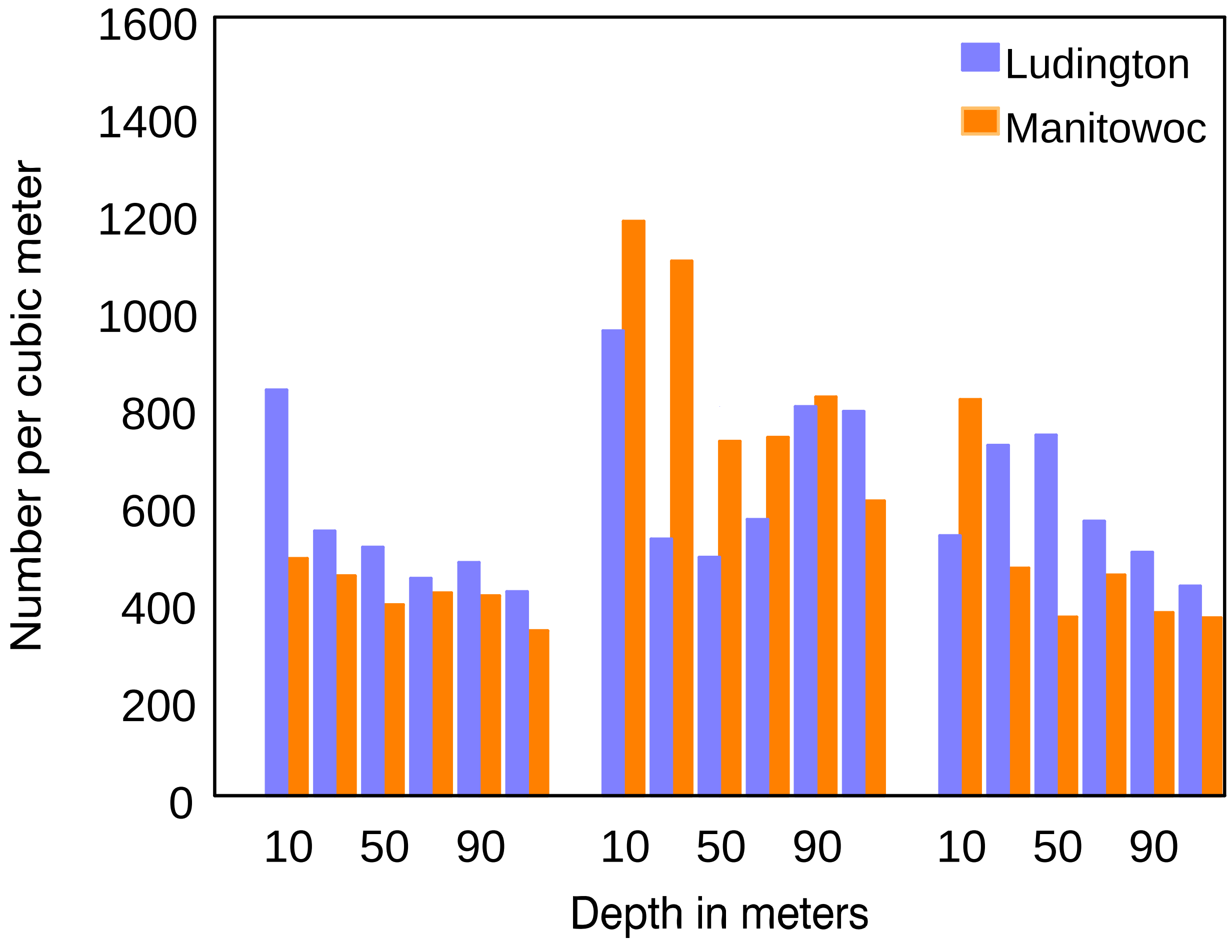


Figure 11.2. Total density (number per m^3) of zooplankton in spring (first group of bars), summer (mid group of bars), and fall (last group of bars) at sites near Ludington, MI., and Manitowoc, WI. in 1993.

Section 12.

Broadband Fish Identification

Species identification has been problematic in fisheries acoustics (Rose and Leggett 1988, Foote 1990, MacLennan and Simmonds 1992). Partitioning acoustically derived abundance estimates with net captured organisms can be biased (Thorne 1987, Nakashima 1990), at times missing whole classes of targets that comprise part of the acoustic signal. Moreover, the spatial and temporal resolution of net sampling is often difficult to compare with the higher resolution and more comprehensive acoustic data.

Two approaches to target identification, other than direct capture that have been under investigation, are discrimination by mean target strength and shoal description. These two methods can be used together, and in conjunction with visual echogram interpretations. Mean target strength has been used to discriminate between species whose acoustic sizes differ, on average, by more than a factor of two. For example, mean target strength correctly discriminated between cod and capelin in the northern Gulf of St. Lawrence with 90% accuracy (Rose and Leggett 1988). However, the same study showed that target strength could not be used to classify groups of cod, capelin, and mackerel, because the target strengths of small capelin and large mackerel (no swimbladder) were similar. Moreover, the inability to isolate a large number of representative single targets within dense schools limits the use of target strength as a species discriminator (Rose 1992).

Shoal description techniques were first used by commercial fishermen to improve catch selectivity. As used by marine scientists, these techniques were initially qualitative and carried out by subjective interpretations of low-resolution echogram marks (Beamish 1966). The potential for more objective classification techniques was recognized in the 1970's (Deuser et al. 1979, Giryn et al. 1981), but the lack of processing power retarded their development. The advent of high-speed analog-to-digital converters and inexpensive and portable digital computers has enabled fast quantitative high-resolution analyses of the shapes and patterns of shoal signals. Rose and Leggett (1988) used quantified shoal characteristics to develop multivariate discrimination functions for shoals of Atlantic cod, capelin, and mackerel. These techniques were based on acoustic interpretation of fundamental biological and ecological characteristics of aggregations of these fishes. Signal descriptors known to have discriminatory power include: school position in the water column (depth, distance from bottom), gross school measures (dimensions and shape), and measures of the signal pattern from within the school (measured in time or frequency domain) (Scalabrin and Lurton, 1994). Quantitative descriptors of fish aggregations can be calculated for signals derived from single of averaged echo-sounder pings (Vray et al. 1990) and from echogram images (Richards et al. 1991).

The overlap in range of sizes as well as overlap in spatial distributions of the pelagic fish community in the Great Lakes renders these acoustic techniques largely ineffectual. Some physical features can discriminate species with a fair degree of certainty (see Section 8 - Midwater Distributions of Pelagic Fishes in Relation to Physical Characteristics). However, enough similarity in the distribution of the various species and their different life stages still requires the use of midwater trawling to classify the echoes. Another acoustic technique that shows promise in species identification is broadband echo sounding. This technology has been recently shown to have potential to classify targets, but has was thought to be too technically demanding to be practical for acoustic surveys (Zakharia 1990, Simmonds and Copeland 1986, 1989, Simmonds and Armstrong 1990).

Scientific Fishery Systems, Inc. (SciFish) is developing an automated broadband fish identification system that would be a significant tool for fish stock assessment. The SciFish broadband fish identification system uses advanced technologies developed by the defense industry to identify fish to species, with additional capabilities for acoustic abundance and size estimation. This system uses broadband transmissions (versus the traditional narrowband approach) to ensonify fish. The broadband echoes are processed digitally to produce frequency spectra that are combined with traditional narrowband information (sonogram images of fish target strength intensity versus depth) and presented to a (fuzzy neural network) classifier for identification. Signatures of fish (fuzzy neural network coefficients) are used to collect signature libraries, which then form the basis for *in situ* acoustic-based fish identification.

A joint research project was initiated between USGS-BRD and SciFish in 1995. The primary objective of this project was to investigate the ability to acoustically identify pelagic Great Lakes fishes utilizing broadband acoustic techniques. A fish identification system developed under this effort represents a unique application to freshwater and combination of three elements: broadband transmission, spectral representation, and neural network identification.

Broadband Sonar System Overview

The broadband system is composed of a broadband sonar transceiver, an analog-digital converter, a sonar transmit cycle waveform signal controller, and a microcomputer (Figure 12.1).

Sonar transceiver – The broadband transceiver is a transducer, whose center frequency is 153.6 kHz, that produces a cone-shaped beam with a 3-dB beam width of 4.1 degrees. The diameter of the circular beam footprint is narrow to reduce ambient noises and to provide greater confidence that fish school targets fill the main beam. As delivered, the 3-dB receiver bandwidth is about 45 kHz (138 kHz to 183 kHz). The higher center frequency also generates a narrower beam for a given size transducer and reduces concern over common noise sources in the lower bands such as waves and shipping. Although the 3-dB bandwidth of the sonar is 45 kHz, there is an adequate signal-to-noise ratio (SNR) for a bandwidth of 80 to 100 kHz. For targets on the maximum response axis (MRA), a 60 dB SNR is maintained out to a range of 110 meters. For targets outside the 4-degree beam width, the echo level will fall off rapidly and the analysis becomes invalid. But, for ensonification of schools of fish where at least some targets are likely to fall on the MRA, this analysis shows that the system has useful range for a full 80 kHz bandwidth. With matched filtering for increased detection of signal characteristics embedded in noise, the effective range could perhaps be doubled.

Three types of transmit waveforms were programmed into the electronics. The available transmit waveforms include pulsed constant wave (CW) at any single frequency between 100 kHz and 200 kHz, linear frequency modulated (FM) sweep (chirp) over the entire range of frequencies with positive or negative frequency slope, and pseudo-noise (PN, phase coded) sequence as is used in the current profiling product.

The CW mode emulates modern echo-sounder and fish finder technology and provides a simple waveform for use evaluating ambient noise and adjusting receiver gain at fixed frequencies of interest. The FM mode provides a well-characterized broadband signal than can be match filtered and whose returns are rich in spectral content. The PN mode is meant to impart maximum spectral energy into the water column for a given pulse length. These returns can be match filtered and are also rich in spectral content.

The transducer housing contains the analog electronics for transmit and receive, transducer tuning, and the four-stage receiver amplifier. Ping transmit waveforms travel to the transducer housing and an analog signal representing the acoustic returns travels up the underwater cable to a VM Chassis. The VM Chassis controls the sonar transmit cycle and sends the appropriate waveform signal. It also accepts serial ASCII commands from the processing platform to configure all aspects of the transmit waveform and provides trigger and raw signal to the processing platform over two coaxial lines.

The transmit power is fixed but the receiver gain can be adjusted in four fixed steps which are set to 18 dB, 41 dB, 64 dB, and 87 dB. For most experimental work, the gain was set to 64 or 87 dB. At any gain setting, preamp input impedance is much greater than the transducer output impedance allowing a gross estimation of the instantaneous sound pressure level from the digitized amplitude.

<u>Processing platform</u> – The computer processing platform was a customized personal computer

running DOS 6.22 and Windows 3.1, with an 486DX2/66 processor. The data acquisition card was a DAP-3200e from Microstar Labs in Seattle. It was fitted with a 12 bit 770 kHz ADC, an external trigger input for the sonar trigger, and 4 MB of RAM which holds the operating system, the custom executable kernels, and buffers the incoming digitized data. The magneto-optical storage device was an HP C1716T 1.3 GB multifunction drive which provides 625 MB of removable storage per cartridge and accommodates both write-once-read-many and re-writeable media.

Software – The software development used the Symantec C compiler version 6 for DOS, Windows, and Win32S. The engineering acquisition and processing software was compiled for DOS and the oscilloscope-like display and user interface are displayed at 800 by 600 resolution. The real-time samples are streamed, at full-resolution, to the hard disk or magneto-optical drive for post-processing which extracts the echoes and performs spectral analysis. Once the echo extraction and feature vector formulation are reliable proven processes they will be included in the real-time processing and the user interface will be under Windows or Windows95. Because of the Pentium processor and the separate 486 used to control the acquisition, there is adequate real-time overhead available to insert the echo extraction and spectral estimation code.

For the fish identification experiments, the incoming pings were streamed to the magneto-optical drive and stored at full resolution to facilitate development of echo extraction and processing algorithms and the analysis of ambient noise and echo characteristics. Each ping is stored along with an encoded ping header that records the pertinent parameters described in the C source code.

Data Processing

The functional flow of echo signals for the fish identification system is summarized below with details of the feature extraction techniques and the classifiers.

Broadband transceiver -The broadband transceiver generates analog echoes, amplifies the echoes, tunes the echoes for the frequency response of the transducer, and transmits the resulting echo from the transducer. The transducer collects the analog echo returns, applies amplification (with adjustable gain) to the echoes, bandpass filters the echoes and passes the result to the A/D converter.

Analog to digital conversion -The bandwidth of the echoes for the engineering prototype is 110-190 kHz. To satisfy the Nyquist sampling criteria and to achieve sufficient amplitude range and resolution, a 12-bit A/D Converter, with 5 V dynamic range, operating at 770,000 samples per second is used for digitization. For the engineering prototype, the A/D converter is co-located on the DSP board.

Echo detection - Echo detection accepts digital signals and produces digital echoes. Echo detection determines when the sonar pulse has bounced off some object and returned. A matched filter will be used to detect echoes. The digitized time-series between the echoes is discarded after estimates of Signal-to-Noise-Ratio (SNR) and depth to target are calculated. Time-varied gain will be applied to extracted echoes. The extracted echoes are passed along to the next functional component with the SNR and depth.

Feature extraction - Feature extraction accepts digital echoes and produces echo parameters. Feature extraction measures specific characteristics of the echo. Fish identification requires a set of features that are unique to fish taxonomy. The primary feature set is frequency spectra (computed with a Fast Fourier Transform). The resulting parameters that are extracted for a given fish species are used to create a signature. The signature for a fish echo is the associated neural network weights.

Signature data base - The signature database stores and retrieves neural network weights (signatures). The neural network classifier determines how to weight the extracted features to provide the best possible classification decision across all collected echoes. As such, the signature database is the neural network weights for each fish species being classified.

Classification - The classifier accepts echo parameters (features) and produces species classifications. A fuzzy neural network learns to classify (identify) fish from the extracted features. The inputs for the neural network are extracted parameters (i.e. shape and spectral information). The outputs of the neural network have one node for each class. During training, many different signatures for a given fish species are presented at the input nodes and the network weights are adjusted to produce a value of one (1.0) for the corresponding output node (the rest will be zero). The adjustment of the neural network connections between the input and output nodes, represents the adjustment of decision regions or decision surfaces between the various classes. The resulting weights, as mentioned above, become the signature for the fish species.

Fish Identification Parameters

A variety of acoustic and biological parameters have been identified as a practical features or methods for the characterization of underwater acoustic signals. We relied on the echo shape and echo spectra as the primary features for echo classification. Additional physical features such as described in Section 8 could be incorporated in the neural network classifier.

Fuzzy Min-Max Neural Network Classifier

The basic structure of a neural network is composed of inputs, nodes, and outputs (Figure 12.2). The interconnected network of inputs (features) and outputs are weighted (as depicted as lines in Figure 12.2). Individual nodes (synonymous with biological neurons) produce an output that is based on the sum of the weighted values passed to them. A network "learns" by adjusting the interconnection weights between the layers. The answers the network is producing are repeatedly compared with the correct answers, and each time the weights are adjusted in the direction of the correct answers. If the problem can be learned, a stable set of weights evolves and will produce reliable predictions (outputs).

Fuzzy min-max neural networks represent a synergism of fuzzy sets and neural networks in a unified framework. The use of fuzzy sets as classes and as clusters has been well known for over 30 years (Zadeh 1965, Ruspini 1969). Fuzzy min-max neural networks create fuzzy set classes and clusters in a similar fashion with a membership function based on a core of hyperbox nodes (figure 12.2). Fuzzy min-max neural network classification (Simpson 1992) creates classes from the union of fuzzy sets. Fuzzy min-max neural network clustering creates clusters from individual fuzzy sets (Simpson 1993). Fuzzy min-max neural network function approximation is an evolution of this family that utilizes fuzzy sets as the basis functions for function approximation (Simpson and Jahns 1993).

Fuzzy sets bring a new dimension to traditional classification systems by allowing a pattern to belong to multiple classes to different degrees. Each fuzzy set is a separate class. In the fuzzy min-max classification neural network, a fuzzy set is defined as a membership function created from the union of hyperbox-based fuzzy sets. If the patterns being classified have only one dimension, the hyperbox membership function collapses to the common trapezoid membership function.

Echo Data Collection

Initial broadband acoustic data were collected in August 1995. These data were collected in conjunction with on-going acoustic studies in Lake Michigan, near Ludington, MI. This pilot study was limited in total effort, but the results were encouraging enough to warrant additional work.

In summer 1996, broadband echo data were collected in two phases in Lake Michigan, near Charlevoix, MI. First, fish were caught, measured, and suspended by a tether within the broadband sonar's beam. The echo data collected was immediately processed and used to train a neural network classifier. Subsequently, *in situ* echo data were collected in conjunction with midwater trawling. The species composition of the trawled fish was recorded and compared immediately with the neural network classifications created from tethered fish data.

Tethered fish data collection - Fish tethering allowed echo data collection from individual fish (Figure 12.3). A line is fastened to an anchor. The fish were attached to a line with an anchor and hung in the dorsal aspect. The anchored line was then dropped directly below the transceiver. The transceiver's beam was adjusted until a strong return is received from the tethered fish. Echo data were collected for each of the signal types (CW, FM, and Barker). Aggregations of as many as five fish were tethered during data collection using this approach. With the individual tethered fish, the position of the fish, its range to the bottom, its species, sex, and size are completely defined prior to echo collection. This information was essential to the neural network training process. The tethering approach provides the control that was needed to capture the massive amount of data that will be used to explore the full capability of the broadband fish identification approach across a wide range of species and under varying bottom conditions.

Free swimming fish data collection - The data from the tethered collections were used to evaluate the capability to identify free-swimming fish during the midwater trawl surveys. For free swimming echo data collection, the transceiver was attached to a towed body and deployed over the side of the vessel (Figure 12.4). Fish echoes were only collected within the depth interval of the trawl path. When the trawl was retrieved, the fish captured in the trawl were measured and the species compositions were compared against the fish identifications made by the broadband sonar.

In situ fish data collection does not provide the same reliability as tethering. During free-swimming data collection, not all the fish that pass through the sonar beam end up in the trawl and not all of the fish found in the trawl passed through the sonar beam. We assumed the fish caught in the trawls represented those in the sonar beam.

Results

During the pilot study in 1995, midwater tows collected predominantly bloaters and alewives, and less commonly, rainbow smelt. The alewives, young-of-the-year (YOY), were found exclusively in the upper ten meters of the water column. Bloaters were the dominant species at depths greater than 34 meters. Some rainbow smelt and adult alewives were found in the upper 15 meters. Trawls were towed at depths from 6 to 85 meters. All the echo data were post-processed and had the parameters extracted. A simple preliminary neural network was able to successfully discriminate between the bloater and alewife echoes with about a 80% certainty rate.

In 1996, a total of 54 alewives, rainbow smelt and sticklebacks were collected and suspended from a tether and 2894 echoes were extracted from these fish (Table 12.1). The echoes extracted were trained using PNN neural network, 128 spectral bins where used as features (derived from a 256 pt FFT), training data was the average spectra from each individual fish (54 training patterns in all), testing data was each of the individual echoes (2894 in all). The classification matrix showed fairly good classifications for rainbow smelt and alewives, but lower correct classification for sticklebacks (Table 12.2). Improved classification results are achieved when the probability of correct classification threshold is raised to 0.70, but with a loss of retained echoes (Table 12.2).

Using the same neural network produced with the tethered fish echo library, the composition of the trawl data was not closely predicted (Table 12.3). The neural network classification of the composition of echoes correctly indicated that the fish were mostly rainbow smelt and sticklebacks, but not in similar proportions seen in the catch.

Summary

From these results, the need for additional free-swimming data become apparent. Unfortunately, there were only 59 echoes extracted for the free-swimming fish within the same depth range as the trawls. Further, we were unable to locate sufficient aggregations of fish before the allotted time for the cruise expired. It is clear that we can classify well when comparing tethered against tethered fish, but the extrapolation from tethered data (for training) to free-swimming (for testing) has not yielded a reliable set of results thusfar. The following analysis emphasizes only alewife, rainbow smelt, and sticklebacks because they are the most difficult to separate using conventional acoustic techniques, and they were the most abundant during our free-swimming data collection exercise. Additional training of the neural network, especially on *in situ* fishes, is needed for more conclusive results. We have collected additional broadband echo data in 1997 and additional free-swimming fish echo collections are planned.

The use of the broadband echo classification system coupled to a neural net, is an innovative and promising technique for obtaining real-time data on the species of fish in the water column. Further development of this technique would yield greatly expanded spatial coverage of the lake by the acoustic survey vessels. One the limiting factors of spatial coverage is the time required to midwater trawl in order to identify species of fish in the water column. If midwater trawling could be reduced to that needed to determine the species composition in groups of mixed species characteristically present in the metaliminion , the spatial coverage during a survey could be nearly doubled. Also, the certainty that we attach to the species composition in the water column would be enhanced since we presently must extrapolate to large areas. The potential benefits are sufficient to continue research in this technique.

Table 12.1 – Numbers, sizes, and echo characteristics by species for tethered fish as part of broadband echo study.

Species	**N**	Mean Length (mm)	Echo Count	Mean Echo Length[1]	Mean Maximum mV	Mean RMS mV
Alewife	24	178	1231	262.8	118.9	51.8
Rainbow Smelt	21	128	1236	258.6	162.2	78.4
Stickleback	9	65	427	266.6	55.7	26.8

[1] echo length in number of samples

Table 12.2 – Classification matrices for tethered fishes. Results are shown for two probability threshold levels.

	Alewife	Rainbow Smelt	Stickleback
		Probability Threshold = 0.48	
Alewife	80%	16%	4%
Rainbow Smelt	5%	91%	4%
Stickleback	6%	22%	72%
Echoes	94%	98%	87%
		Probability Threshold = 0.70	
Alewife	91%	5%	3%
Rainbow Smelt	4%	93%	3%
Stickleback	5%	7%	88%
Echoes	64%	67%	47%

Table 12.3 – Comparison of species compositions of fish collected in midwater and predicted by neural network.

	Alewife	Rainbow Smelt	Stickelback	Unknown[2]
Actual Catch Proportion	0%	69%	31%	
Predicted Proportion	5%	44%	49%	2%

[2]unknown classifications are those echoes that received neural network outputs of zero probability in all classes.

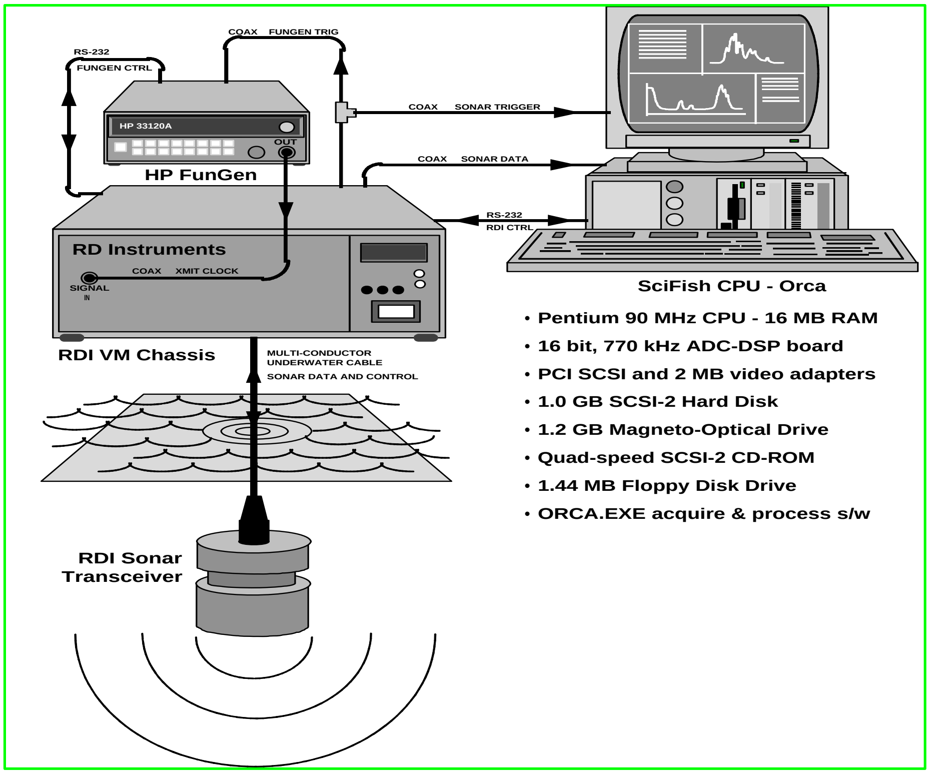


Figure 12.1 – Schematic showing broadband sonar system.

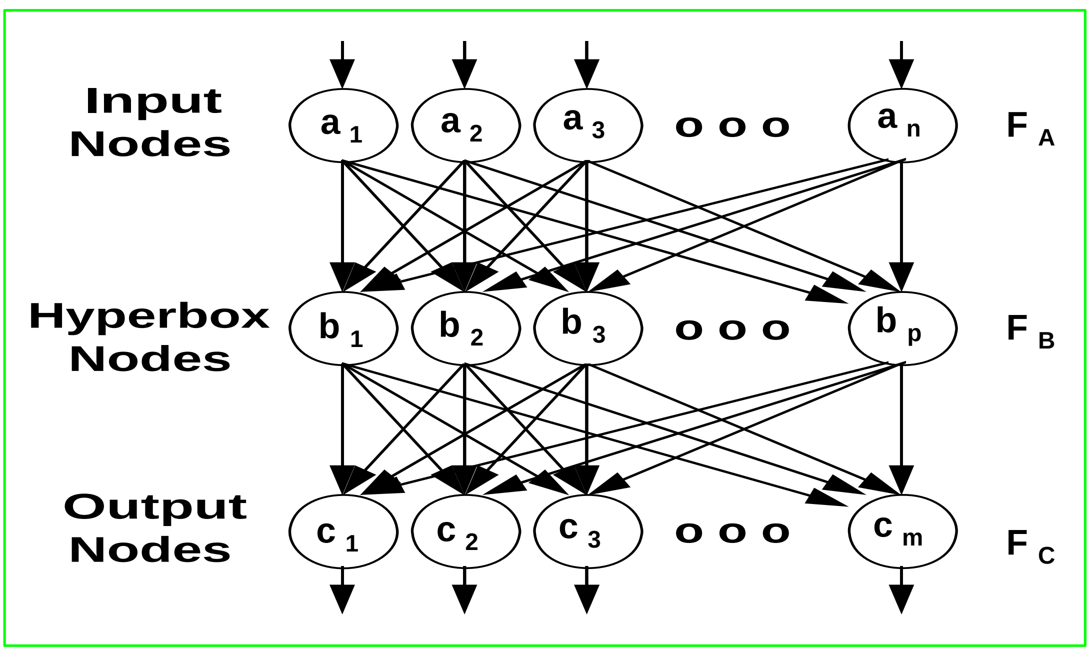


Figure 12.2 – Illustration of a fuzzy min-max neural network.

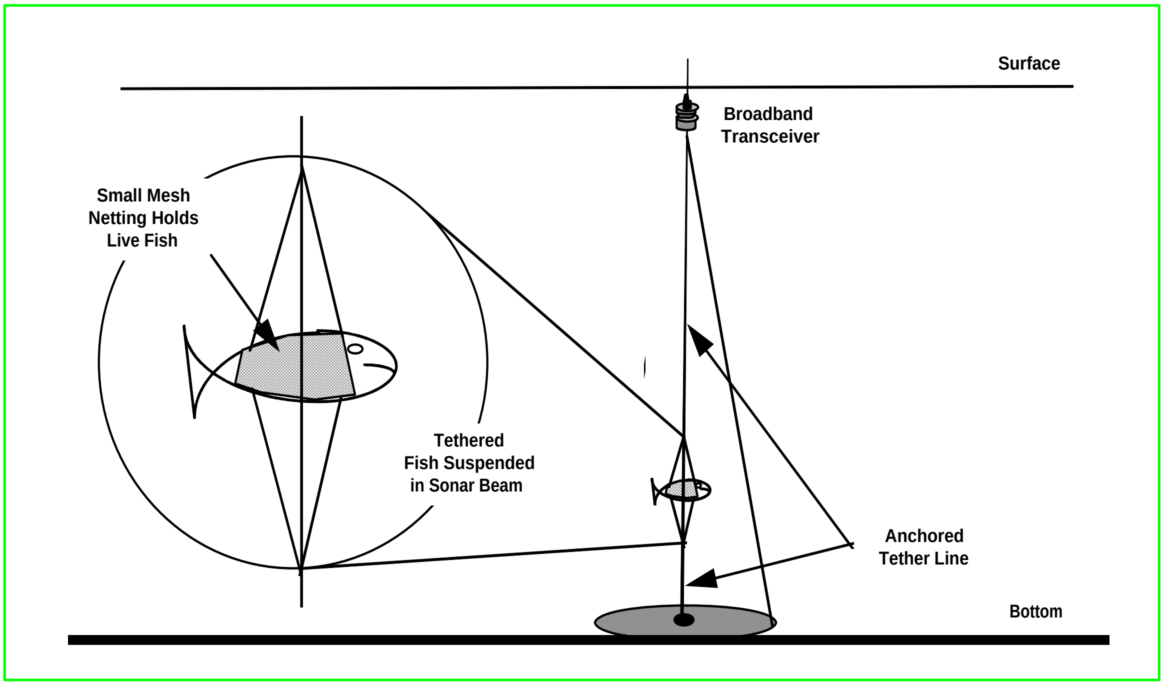


Figure 12.3 – Illustration of fish tethering configuration used for echo collections of individual fish in broadband fish identification studies.

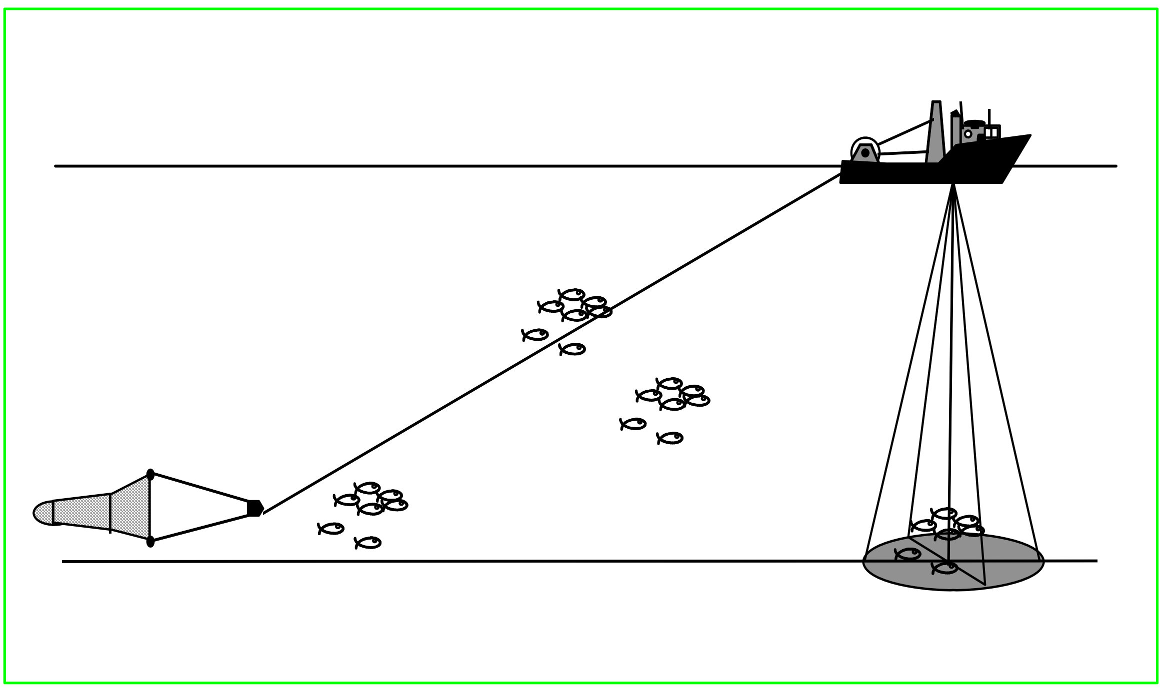


Figure 12.4 – Illustration of *in situ* fish echo collections as part of broadband fish identification studies.

Section 13.

Conclusions and Recommendations

Acoustic techniques' advantages of a greater areal coverage and sensitivity to a wide range of sizes of fish and fish densities were demonstrated in this study. We were able to complete up to 21 individual transects as well as cover a wider range of depths in the approximately same amount of time required to complete the annual fall bottom trawl surveys at seven sites on Lake Michigan – this greater coverage allows for examination of spatial patterns in fish distribution over the large geographic area of Lake Michigan. The integration of acoustics and midwater trawling was very effective for quantifying the abundance of the pelagic species, most notably juvenile alewives. Further, the midwater assessment of the fish community has added additional insights into the status, dynamics, and ecology of the important prey fish species in Lake Michigan.

The problems associated with acoustic surveys were also present. The degree of complexity of acoustic sampling leads to potentially greater technical difficulties than compared to more traditional fishery survey techniques. Thorne (1983) warned of the potential for problems due to unfamiliarity with the physical concepts, and electrical and mathematical aspects to untrained fisheries professionals, particularly in light of it's recent (and on-going) development and engineering basis. As fisheries professionals with experience and training in acoustics, we still suffered problems in operating the acoustic systems in this study, especially in the earlier years. Many of our problems concerned proper equipment setup and coordination of the system parameters between two different units. Our recognition of inappropriate values at the time of the survey was important in mitigating or correcting hardware and software faults. This recognition came only by practice. The inability to survey near bottom also negatively impacted our surveys. This problem is related to acoustic system parameters (mainly pulse width) and was mostly confined to situations where fish aggregated near bottom. However, improvements in bottom tracking algorithms have reduced, and more recently almost eliminated, the inability to discriminate between bottom and fish echoes.

Fish behavioral patterns influenced the timing and effectiveness of the acoustic surveys. We found night-time pelagic distribution of prey species depended highly on thermal structure. In spring, the fish do not move far off bottom, undoubtedly in response to the thermal conditions, and the distributions of the different species are much less distinct and may require more trawling effort. Mid-summer was characterized by a sufficiently developed thermal structure and adequate vertical movements of the fish, but the shortness of the nighttime period confined the survey times. However, the combination of a broad, vertical distribution of the fish into the water column at night, the segregation of the various species in relation to the thermal stratification, and the availability of younger life stages to the sampling gear made late-summer or fall the optimal time to conduct acoustic surveys.

Our results also demonstrate the parochial nature of fish backscattering and use of target strength-fish size relations developed beyond the immediate application should be done with caution. We found that the observed target strength values for the smaller sizes of fish were substantially smaller than predicted by Love's equation which could result in an underestimate of fish biomass if these relations were applied to other populations without verifying their accuracy. Therefore, the backscattering properties of the species of interest must be carefully considered when planning any acoustic-based assessment.

The acoustic measures of backscattering with 420 kHz, in contrast to 120 kHz, were not consistent with observed fish distributions in Lake Michigan. This was important since an accurate measure of mean backscattering is required to scale echo-squared integration values for density estimates. In addition, acoustic-based estimates of fish size composition from target strength for 420 kHz would not be dependable. Therefore, any improved resolution of a higher frequency must be weighed against a greater variability in backscattering amplitude from sensitivity to fish orientation. We found 120 kHz to be a good compromise between target resolution capability and dependable measures of target backscattering.

The use of rubber-compound windows installed in vessels for acoustic surveys saved time, increased safety, and broadened the weather window for operations. However, the operating frequencies and ambient water temperatures need to be considered. Signal attenuation by the rubber become pronounced with increased frequency and decreased temperature. Based on our results, a 420 kHz system could be expected to lose up to 3-4 dB through a 5.1-cm thick rubber diaphragm; signal loss was negligible for 120 kHz.

Cluster analysis was useful in defining regions of Lake Michigan based on prey fish distributions and stratification of Lake Michigan using these regions improved the precision of 1993 lakewide biomass estimates for all three species. Despite differences in the regional abundances of the individual prey species, the geographic stratification provided an optimal design for measuring the abundance and biomass of all major species in a single survey. We recommend the consideration of these strata in future lakewide sample surveys, in which the number of transects in each region are determined by the optimal allocation suggested by the survey objectives, whether they are focused on a particular target species or the estimation of total prey biomass. Stratification schemes for surveys rely on a depth profile database of sufficient resolution to afford the flexibility necessary to determine an optimal survey design. Without an appropriate GIS database, it would be impossible to obtain a reliable lake-wide biomass estimates from the acoustics surveys.

Fishery acoustics also suffers from the inability to readily discriminate species in mixed-species situations. One of the major factors constraining the efficiency of the acoustic surveys was the time required to deploy midwater trawls to identify species of fish in the water column; often a second vessel is required to allow a transect to be completed within the available hours of darkness. If midwater trawling could be reduced to only that needed to determine the species composition in groups of mixed species characteristically present in the metaliminion, the spatial coverage during a survey could be greatly increased. Also, the certainty that we attach to the species composition in the water column would be enhanced since we presently must extrapolate data from the midwater trawl catches to large areas. We were able to recognize some predictable pattern to species distributions, but the reliance of the midwater trawl catches to classify echoes in all areas of the water column from a discreet number of midwater tows adds another source of error that needs to be investigated.

We investigated two approaches to identifying individual species in the water column. One approach was to model the species composition in specific pelagic zones defined by a variety of physical habitat characteristics. Our results indicate that night-time vertical migrations and the resulting pelagic distributions of the planktivores are influenced by a variety of factors, of which physical habitat factors and feeding behaviors are important components. The models adequately predicted the percent of alewife and bloater in the midwater trawl catch. However, they were less successful in predicting the percent of rainbow smelt in the catch. A drawback to this modeling procedure is the need to periodically re-evaluate and update the classification model to account for inter-annual changes in the abundance of individual species and changes in relative species composition. The second approach to determining species composition in the water column was to develop a broadband fish identification system, integrated with a neural net-based predictive model. Development of this technique would render cost savings in both sampling time and possibly the need for a additional survey vessel.

Our results indicate that the development of lakewide estimates of the abundance of the major prey species was not significantly affected by the large distances between sampling transects. Intensive sampling within a much smaller area in 1993 indicated that even though fish densities measured at individual transects were highly variable, estimates of fish densities within areas the size of our sampling grids suggested that widely-spaced transects, on average, provide reasonable good estimates of larger-scale densities. When designing a study we recommend conducting some preliminary sampling to examine the variability in fish density prior to embarking on a full sampling regimen.

The fall acoustic biomass estimates appear to be reasonable and provide reliable fish stock status and trend information. When compared to bottom trawl estimates, the acoustic estimates are very similar for certain species, and differences between the two gears can be attributed to known or deduced patterns in the vertical distribution of these species. Mutual agreement in both trends and estimated biomass derived independently from bottom trawls and acoustics for bloaters lends credence to our ability to assess the status of this species accurately with either gear. The similarity in the trends, but greater magnitudes of the acoustic rainbow smelt biomass estimates suggests that this species is pelagic and can absolute numbers can be assessed more accurately by acoustic techniques. Juvenile alewives are also pelagic and are better assessed by acoustic techniques, which has implications for better understanding of survival and stock-recruitment relations for this species. Adult alewife biomass estimates were greater for bottom trawl surveys and appear to be underestimated in the acoustic estimates. Because of their patchier distribution they may have been under represented in midwater trawl samples.

Precision of the biomass estimates generated in this study was reasonably high, and CVs associated with the biomass estimates of the three major planktivores were much improved when the areal stratification from the cluster analysis was applied to existing data. Thus, we recommend that the geographical stratification scheme defined in this study be used when designing future acoustic surveys in Lake Michigan. Several of our analyses indicated that fish densities and species composition are more variable in the area near Manitowoc, and indicate that area requires additional sampling to reduce the variability of the estimates.

Acoustic techniques are capable of sampling only those fishes in the pelagic zone. Dermsal species, or those lacking a swimbladder cannot be reliably sampled acoustically. To provide measurements of stock status for these species, bottom trawls remain the most reliable gear. Thus, a full assessment of the prey fish community will require a survey approach that incorporates both acoustic methods and bottom trawls. On Lake Michigan we recommend this integrated approach in order to maintain the integrity of existing long-term databases, while incorporating better estimates of the pelagic species and life stages for which acoustic techniques provide better estimates.

Acoustic techniques, when coupled with midwater trawling and a sound, geographically stratified sampling design, will provide reliable lakewide biomass estimates for the major pelagic prey species in Lake Michigan at an acceptable level of certainty. Further refinement of the relation between acoustic target size and fish size, the development of the use of broadband techniques to identify species in the water column continuously and more quickly, and the trend of acoustic equipment becoming more technologically sophisticated but easier to operate, will ensure that the level of accuracy and precision (and thus reliability) of survey estimates will only increase.

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Reports to Lake Committee

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Argyle, R, G. Curtis, and G. Fleischer. 1994. Development and implementation of an integrated (acoustic and trawl) prey fish assessment strategy for Lake Michigan: 1993 interim progress report. Presented at the Great Lakes Fishery Commission annual Lake Committees meeting, March 1994, Ann Arbor, MI.

Argyle, R. L., G. L. Curtis, and G. W. Fleischer. 1995. Integrated acoustic and midwater trawl prey fish assessment in Lake Michigan: 1994 interim progress report. Lake Committee Meetings, Great Lakes Fishery Commission, Milwaukee, Wisconsin, March 27, 1995.

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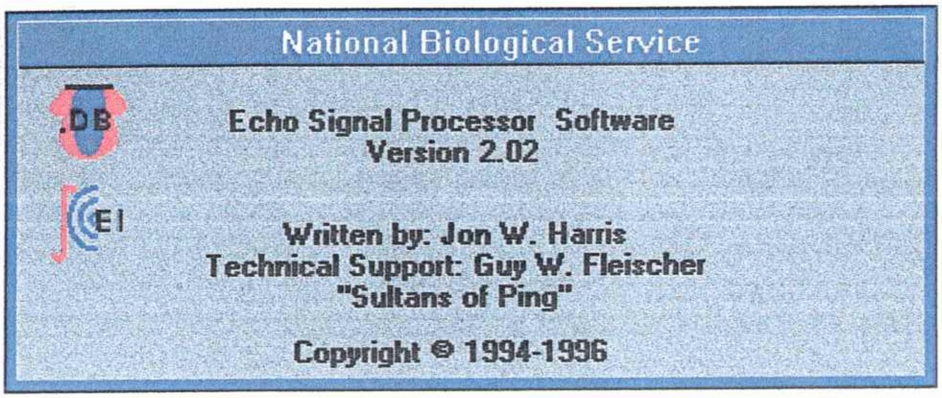
Appendix

Echo Signal Processing Software Users Guide

Echo Signal Processing Software Users Guide



Great Lakes Science Center
1451 Green Road
Ann Arbor, Michigan 48105

April 1996

Introduction

NBS/ESP is the result of a collaborative effort by BioSonics ®, Inc. and the Great Lakes Science Center. NBS/ESP is software designed specifically for the analysis of dual-beam target strength and echo integration acoustic data collected with the BioSonics ® ESP system. Like the ESP product, NBS/ESP is operated in Microsoft Windows™. This document assumes that the reader is familiar with the Windows™ environment. The NBS/ESP package has almost all functions setup for hot keys and mouse functions. There are only a few points where typing is needed. An effort was also made to allow the package to be run from a keyboard with minimal mouse usage. This should help while using the software on board the ship in less than ideal conditions, where mouse pointing is difficult.

What Does NBS/ESP Do?

Primarily, NBS/ESP was designed to replace the ESPTS and CRUNCH software provided to BioSonics® ESP users. NBS/ESP is used to calculate target strength and echo integration values from the dual-beam and echo integration files created during hydroacoustic sampling with the ESP system. Because NBS/ESP is graphics-based software, the user has more flexibility and greater ease in the target strength and echo integration analyses needed for acoustic-based fish abundance estimates. But NBS/ESP is more! NBS/ESP takes full advantage of graphical user interface power and includes tag viewing and file editing capabilities to assist in acoustic data file management. Post-collection comparisons of different threshold values and filters are easy. NBS/ESP also allows the results to be simply formatted for straight-forward printing with spreadsheets and word processors (previous users of ESPTS and CRUNCH will recognize these formats) or the results can be formatted as data tables for import into relational databases, allowing additional and powerful analyses of fish abundance.

What Are NBS/ESP Computer Requirements?

NBS/ESP needs only the same computing capabilities as the ESP system - an AT compatible computer with Microsoft Windows™ version 3.x or higher. As in all Windows™ applications, faster processors and more memory will always be advantageous!

Who Is Responsible For NBS/ESP?

NBS/ESP is the collaborative product of Mr. Guy Fleischer, Fisheries Biologist at the Great Lakes Science Center, Mr. James Dawson of BioSonics®, who kindly provided the FORTRAN source code for the ESPTS and CRUNCH programs that formed the basis of NBS/ESP, and Mr. John Harris, Environmental Research Institute of Michigan (ERIM), who translated the FORTRAN into C++ and wrote the additional code for this package. Please direct comments, questions and other inquiries to Guy Fleischer, Great Lakes Science Center, 1451 Green Road, Ann Arbor, MI 48105; phone (313) 994-3331 ext. 244; e-mail address guy_fleischer@nbs.gov.

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GETTING STARTED

Installing NBS/ESP

You will need two files to run NBS/ESP: the program file NBS2.EXE and an initialization file NBS2.INI. You can install manually by copying the NBS2.EXE to any directory of your choice – we recommend you use the same directory where the ESP programs reside. Next, copy the NBS2.INI file into your Windows directory. An automated installation is detailed in Appendix A.

Making NBS/ESP Run

Before NBS/ESP can be used for any calculations, the initialization file (NBS2.INI) must be updated with the calibration information for your system. Edit the INI file with any text editor. The initialization file lets you choose and make calculations from any number of systems, such as multiplexed systems (up to 2 separate transducers with this version of the software) or for different calibrations of the same unit. The INI file is organized into the following sections:

[Recent File List]
list of directory and name of most recently used link files {updated automatically}

[Settings]
PreviewPages=2{do not change}

[Lastsetup]
setup1=*name of setup* {updated automatically}
setup2=*name of setup* {updated automatically}

[number of setups]
num=*this number must indicate number of setups listed below*

[setup names]
setup1=*discription of a single setup, used for selection in NBS/ESP program*
setup2=*second discription*

[*name of setup*]
nser=*serial number of sounder*
caldat=*date of calibration*
tfre=*frequency of transmitter in kHz*
alpha=*absorption coefficient*
recran=1.0
tser=*serial number of transducer*
cable=*cable length in meters*
nbeam1=*nomimal angle of narrow beam in degrees*
nbeam2=0.0
wbeam1=*nominal angle of wide beam in degrees*
wbeam2=0.0
A= *numerical A coefficient for narrow beam directivity power function*
bb=*numerical B coefficient for narrow beam directivity power fuction*
bsqn=*numerical value of narrow beam pattern factor*
bsqc=*numerical value of composite beam pattern factor*

An example of an INI file is shown in Appendix A. Notice the use of remark (rem) lines to clarify the information contained in the various sections of the INI file. Use easily recognizable and distinguishable setup descriptions since these descriptions will be shown in a pull-down menu in the program! The transducer serial number, calibration date and sounder serial number is a unique identifier to every system and is a highly recommended format for users with many setups.

As a last check, please make sure that:

- ✓ The" num= " shows the correct number of setups;
- ✓ All numeric values are correct;
- ✓ Setup names are identical (no typographical errors) in the list of setup names and the heading for each section of calibration data.

The final step is to make an NBS/ESP icon.

For Windows 3.x: With the program group of your choice activated (the ESP group is recommended), select File, New, Program Item from the Program Manager. Enter complete directory and path for NBS2.EXE in Command Line (or use Browse...). Click on Change Icon and select icon. Enter title for icon in Description box and click OK for each menu.

For Windows 95: the icon will be automatically appear. Make a shortcut and place in most convenient location.

NBS/ESP icon

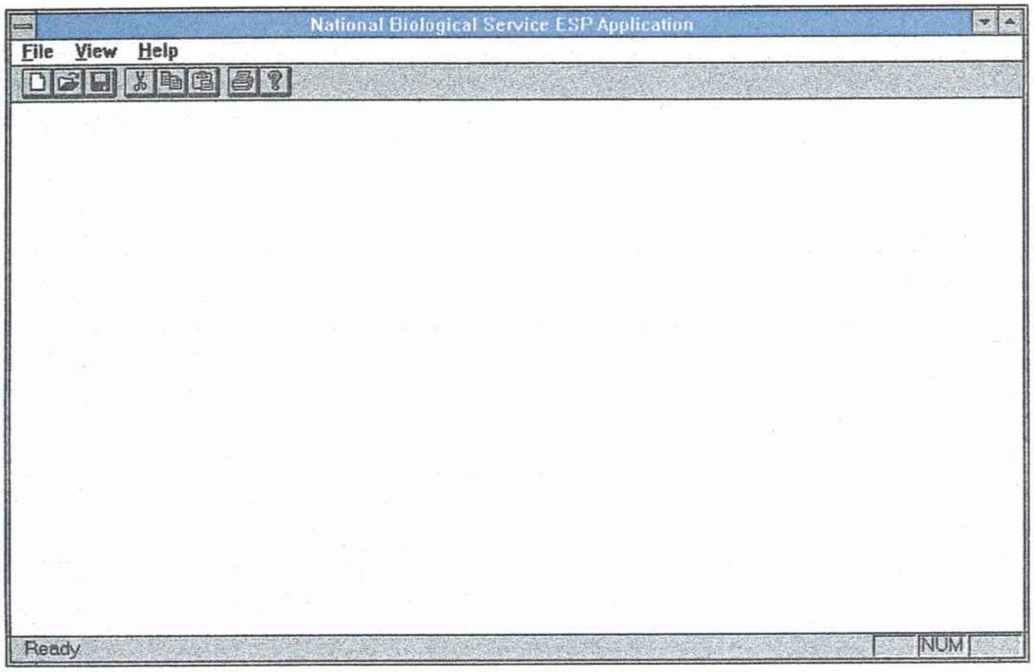
You are now ready to use NBS/ESP!

PROGRAM BASICS

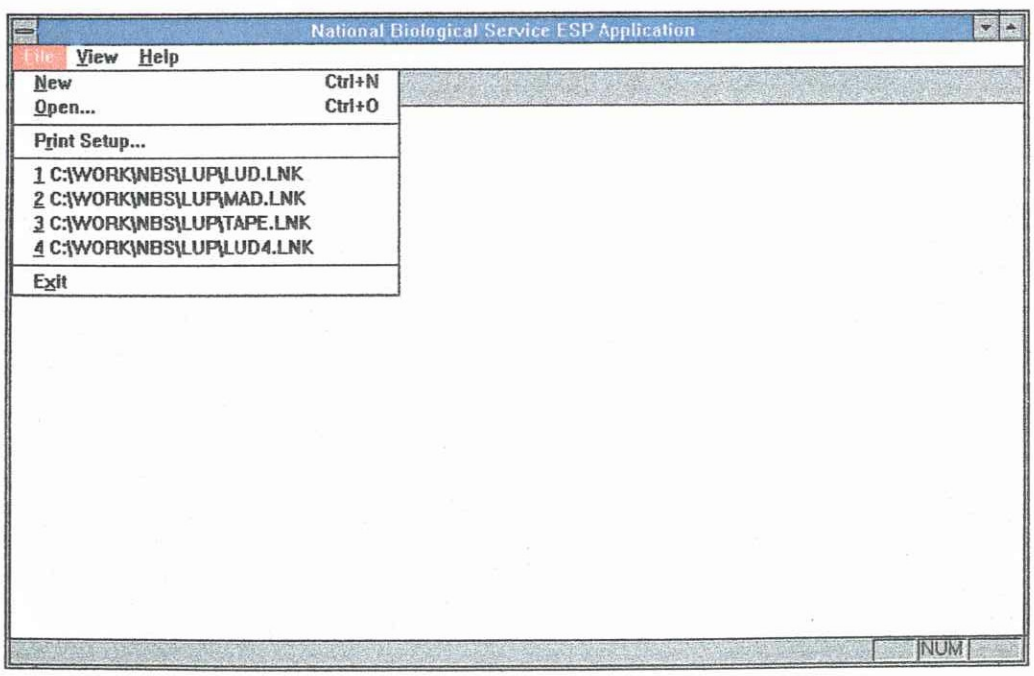
Estimates of Fish Abundance with NBS/ESP are as easy as 1,2,3.

1. Link dual-beam and echo integration files.

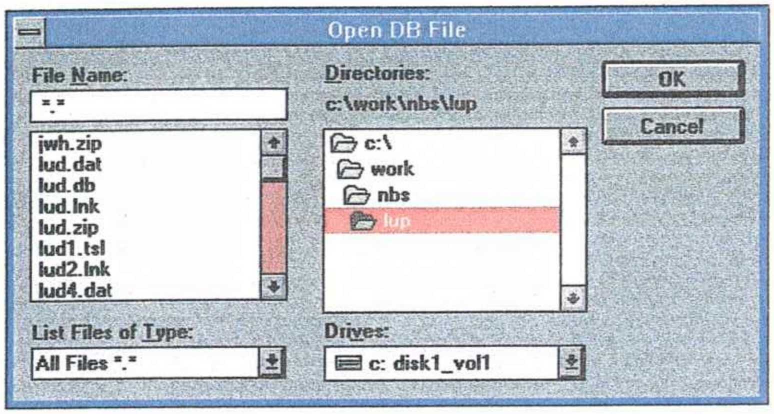
Double-click on NBS/ESP icon. You will see the entry menu window.

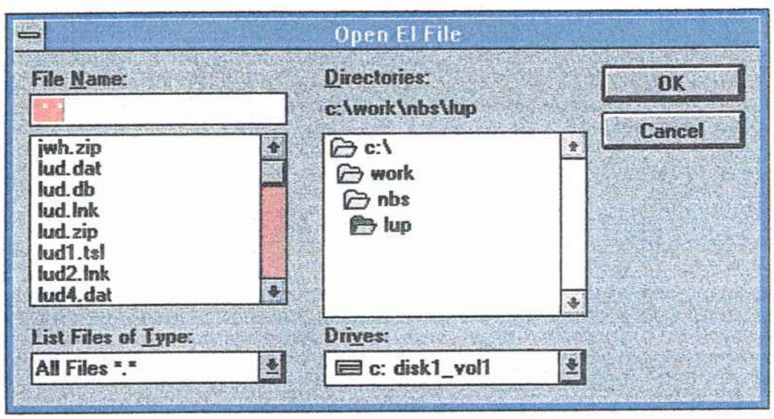


Click File to obtain the file selection menu.

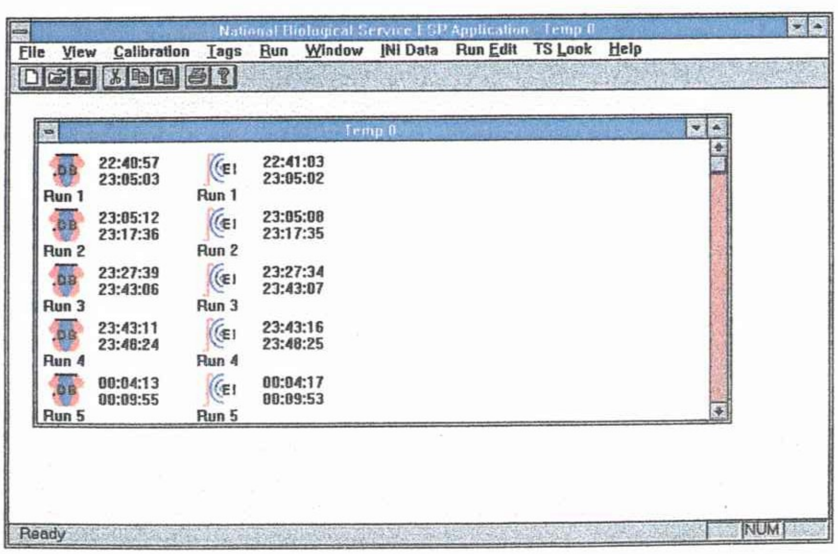


Click New and select related dual-beam and echo integration files.

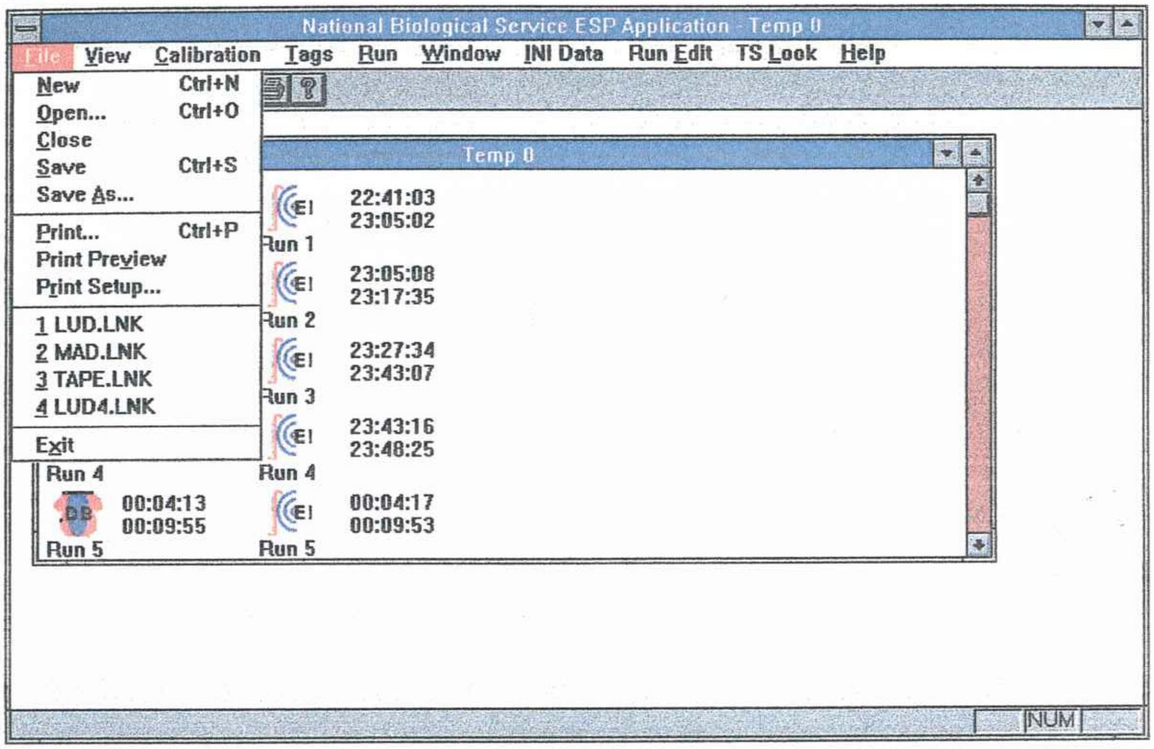


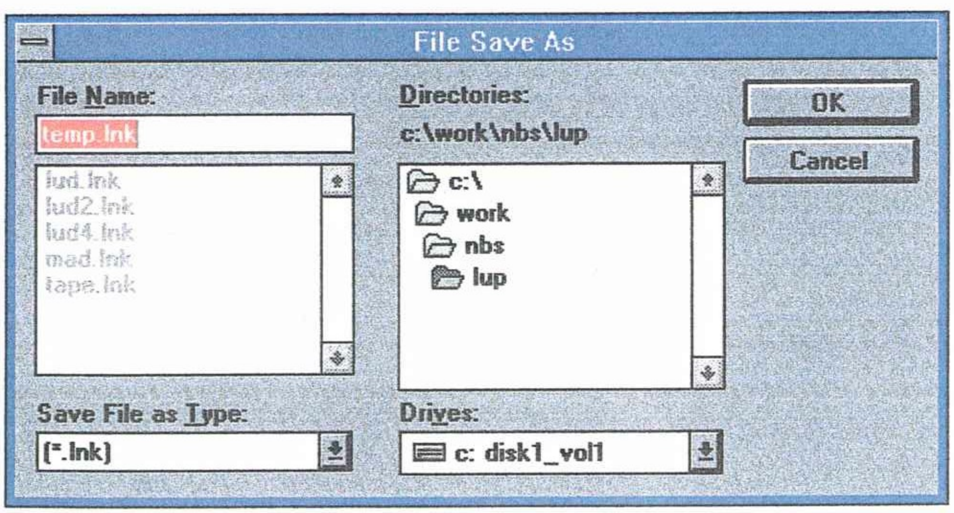


The dual-beam and echo integration files will be loaded and displayed by run in juxtaposed columns. If the files contain several runs that extend beyond the window, use the scroll bar to view entire set of runs. Note the number of runs and the start and stop times for the dual-beam and echo integration files. The number of runs for each file should be identical and the listed start and stop times for each set of runs should be comparable!



To create a permanant Link File for a particular set of dual-beam and echo integration files, select Save As from the File menu and enter a file name (default extension is .LNK).

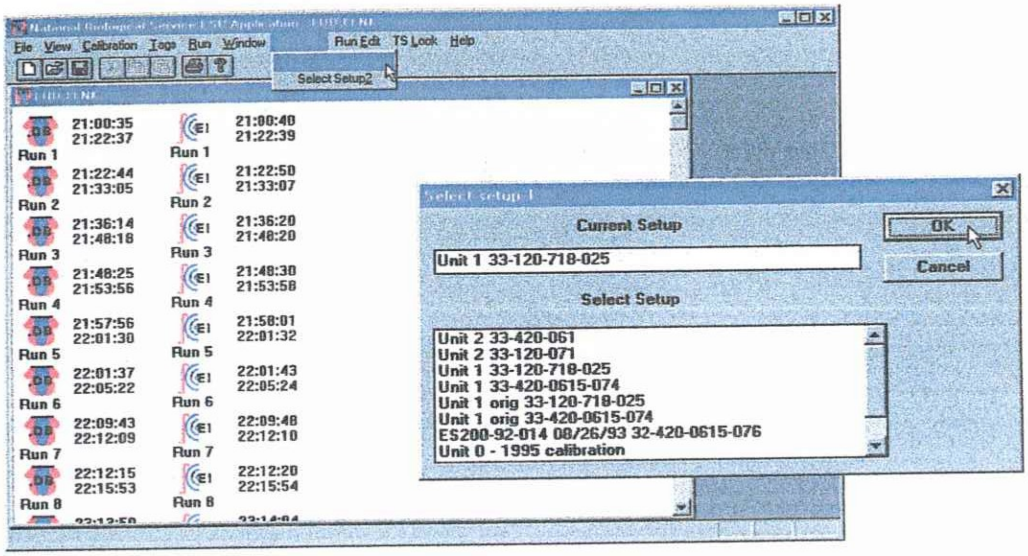




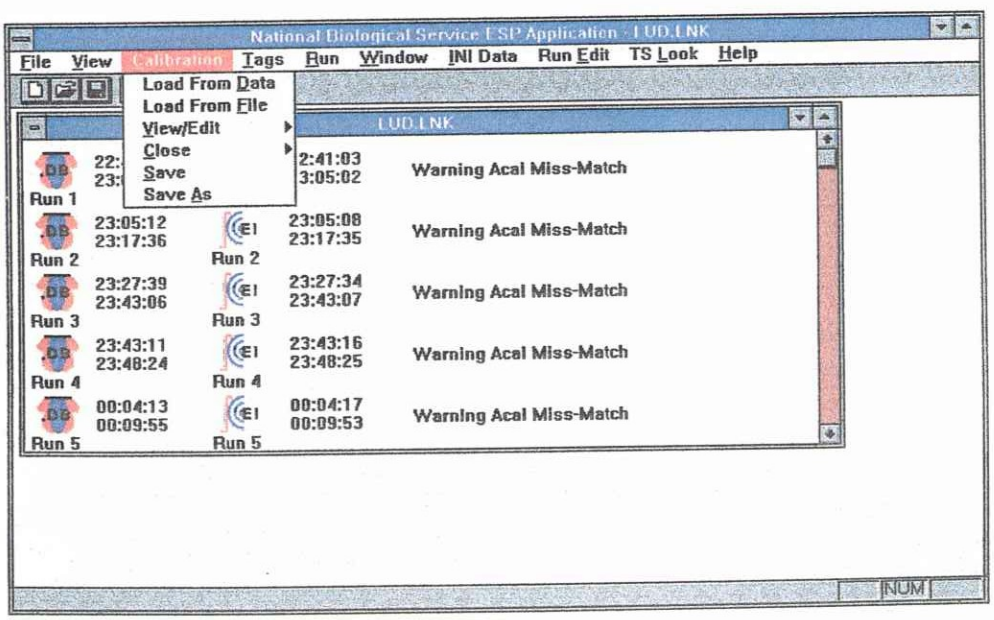
This link can be retrieved for subsequent re-analyses from the Open command under the menu bar or, if recently established, will be displayed in the recent file list of the file menu.

2. Load calibration data.

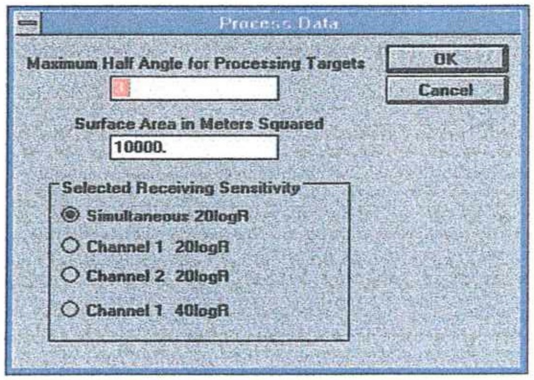
Click on the INI Data menu. Click on Select Setup 1 to obtain a list of setups. Select the description of the system to be used for the analysis. If multiplex, complete this procedure for Setup 2. Important -- this system configuration will remain the default setup until changed by user (for analysis with different system setup). The user should aways check that the correct systems are selected for the current analysis!



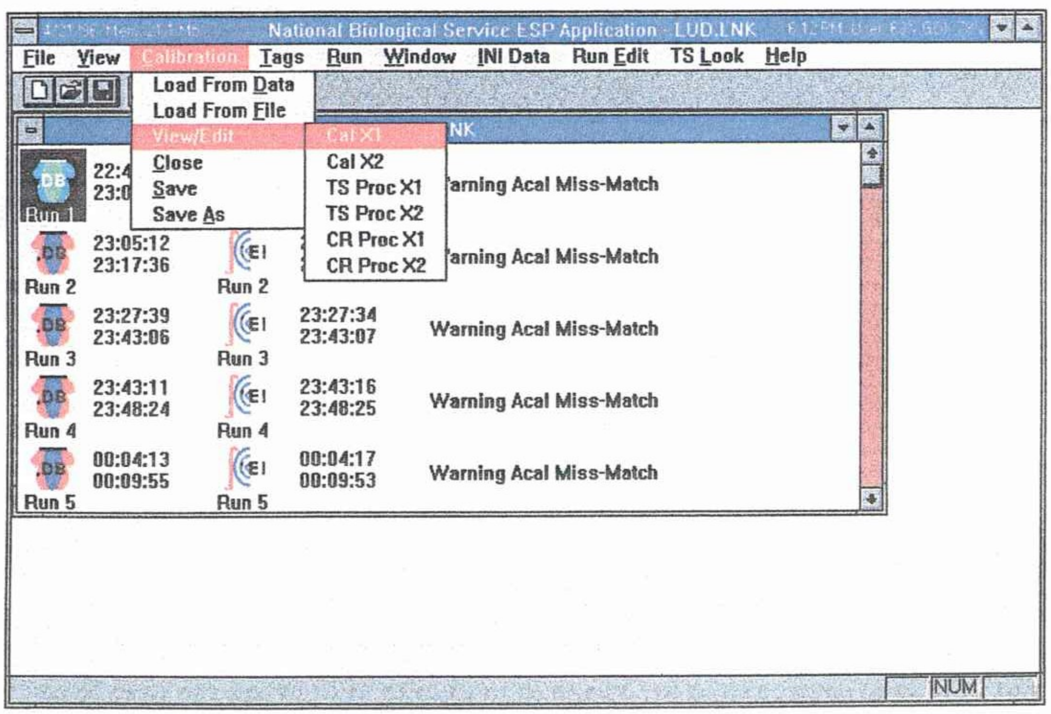
Click on Calibration. Select Load From Data. This action will load all calibration values directly from the dual-beam and echo integration files.



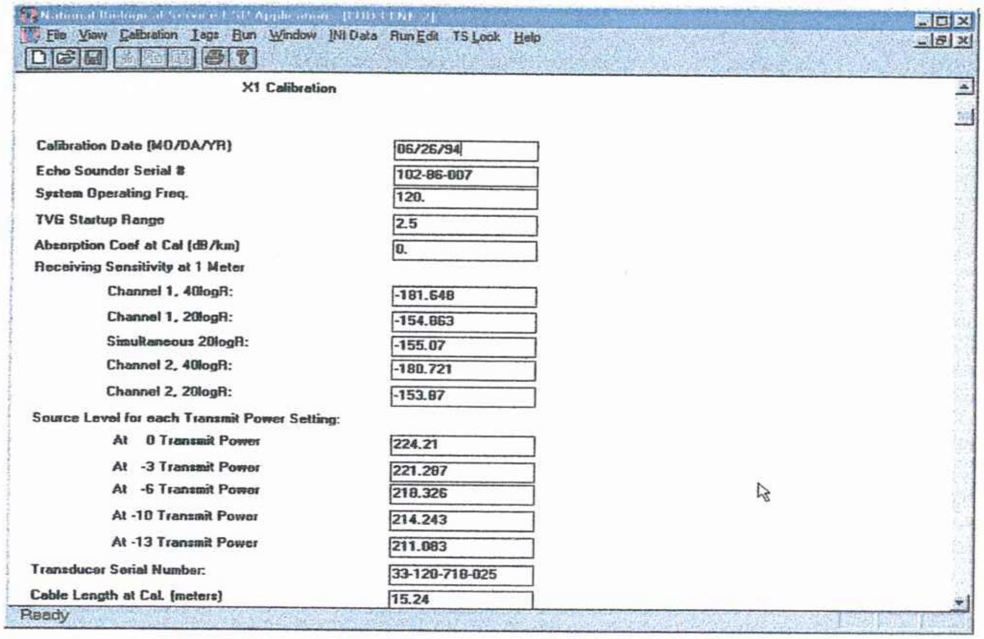
In addition, the user will be prompted for the maximum half-angle for echoes to be considered for target strength measurement (default is 3 degrees), surface area for density estimates (default is 10,000 square meters), and receiver sensitivity for 20logR data (default is simultaneous 20logR).



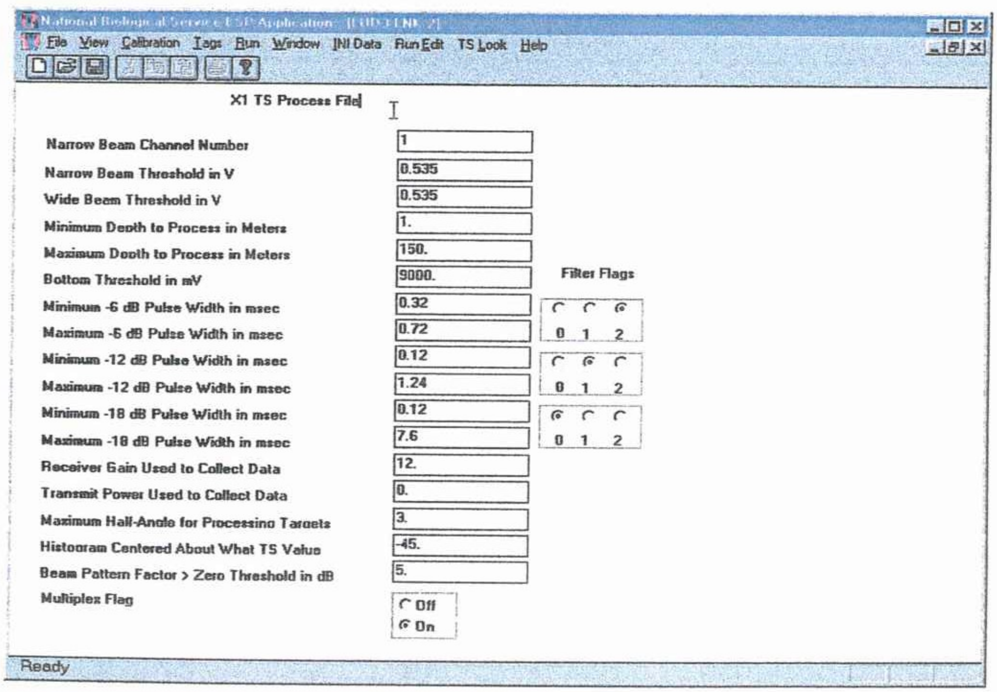
To view the calibration and processing values, hi-light a dual-beam run by clicking on the icon (it will change to a black background), and click on View/Edit.



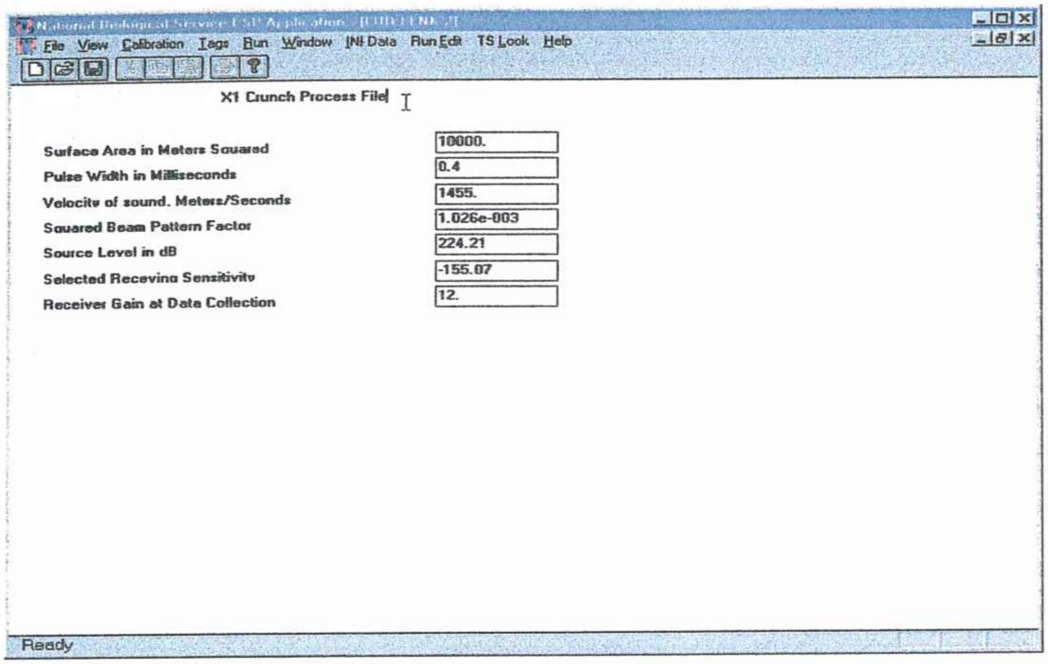
Select CAL X1 to view the calibration values for setup 1.



Select TS PROC X1 to view the target strength processing values for setup 1.



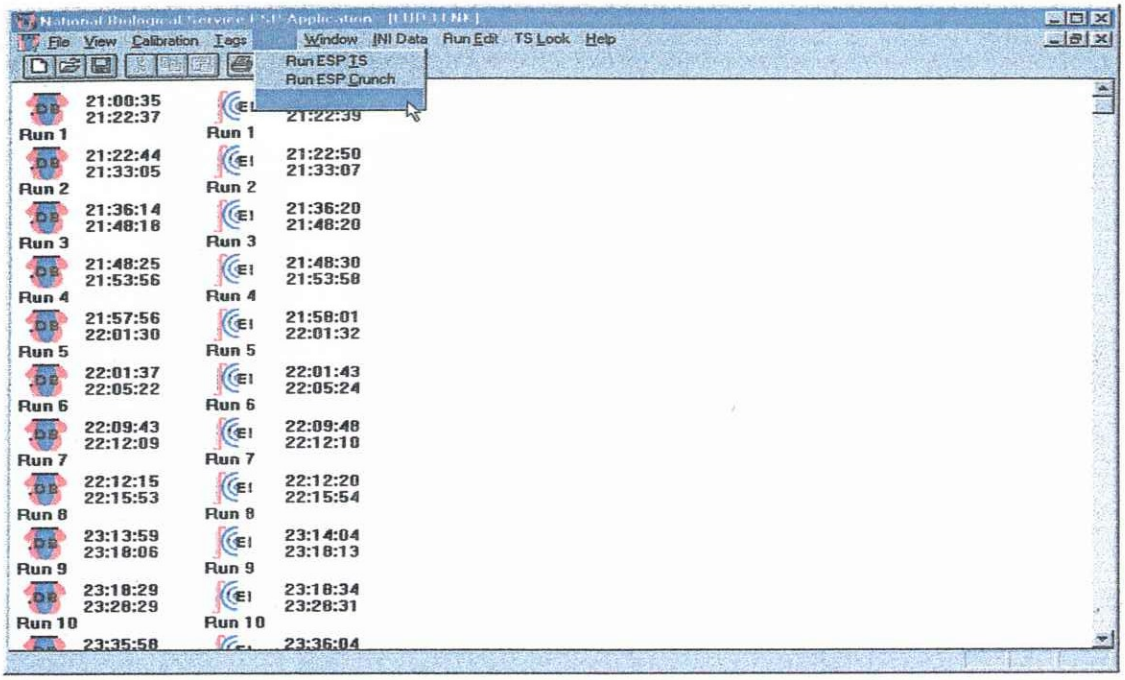
Click on the dual beam run (to toggle the hi-light off) and hi-light a echo integration run. Select CR PROC X1 to view the echo integration processing values for setup 1.



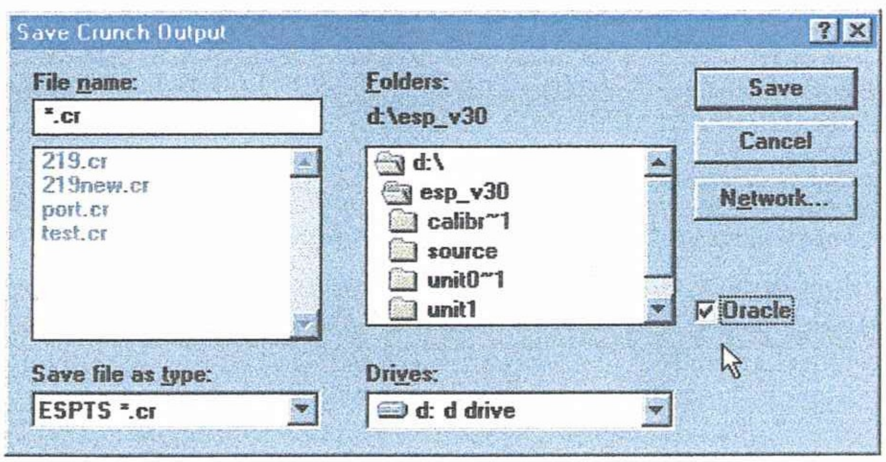
The calibration and processing values shown are those written to the binary dual-beam and echo integation files. These are the values entered into the ESP configuration files (*.CDB and *.CEI) used during the acquisition of the acoustic data. As is evident from the title, the View/Edit function also allows editing of these values, but this topic will be discussed in the Program Details section. Follow same procedure to view X2 calibration and processing values. Close all windows when finished viewing.

3. Make calculations and save results to ASCII file.

Select Run from the menu heading. Click on Both to initiate calculation of first target strength (backscattering cross section) values that will then be applied to scale the echo integration voltage squared values to produce estimates of fish abundance.



The user will be prompted to provide a name for the resulting ASCII file. These results have a default *.CR extension. By default, the output will include headers. If the Oracle box is selected (as shown) a flat ASCII file without headings will be saved.



To view or print a copy of the results, import the output file into any word processor or spreadsheet program. Users of CRUNCH will recognize the format of the results!

PROGRAM DETAILS

The following section provides the in-depth aspects for use of the NBS/ESP application. These details are organized by function as listed by the main menu headings.

THE FILE MENU

The first step in using the NBS/ESP application is to load the echo data and process it. To start the loading process, press the File menu item. As an example of the keyboard operation the user could press the ALT key and then the F key and get the same function as clicking the mouse. (Figure F1)

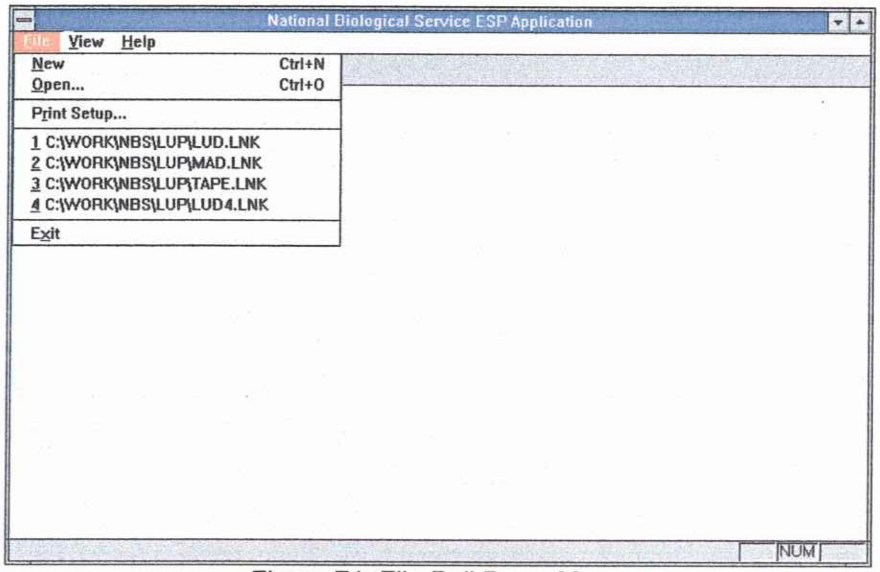


Figure F1: File Pull Down Menu

Start with the New option. Pressing on this option will cause a file selection box will appear. This box will allow the selection of the dual beam (DB) file you wish to process. (Figure F2)

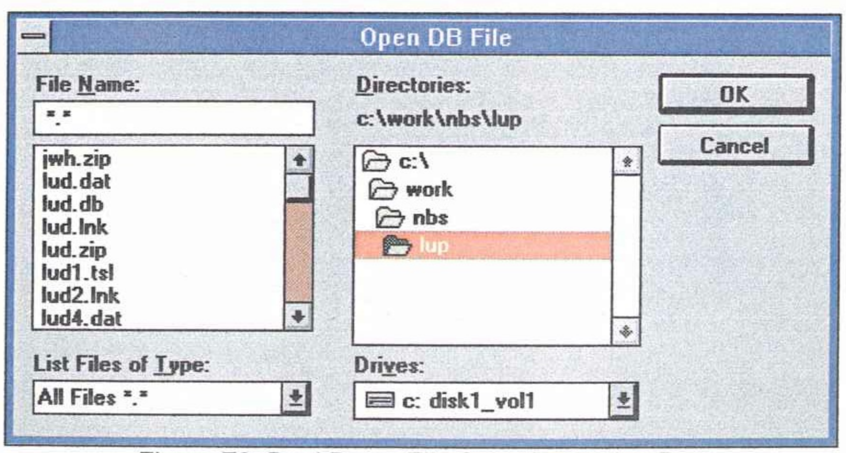


Figure F2: Dual Beam File Selection Dialog Box

After selecting the DB file the user is presented with the Echo Integration (EI) file selection dialog box. (Figure F3)

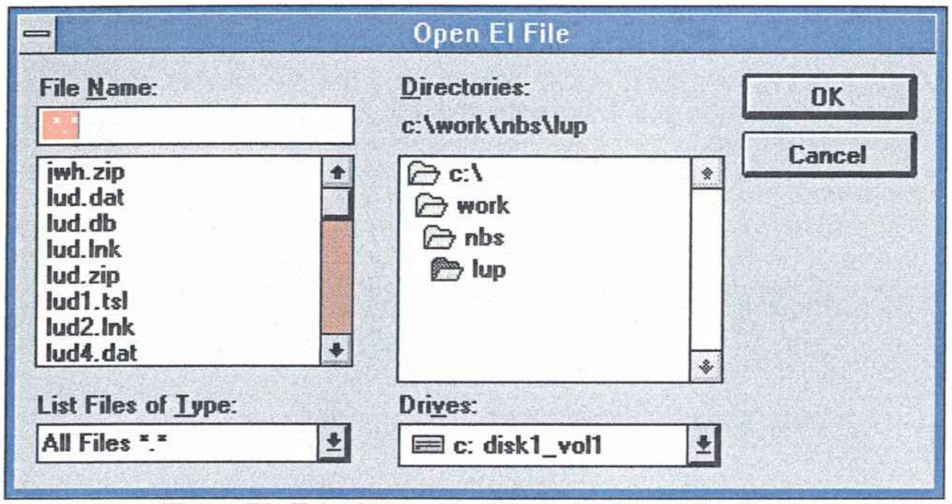


Figure F3: Echo Integration File Selection Dialog Box

The user should select the Echo Integration file the goes with the DB file selected in the last step. It should be noted, that if only the DB data is to be process, you may hit the Cancel button on the EI selection dialog box and no EI data will be loaded.

Once the user has made both selections the DB and EI data will be loaded. If the NBS/ESP can not open one or both of the files, an error dialog box will pop up and warn the user. If this error occurs the program will load any files that can be opened and skip those that could not be opened. If this error occurs the user may want to stop processing. This can be done by selecting the FILE menu item and pressing the CLOSE option. Other windows' tools can then be used to determine if the files you want are really there and of the proper size.

Once the data files are open the Echo Display window will appear in the work space area. (Figure F4) The first time new is used it will be labeled Temp 0. This window label name, as with many window applications, is set up as a counter. If you were to open another set of files using the new function, during this session of the NBS/ESP, it would come up as Temp 1.

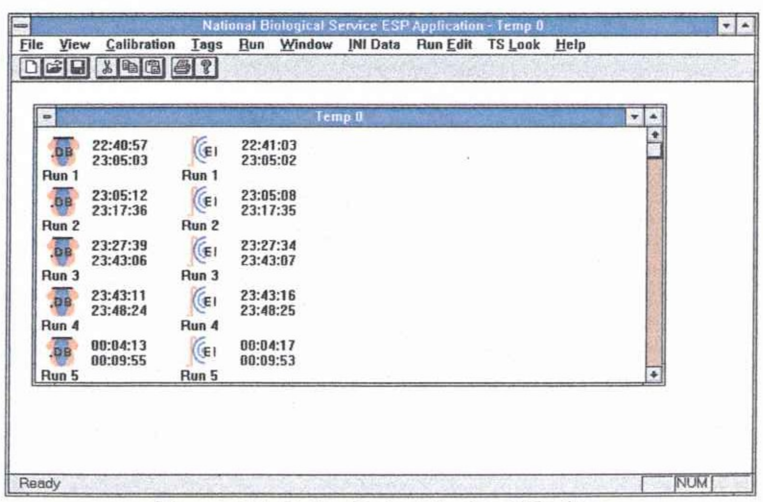


Figure F4: Echo Data Display Window

Lets look at a few things in Figure 6. First, note that there are many more menu items across the top of the NBS/ESP window as compared to Figure 2. We will look at each of these in the following pages. Next, look at the Echo Data Display Window in Figure 6. You will see that each run in the Dual Beam file is represented by the DB Icon with the run number just below. Off to the right if the DB icon is the start and stop time for that run. For the Echo Integration data, the user will see an EI Icon for each run and to the right of EI icon is the start and stop time for each run. A slider bar on the right side of the Echo Data Display Window will allow the user to scroll through all the loaded runs. At this point we are almost ready to start processing our data. First lets look at three new options you will find if you press the FILE menu item (Figure F5).

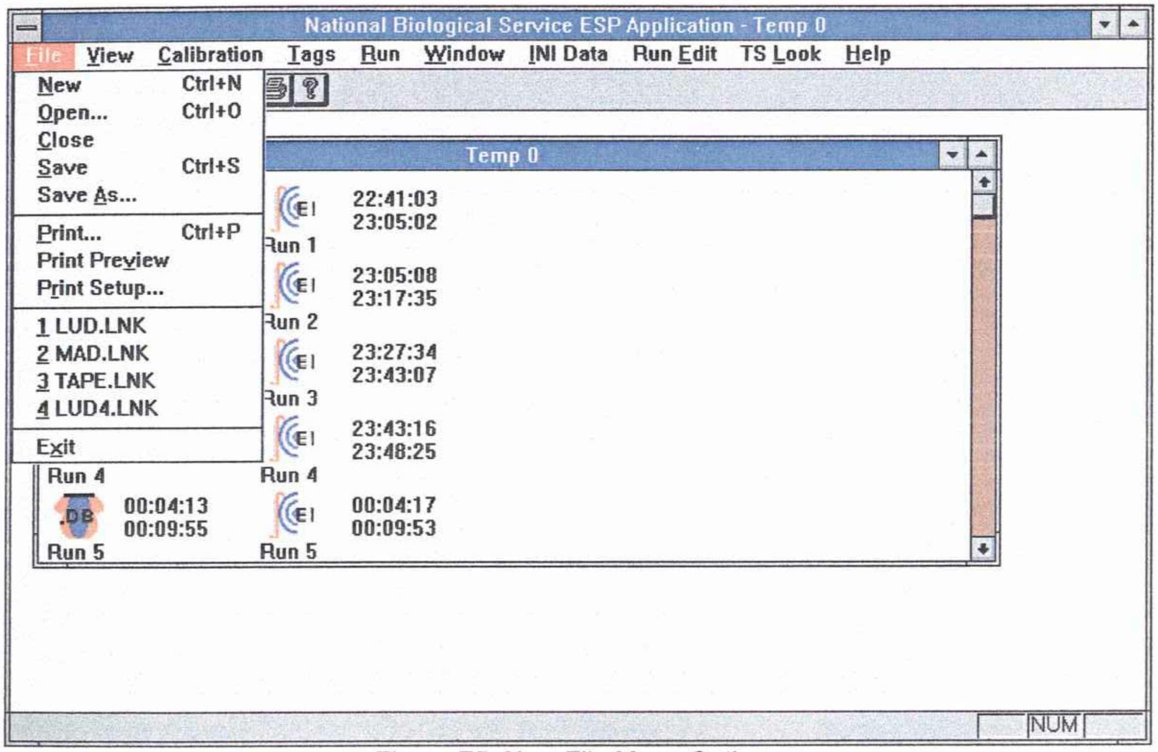


Figure F5: New File Menu Options

Any time a data set is open these new FILE options are available. The First of these is the Close option. As one could guess, this will close the Echo Data Display Window and the data files that they represent.

The next two buttons SAVE and SAVE AS are there so the user can save the link you have made between the DB and EI Files. We call it a link because these two options only save the path and names of the two files the user has selected. We normally use the .lnk extension to identify this as a link file. If you press the SAVE Option the link is saved to the current display window name. In this case that would be Temp0.lnk. To give this link a more meaningful name the user may select the SAVE AS option. This will bring up a Save As file selection dialog box. (Figure F6) Enter the name that this link is to be saved to and press the OK Button. After the SAVE As dialog box closes, the name on the top of the Echo Data Display Window change to the name just entered.

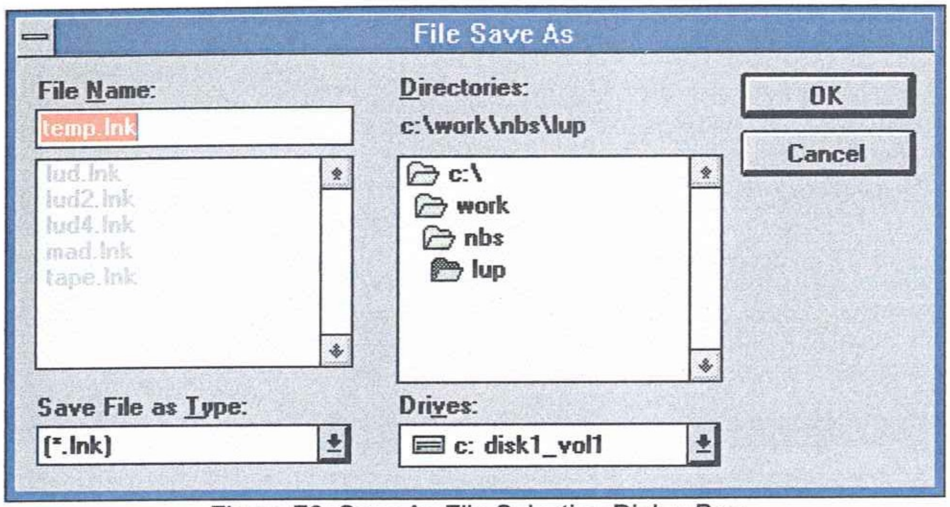


Figure F6: Save As File Selection Dialog Box

In addition, there are two other methods of loading data. Both of these methods assume that you have used the NEW option in the past and saved the link to a .lnk file. Looking again at Figure F1, You will see there is an Open Option. Pressing this option will bring up the Open link file selection dialog box. (Figure F7). Select the lnk file that contains the link you with the analyze and that data will be loaded.

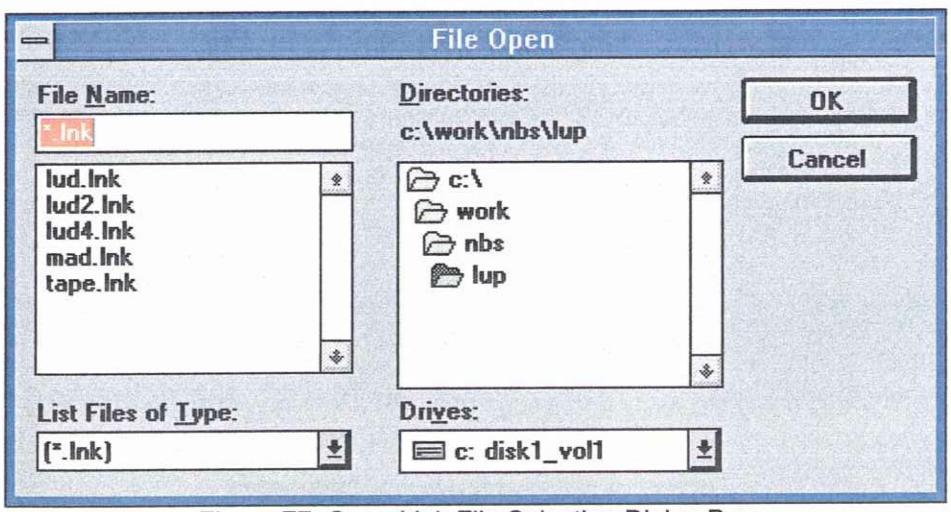


Figure F7: Open Link File Selection Dialog Box

Once again, Look back at Figure F1. You will see four link files listed just above the EXIT option. The NBS/ESP software keeps a list of the last four .lnk files used. By selected one of these you can load the data from that link.

THE CALIBRATION MENU

With the data loaded we can now analyze the data. The first step in this process is to select and enter the Calibration and Process data. The NBS/ESP program allows three ways in which this can be done. Press on the CALIBRATION menu item. (Figure C1) The first option is to use the information that was stored with the echo data during the data collection. This is a new option that was not available in the old BioSonics software.

Also note the warning that has appeared in Echo Display window. This Warning will appear when the data is loaded. It means that the Acal data stored in the DB runs does not match the data stored in the EI runs. This can happen because the EI and DB data are set up separately. The miss-match can be examined by using the Tags menu item, discussed later.

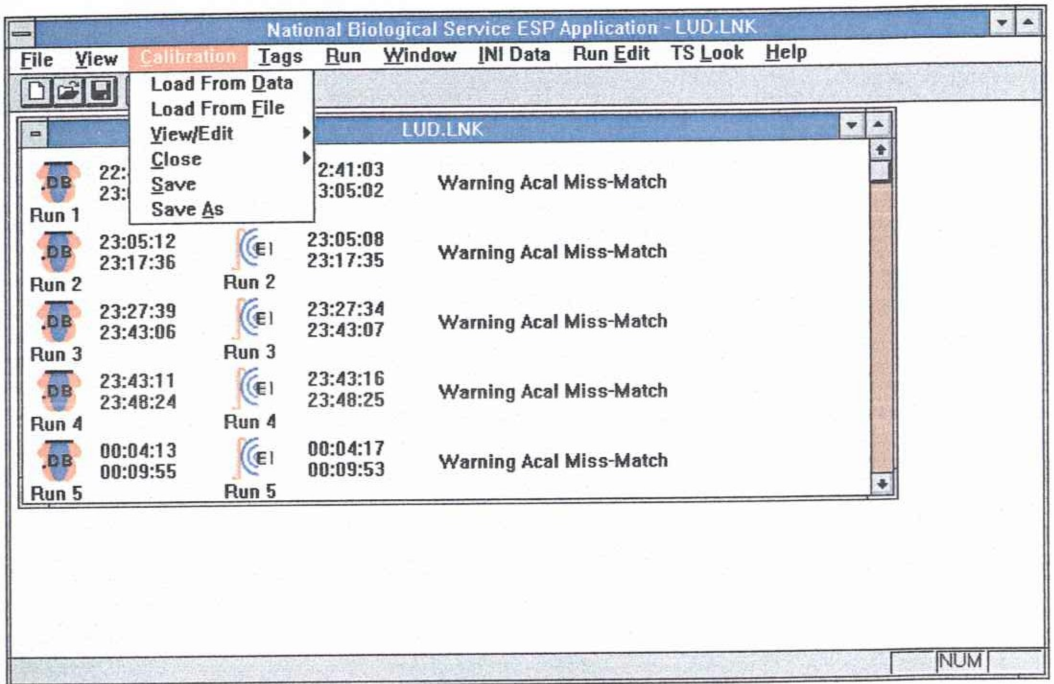


Figure C1: The Calibration Menu Options

To use the calibration and process data saved in the files press the LOAD FROM DATA Option. This will bring up the Process Data Window. (Figure C2)

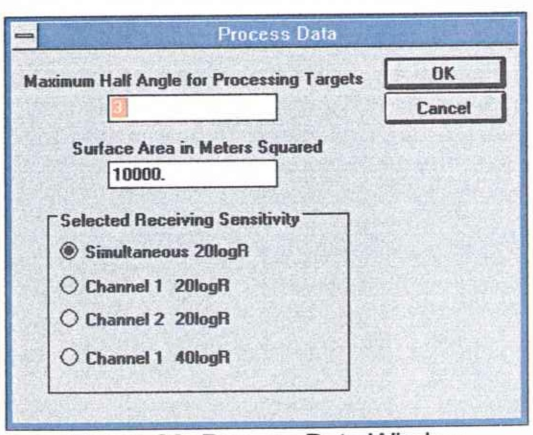


Figure C2: Process Data Window

In this window the user is prompted for data that is not included in the data files, Maximum Half Angle and Surface Area. The user is also asked to select the proper Receiving Sensitivity for the loaded data. Once this data is entered press the OK button. This will load the all of the calibration data into the NBS/ESP program.

The second method of loading Calibration data is to use calibration data that you have previously stored in files. This can be done by selecting the LOAD FROM FILE option. You will be presented with a file selection box for each calibration and process file needed. (Figure C3) *These files are not compatible with the calibration files used in the old BioSonics programs.* The Calibration files saved using the NBS/ESP program are specific to this application. We will discuss how to save these file shortly.

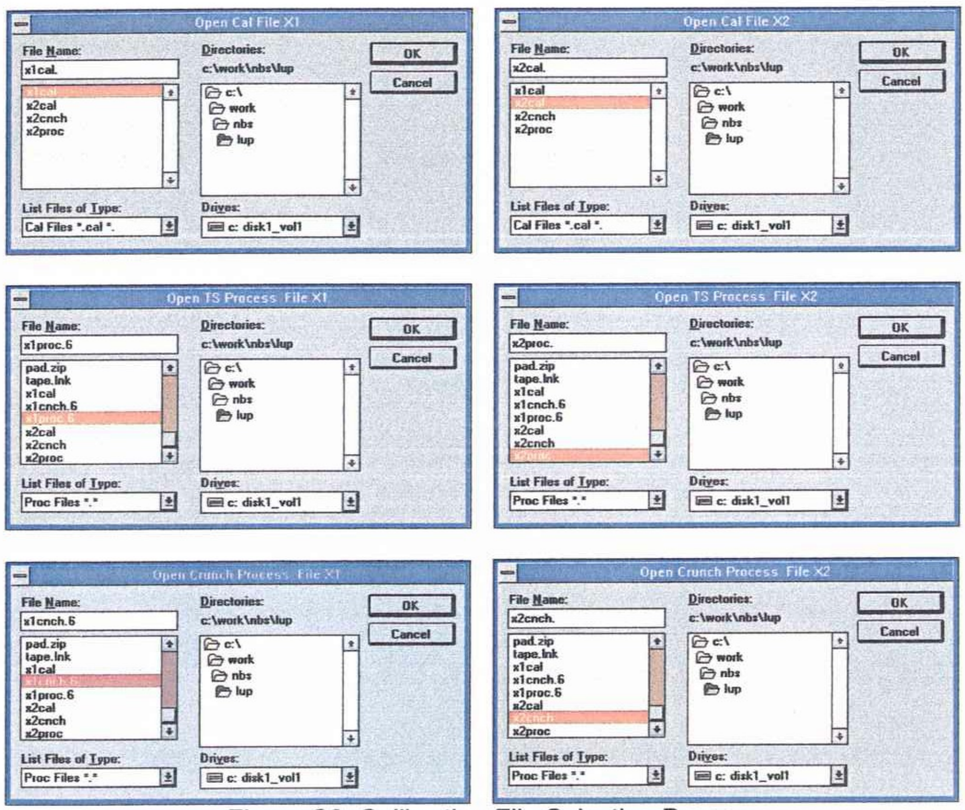


Figure C3: Calibration File Selection Boxes

You can combine the first two methods to obtain a special calibration setup without having to save all the files. This case might occur, for example, where a setup error is found in the data that was stored with the collected data, or where additional filter constraints are used for processing that are different at time of data collection. The changes made in more than one data set will need to be corrected for all the effected data sets. Start by using the LOAD FROM DATA option. This will load the calibration and process information stored with the collected data. Next, select the LOAD FROM FILE option. For our example let's assume the error is in the Cal data for X2. When the Open Cal X1 window appears, press the Cancel Button. Now use the Open Cal X2 window to select a calibration file that has the error fixed. We will cover how to edit and save these files below. For the rest of the Process windows press the Cancel buttons. The NBS/ESP program will now use the data stored with the collected data for Cal X1 and all the Process files and use the corrected Cal X2 data from the file loaded.

The final method, to set up the calibration and process data, is to enter it by hand using the VIEW/EDIT CALIBRATION OPTION. (Figure C4) This Option serves three purposes. It allows the user to enter the calibration and process data by hand. It provides a means to examine the calibration data loaded by ether the LOAD FROM DATA or LOAD FROM FILE options. VIEW/EDIT option allows the user to edit any of the data entered from all the above methods. Selecting the VIEW/EDIT option will bring up a second selection menu. (Figure C4)

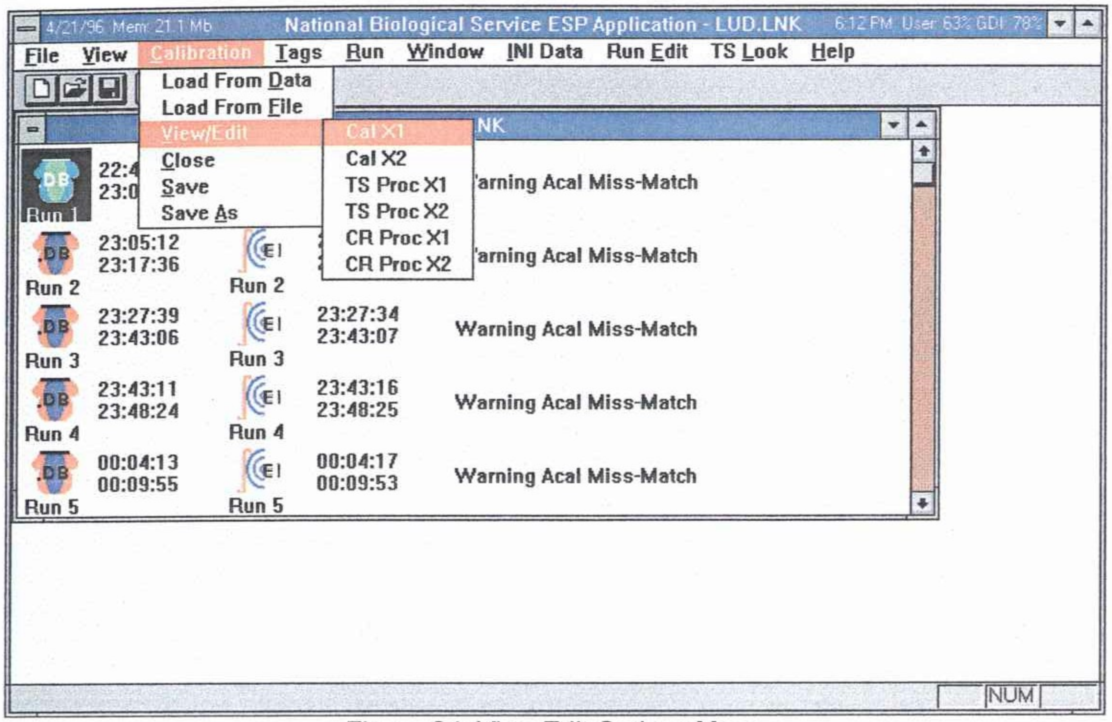


Figure C4: View Edit Options Menu

From the View/Edit Options Menu the user can select which calibration or process files that is to be examined or edited. If the user selects this option after using the LOAD FROM DATA option, the user must select a DB or EI run. Because the calibration or process data can change from run to run the user must select the run to be used. This is done by clicking on the DB or EI icon for the run that is to be viewed. When an Icon is selected its color will be inverted (Figure C5).

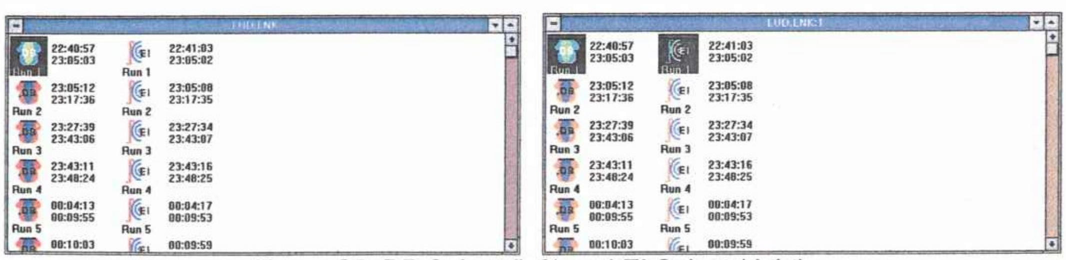


Figure C5: DB Select (left) and EI Select (right).

When the user selects the View/Edit Option a Form Window will appear (Figures C6, C7 and C8). The data in these forms can now be edited. Once the user is done making changes the calibration or process windows MUST be closed before the changes will take effect. This can be done by selecting the close Option in the calibration menu (Figure C9) or double clicking on the upper left window box. Only when the window is closed, will the changes in the calibration or process data take effect. Once a change has been made to the calibration or process data, loaded with the LOAD FROM DATA option, the data on the changed form will be apply to all runs.

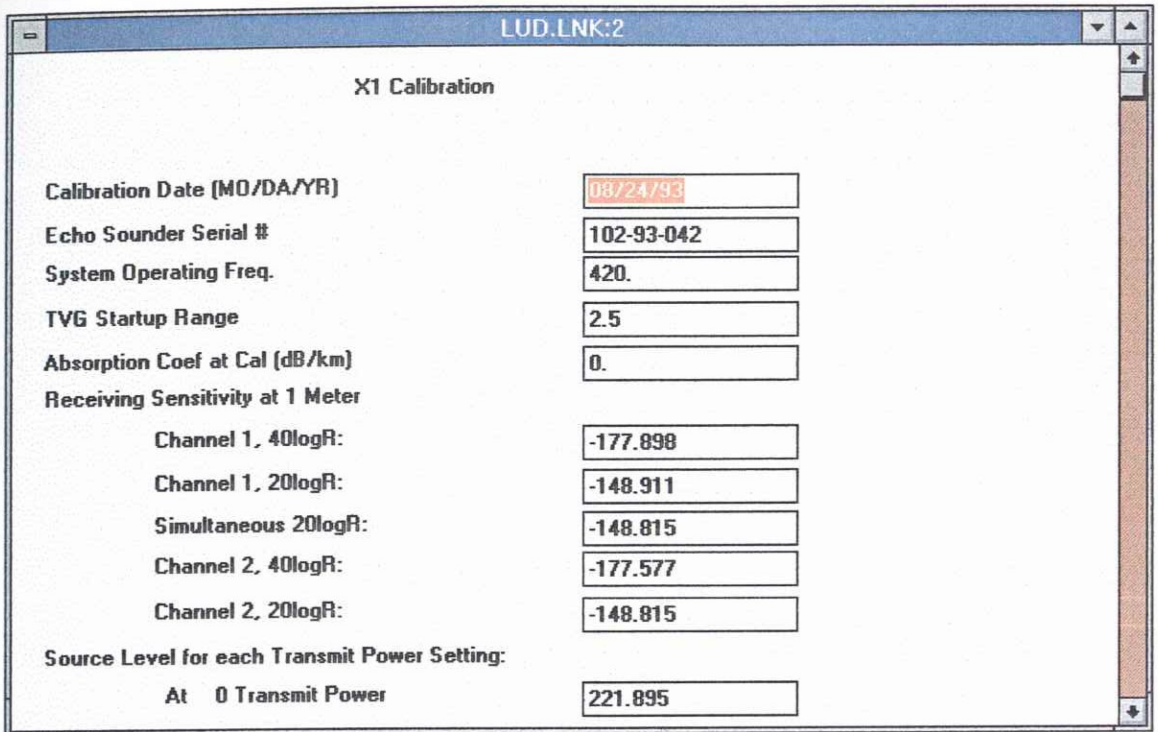


Figure C6: Calibration Form Window

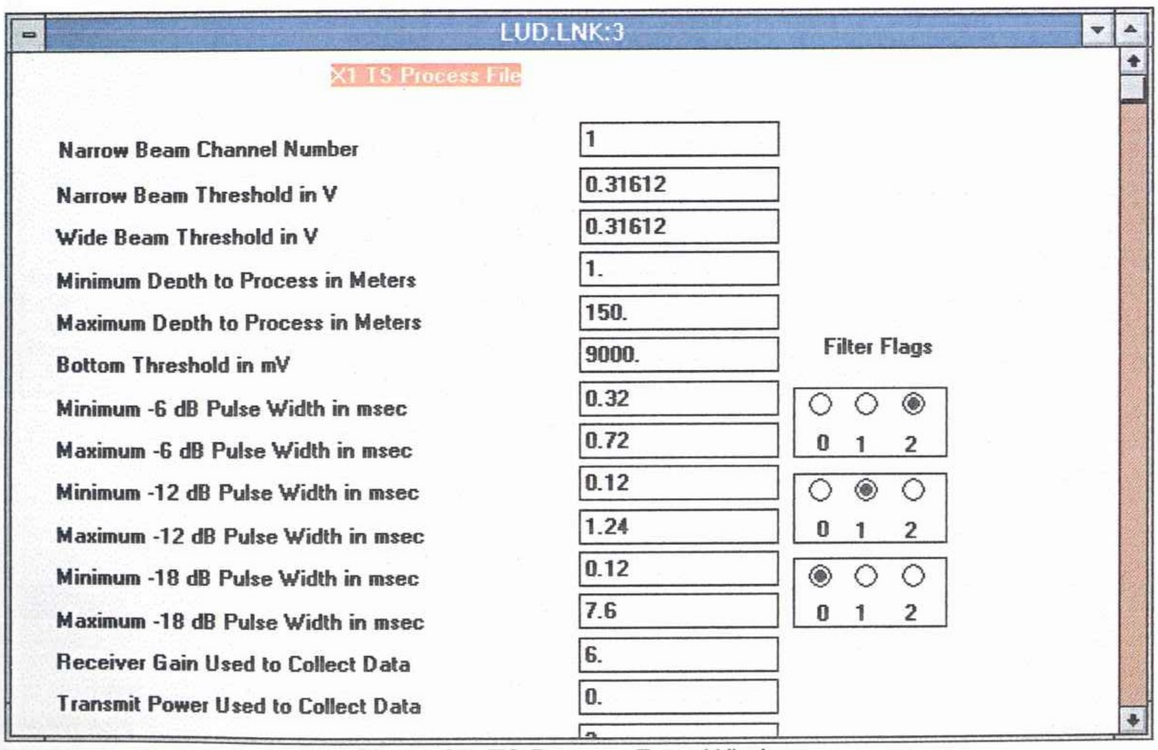


Figure C7: TS Process Form Window

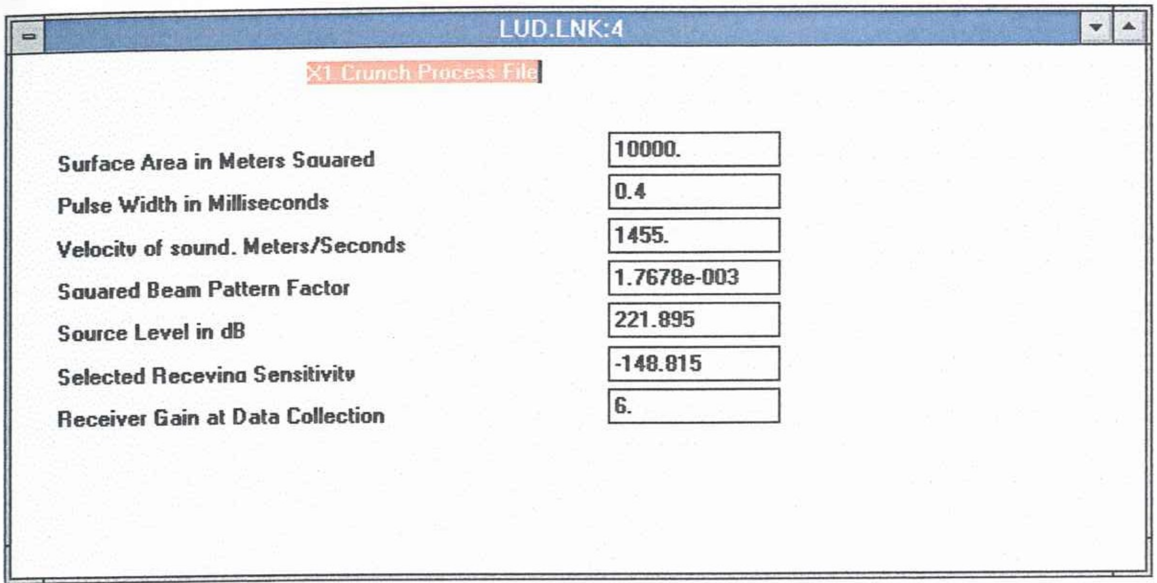


Figure C8: Crunch Process Form Window

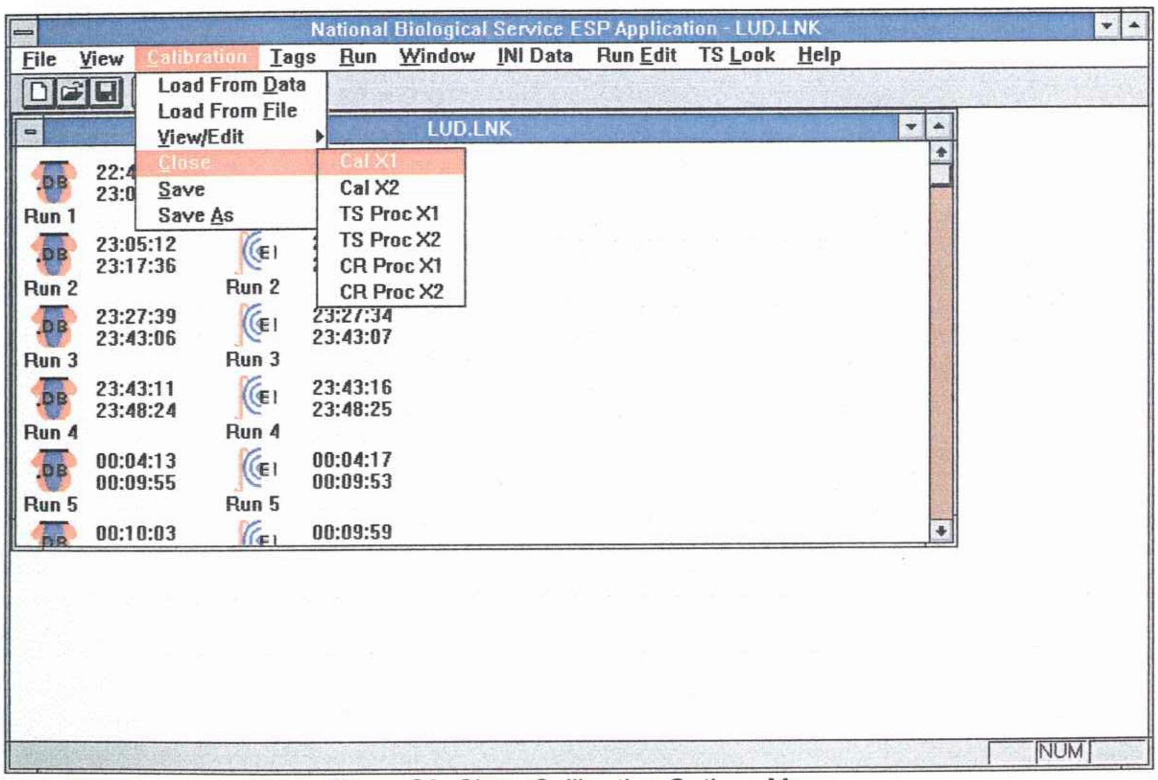


Figure C9: Close Calibration Options Menu

If the user wants to save to a file any of the data entered or any of the changes made, a SAVE and SAVE AS option are available under the Calibration menu.

The SAVE AS option will prompt the user with a series of file selection boxes very similar to those used to LOAD DATA FROM FILE (Figure C10).

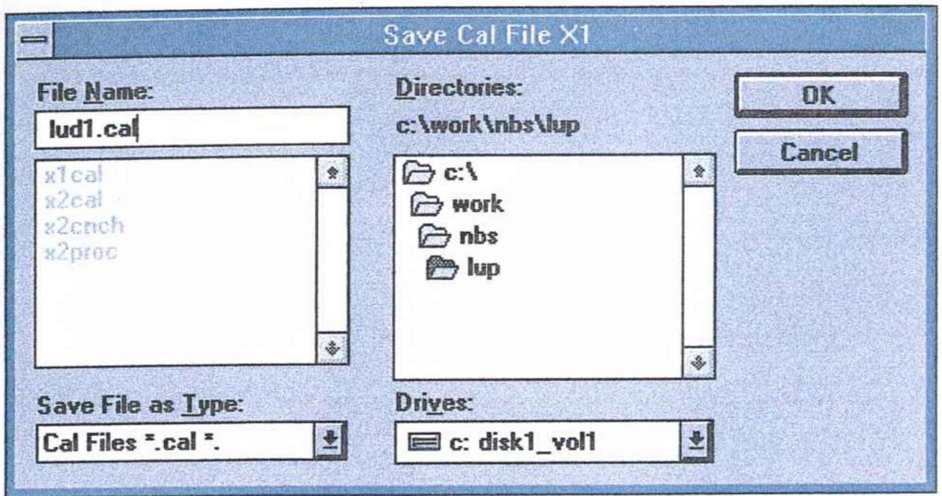


Figure C10: Example Save Calibration File Selection Box

Once all the calibration and process files have been defined a final check box will appear. (Figure C11).

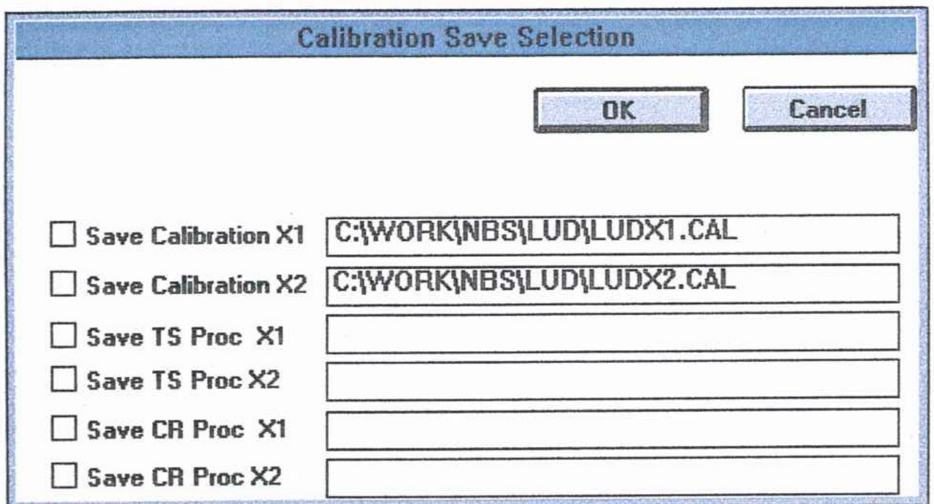


Figure C11: Calibration Save Check Box

To save the files you have changed the user must now click on the box in front of the files to be saved. An X will appear in the box to let the user know what files are selected. The File names and paths in the text window following the Save label can NOT be edited.

If the user selects the SAVE option, this dialog box (Figure C11), will appear and you can check off the files you wish to be saved. If the text box, for the item that is to be saved, does not have a path and file name in it, the user must cancel and use the SAVE AS function.

If you change the calibration or process data and do not save it, when the NBS/ESP program is closed or exited, a warning dialog box will appear. This notice will give the user the option to save any changes that were made before they are lost.

THE TAGS MENU

The TAGS menu is designed to allow the user to look at the data tags stored with the echo data. The user must select the DB or EI run that is to be viewed. The run selection is done as shown in the calibration process. Once the DB or EI run is selected the user should press the TAGS Menu item (Figure T1).

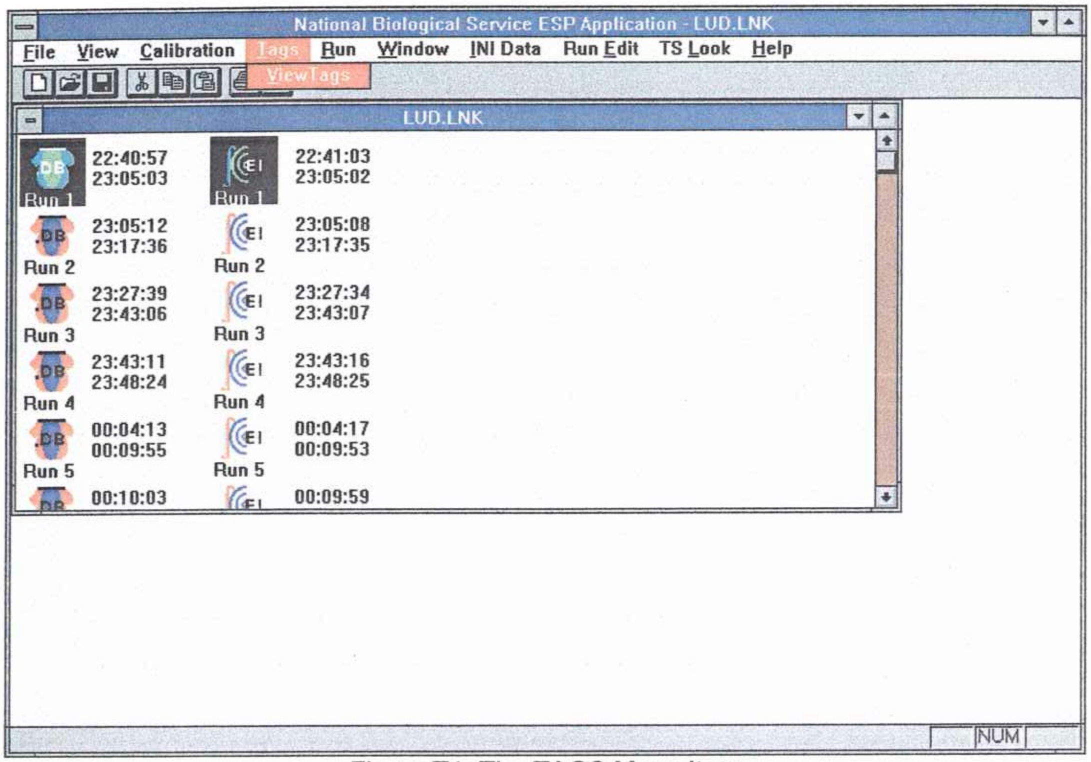


Figure T1: The TAGS Menu Item

If the user clicks on the View Tags Option, the DB or EI Tags selection dialog box will appear (Figure T2).

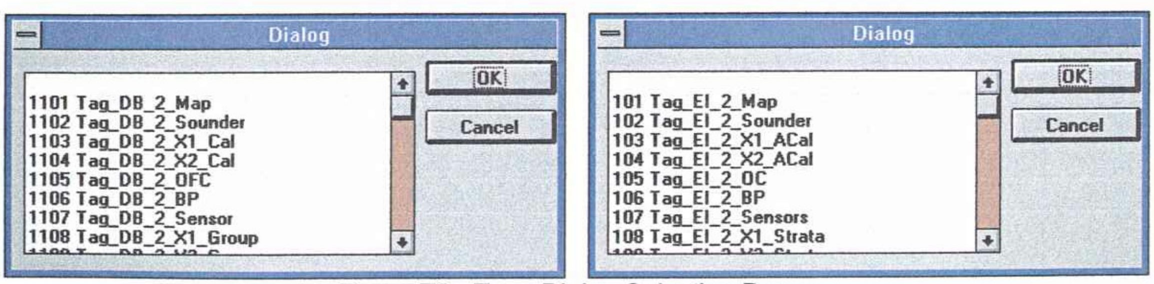


Figure T2: Tags Dialog Selection Boxes

The user is now asked to select which data tag they wish to view. A few tags are not viewable. A message will be displayed informing the user that the data for the selected tag is not available. Once the tag is selected by ether double clicking on the tag name or selecting the tag name and pressing OK, A Tags viewing box will appear. (Figure T3)

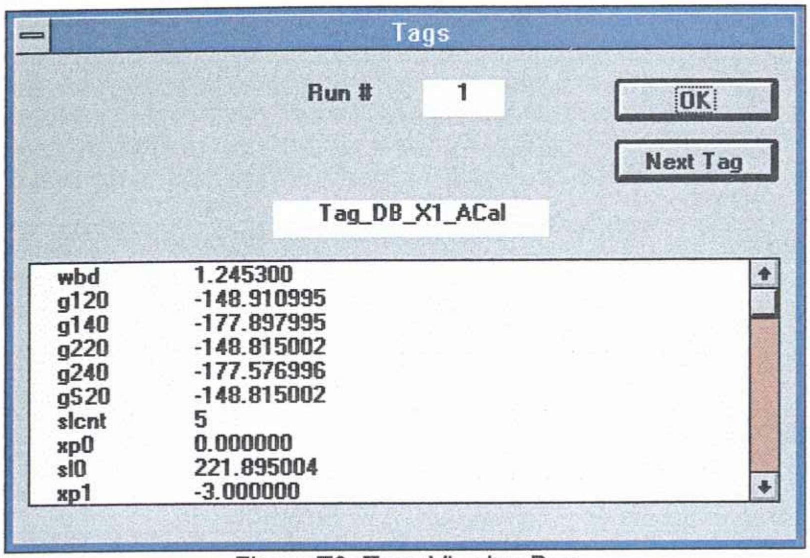


Figure T3: Tags Viewing Box

The definitions for the tags ID's can be found in the BioSonics documentation, Appendix G: ESP OUTPUT FILE FORMAT. The Tags viewing box has two buttons. The OK button will close the Tags Viewing window and return you to the main NBS/ESP window. The Next Tag button will take you back to the Tag Selection boxes of Figure T2. In this way you can look at several tags quickly.

THE RUN MENU

With the echo files loaded and the calibration data selected the user is now ready to analyze the data. The Run menu item provides the user with three options (Figure R1).

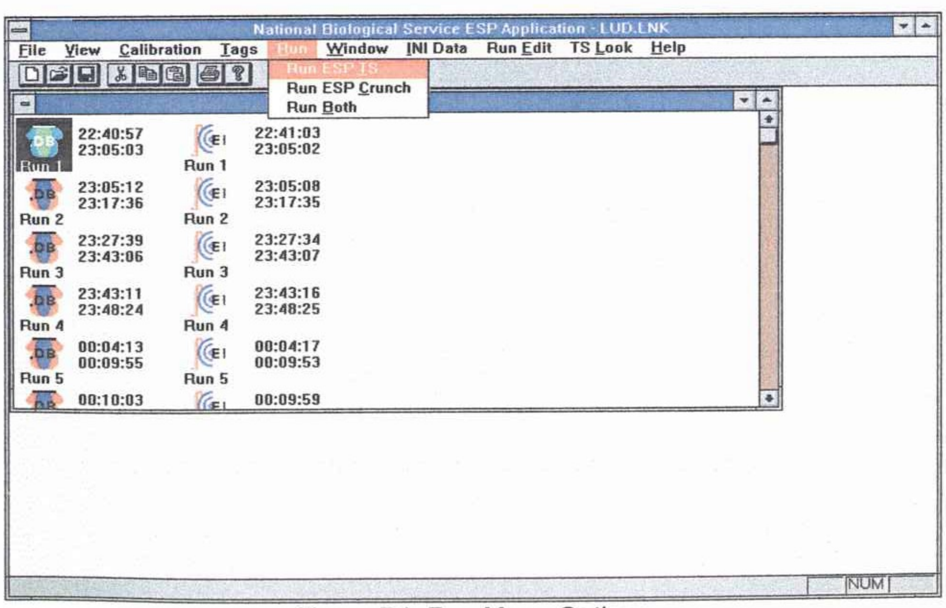


Figure R1: Run Menu Options

RUN ESPTS is the first option. This will run the loaded DB runs through the target strength software. When this option is selected a Run Information dialog box will appear. It tells the user what files it is being worked on and what run is being processed. If the calibration data has not been selected an error dialog box will appear informing the user that no calibration or process data has been loaded. Once the run is complete a Save file selection dialog box will appear, allowing the user to save the processed TS data to a file (Figure R2).

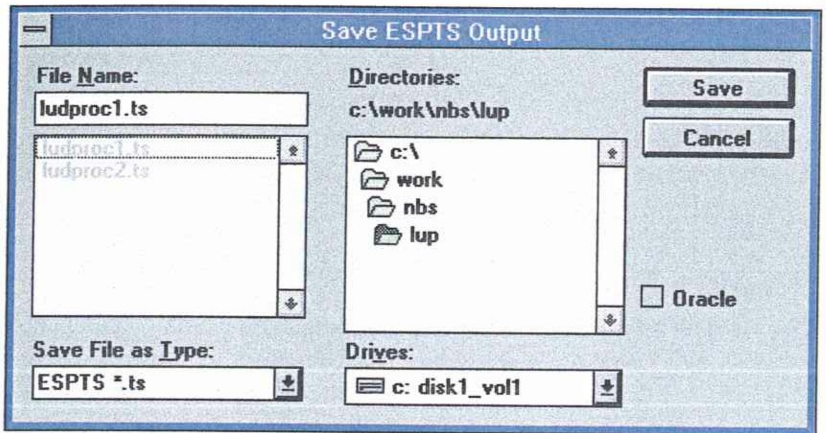


Figure R2: Save ESP TS Output File Dialog Box

The default file extension is .ts. The data is saved to the named file in ASCII format with labels for each column of data. The Oracle check box -- on the lower left of the file dialog box -- is used when data is to be save for use with a relational data base system. With this option checked, the data is output in a form that can easily be imported into Oracle or other data base software. All the Oracle outputs contain calibration and process information at the top of each output file. The Output format of all data files can be found in Appendix B of this document. If the user selects a file name that already exists on the system, a warning box will appear. This box will allow you to go back and select a new file name, if you do not wish to overwrite the selected file.

The next option is the RUN ESP Crunch option. This will take the output from the ESP TS run and the EI data and run them through the Crunch process. Again, the user will see an information box appear. This box will tell the user the names of the files being processed and the run numbers as they are run through Crunch. At the completion of the Crunch process the Save Crunch Output file selection dialog box will appear. (Figure R3) If the Crunch process is run before the TS process only those Crunch functions that do not need TS data will be performed. The output will reflect this by placing zero values in location where data could not be processed.

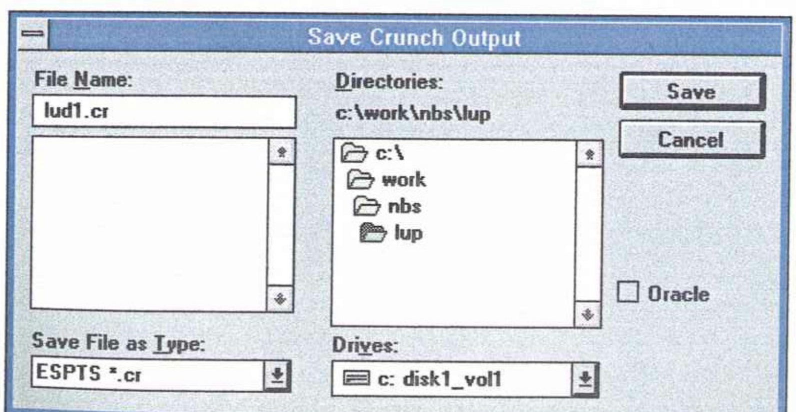


Figure R3: Save Crunch Output File Selection Dialog Box

This Save box is treated in the same manor as the TS save box. The default file extension for the crunch output is .cr. The output is ASCII text with text headers and column sums. As with the TS Save, if the Oracle box is selected, the Crunch output will be written out in a form that is easily imported into an Oracle database. As mentioned above, all the output file formats can be found in Appendix B.

The last option on the Run menu is the RUN BOTH option. This option allows the user to run both the TS and Crunch process automatically. With the RUN BOTH option the user will see the TS information box while the TS process in running and the Crunch information box while the Crunch process is running. After both the TS process and the Crunch process are finished the Save Crunch Output box of Figure 26 is displayed. When the RUN BOTH option is selected the user is not given the option to save the TS data to a file. Crunch output will only be saved for those runs that have both DB and EI data.

THE INI DATA MENU

The INI Data menu items allow the user to utilize the NBS/ESP INI file as a place to store the setup information for each of the BioSonics hardware items they have. Pressing on the INI Data menu will bring up the option for this menu (Figure I1)

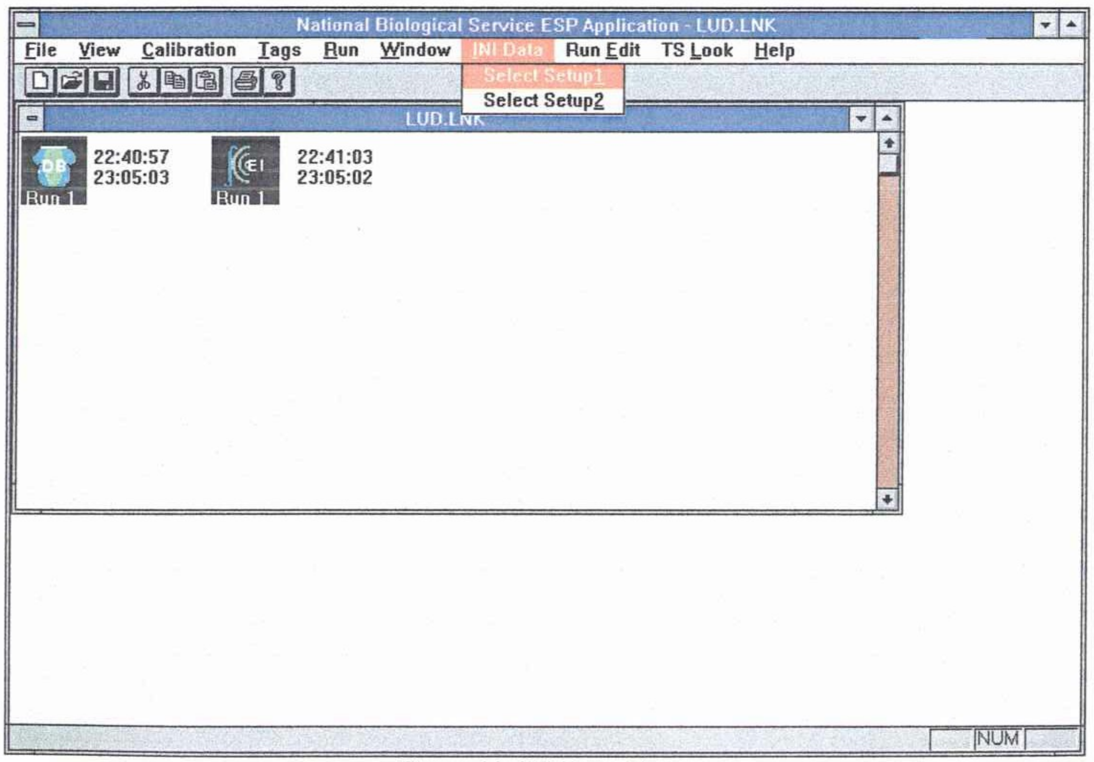


Figure I1: INI Date Menu

The Select Setup1 is for X1 and Select Setup2 is for X2. Pressing one of the two select options will bring up the Select dialog box (Figure I2).

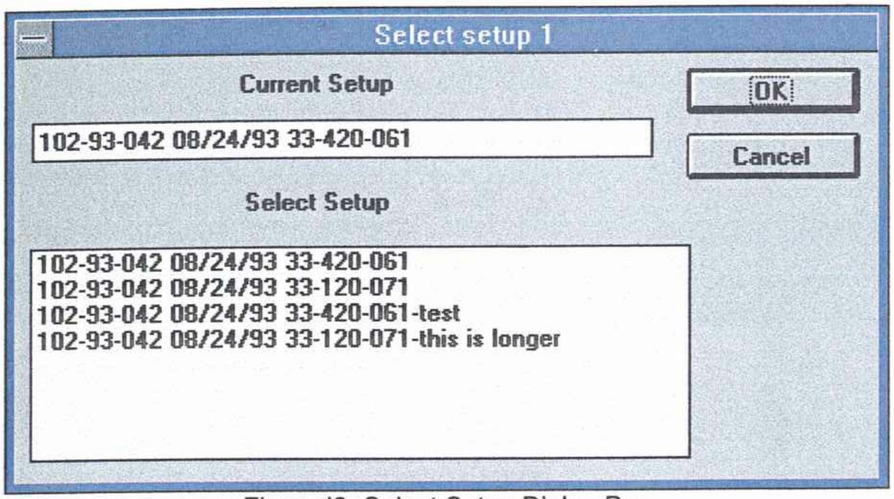


Figure I2: Select Setup Dialog Box

In this box the user will see the currently selected setup information id and in the box below a list of other possible setup selection ids. The user can choose the id that matches the currently loaded data. This will cause the selected setup information stored in the INI file to be load into the NBS/ESP program. The format of the INI file and how to add or modify setup information in it can be found in Appendix C.

If the system you are using is not multiplexing, you can ignore the Select Setup2 option. The data loaded from that option will only be used if X2 data is present.

THE RUN EDIT MENU

This set of options allows the user to graphically manipulate the run list in a DB or EI file. The user can remove bad runs from a list, examine a subset of runs or save a set of runs to a new file name for special processing. Pressing on the Run Edit menu item the user will see the following options (Figure R1).

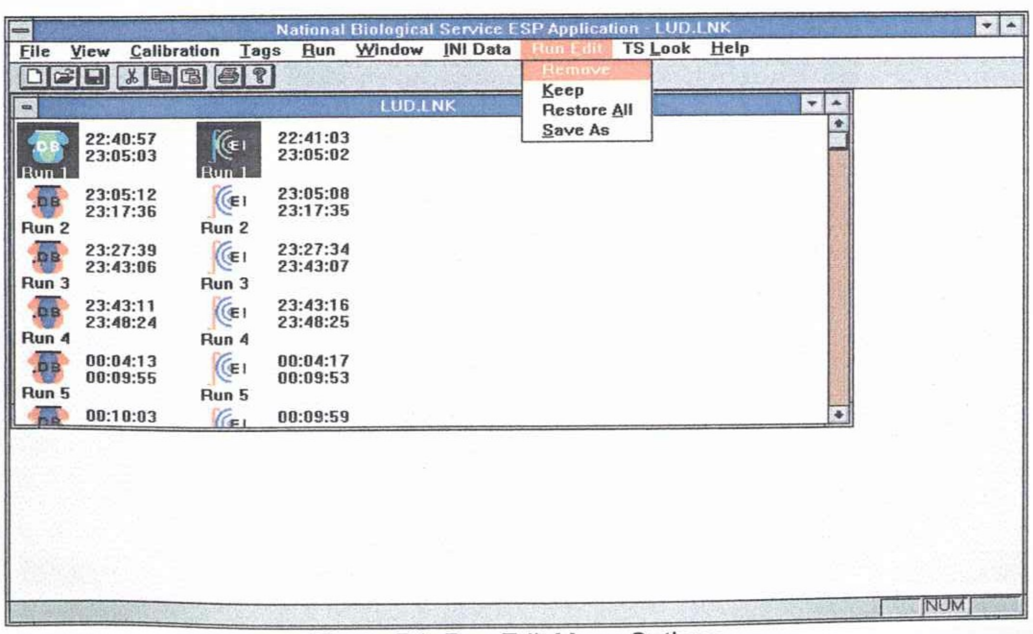


Figure R1: Run Edit Menu Options

The first option on the list is the REMOVE option. The user must select the run that is to be removed by clicking on it. This, as before, will cause the DB or EI icon to reverse colors (Figure R2) once the runs have been selected, click on the REMOVE option and the selected runs will be remove. After the runs have been remove the run list is renumbered so all runs are in consecutive order (Figure R2). This process has not really removed the data from the file. It has only remove the selected runs from being analyzed by the NBS/ESP program.

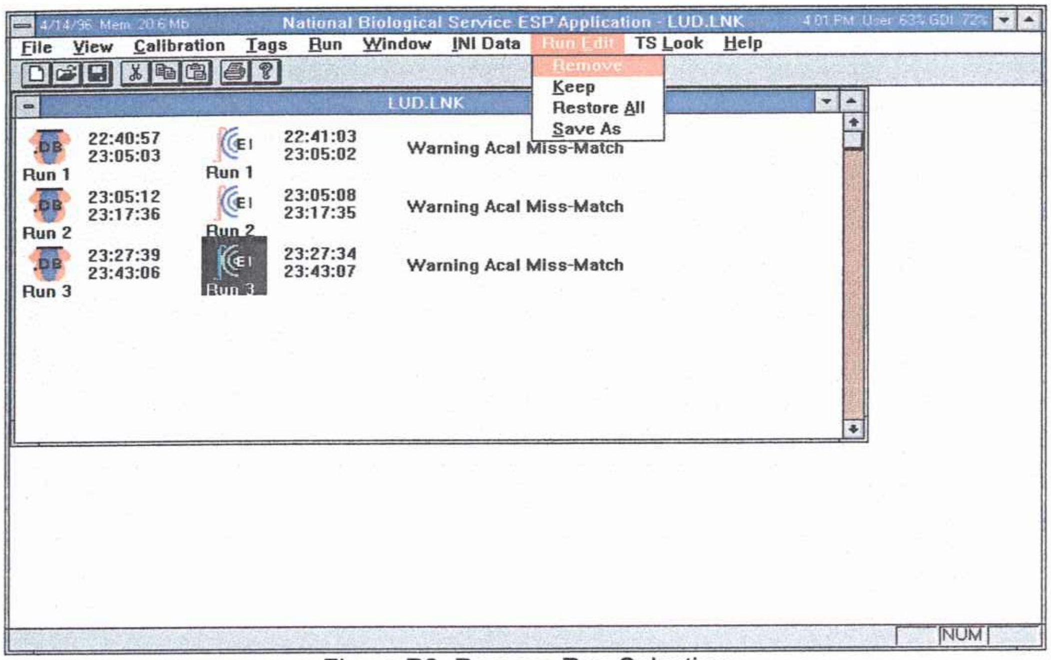


Figure R2: Remove Run Selection

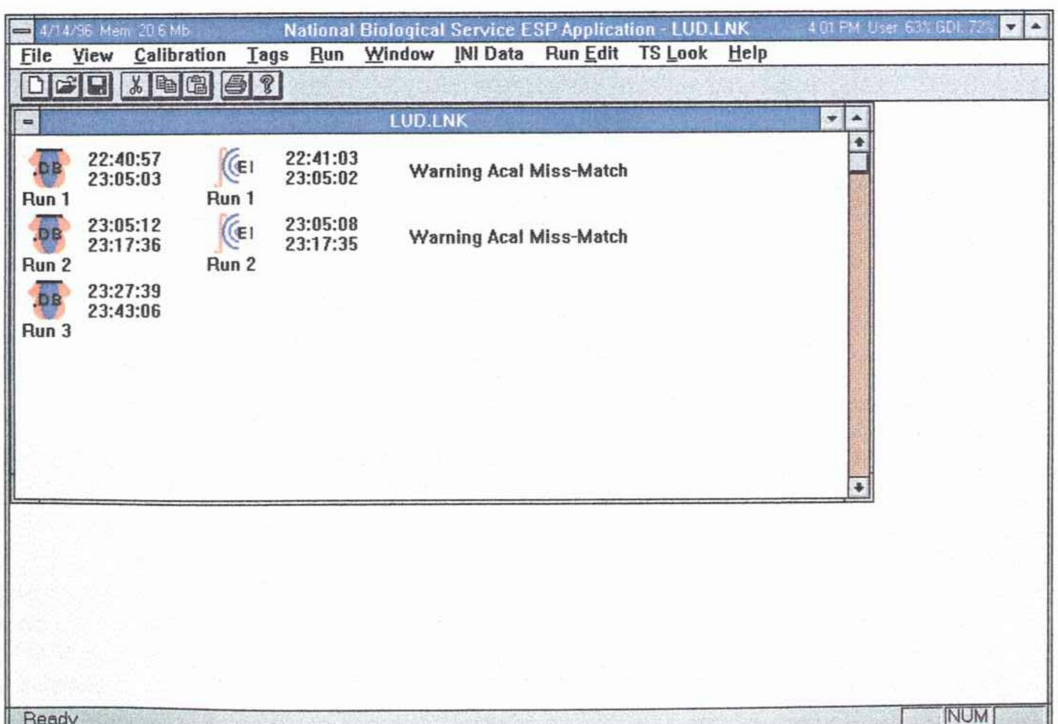


Figure R3: Echo Data Display After the EI Run is Remove

The KEEP option is used when you want to keep the selected runs and remove all run that are not selected. This option is much easier than the REMOVE option, when you want to analyze only one or two runs from a complete DB or EI file. With the KEEP option you select the runs that you wish to keep and then press the KEEP menu option. (Figure R4)

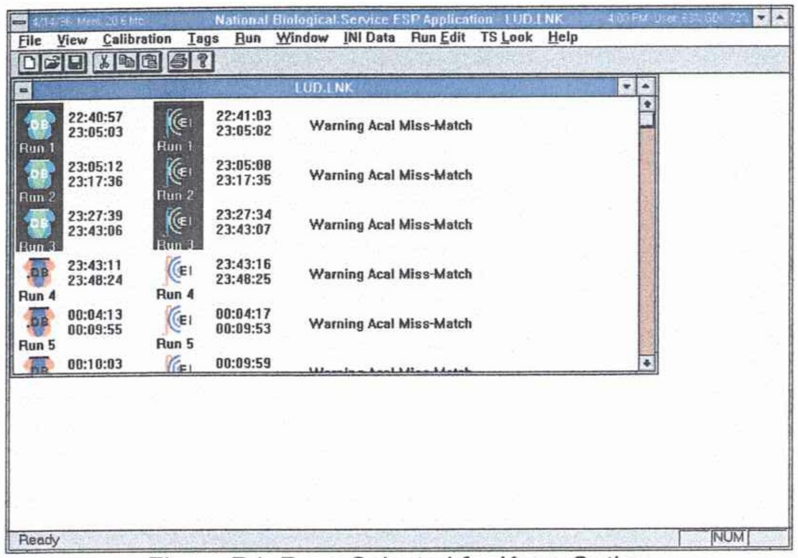


Figure R4: Runs Selected for Keep Option

The NBS/ESP program will remove from the Echo Display all the files not selected and renumber the runs so they are in consecutive order (Figure R5).

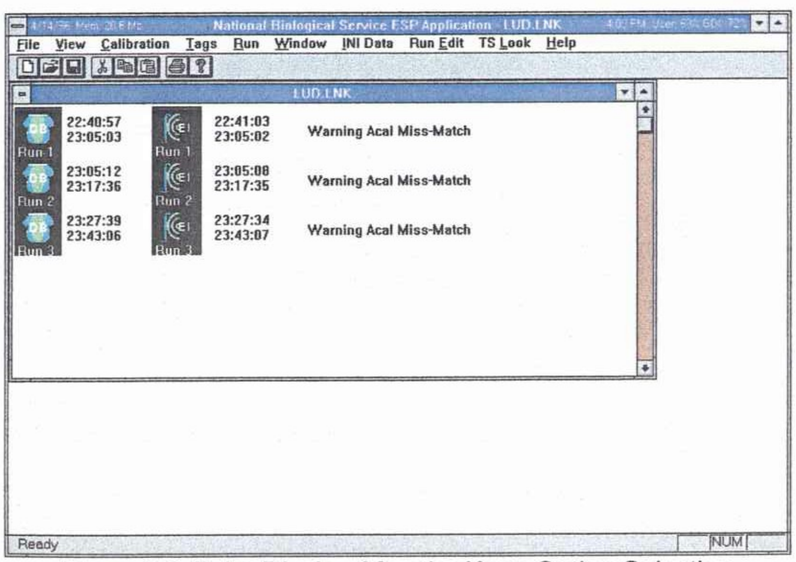


Figure R5: Echo Display After the Keep Option Selection

Once again, the data was NOT removed from the data file. The removed runs are only flagged as removed and thus not used in any of the analysis that will occur from this point forward. Because the data has not really been removed it can be easily be restored with the RESTORE ALL option. This option will remove the flag from all the missing data and return all the run icons to the Echo Display window (Figure R6).

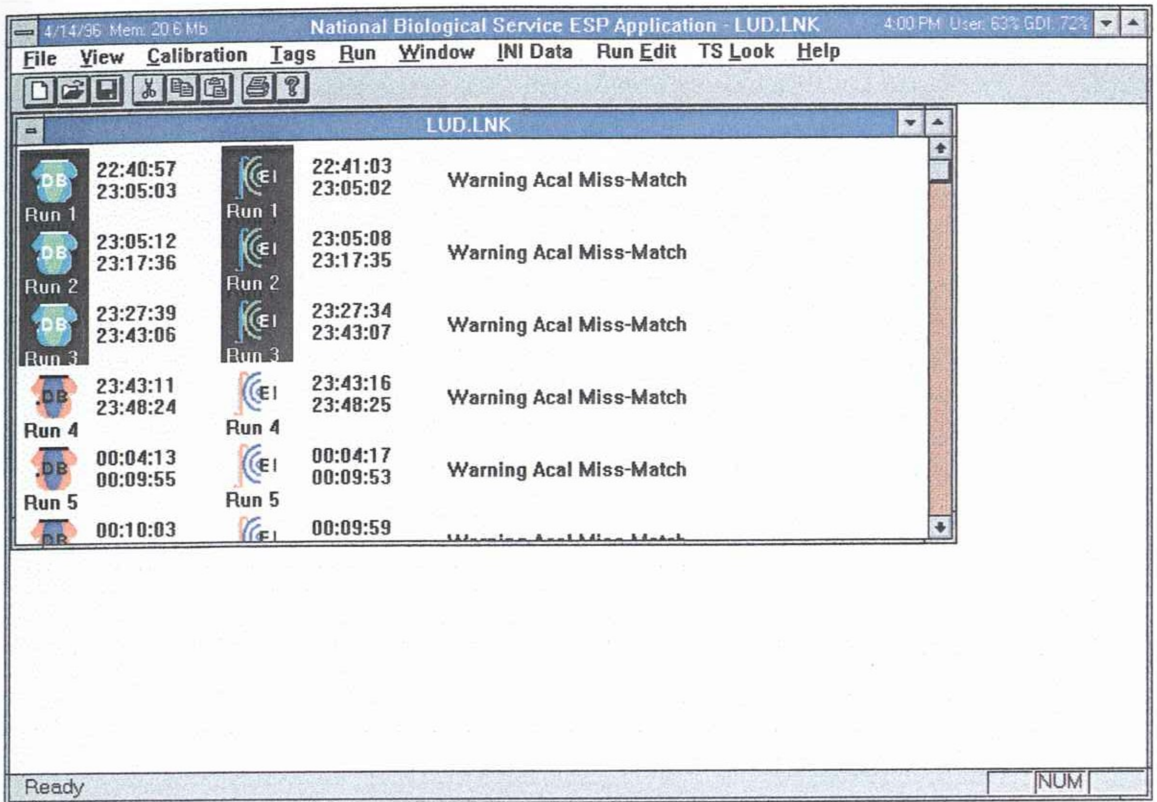


Figure R6: Echo Display After Restore All Option

The last option on the RUN EDIT menu is the SAVE AS option. This option will allow the user to save only those runs that appear in the Echo Display window to a new file name. When the SAVE AS option is selected, a file dialog box for both the DB and EI files will appear (Figure R7).

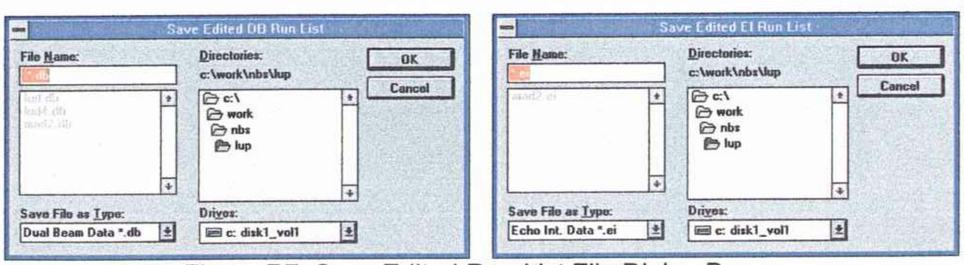


Figure R7: Save Edited Run List File Dialog Boxes

As with the above save functions, a warning dialog box will appear if the file name the user has selected already exists on the system. This dialog box will give you the option to return to the file selection box or over write the file on the system. Once the new run data has been saved it can now used in future NBS/ESP runs. The NBS/ESP program does not automatically load the new saved files. This means that the data for all the runs is still in the NBS/ESP program. To use the new files that were just created the user must go back to the FILES menu and load the new files with the NEW option.

THE HELP MENU

The current help menu contains only one option (Figure H1).

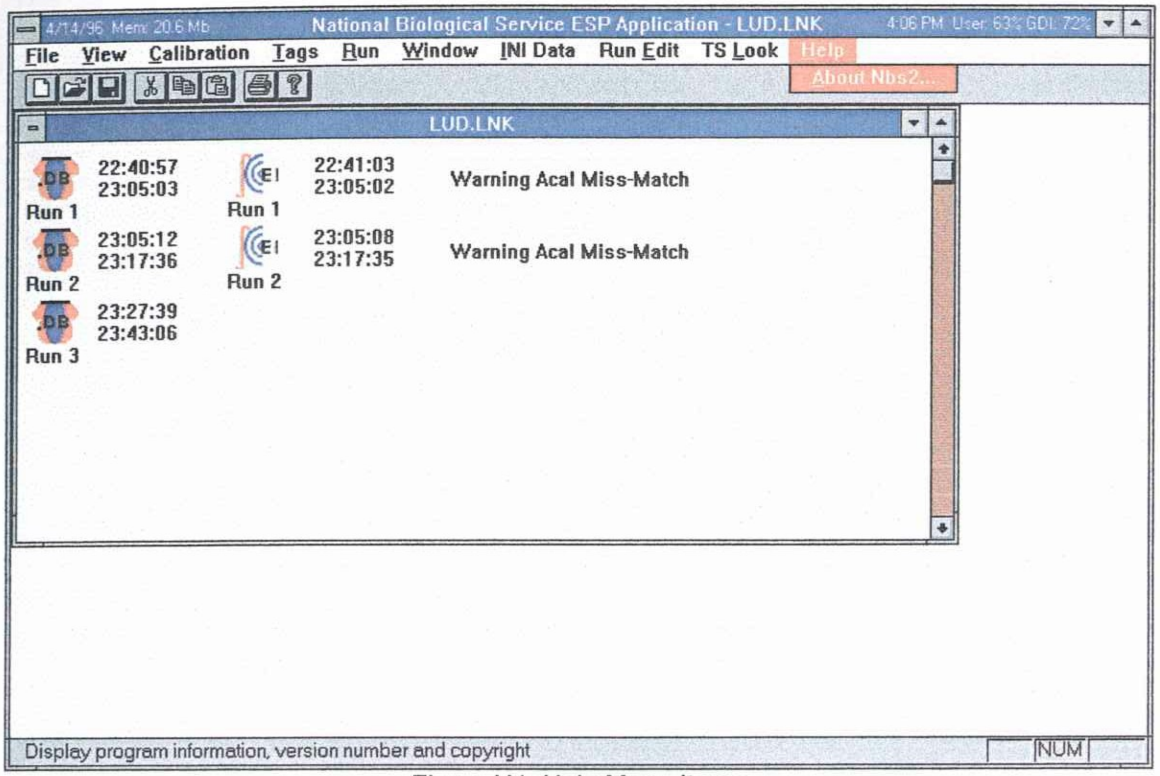


Figure H1: Help Menu Items

Selecting the About NBS2 option will display the Program information box (Figure H2).

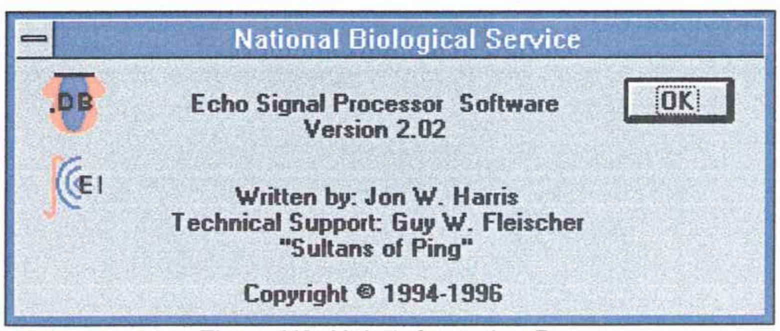


Figure H2: Help Information Box

It is the intent of the authors that the help menu will soon contain a hypertext copy of this document and its appendices.

APPENDIX A: NBS/ESP INSTALLATION

The NBS/ESP distribution comes in a self extracting archive on a single 3.5" diskette. This diskette contains the archive, NBS.EXE and the text that forms this Appendix as a plain text file called READ.ME.

The first step is to create a directory and copy the NBS archive onto it. This can be done with the File Manger. Once copied, the user is ready to execute the archive. This is done by selecting the File Menu on the Program Manager window and then selecting the run option. The user will be prompted to enter a file to run. (Figure AX1) The user should type something like C:/NBS/NBS.EXE. The archive will execute and unpack itself. The current version of the archive contains the NBS/ESP program as NBS2.EXE and an example INI file as NBS2.INI. When the help documents are complete they will also be included in this archive.

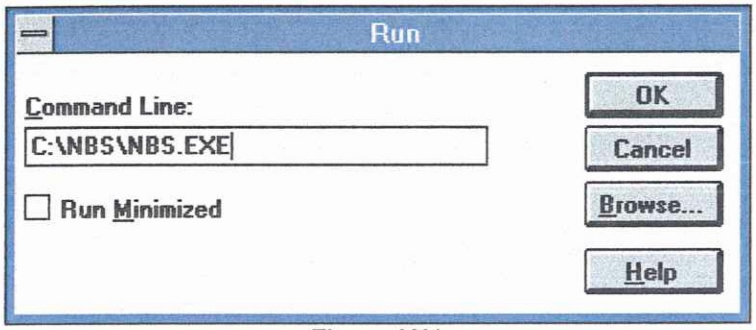


Figure AX1

The user should now copy the NBS2.INI file to their WINDOWS directory. Details of needed steps to set up the INI file with the user's data is described later in this section. The users should make the needed changes to the INI file before running the NBS2.EXE program. The example file will allow the NBS2 program to run without error, but will not contain the correct setup information for your hardware.

For Windows 3.x, the final step in the installation is to create the NBS program group and place the NBS icon into the NBS program group box. This is done by selecting the File Menu on the Program Manager. Now, click on the new option. A New Program Object window will appear (Figure AX2).

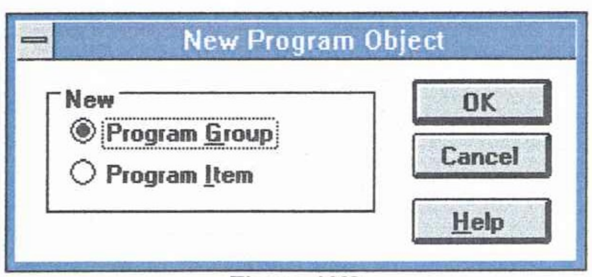


Figure AX2

Select the Program Group item and press OK. Another box called the Program Group Properties box will appear (Figure AX3).

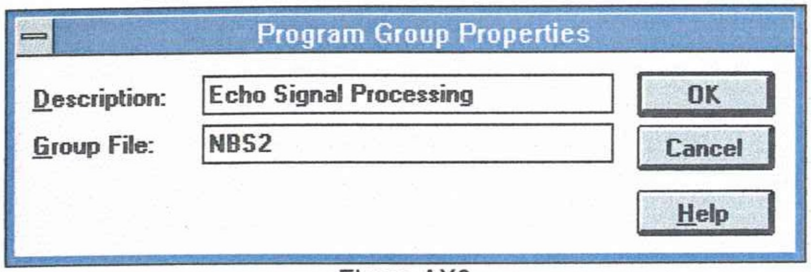


Figure AX3

Enter Echo Signal Processing in the Description text box and NBS2 in the Group File box. Press the OK button. This will create a new program group box (Figure AX4).

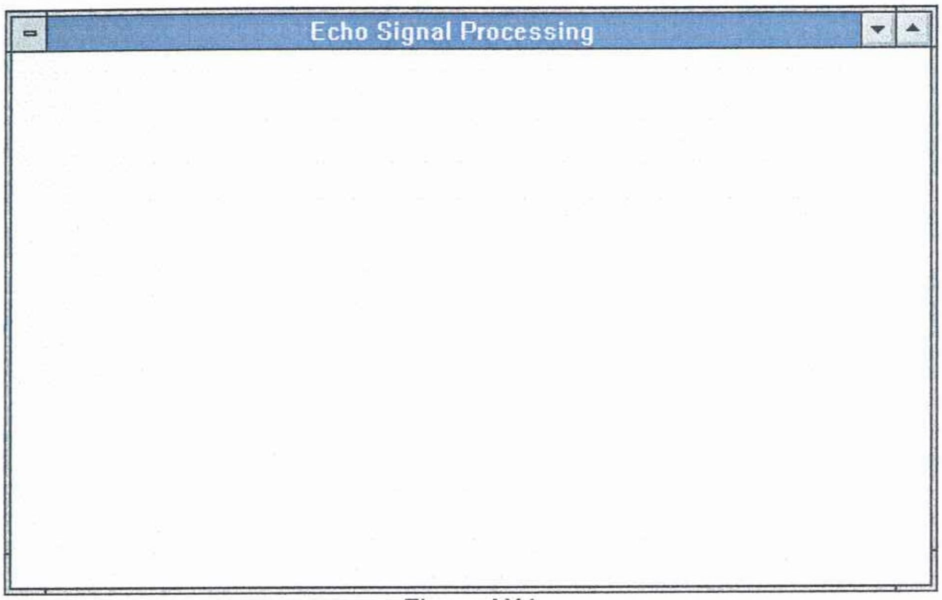


Figure AX4

We now return the File menu and the New option. This time we select the Program Item and press OK (Figure AX5).

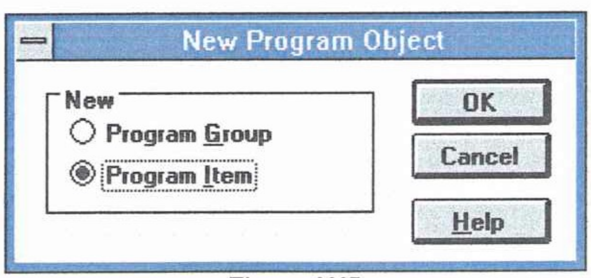


Figure AX5

This will bring up the Program Item Properties box (Figure AX6).

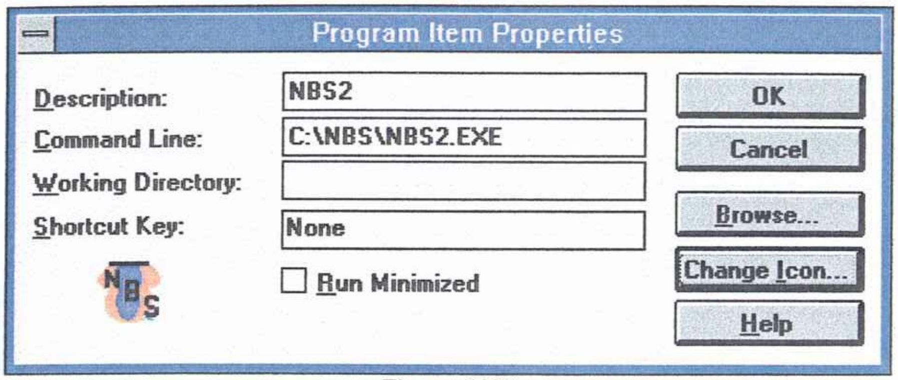


Figure AX6

In the Description text box, enter NBS2. Next, we hit the Browse button. This will bring up a file selection box. Point to C:\NBS\NBS2 and click OK. This will fill in the Command Line text box. Finally, we push the Change Icon button and select the NBS Icon (Figure AX7).

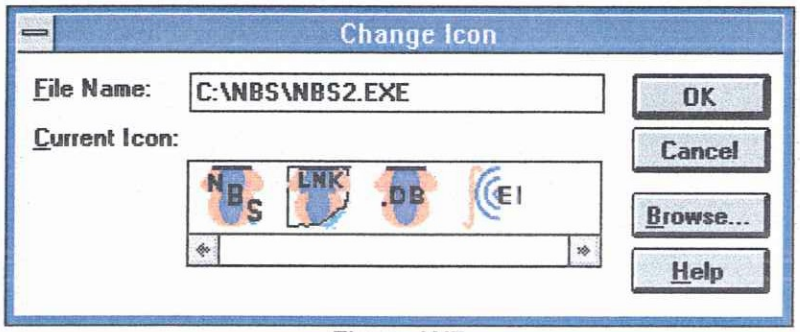


Figure AX7

This will load the NBS icon. A quick press on the OK button and we are done with the installation (Figure AX8).

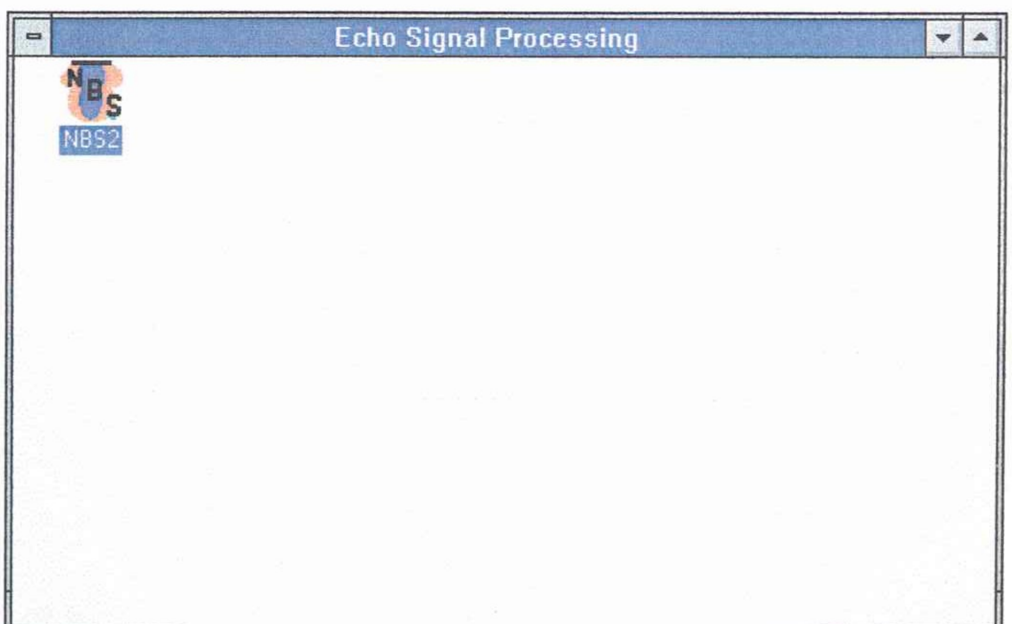


Figure AX8

INI FILE

The INI file for the NBS/ESP program contains standard program initialization data and hardware calibration data. *These calibration data are entered by the user.* The following discussion will provide the user with all the information needed to enter their hardware calibration data.

First let us look at an example INI file. This example demonstrates the ability of NBS/ESP to accommodate several different hardware and calibration setups.

```
[Recent File List]
File1=D:\ESP_V30\UNIT1\CAMS93G1\LUD3.LNK
File2=D:\ESP_V30\VOYAGEUR\BLOCK6\6E.LNK
File3=D:\ESP_V30\VOYAGEUR\BLOCK6\6D.LNK
File4=D:\ESP_V30\VOYAGEUR\BLOCK6\6C.LNK

[Settings]
PreviewPages=2

[Lastsetup]
setup1=Unit 1 33-120-718-025
setup2=Unit 1 33-420-0615-074

[number of setups]
rem this number must match actual listed setups
num=10

[setup names]
rem Unit 2
setup1=Unit 2 33-420-061
setup2=Unit 2 33-120-071
rem
rem Unit 1
setup3=Unit 1 33-120-718-025
setup4=Unit 1 33-420-0615-074
rem Unit 1 original calibration
setup5=Unit 1 orig 33-120-718-025
setup6=Unit 1 orig 33-420-0615-074
rem
rem Clif Schneider
setup7=ES200-92-014 08/26/93 32-420-0615-076
rem
rem Unit 0 - 1995 calibration
setup8=Unit 0 - 1995 calibration
rem Unit 0 1991 Calibration
setup9=Unit 0 - 1991 calibration
rem
rem Unit Leased in 1987
setup10=Lease Unit - 1987

[Unit 2 33-420-061]
nser=102-93-042
caldat=08/24/93
tfre=420
alpha=0.0
recran=1.0
tser=33-420-061
cable=38.0
nbeam1=6.0
nbeam2=0.0
wbeam1=15.0
wbeam2=0.0
A=1.7856
bb=0.4768
bsqn=0.001001
bsqc=0.001768


[Unit 2 33-120-071]
nser=102-93-042
caldat=08/24/93
tfre=120
```

```
alpha=0.0
recran=1.0
tser=33-120-071
cable=38.0
nbeam1=7.0
nbeam2=0.0
wbeam1=18.0
wbeam2=0.0
A=1.868
bb=0.454
bsqn=0.001049
bsqc=0.002047

[Unit 1 33-120-718-025]
nser=102-86-007
caldat=06/26/94
tfre=120
alpha=0.0
recran=1.0
tser=33-120-718-025
cable=15.24
nbeam1=7.0
nbeam2=0.0
wbeam1=18.0
wbeam2=0.0
A=1.7423
bb=0.5683
bsqn=0.0011346
bsqc=0.001953


[Unit 1 33-420-0615-074]
nser=102-86-007
caldat=06/26/94
tfre=420
alpha=0.0
recran=1.0
tser=33-420-0615-074
cable=15.24
nbeam1=6.0
nbeam2=0.0
wbeam1=15.0
wbeam2=0.0
A=1.6509
bb=0.5410
bsqn=0.0009759
bsqc=0.0015861

[Unit 1 orig 33-120-718-025]
nser=102-86-007
caldat=07/07/92
tfre=120
alpha=0.0
recran=1.0
tser=33-120-718-025
cable=15.24
nbeam1=7.0
nbeam2=0.0
wbeam1=18.0
wbeam2=0.0
A=1.150408
bb=0.648738
bsqn=0.001026
bsqc=0.001920

[Unit 1 orig 33-420-0615-074]
nser=102-86-007
caldat=07/07/92
tfre=420
alpha=0.0
recran=1.0
tser=33-420-0615-074
cable=15.24
nbeam1=6.0
nbeam2=0.0
wbeam1=15.0
```

```
wbeam2=0.0
A=1.324785
bb=0.589037
bsqn=0.001636
bsqc=0.002410

[ES200-92-014 08/26/93 32-420-0615-076]
nser=ES200-92-014
caldat=08/26/93
tfre=420
alpha=0.0
recran=1.0
tser=32-420-0615-076
cable=38.0
nbeam1=6.0
nbeam2=0.0
wbeam1=15.0
wbeam2=0.0
A=1.9828
bb=0.48050
bsqn=0.001211
bsqc=0.001840

[Unit 0 - 1995 calibration]
nser=101-85-057
caldat=10/26/95
tfre=120
alpha=0.0
recran=1.0
tser=19-120-1025-008
cable=17.0
nbeam1=10.0
nbeam2=0.0
wbeam1=25.0
wbeam2=0.0
A=2.8259
bb=0.5044
bsqn=0.00259178
bsqc=0.0041793

[Unit 0 - 1991 calibration]
nser=101-85-057
caldat=04/23/91
tfre=120
alpha=0.0
recran=1.0
tser=19-120-1025-008
cable=34.0
nbeam1=10.0
nbeam2=0.0
wbeam1=25.0
wbeam2=0.0
A=1.4091
bb=0.8402
bsqn=0.002402
bsqc=0.004009

[Lease Unit - 1987]
nser=102-86-008
caldat=08/20/87
tfre=120
alpha=0.0
recran=1.0
tser=10-120-102
cable=15.24
nbeam1=10.0
nbeam2=0.0
wbeam1=25.0
wbeam2=0.0
A=2.583
bb=0.493
bsqn=0.002167
bsqc=0.003147
```

```
[TSProc X1 Defaults]
hc=-45.0
bpf=5.0
mha=3.0


[TSProc X2 Defaults]
hc=-45.0
bpf=5.0
mha=3.0


[CRProc X1 Defaults]
area=10000

[CRProc X2 Defaults]
area=10000
```

The first thing we will look at is the title headings. Title headings are those text items that are in square brackets []. For example the first title heading in the NBS2.INI file is

[Resent File List]

The data below this header is a list of the last four files used. Each entry in this list starts with a name. In the case of the Recent File List the names are File1, File2, File3, and File4. This entry name is followed by an equal sign followed by the data for each entry name.

The user can edit the Recent File List. The user can enter a set of paths and file names that will appear when the program starts. This is not normally done because each time the program is run this list is up-dated with the last files used. So changes under this heading are not permit. One this that is commonly done is to delete the paths and file names. This is done to clear the last files used so they will not show up the next time the program is used.

The next title heading is an internal variable to the NBS/ESP program and should not be edited. It is the [Settings] title.

With the next title heading we start to look at the hardware calibration data. This next title is the [Lastsetup] heading. This should contain two data line's setup1 and setup2. These relate to the X1 and X2 setup names found on the INI menu item in the NBS/ESP program. Once the user has completed all his setups below these two data fields can be filled in with names of the two calibrations that are to be used at start up time. Like the Recent File List, these two lines are updated when the user changes the INI setup with the INI menu item. So any setups' names entered will not be permanent.

We now get to the setup data itself. The [number of setups] item has one data line that contains the number of setup that follow. This number must match the number of setup that are to be found in the INI file. A number in this line that is less than the number entered will limit the user to only some of the setups entered. A number larger than the true number of setups entered will cause the program to fail.

It is now time to enter the names of the setups. This is done under the [setup names] header. There should be one name for each setup called out in the number of setup's header. The name itself can be anything that the user wishes. In the example we have used the serial number of the hardware and the date of calibration. This line can not be more than 80 characters long.

Once the user has named each setup file, we must enter the data for each setup. This starts with a title header that is the same as the name given in the pervious step, as example [Unit 2 33-420-061]. The data entered below are the calibration data for that hardware set.

nser	= Serial Number of the Transmitter
caldat	= Date of this Calibration Data
tfre	= System Operating Frequency
alpha	= Absorption Coefficient at Cal (dB/km)
recran	= Calibration Receiver Range
tser	= Transducer Serial number
cable	= Cable Length
nbeam1	= Narrow Beam Width
nbeam2	= (leave blank)
wbeam1	= Wide Beam Width
wbeam2	= (leave blank)
A	= A Coefficient for Power Equation
bb	= B Coefficient for Power Equation
bsqn	= Average Squared Narrow Beam Pattern Factor
bsqc	= Average Squared Composite Beam Pattern Factor

This same data are entered for each setup as can be seen in the example file.

The next items are so the user can setup their own defaults for these items. First is the [TSProc X1 defaults] and the [TSProc X2 defaults]:

hc	= Histogram Center About What TS Value
bfp	= Beam Pattern Factor > Zero Threshold in dB
mha	= Maximum Half Angle for Processing Targets

The Last item in the INI file is the [CRProc X1 Defaults] and [CRProc X2 Defaults]:

area	= Surface Area in Meters Squared.

APPENDIX B: FILE FORMATS

LINK FILE FORMAT

The default file extension for the link file is .LNK. This file is created by the NBS/ESP program as a stream output file. It should NOT be edited by the user because it is a stream output file. The link file contains the path and name for a DB and EI file set. An example of the link file is below.

```
□C:\WORK\NBS\LUP\LUD.DB□C:\WORK\NBS\LUP\LUD.DAT□
```

CALIBRATION FILE FORMAT

The default file extension for the calibration file is CAL. This file is a standard ASCII output file. The user can edit this file.

Line 1. Hardware calibration date
Line 2. Echo Sounder Serial #
Line 3. System Operating Freq.
Line 4. TVG Startup Range
Line 5. Absorption Coefficient at Cal (dB/km)
Line 6. Calibration Receiver Range
Line 7. Receiver Sensitivity at 1 Meter Channel 1, 40logR
Line 8. Receiver Sensitivity at 1 Meter Channel 1, 20logR
Line 9. Receiver Sensitivity at 1 Meter Simultaneous, 20logR
Line 10. Receiver Sensitivity at 1 Meter Channel 2, 40logR
Line 11. Receiver Sensitivity at 1 Meter Channel 2, 20logR
Line 12. Source Level at 0 Transmit Power Setting
Line 13. Source Level at -3 Transmit Power Setting
Line 14. Source Level at -6 Transmit Power Setting
Line 15. Source Level at -10 Transmit Power Setting
Line 16. Source Level at -13 Transmit Power Setting
Line 17. Cable Length
Line 18. Transducer Serial Number
Line 19. Transducer Type
Line 20. Narrow Beam Widths, or Long Axis of Narrow Ellipse
Line 21. Short Axis of Wide Beam Ellipse
Line 22. Wide Beam Drop-off in dB
Line 23. A Coefficient for Power Equation
Line 24. B Coefficient for Power Equation
Line 25. Average Squared Narrow Beam Pattern Factor
Line 26. Average Squared Composite Beam Pattern Factor

TS PROCESS FILE FORMAT

The default file extension for the TS Process file is TSP. This file is a standard ASCII output file. The user can edit this file.

Line 1. Narrow Beam Channel Number
Line 2. Narrow Beam Correction Multiplier
Line 3. Wide Beam Correction Multiplier
Line 4. Narrow Beam Threshold in V
Line 5. Wide Beam Threshold in V

Line 6. Minimum Depth in Meters
Line 7. Maximum Depth in Meters
Line 8. Bottom Threshold in mV
Line 9. Minimum -6 dB Pulse Width in msec
Line 10. Maximum -6 dB Pulse Width in msec
Line 11. Minimum -12 dB Pulse Width in msec
Line 12. Maximum -12 dB Pulse Width in msec
Line 13. Minimum -18 dB Pulse Width in msec
Line 14. Maximum -18 dB Pulse Width in msec
Line 15. Receiver Gain Use to Collect Data
Line 16. Transmit Power Used to Collect Data
Line 17. Maximum Half Angle for Processing Targets
Line 18. Histogram Center About What TS Value
Line 19. Beam Pattern Factor > Zero Threshold in dB
Line 20. dB Pulse width Filter Flag (0,1,2)
Line 21. dB Pulse width Filter Flag (0,1,2)
Line 22. dB Pulse width Filter Flag (0,1,2)
Line 23. Multiplex Flag 0-Off 1-On

CRUNCH PROCESS FILE FORMAT

The default file extension for the CRUNCH Process file is .CRP. This file is a standard ASCII output file. The user can edit this file.

Line 1. Surface Area in Meters Squared
Line 2. Pulse Width in Milliseconds
Line 3. Velocity of Sound, Meters/Second
Line 4. Squared Beam Pattern Factor
Line 5. Source Level in dB
Line 6. Selected Receiving Sensitivity
Line 7. Receiver Gain at Data Collection

ESPTS OUTPUT FILE FORMAT

The default file extension for the ESPTS output file is .TS. This file is a standard ASCII output file. This file contains the results of the ESPTS process.

Line 1. Path and File Name of Data Processed
Line 2. Label for Each Run
Line 3. Column Labels
Line 4. Data

These data are backscattering at meter depth intervals. At the start of the next run the line format will start over at line2.

ESPTS ORACLE OUTPUT FILE FORMAT

The default file extension for the ESPTS output file is .TS. This file is a standard ASCII output file. This file contains the results of the ESPTS process.

I. Calibration and Process Data Used in TS Process
   A. A Zero to indicate calibration data
   B. Run Number

C. Primary or Secondary Strata (Not user in TS Processing)
D. Channel Number
E. Narrow Beam Threshold in V
F. Wide Beam Threshold in V
G. Minimum Depth to Process in Meters
H. Maximum Depth to Process in Meters
I. Bottom Threshold in mV
J. dB Pulse Width Filter Flag
K. Minimum -6 dB Pulse Width in msec
L. Maximum -6 dB Pulse Width in msec
M. dB Pulse Width Filter Flag
N. Minimum -12 dB Pulse Width in msec
O. Maximum -12 dB Pulse Width in msec
P. dB Pulse Width Filter Flag
Q. Minimum -18 dB Pulse Width in msec
R. Maximum -18 dB Pulse Width in msec
S. Receiver Gain Use to Collect Data
T. Transmit Power Used to Collect Data
U. Maximum Half Angle for Processing Targets
V. Histogram Center About What TS Value
W. Beam Pattern Factor > Zero Threshold in dB
X. Wide Beam Drop-off in dB
Y. A Coefficient for Power Equation
Z. B Coefficient for Power Equation

II. TS Data
A. Run Number
B. Depth in Meters
C. SigmaX1
D. SigmaX1^2
E. countX1
F. SigmaX2
G. SigmaX2^2
H. countX2

Line 1 is repeated for each run. Line 2 is repeated for all depth strata and for all runs.

CRUNCH OUTPUT FILE FORMAT

The default file extension for the CRUNCH output file is .CR. This file is a standard ASCII output file. This file contains the results of the CRUNCH process.

Line 1. Path and File Name of EI Input File
Line 2. Path and File Name of DB Input File
Line 3. Run Label
Line 4. Column Headers
Line 5. Column Headers (cont.)
Line 6. Crunch Output Data

CRUNCH ORACLE OUTPUT FILE FORMAT

The default file extension for the CRUNCH output file is .CR. This file is a standard ASCII output file. This file contains the results of the CRUNCH process.

I. Calibration and Process Data Used in CR Process
   A. A Zero to indicate calibration data
   B. Run Number
   C. Primary or Secondary Strata
   D. Channel Number
   E. Narrow Beam Threshold in V
   F. Wide Beam Threshold in V
   G. Minimum Depth to Process in Meters
   H. Maximum Depth to Process in Meters
   I. Bottom Threshold in mV
   J. dB Pulse Width Filter Flag
   K. Minimum -6 dB Pulse Width in msec
   L. Maximum -6 dB Pulse Width in msec
   M. dB Pulse Width Filter Flag
   N. Minimum -12 dB Pulse Width in msec
   O. Maximum -12 dB Pulse Width in msec
   P. dB Pulse Width Filter Flag
   Q. Minimum -18 dB Pulse Width in msec
   R. Maximum -18 dB Pulse Width in msec
   S. Receiver Gain Use to Collect Data
   T. Transmit Power Used to Collect Data
   U. Maximum Half Angle for Processing Targets
   V. Histogram Center About What TS Value
   W. Beam Pattern Factor > Zero Threshold in dB
   X. Wide Beam Drop-off in dB
   Y. A Coefficient for Power Equation
   Z. B Coefficient for Power Equation
   AA. Surface Area in Meters Squared
   BB. Pulse Width in Milliseconds
   CC. Velocity of Sound. Meters/Second
   DD. Squared Beam Pattern Factor
   EE. Source Level in dB
   FF. Selected Receiver Sensitivity
   GG. Receiver Gain at Data Collection

II. CRUNCH DATA
   A. Run Number
   B. Channel Number
   C. Primary Secondary Stratum ID (1 Primary 2 Secondary)
   D. Stratum Depth Top
   E. Stratum Depth Bottom
   F. Stratum Volume

G. Mean Sigma
H. Number of Fish Used
I. Standard Deviation Sigma
J. Constant A
K. Integrator Output
L. Number of Sequence
M. Var. of Integration Mean
N. Density of Fish
O. Quantity Numbers
P. Fish Quantity Variance
Q. Confidence Limit (95%)

Line 1 is repeated for each run. Line 2 is repeated for all depth stata and for all runs.

TS LOOK OUTPUT FILE FORMAT

The default file extension for the TS LOOK output file is .TSL. This file is a standard ASCII output file. This file contains the results of the TS LOOK process.

Line 1. Path and File Name of DB Input File
Line 2. Run Label
Line 3. Stratum Depth Label
Line 4. TS Strength Histogram Header
Line 5. TS Strength Histogram Labels
Line 6. TS Strength Histogram Data
Line 7. Histogram of Beam Pattern Factors > dB label
Line 8. 0 to 1 dB
Line 9. 1 to 2 dB
Line 10. 2 to 3 dB
Line 11. 3 to 4 dB
Line 12. 4 to 5 dB
Line 13. Total Number of Recorded Echoes
Line 14. Number of Echoes Used for Statistics
Line 15. Average Back Scatter Cross Section
Line 16. Back Scatter Cross Section STD Dev
Line 17. Average Target Strength in dB
Line 18. Target Strength STD Dev in dB
Line 19. Number of Echoes with BP > 0 dB
Line 20. All Echoes Label
Line 21. Full Angle of Cone
Line 22. Estimated Volume in Cubic Meters
Line 23. Density in Fish per Cubic Meters
Line 24. Equivalent Stratum Length (%/100)
Line 25. Accepted Echoes Only Label
Line 26. Full Angle of Cone
Line 27. Estimated Volume in Cubic Meters
Line 28. Density in Fish per Cubic Meters
Line 29. Equivalent Stratum Length (%/100)

TS LOOK ORACLE OUTPUT FILE FORMAT

The default file extension for the TS LOOK output file is .TSL. This file is a standard ASCII output file. This file contains the results of the TS LOOK process.

I. Calibration and Process Data Used in TS Process
   A. A Zero to indicate calibration data
   B. Run Number
   C. Primary or Secondary Strata (Not user in TS Processing)
   D. Channel Number
   E. Narrow Beam Threshold in V
   F. Wide Beam Threshold in V
   G. Minimum Depth to Process in Meters
   H. Maximum Depth to Process in Meters
   I. Bottom Threshold in mV
   J. dB Pulse Width Filter Flag
   K. Minimum -6 dB Pulse Width in msec
   L. Maximum -6 dB Pulse Width in msec
   M. dB Pulse Width Filter Flag
   N. Minimum -12 dB Pulse Width in msec
   O. Maximum -12 dB Pulse Width in msec
   P. dB Pulse Width Filter Flag
   Q. Minimum -18 dB Pulse Width in msec
   R. Maximum -18 dB Pulse Width in msec
   S. Receiver Gain Use to Collect Data
   T. Transmit Power Used to Collect Data
   U. Maximum Half Angle for Processing Targets
   V. Histogram Center About What TS Value
   W. Beam Pattern Factor > Zero Threshold in dB
   X. Wide Beam Drop-off in dB
   Y. A Coefficient for Power Equation
   Z. B Coefficient for Power Equation

II. TS Look Data
   A. Run Number
   B. Channel Number
   C. Top Stratum Depth
   D. Bottom Stratum Depth
   E. Total Number of Recorded Echoes
   F. Number of Echoes Used for Statistics
   G. Average Back Scatter Cross Section
   H. Average Back Scatter Cross Section in dB
   I. Back Scatter Cross Section STD Dev
   J. Average Target Strength in dB
   K. Target Strength STD Dev in dB
   L. Number of Echoes with BP > 0 dB
   M. All Echoes Full Angle of Cone
   N. All Echoes Estimated Volume in Cubic Meters
   O. All Echoes Density in Fish per Cubic Meters
   P. All Echoes Equivalent Stratum Length (%/100)
   Q. Accepted Echoes Only Full Angle of Cone
   R. Accepted Echoes Only Estimated Volume in Cubic Meters
   S. Accepted Echoes Only Density in Fish per Cubic Meters
   T. Accepted Echoes Only Equivalent Stratum Length (%/100)