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APPLICATIONS OF HYDROACOUSTICS IN MARINE ECOLOGICAL STUDIES: A PERSPECTIVE ON THE PRESENT STATUS AND FUTURE DIRECTIONS

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Abstract: Marine ecological studies of zooplankton and fish can greatly benefit from the application of hydroacoustic measurements. These measurements can be accomplished using off-the-shelf hardware and software. Hydroacoustic sampling equipment is widely available utilizing various methods, for example, single beam, dual beam, and split beam systems. Each method has attendant limitations and advantages in terms of the kinds of information produced and the costs associated with the acoustic equipment and the data processing following data collection. Combining direct samplers (*i.e.*, nets) with hydroacoustic instruments can produce highly productive insights into relationships of organisms and their environment as well as inter specific relations. Autonomous vehicles can be fitted with acoustic systems and other sensors to permit sampling in difficult environments (*e.g.*, under ice). This can be especially useful for obtaining information on distribution of organisms in a minimally disturbed environment. It is important to note that hydroacoustic observations, especially when coupled with other underway or continuous sampling of the environment and biota, produce prodigious quantities of data. Effective management of such large data sets requires flexible and efficient tools to store, analyze, and permit statistical and other comparisons between and within sets of observations. This paper presents some examples of currently available tools for making hydroacoustic observations utilizing a number of different sensors, examples of how the resulting data can be efficiently managed to allow detailed imaging of acoustic data, and how that information can be extracted and related to other observational or analytical data.

1. Introduction

Methods of analyzing acoustic data by echo-integration have a long history of development (MIDTTUN and NAKKEN, 1968; THORNE, 1971; MACAULAY, 1978; CUSHING, 1978; MATHISEN, 1980; JOHANNESSON and MITSON, 1983; MACLENNAN and SIMMONDS, 1992). Analysis of the acoustic data, usually derived from transect surveys, can produce estimates of biomass along the survey track by intervals of time (or distance). In addition, vertical profiles of distribution and abundance can be calculated for depth slices of selected thickness. These vertical profiles can then be used in statistical comparisons with hydrographic or other data. Examples of such studies at many scales and frequencies can be found in BARRACLOUGH *et al.* (1969), HOLLIDAY and PIEPER (1980), MACAULAY *et al.* (1984), RICHTER (1985a, b), GREENE *et al.* (1988), and COCHRANE *et al.* (1991). Larger scale surveys (tens to hundreds of kilometers) have been done for zooplankton populations (MATHISEN and MACAULAY, 1983; and numerous examples in MILLER and HAMPTON, 1990) and for fish populations (*e.g.* JOHANNESSON and ROBLES, 1977; TRAYNOR, 1983) in coastal and oceanic environments.

Statistical confidence limits provide comparisons between and within areas, and false-color images are an effective means of illustrating abundance and distribution of acoustically detected concentrations of zooplankton, micronekton, and fish. The basic hardware for echo integration requires an electronic system and transducer calibrated to defined standards. Systems are usually calibrated with standard targets (MACLENNAN, 1981; FOOTE, 1982; FOOTE *et al.*, 1987). Other methods of calibration have been used in the past (*e.g.*, ANSI, 1972), but they are subject to considerable error (BLUE, 1984). The measurement of the strength of an echo returning from any depth is converted to an estimate of backscattered sound by applying corrections for the electronics and transducer. In most applications the transducer acts as both projector and receiver although separate transducers for each function may be used. Single frequencies are commonly employed, though a more recent trend is to utilize more than one frequency simultaneously. Typically, frequencies from 38 kHz to 1–2 MHz have been applied in hydroacoustic investigations with biological emphasis. Survey sampling (where maximal depth range is desirable), dictates the use of frequencies below 200 kHz, while point or profile sampling (where ranges of 10's of m or less is acceptable) can make use of frequencies above 200 kHz.

This paper will describe various hydroacoustic means of observing and enumerating sound scatters that are predominantly zooplankton, and suggest how they might be used in investigations of the marine ecosystem. The intent is to give an overview of what types of instruments are available for this purpose and to describe how one can make best use of the large volumes of data derived from such sampling.

2. Sampling Instruments

A selection of environmental, biota and hydroacoustic samplers, which have been recently deployed in a number of environments, is shown in Fig. 1. AV-fin or other towed body can be used as an effective and transportable platform for deploying hydroacoustic sensors. There are advantages and disadvantages to using towed acoustic sensors, but the primary advantages are the ability to deploy them from a variety of ships of opportunity and the ease of calibration (compared with dedicated hull mounted acoustic systems). It is not possible in this paper to explore all the possible configurations of towed bodies for this purpose, however an important consideration is the ease with which the towed system may be deployed and its stability under different sea conditions and ship speeds. It the towed system becomes excessively large or difficult to deploy, the better choice may be to use a hull mounting for the transducer or transducers.

Fixed or drifting buoys with environmental sensors for measuring tempera-

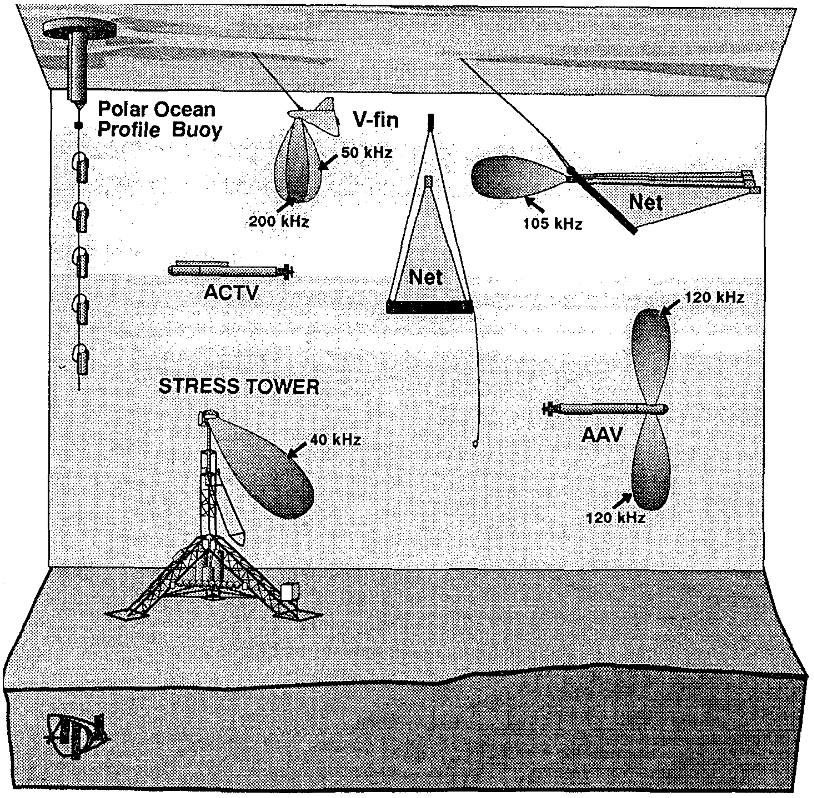

Fig. 1. A diagrammatic illustration showing a selection of instruments available and frequently employed to make hydroacoustic and environmental observations. These consist of towed acoustic arrays autonomous vehicles and bottom mounted platforms as well as instrumented and uninstrumented nets for collecting target organisms. The autonomous vehicles are, ACTV, containing a complete CTD system and an acoustic instrumented version labeled AAV.

ture and salinity (and other environmental variables) can provide important information for interpreting the results of acoustic sampling. In some environments (*e.g.* under ice), autonomous vehicles (such as the Autonomous Conductivity and Temperature Vehicle or ACTV developed at the Applied Physics Laboratory) may be required to obtain this information from undisturbed or otherwise inaccessible portions of the environment. An autonomous vehicle equipped with acoustic sensors (such as the Autonomous Acoustic Vehicle or AAV, in development at the Applied Physics Laboratory) can, similarly, be used to observe sound scatter under ice.

Nets, especially acoustically instrumented ones, can be used to collect biological samples for use in converting sound scattering measurements into estimates of biological abundance. The requirements are that such samplers be capable of collecting the organisms that produce the observed scatter or reflection, and that they capture representative samples; the latter has often proved to be difficult in many situations.

Bottom mounted sensors, especially those that can be left in place for long periods like the Sediment Transport Events on Slopes and Shelves (STRESS) tower, can be effective tools for observing near-bottom or bottom activities of organisms.

Changes in the topography of the bottom due to the activity of brittle stars and heart urchins have been observed with this device.

3. Selected Studies

The STRESS tower utilizes a split beam transducer to observe scattering phenomena near and on the bottom. It is equipped with data storage facilities and a rotation device to produce a view of the bottom around the tower 145 m in diameter. Coherent cross-correlation of the data is used to compare daily images. Areas reworked by colonies of benthic animals (heart urchins and brittle stars are the dominant larger fauna) show strong contrasts in the correlation analyses. The smallest areas of difference may be sites of reworking by single animals. Larger areas of difference show the activity of colonies or concentrations of benthic fauna (Jackson, pers. commun.).

The ACTV was used in the Arctic to examine the temperature and salinity under a lead. Figure 2 shows the temperature and salinity data from a sampling run beneath a lead in an otherwise ice covered area. The vehicle traversed approximate 0.5 km under the ice. Figure 2 also shows possible rafting of pulses of water adjacent to the lead. The Polar Ocean Profile Buoy was used to monitor temperature and salinity at an adjacent location and at fixed depths during the period of the experiment (Morison, pers. commun.).

The combination of a towed hydroacoustic system (to observe) and a multiple opening and closing net (MOCNESS) for direct sampling is shown in Fig. 1. The net

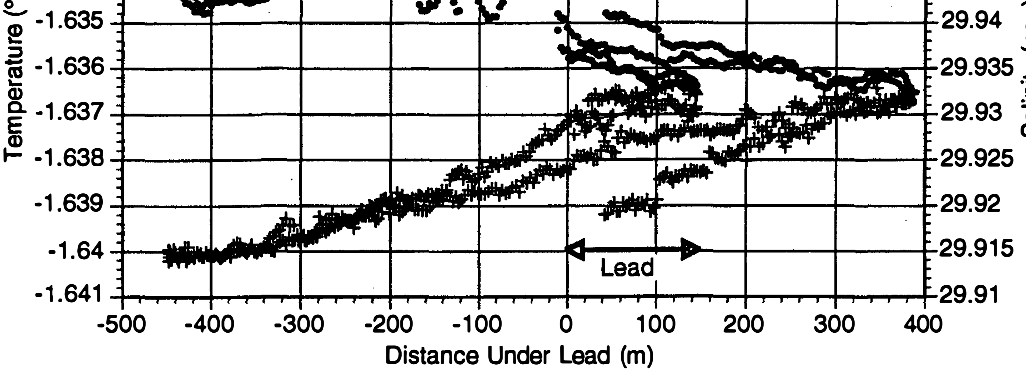

Fig. 2. A combined plot of salinity and temperature collected with the ACTV, showing the approximately 0.5 km extent of the vehicle traverse under the ice and the temperature and salinity encountered during the preprogrammed track (figure courtesy J. Morison, Applied Physics Laboratory, University of Washington).

was also equipped with a single frequency acoustic system to observe targets in the path of the net. By placing a second system directed across the mouth of the net, it would be possible to determine the presence or absence of net avoidance. Other results of this project are described in SHULENBERGER *et al.* (1984).

Figure 3 illustrates the use of a suspended acoustic system and downward fished net to observe the presence of euphausiids in the vicinity of pack ice in the Antarctic. The suspended acoustic system consisted of a surface float with a suspended disk with the transducers (120 kHz and 200 kHz) attached. The mass of the transducers was sufficient to provide stability to the suspended disk and the suspension system allowed the combined array to float free from the nearby ship. The downward fished net was of a design developed by MACAULAY (1978) to compare net catches with acoustic observation. Fundamentally, it is an opening closing net which fishes downward rather than upward (as with traditional ring net designs). This downward fishing method was found to catch 20 to 400 times more individuals of some zooplankton. DALY and MACAULAY (1988) provide an example of the use of such a net with a similar acoustic system. The net dimensions were 1 m on as side and the net mechanism was operated by a messenger operated double release mechanism. This example is drawn from the Antarctic Marine Ecosystem Research at the Ice Edge Zone (AMERIEZ) project in which distribution of zooplankton and other features at ice edges were examined in fall, winter, and spring. The illustrated autonomous vehicle (AAV) was

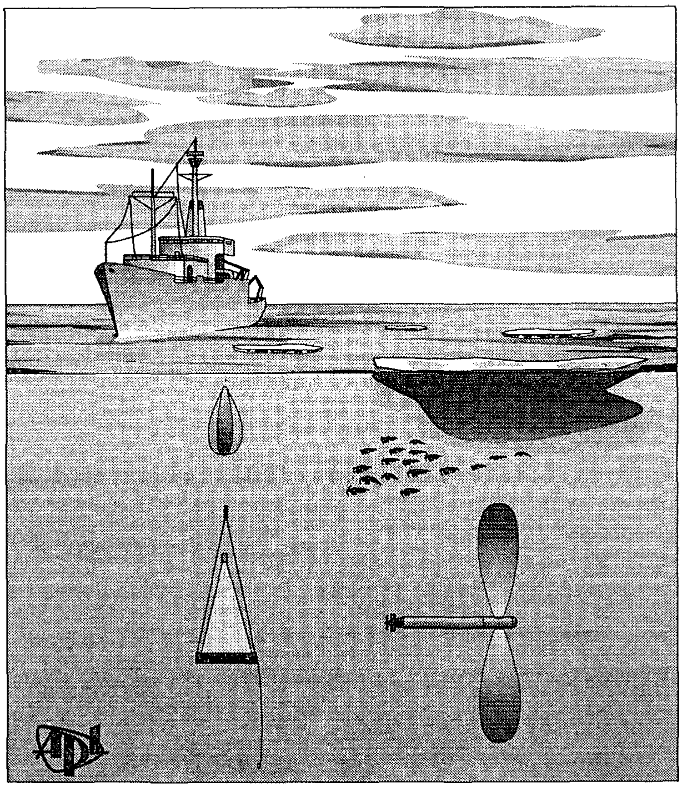

Fig. 3. Illustration of the use of a suspended acoustic system and downward fished net to observe the presence of euphausiids in the vicinity of pack ice in the Antarctic. The AAV is also shown. Populations of krill are indicated below the ice in the foreground.

to be used in a summer cruise, but the fourth season program was not funded, however, the vehicle development continued and resulted in the ACTV and major components for an acoustic version of the vehicle.

4. Data Analysis

The relation of target strength to size for large and small zooplankton and how they might be modeled is shown in Fig. 4. Target strength is used to scale the measurement of sound pressure level (in units of dB or as a function of signal amplitude) to units of biomass (in units of pressure level per unit of biomass). This parameter is well known for many targets (especially fish) but is still unstudied or unknown for many others (mostly zooplankton, but see WIEBE *et al.*, 1990). It represents a combination of modes of scattering depending on the frequency used, the size of the target and the orientation of the target in the acoustic beam (STANTON, 1989a, b; MACAULAY, 1993). Figure 4 shows how target strength varies with size or

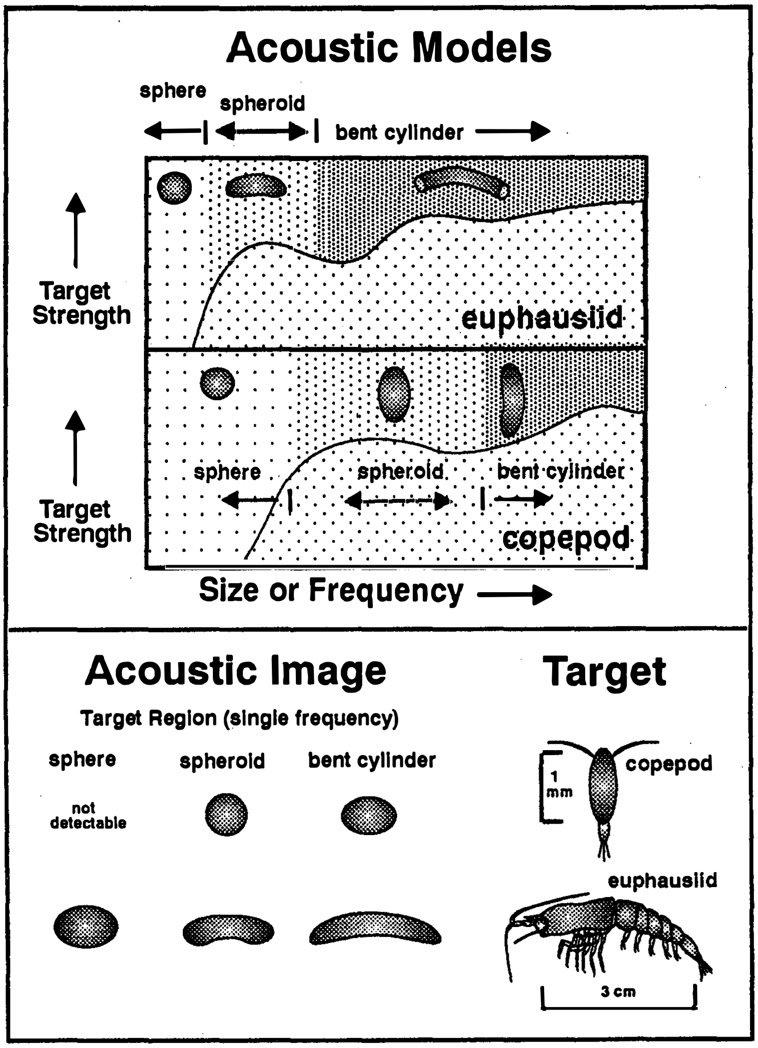

Fig. 4. The relation of target strength to size for large and small zooplankton and how they might be modeled.

frequency for two common zooplankters. As the size of the organism (or the frequency of ensonification) increases, the target is resolved first as a spherical object then as an elongate (sometimes bent) spheroid, and finally as a bent cylindrical object. The lower part of Fig. 4 attempts to show how the two zooplankters might be resolved as acoustic targets as size of the target increases while holding frequency constant or for constant size while increasing the frequency of ensonification. Current acoustic models suggest that the simplified modeling of zooplankton as spherical objects is probably insufficient, unless the target is small relative to the wavelength of the ensonifying frequency. The measurement of target strength can be accomplished by single, dual, or split beam methods (Fig. 5). In the single beam case, there can be considerable uncertainty as to whether an individual target is a small target on axis or a large target off axis. A dual beam system allows some determination of that situation as well as separating cases where there are two or more targets at nearly the same range. Dual beam systems provide two channels of data, one from each transducer. The position in the beam is resolved using the signal intensity in relation to the beam patterns for the narrow and wide portions of the transducer. The angular resolution forms an acceptance/rejection criterion, such that targets with narrow beam intensity below a pre-established level (usually 3–6 dB down from the wide beam intensity) are rejected as being too far off axis to obtain a reliable estimate of target strength. Split beam systems resolve positional uncertainties by providing a more complete definition of the spatial distribution of targets (TRAYNOR and EHRENBERG, 1979; MACLENNAN and SIMMONDS, 1992). In the split beam case, a bi-axial system of phase centers is established between the fore and aft phase centers (providing a fore and aft axis) and the left and right phase centers (providing a second axis at right angles to the first one). The electrical phase difference for each axis is converted to an angular bearing to the target relative to a perpendicular to the transducer face. These angular bearings plus the slant range to the target (provided by the sum beam) allows mapping of the position of the target in a Cartesian or polar co-ordinate system, removing the positional ambiguity of the target. The transducer is often constructed as an array of elements especially at low (50 kHz or less) frequencies. It may also be constructed from a single piece divided into quarter elements. There is no clear preference between circular or rectangular designs (E. PENCE, pers. comun.) so long as stable phase centers can be established between the two halves of the transducer for each axis. If the spacing and size of the elements provides a distance between phase centers of less than 1/2 wavelength for each axis the transducer will produce unambiguous phase angles over a wide range of directions from the main axis of the transducer, however this will result in a very wide beam pattern—possibly too wide for a particular application. The more common practice in fisheries applications is to locate the phase centers a few wavelengths apart by using a narrow beam transducer design and minimize ambiguity by limiting acceptable phase angles for valid targets to those known to be within the range of the main lobe of transducer sensitivity. In all cases, the transducer design needs to have minimal side lobes because the angular position and level of the side lobes establishes the usable signal level and phase angle limits for determining target strength. The use of asymmetrical transducer arrays (wider in one axis) is also possible and can provide

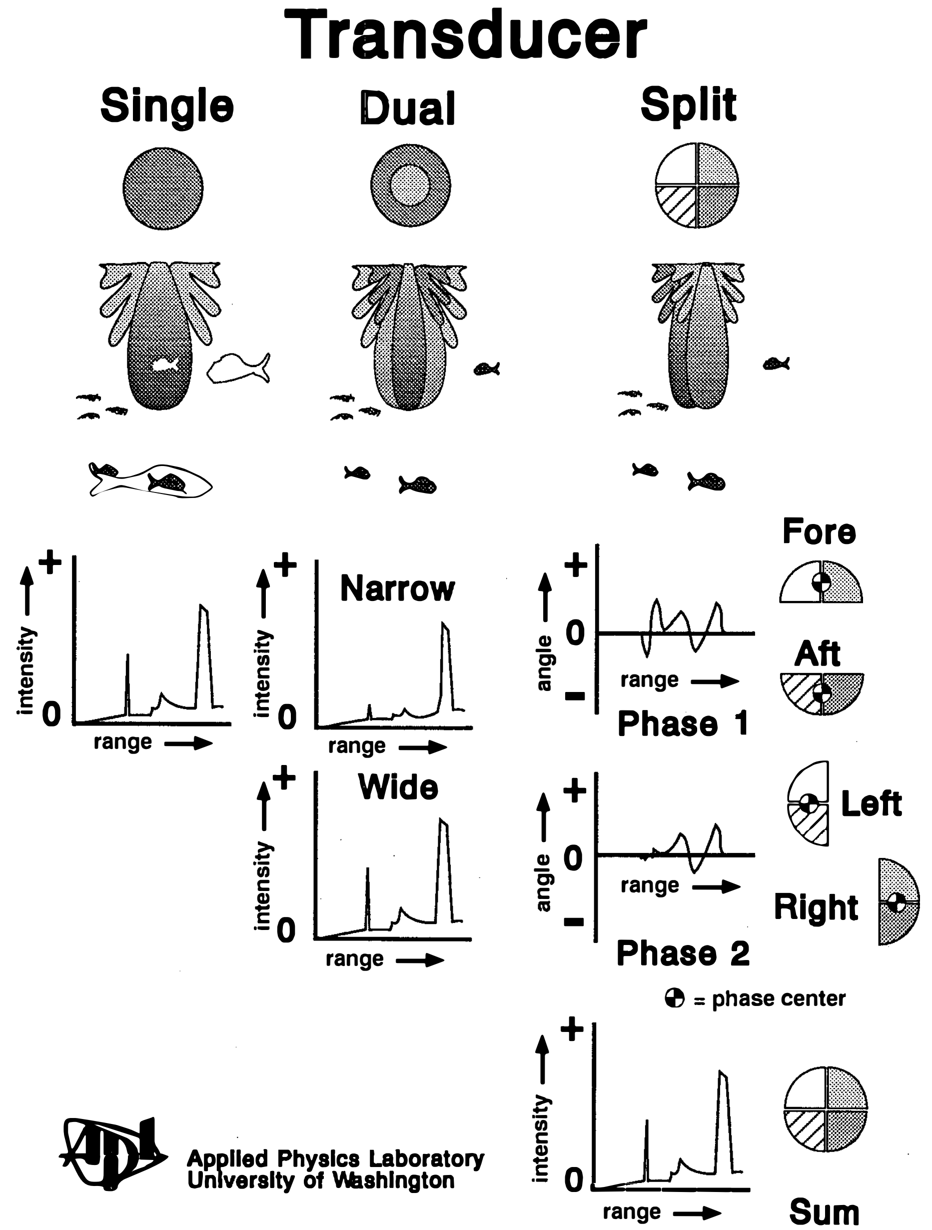

Fig. 5. Schematic diagram of target strength measurement as it might be observed by single, dual, and split beam methods for an identical set of targets. In each case, the signals produced by each type of system are indicated below each case as a plot of intensity or phase angle with range. In the split beam system, the location of the phase centers for each partial beam are shown.

increased beam width for either axis. Such asymmetric arrays have applications in riverine or estuarine environments where water depth may be a limiting factor.

Figure 5 shows a comparison of single, dual, and split beam systems and how echo signals might appear for the same set of targets using each kind of system. The first target, in each case, is a small fish well off the main axis of all systems. In the single beam system, it is not clear whether this is a small fish on axis or a larger fish off axis. The dual beam system resolves this as a probable small target off axis (appears in wide beam signal and poorly in the narrow beam signal). The volume scatter from a number of small targets at mid range is resolved as being off axis in the dual beam case. For the two targets at maximum range, the dual beam system may not resolve whether this is one larger target or two smaller targets. The split beam system can resolve the angular bearing to each of these targets and would probably resolve the two targets as two separate targets, so long as the separation between the two is sufficient to provide distinct phase angle differences. The plots below each example are to show how intensity and/or phase signals might appear for this set of targets with each type of system. The phase angles for a target directly on axis for the split beam array would produce 0° phase angles for both axes, other positions would produce phase angles with different magnitude and sign and the range to the target would be shown in the sum beam signal. These phase angles could then be converted to a angle of offset from the two axes in Cartesian or polar coordinates to specify location of each identified target.

Currently, we lack well accepted target strength relationships for many zooplankton and micronekton. Nevertheless, directed sampling of target organisms (using nets or video images) coupled with sound scattering measurements (in their original units of dB) can provide insight into interactions between organisms, and between organisms and their environment. Among these are rates of vertical migration, the effect that the presence of one organism has on the distribution of others, spatial and temporal scales of distribution for component populations, and the effect of environmental gradients on the behavior of organisms—all without scaling the measured echo intensity to other than measured units. The physical environment itself can also be examined acoustically. The target strength of pycnoclines can be measured by acoustic reflection and may have a target strength of −75 to −85 dB at 200 kHz (Penrose and Beer, 1981). Internal waves and their fine structure have been measured by acoustic methods (Kaye, 1979; Orr, 1981). The relationship of organisms and their environment has been productively examined using spectral analysis (Platt and Denman, 1975; Denman and Powell, 1984; Weber *et al.*, 1986). It is hoped that the increasing availability and use of split beam systems for target measurements will increase our understanding of the biological and behavioral variations in target strength magnitude as well as quantifying it for use in large and small scale hydroacoustic surveys.

Hydroacoustic data collection produces files containing many megabytes of data. The quantity of data is too great to manage by inspection of the numbers directly. For that reason, imaging methods are frequently used to assist in processing large data sets; viewing the data as color scaled numbers facilitates identification of data that may contain noise or bad values. It is also helpful if a visual representation of integrated data and the echo-by-echo data are available while the data are being collected. This permits rapid identification of problems in the collection and analysis as well as providing immediate feedback on the location of target organisms.

Data collected by these instruments can be coordinated into a number of displays and illustrations. It is extremely important to consider what kinds of analyses are going to be used before beginning to use hydroacoustic sampling methods. In most cases (depending on the computer platform), there are extensive data analysis and display programs that can be purchased off-the-shelf. It may be useful to consider developing dedicated display or analysis software once the desired sequence of data processing is selected (*i.e.* to allow efficient batch processing of large quantities of data, as from large scale surveys). Commercial software is often less suitable for repetitive analysis and is frequently designed to do one time analysis of a limited number of data sets. However, these commercial programs may provide valuable experience with what types of analyses are productive, and they can provide a means for data exchange with other investigators, hence the value of having access to them.

Database software can be used to provide text formatting to create input files for statistical packages or for use with graphic presentation programs. An example of this approach is shown in Fig. 6, which shows stacked contour plots for two consecutive surveys of an area around a fixed buoy placement. The top surface in each plot is acoustic biomass from the surface to 50 m, and the middle is the biomass from 50 m to the bottom. The lowest surface shows the cruise track and the area bounding the contour plot values where features are based on observation rather than predicted by the contour program. Environmental data for this example are shown in Fig. 7. Surface temperature (top contour surface), surface salinity (middle contour surface), and the bottom topography (lower contour surface) are shown.

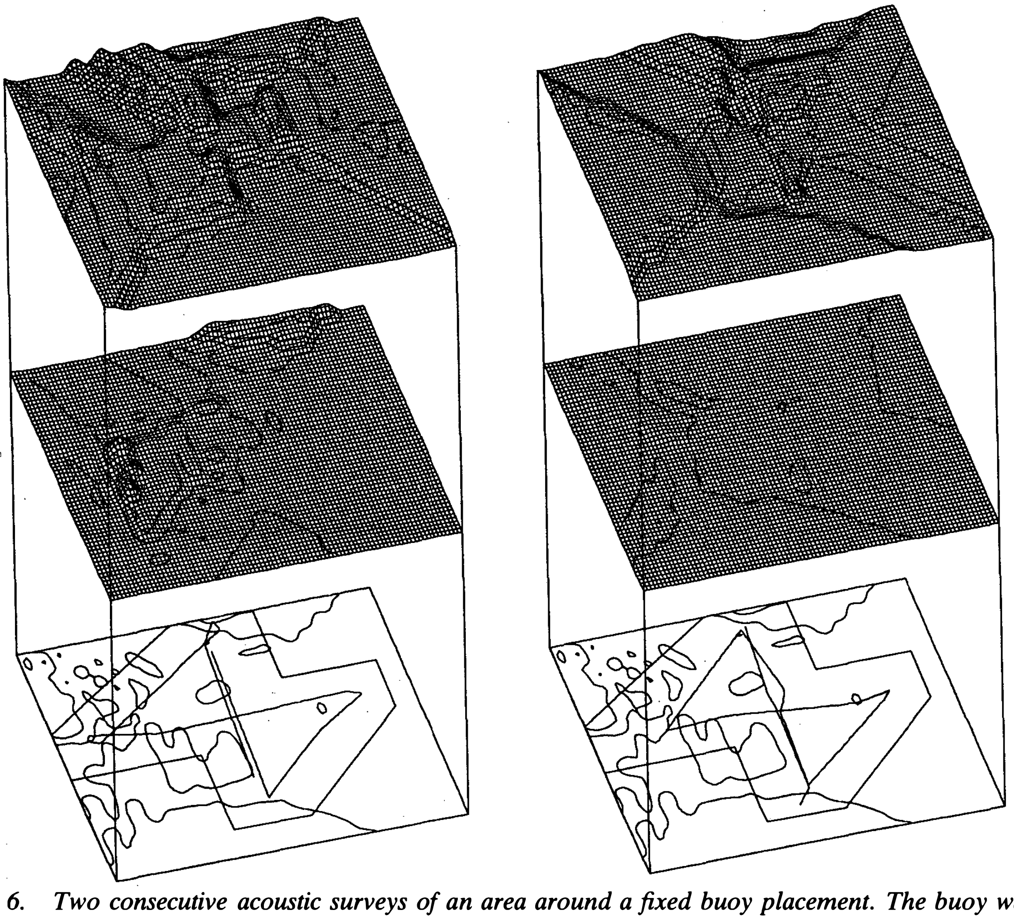

Fig. 6. Two consecutive acoustic surveys of an area around a fixed buoy placement. The buoy was located at the center of the cruise track. In each of the two stacked contour plots, the upper surface is acoustic biomass from the surface to 50 m, the middle surface is biomass from 50 m to the bottom. The bottom surface shows the cruise track and a bounded area where contour plot values are assumed to be most strongly related to observations rather than extrapolations by the contouring program.

A contour plot of the abundance of copepods, from an acoustic survey done while tracking a radio tagged right whale, is shown in Fig. 8. These data were collected during the South Channel Ocean Productivity Experiment (SCOPEX). Three sections of the associated data were identified as representative of different activity by the whale as shown by the cruise track pattern. The data from each of these segments were analyzed by spectral analysis to compare the dimensional structure of patches in each area. Figure 9 shows the results of the spectral analysis and demonstrates the distinctly different distribution pattern in each of the three areas. This is only one of a number of statistical tests or graphical analyses that can be done on data from a set of database files. In each case, the database program is used to contain the data and to format the necessary files. Data products such as charts and graphs produced from the analyses can be incorporated into a database to facilitate retrieval and then indexed to the source database. Other details of this study are given in MACAULAY *et al.* (1993).

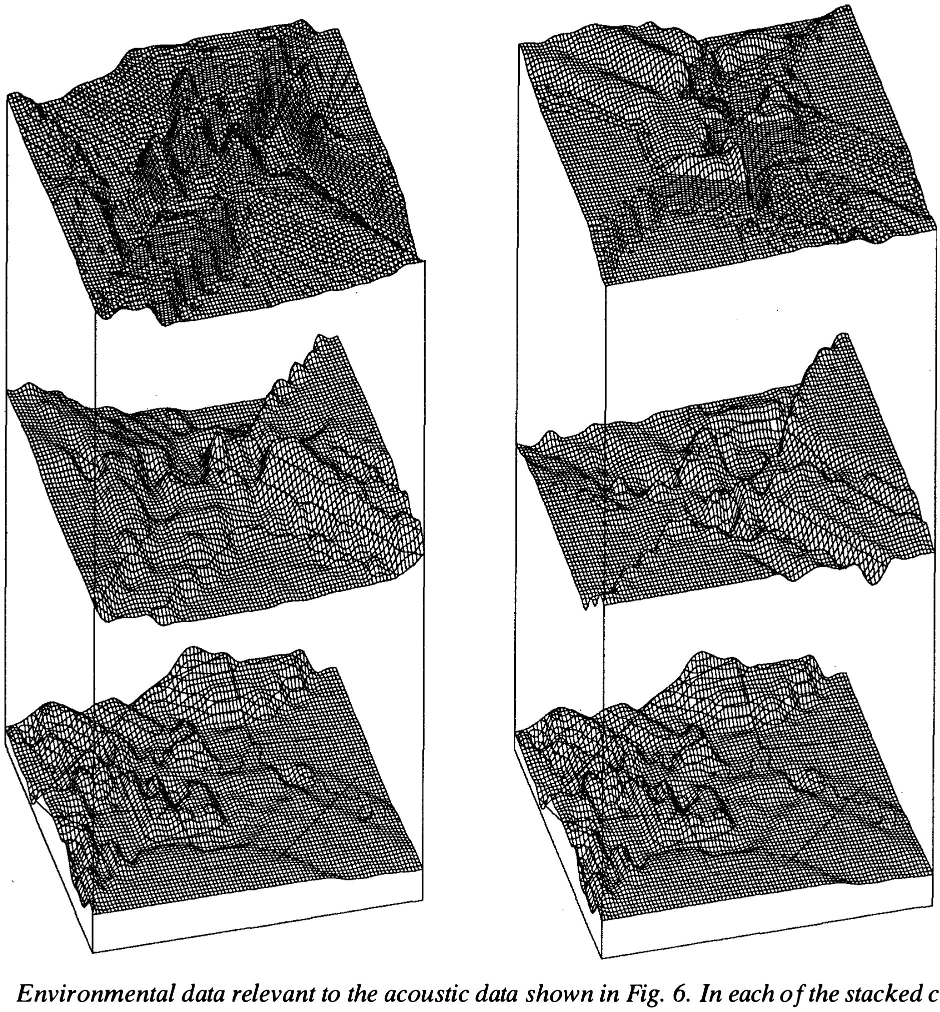

Fig. 7. Environmental data relevant to the acoustic data shown in Fig. 6. In each of the stacked contour plots, the upper surface is temperature, the middle surface is salinity, and the bottom surface is topography in the sampled area on each of the sampling intervals. Temperature and salinity data were taken from surface (hull) mounted sensors.

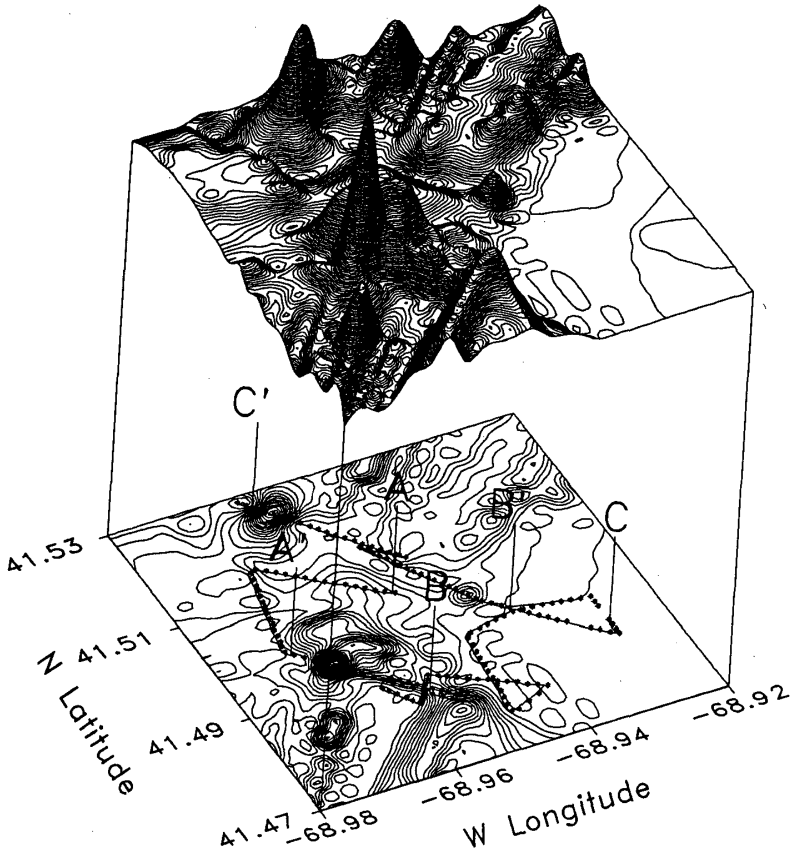

Fig. 8. Plot of the abundance of copepods associated with an acoustic survey conducted while tracking a radio tagged right whale. The upper surface shows a stacked contour plot of copepod abundance and the lower surface shows a flat contour plot overlain with the cruise track with three start and stop locations for the segments (A, B, and C) referred to in Fig. 9. These segments corresponded to areas where the whale exhibited different behavior as it moved along the path indicated.

5. Conclusions

The hardware and software for making hydroacoustic observations is readily available; except in very special cases, there is currently little need to develop new hardware for basic acoustic observations. The cost effective solution is to adapt what is available. There is considerable need to use hydroacoustic observations more routinely in oceanographic and limnological studies. A great deal of ecologically revealing information regarding interactions between zooplankton, fish and physical features in the environment can be obtained with minimally quantitative system. The areas of target strength measurement, especially using split-beam systems, and the refinement of transducer design for biological observations are still in need of further development. This paper has presented some examples from those available; many others are also available. Numerous, commercially available visual display software packages make it possible to interpret and understand the trends and features of large quantities of data. Database systems provide a convenient means of coordinating analysis and maintaining a large amount of information. In addition, many

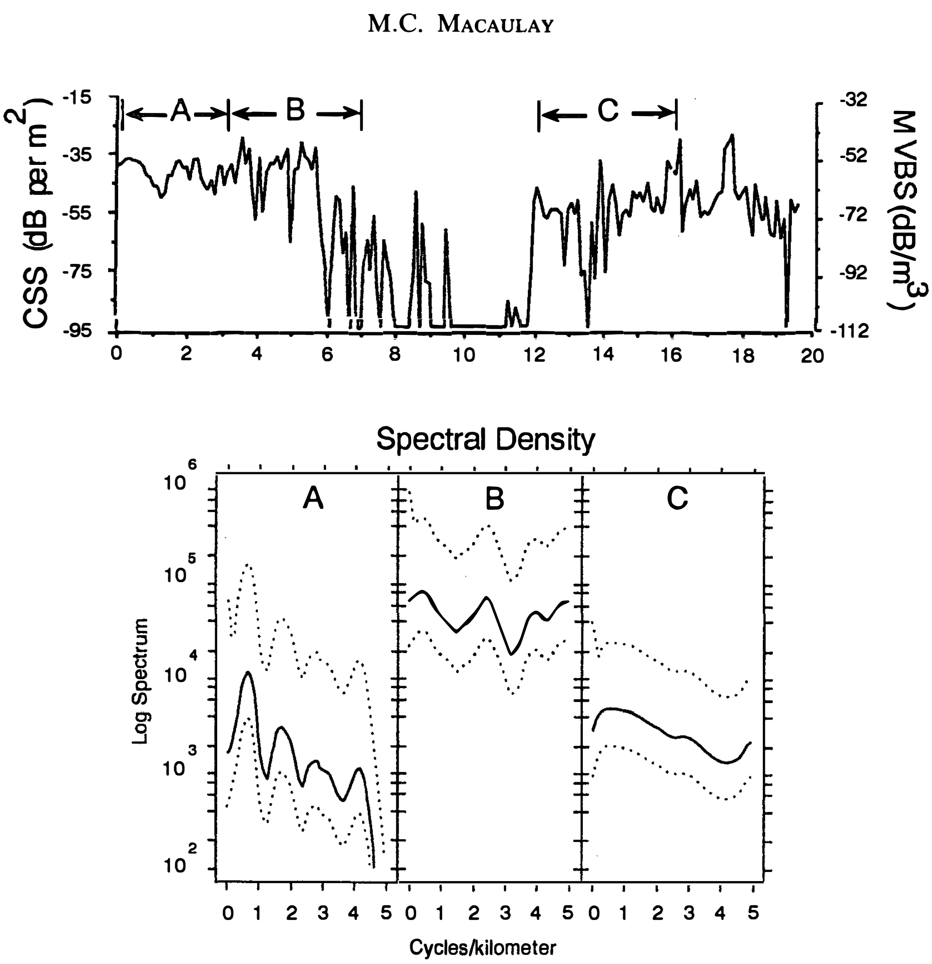

Fig. 9. Plot of the abundance of copepods as a linear function of distance along the trackline and results of the spectral density analysis for the three segments shown in Fig. 8. Target strength free backscatter as column scattering strength (CSS, dB/m^2) and mean volume backscattering strength (MVBS, dB/m^3) for the survey line segments are shown in the upper plot including distance from the start of the survey as km. The results of the spectral analysis, given in the lower plot in this figure show a distinctly different spectral pattern of spatial distribution for each of the three segments. These differences correlated well with distinctly different whale behavior as it traversed the path shown in Fig. 8.

independent software packages can be linked together through the use of such a system. An important consideration is that database systems should be transportable (preferably *via* network) to as many platforms as possible in order to facilitate information exchange. The system briefly outlined herein is such a system; its database program is available for PC, Macintosh, and workstation platforms. The system described is a practical working solution to managing large quantities of data and examining that data for patterns and relationships between organisms and their environment. Issues of data quality and validation, conducted in an efficient manner from the beginning of data collection to the end of data processing, cannot be stressed enough. Databases are of little value if the quality of data in them is questionable.

Acknowledgments

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