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THE USE OF HIGH FREQUENCY ACOUSTICS IN THE STUDY OF ZOOPLANKTON SPATIAL AND TEMPORAL PATTERNS

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Abstract: Knowledge of the three-dimensional spatial structure of zooplankton populations and the change in this structure through time is fundamental to studies of plankton community dynamics. Although conceptual models portraying the time/space scales of plankton pattern and variability exist, data sets required to test their relationship to reality are lacking. High frequency acoustical systems (~100 kHz to 1 MHz) are capable of simultaneously resolving individual zooplankton and mapping substantial ocean volumes. This approach provides investigators with new tools for investigating the processes controlling zooplankton distribution and abundance. The versatility of bioacoustical systems is exemplified by the variety of deployment modes already in existence, including use on submersibles, remotely operated vehicles, towed-bodies, net systems, moorings, and buoys. The processing and interpretation of bioacoustical data require substantial development. Theoretical models of volume backscattering from zooplankton and visualization of three-dimensional data sets are needed. A fundamental limitation in existing systems is the inability to discriminate and identify species. This is a basic impediment to the quantification of community composition.

1. Introduction

Until recently, the use of high frequency acoustics to study the distributions of zooplankton and micronekton has been infrequent, in part due to the lack of appropriate instrumentation. The rapid pace of technological development of high speed microprocessors, accessory electronic components, and concomitant software has made a new generation of acoustical instruments possible. In this paper, we will describe some the acoustical systems that we have been using to study zooplankton spatial and temporal variation. We will then briefly review some results of their application.

When contemplating the use of acoustical tools and techniques, it is important to consider when and where they will be most useful to determine the patterns and processes affecting marine zooplankton. The conceptual model in Fig. 1 can be used to focus on areas of the ocean ecosystem where our knowledge base is relatively good and others where it is poor. It can be used to highlight where acoustical systems may be expected to play an important role. In this illustration, the vertical axis represents the water column and the major

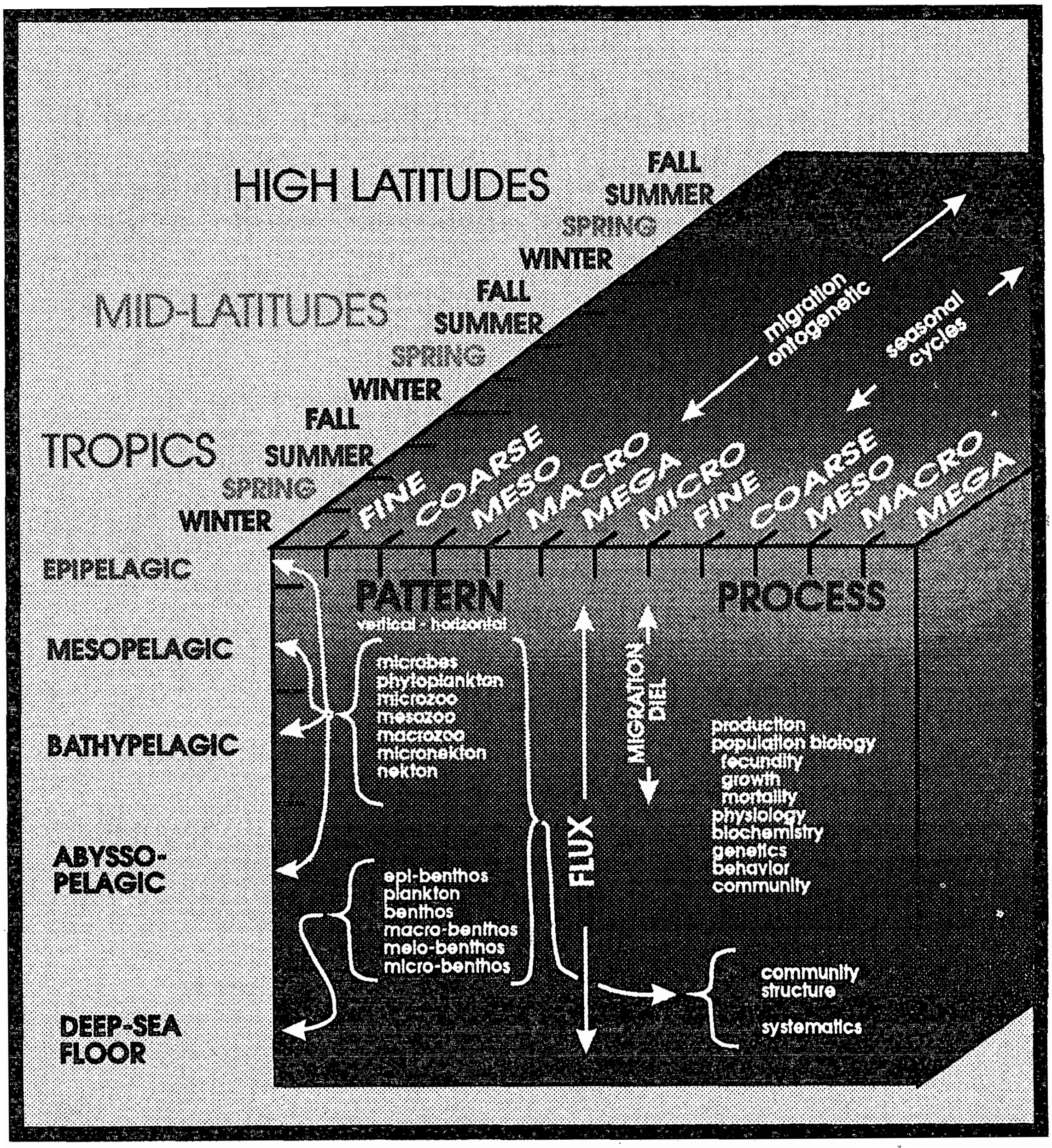

Fig. 1. Schematic representation of temporal and spatial scales of pattern and process in ocean ecosystems.

habitats, *i.e.* epipelagic, mesopelagic, bathypelagic, etc. There is spatial pattern associated with each of these surface to seafloor habitats involving microbes, phytoplankton, microzooplankton, mesozooplankton and so on up to the nekton. These patterns occur on many spatial scales from the micro-scale to the mega-scale with the micro-scale on the order of a meter and the mega-scale inclusive of whole ocean basins as indicated on one horizontal axis (Haury *et al.*, 1978). Dynamic processes that provide a connecting link between the vertical habitats are the flux of organic matter from the surface to the sea floor and the diel vertical migration behavior of the zooplankton. Knowing the patterns of distribution and abundance of these organisms across all spatial scales is necessary. The change in pattern with time is also a fundamental concern and the other horizontal axis schematically portrays the time element for the major geographical regions *i.e.* tropical, mid-latitudes, and high-latitudes. Clearly seasonal cycling is a dominant temporal pattern that varies greatly from one region to the next. Ontogenetic migration of zooplankton is an important behavioral pattern that can exert a major influence on mid- and high-latitude ecosystems.

It is well known that a knowledge of pattern is insufficient to explain ecosystem dynamics. Information about processes, in terms of growth, reproduction, and mortality rates or in terms of biochemical or physiological rates, is also needed. Research efforts that provide both structure and process data about populations offer the highest potential for achieving a new understanding of ecosystem structure and function.

In considering what is known about ocean biological structure and how the ecosystems and their populations work, it can be argued that most is known about organisms in the near surface waters of the ocean. Knowledge diminishes with increasing ocean depth until the seafloor is reached where once again, our knowledge is improved. Also, knowledge is geographically skewed. In the northern hemisphere, the knowledge base for tropical regions is probably less than that for temperate and boreal regions, and most arctic regions are poorly known. In the southern hemisphere, the knowledge base is generally poorer compared with the northern hemisphere, except in the Antarctic where much international research has been politically motivated. In addition, more is known about high latitudes in late spring, summer, and early fall. Late fall, winter, and early spring are periods when conditions are so rough that, for the most part, these regions are left unexplored. Knowledge also diminishes with scale. More is known about the large-scale distributions of organisms than on intermediate scales. Very little is known about micro-scale distributions and the factors which control them.

In charting a course for the future, it is important to focus on those areas in which there is a lack of basic knowledge. For future biological oceanographic science, a major problem is that the regions needing most attention are areas that are very inhospitable. For example, only about half the sea surface of the ocean is accessible for study by manned ships and other platforms. The unavailable half is that part of the ocean at sea state four or five and higher. Thus, there is a very large fraction of the ocean that we have not been able to study effectively. Yet it is precisely during those high sea states, when storms make work impossible and a high level of turbulence is in the environment that measurements are critically needed. Methodologies to study inhospitable areas remotely, *i.e.*, independently of human presence, are increasingly being considered. It is now necessary to also think about new technologies that will enable access to the areas under all environmental conditions. This is a major reason why acoustical tools and techniques have increasingly attracted the attention of biological oceanographers.

Where do acoustics fit into a scheme of ocean sampling? An illustration, (Fig. 2) developed by HAURY (1982), puts into context the different sampling systems in terms of frequency of sampling, ease of analysis of the samples, time

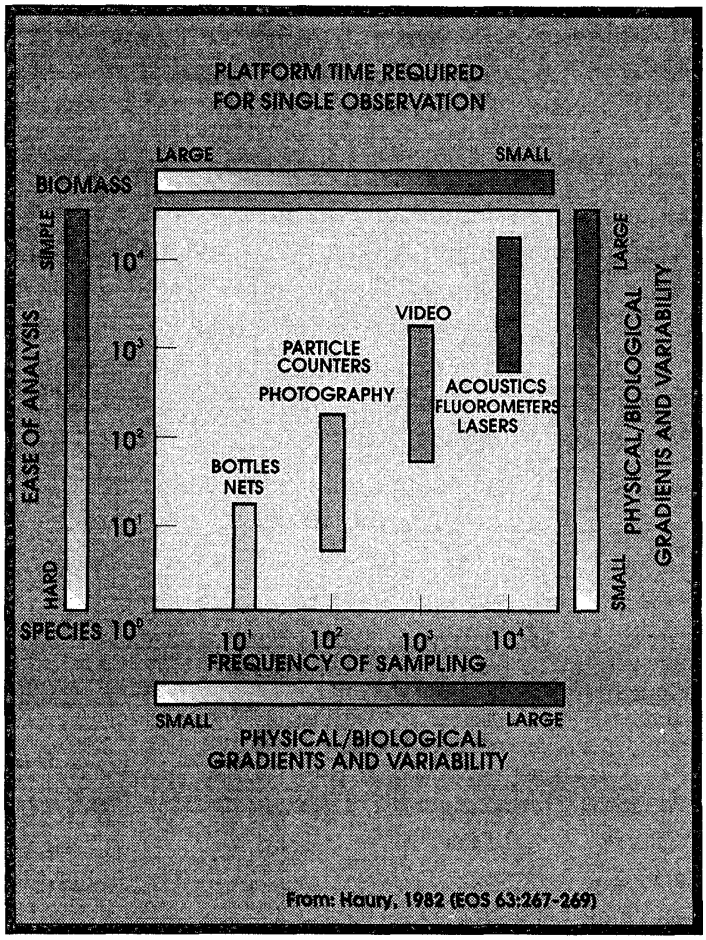

Fig. 2. Relationship between methods of sampling and various measures of their effectiveness to provide a context for evaluating the role of acoustical methods in addressing biological oceanographic problems. Redrawn with permission from HAURY (1982).

required to make an observation, and kinds of physical and biological gradients and variability that may be examined. With bottles and nets, frequency of sampling is low, ease of analysis is hard, and time required to analyze a sample is large; it is thus difficult to examine sharp gradients. Photography, as currently used, provides improvements in many of these yardsticks, and video systems even more so. Acoustics, among others, provide very high frequency measurements, the analysis problems are relatively easy per observation, and strong gradients can be observed over short spatial distances with this technology. It is very important, however, to recognize that, in one sense, there is a diminution in the resolution and quality of information obtained as the tools become more technologically sophisticated. With bottles and nets, planktonic individuals cannot only be counted, they can be identified, staged, and measured for their physiological and biochemical rates, and other elements that are very important to our understanding of how these biological entities function in the ocean. Given only film or video images, many fundamental biological measurements cannot be made. With acoustics, we can now do very little more than measure the biomass, numbers, and size of the zooplankton targets we ensonify. The technology is not currently available to identify and discriminate species, although there are some promising developments that may give some better resolution, first, perhaps, at the taxonomic level. Given today's state-of-the-art instruments, estimates of biomass, numbers, and size can be made and we will focus on these measurements in the present review.

2. Acoustical Measurement Methodology

Several different instrument designs and analysis techniques exist to provide acoustical estimates of plankton biomass, numbers, and size distribution. In this paper, the dual-beam method will be central to the discussion, since this is the system we have used to make most of our measurements. The design of the dual-beam system is based on work by EHRENBERG (1974) and TRAYNOR and EHRENBERG (1979).

A superior aspect of the dual-beam method is evident when it is compared to the capabilities and limitations of a single-beam, single-frequency system. In the process of ensonifying the water column, electrical energy is converted to acoustic energy in a transducer. Returning acoustical energy from an individual is converted back into an electrical signal, a voltage, which is the primary measurement giving rise to an estimate of target strength. With a single-beam, single-frequency transducer, there is an inherent ambiguity about what the size of the animal is when measuring its target strength (Fig. 3). When on the edge of the beam, an animal of a given size will give a certain return voltage. When the same animal is on the axis of the beam, the return voltage is larger. A large animal on the side of the beam, thus could produce the same voltage return as a smaller animal in the middle of the beam (Fig. 3). With only a single-beam transducer, a given return cannot be used to discriminate individual size, although statistical procedures have been developed to provide estimates of animal assemblages size distribution (CLAY, 1983; STANTON, 1985a, b). The dual-beam design provides a hardware solution to this problem (as does the split-beam design, FOOTE *et al.,* 1986). Here, sound is emitted with the narrow beam and both the narrow and wide beams receive the return (Fig. 3). It is the difference between the narrow and wide beam voltages that provides information about where in the beam the target resides (*i.e.*, the off-axis angle). With a measurement of the off-axis angle, the target strength can be corrected for what it would have been if the individual had been on axis. The target strength of an animal that is detected with both beams can be estimated directly with accuracy determined largely by the sensitivity and calibration of the system. The precision of the estimate will be affected by factors such as equipment stability, characteristics of the transmitting medium, and TS variation as a function of animal aspect and frequency.

This method is quite different from the multi-frequency system that HOLLIDAY and PIEPER have developed in the course of their pioneering work (GREENLAW and JOHNSON, 1983; HOLLIDAY *et al.*, 1989). Using many transducers operat-

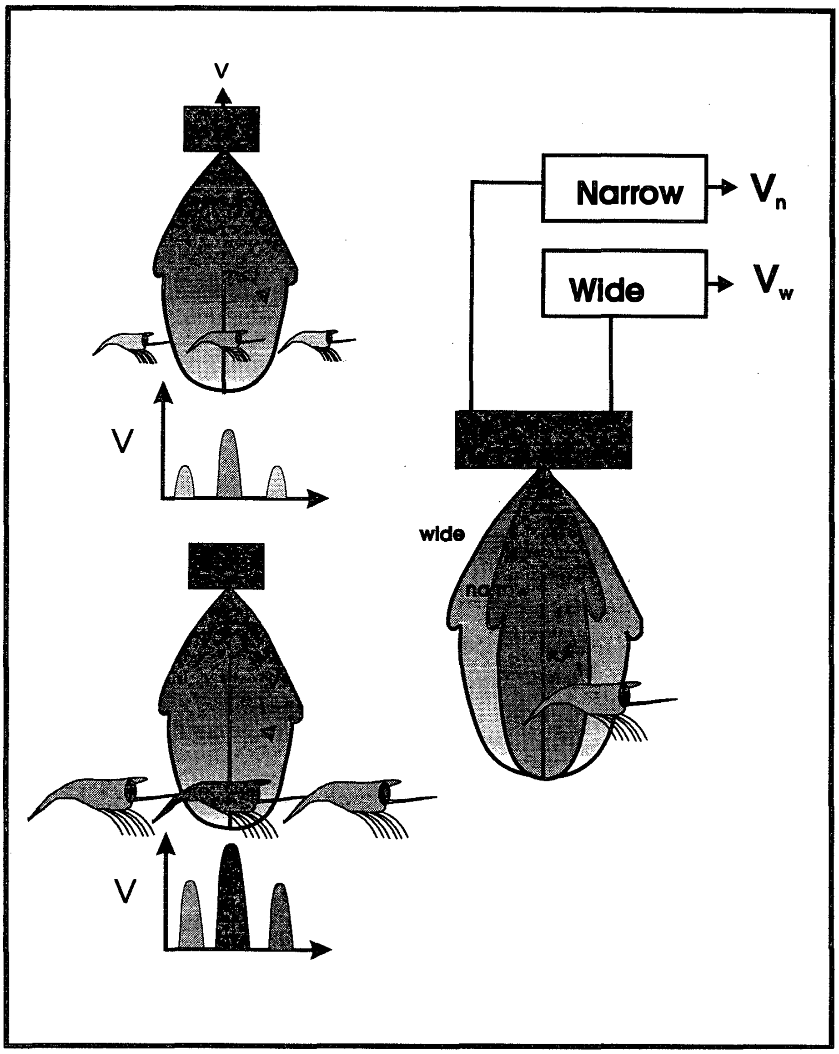

Fig. 3. *Comparison of single-beam and dual-beam echosounders illustrating the fact that with a single beam, an echo from a large individual at the edge of the beam cannot be distinguished from a small individual at the center of the beam. With the dual-beam system, the ratio of the voltage returned on the narrow and wide beams permits the individual's off-axis angle (θ) to be calculated and its absolute acoustic size to be determined.*

ing at different frequencies (100 kHz to 10 MHz), they measure the acoustic volume backscatter at each frequency. This information coupled with an assumed theoretical model of how sound of different frequencies is backscattered from individual zooplankton enables them to solve the inverse problem and determine what the animal size distribution must have been to have produced the observed backscatter. There are some inherent problems associated with doing the inversion. For one thing, the model must be appropriate for all of the scatterers. However, our ideas about the appropriate model for characterizing how sound is scattered from plankton are changing very rapidly as we begin to experiment with animals and look at how they scatter sound at different frequencies (STANTON, 1988, 1989a, b, 1990; WIEBE *et al.*, 1990; CHU *et al.*, 1992). The dual-beam technique has been the current method of choice for many of our applications, but it is important to recognize that other techniques are also quite valid and may be more appropriate for certain applications.

In terms of analysis, our data signal processing techniques are elementary (Fig. 4). A pulse is emitted and over time a series of returns is received from individuals spaced at different distances from the transducer. Each return has a characteristic shape. The first step is to see if the intensity of a return is greater than the noise threshold. If the return is greater than the noise threshold, then a second step involves looking at the peak intensity and the width of the signal at −6 dB and −12 dB below the peak. There are limits to how wide or narrow these values can be, given the transmit pulse width. If they are too narrow, the signal is considered a noise spike and is rejected. If they are too wide, then the signal is considered a multiple target and is also rejected. It is critical, therefore, to have good calibrations and high-quality estimates of noise in the electronics. In the future, more sophisticated processing of the acoustical returns will be developed, but for now these are the two defining steps.

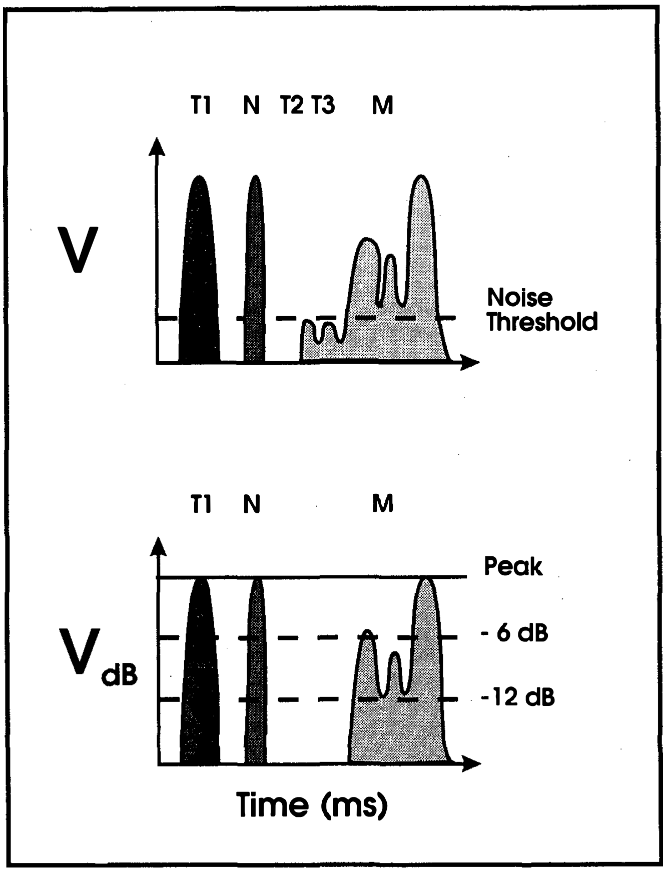

Fig. 4. Schematic drawings of the amplitude criteria for single-target acceptance (Top Panel) and the pulse duration criteria for single-target acceptance (Bottom Panel) by the BioSonics dual-beam processor software. Illustrated are single targets (T's), a noise spike (N), and a multiple echo (M). Echoes above the noise threshold are tested with the pulse duration criteria. Only the single target echo (T1) is accepted using both criteria.

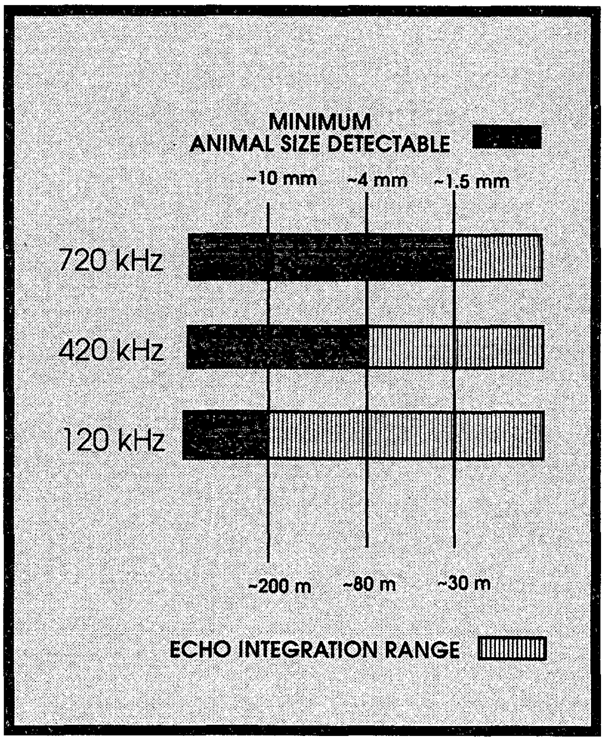

Fig. 5. Relationship between the acoustic frequency used to ensonify an ocean water column, the approximate minimum animal size detectable, and the approximate range of echo integration as illustrated with three frequencies.

One other aspect of underwater sound important to keep in mind is the interdependence of sound frequency, the minimum detectable target size, and the range of operation (Fig. 5). Illustrated are three different frequencies: 120 kHz, 420 kHz, and 720 kHz, and estimates of the minimum size of the animal that is detectable with these three frequencies. An animal that is too small, compared with the wavelength of sound that is put into the water, will essentially be undetectable. Either no voltage or a very small voltage relative to its size will be recorded in the echo sounder. As the frequency increases, the size of the animal that is detectable becomes smaller. With 120 kHz, a ~10 mm individual can be detected; with 420 kHz, the minimum size is about 4 mm; with 720 kHz, minimum size is about 1.5 mm. The price paid for increased size resolution is decreased range of operation. At 120 kHz, echoes are detectable to a range of about 200 m, whereas at 420 kHz, this range decreases to about 80 m, and at 720 kHz the range is only about 30 m. This fundamental limitation puts strong constraints on how the instrumentation can be configured and how it can be used to analyze animal distributions in the water column.

A final point involves the interaction between size resolution as a function of range and the noise of the system. For any frequency, as the sound propagates away from the transducer, the size range of animals that can be detected is reduced because with distance the noise increases and echoes from smaller individuals will fall below the noise threshold. Furthermore, with increasing distance from the transducer, the volume ensonified increases, thus increasing the probability that a return is from more than one individual. One way to evaluate the multiple target bias is to make acoustics measurements at sub-surface depths with the transducer aimed horizontally. Since only random changes in size frequency are expected in the horizontal, an estimate of the multiple target bias can be determined from the range at which there is an increased fraction of larger individuals in the size frequency distribution and an increase in the number of echoes rejected as multiple targets.

3. Instrument Systems and Platforms

In our research, we have deployed dual-beam systems in a variety of platforms and acquired data using several different sampling schemes.

3.1. Towed bodies

3.1.1. Dead-weight towed body

The BioSonics dead-weight, towed body (Fig. 6) that we have used several times can carry several single or multi-beam transducers ranging in frequency from 38 to 1000 kHz. We have used it with 120 kHz and 420 kHz transducers. The system has been towed at eigh+ knots and has a very clean profile as it streams through the water. We have used this system extensively in a project examining the effects of abrupt topography on oceanic zooplankton distributions. Some results of this work are presented below.

Fieberling Seamount study: The BioSonics towed body was used to conduct an acoustic survey over Fieberling Seamount 500 nm west of San Diego, California (32°26′N, 127°46′W). The top of the seamount was at 430 m and the bottom was at ~4000 m. Complementary star patterns were completed on two

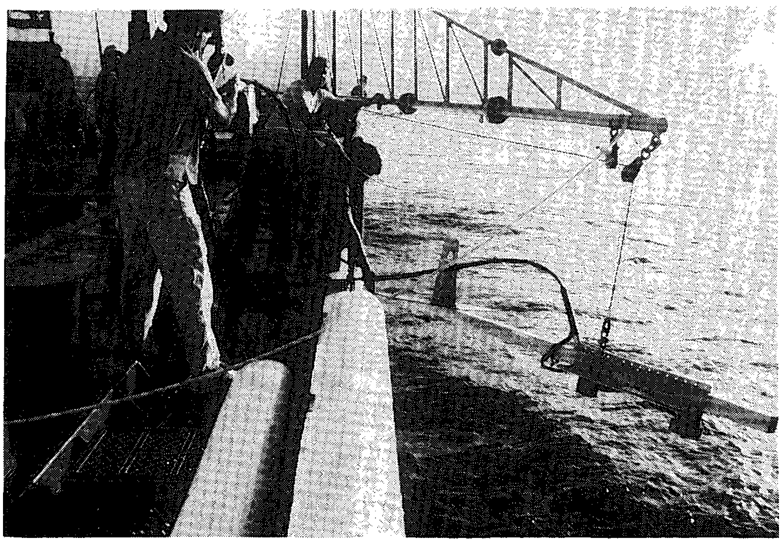

Fig. 6. The BioSonics towed body equipped with 120 and 420 kHz transducers being deployed from the RV THOMAS THOMPSON in waters over Fieberling Seamount (September 1991).

successive nights, each requiring a period of about six hours. Acoustic data were collected at 120 kHz and echo integration values were calculated in 1 m depth intervals and averaged in 30 s intervals. The irregularly spaced data were combined into a single data set. Several graphical techniques were used to display the data. The first involved portraying the data as water column integrated acoustic volume backscattering along the trackline. Areas of low and high volume backscattering were evident and provided an indication of the patchiness structure of the zooplankton biomass over the seamount (Fig. 7a). It was difficult from this presentation to visualize the structure and gain an appreciation of its scale relative to the seamount in spite of the fact that the bottom topographic data were integrated into the plot (the act of merging different data sets and using the information in a combined analysis and display is termed "data fusion"). The trackline data were used to produce a regular spaced grid of data that could be contoured. Overlaying the seamount contours on the volume scattering plot provided an improved, but still unsatisfactory, view of the relationship between the animal patches and the seamount topography. A third attempt involved portraying the bathymetry and volume scattering in a 3D image (Fig. 7b). The seamount took shape and its relationship to the shallow layer (50 m) ensonified during the acoustic survey was evident. Patch structure itself was also more evident in this visualization. The computer program used to make this plot can be used to rotate the plot so that the data can be viewed from many different vantage points. A next step is to do this analysis at sea so the images are available at the end of the survey. Armed with the visual image of the volume scattering structure over the seamount, more intense study of the patches and the organisms responsible for the volume scattering could be done.

3.1.2. Hydrodynamic V-Fin towed body

A 5-foot ENDECO V-fin towed body that we have used several times can carry a dual-beam, 420-kHz and 1-MHz echo sounder of custom design and built by BioSonics Inc.(Fig. 8). It was designated the ROV sounder because it was originally built for use on an ROV described below. The transducers were mounted inside the towed body and oriented vertically (to look down) through an open cutout on the aluminum panel. In this form, it has been used to acoustically map the fine-scale vertical spatial patterns along the tow trackline. A significant aspect of this form is the fact that the sounder is contained in an underwater pressure housing which significantly decreases the noise within the sounder electronics and eliminates most of the electrical noise associated with the ship. The towed body is also equipped with an environmental sensing instrument package normally used on MOCNESS (WIEBE *et al.*, 1985). The sensors measure temperature, conductivity, depth, and fluorometry. The information is measured at four second intervals along the trackline. This system was used recently in a two-ship experiment on Georges Bank, and some of these data are presented below.

Small-scale vertical striations across Great South Channel (Georges Bank): Our work at Great South Channel provides an example of how acoustics can be used to "see" biological events that we had not envisioned when laying out the

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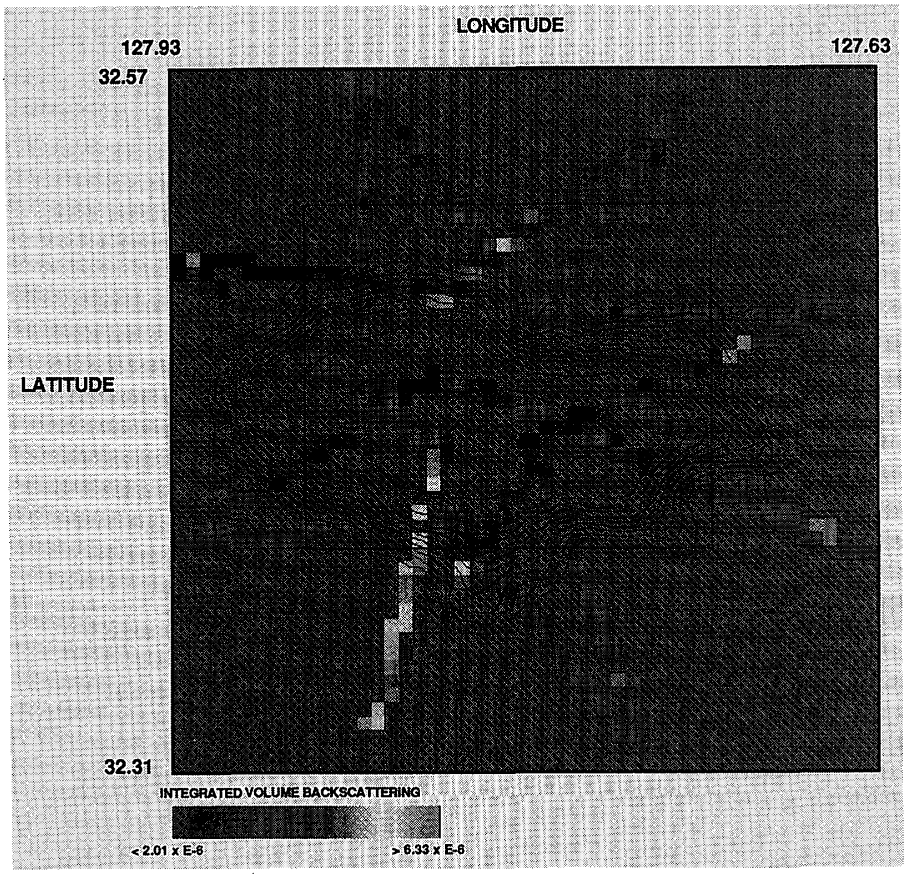

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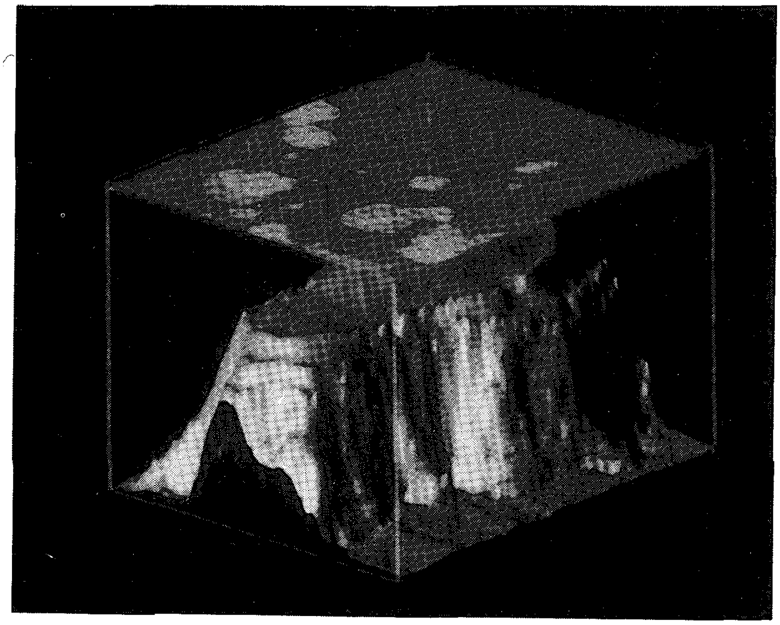

Fig. 7. a) The star sampling pattern conducted over Fieberling Seamount on two successive nights with the acoustic volume backscattering intensity (120 kHz) mapped as a color-scale field along the ship's path. b) a 3-D visualization plot of the acoustic data with the topography of the seamount underneath.

a)
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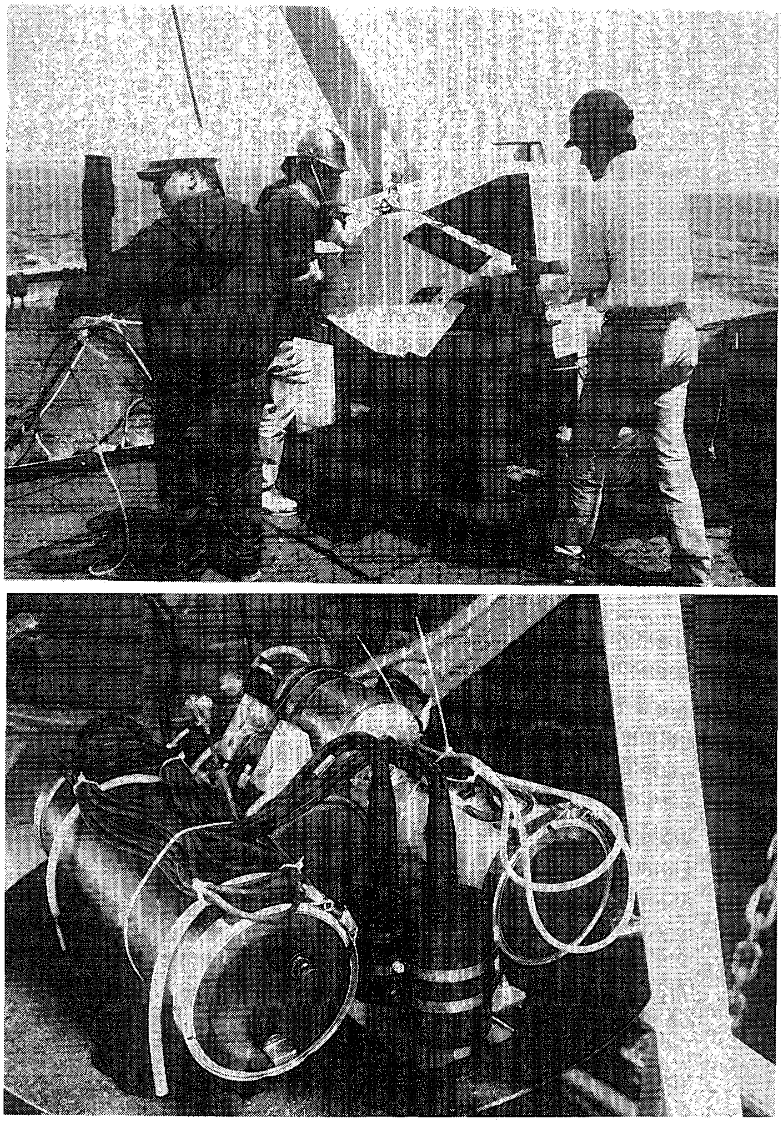

Fig. 8. a) The ENDECO towed body ready for deployment from the RV/ALBATROSS IV in waters over Georges Bank in May, 1992. b) The electronics mounted inside the ENDECO towed body with the BioSonics echo sounder on the left, the MOCNESS underwater electronics system on the right, a Sea Tech fluorometer on top, and two downward looking transducers (420 kHz and 1 MHz) in the middle. Not visible, but mounted on the front of the towed body are Sea Bird temperature and conductivity sensors.

work plan. A transect tow with the ENDECO towed body was started in the middle of the day on the eastern edge of the Great South Channel (lying at the western edge of Georges Bank) and went perpendicularly across the channel to the west (Fig. 9). The ship was steaming at about two knots for about four hours. There was no wind, the sea was calm, the sky was cloudless, and the sunshine very bright. A series of acoustical images (five min CRT computer bitmap snapshots ~300 m horizontal by 50 m depth) taken as we collected data (Fig. 10) provided evidence for a coherent pattern of very small-scale vertical lineations along the entire transect. This pattern was substantially different from

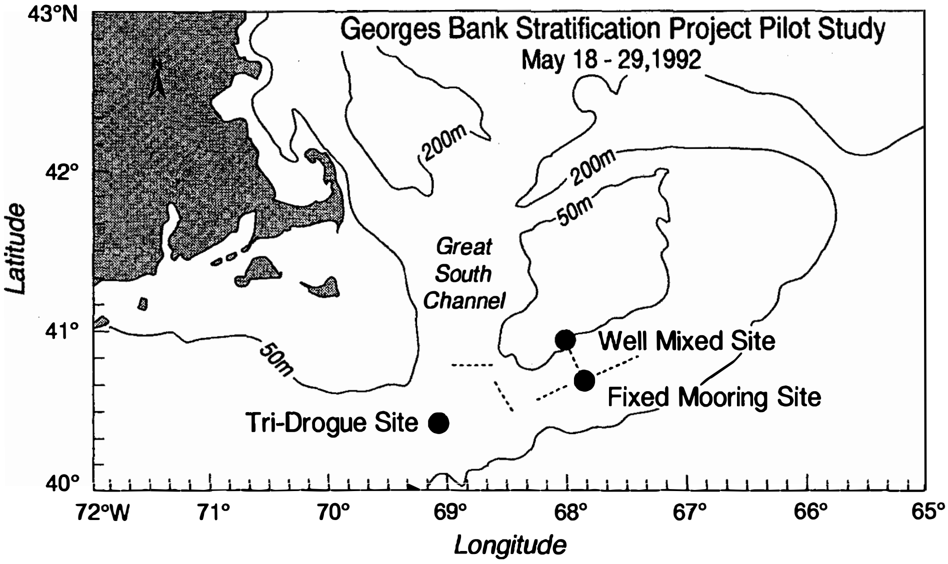

Fig. 9. *Location of the transect across Great South Channel (Georges Bank - dashed line running east to west) in relation to other sampling sites occupied during the May 1992 cruise aboard RV* ALBATROSS *IV.*

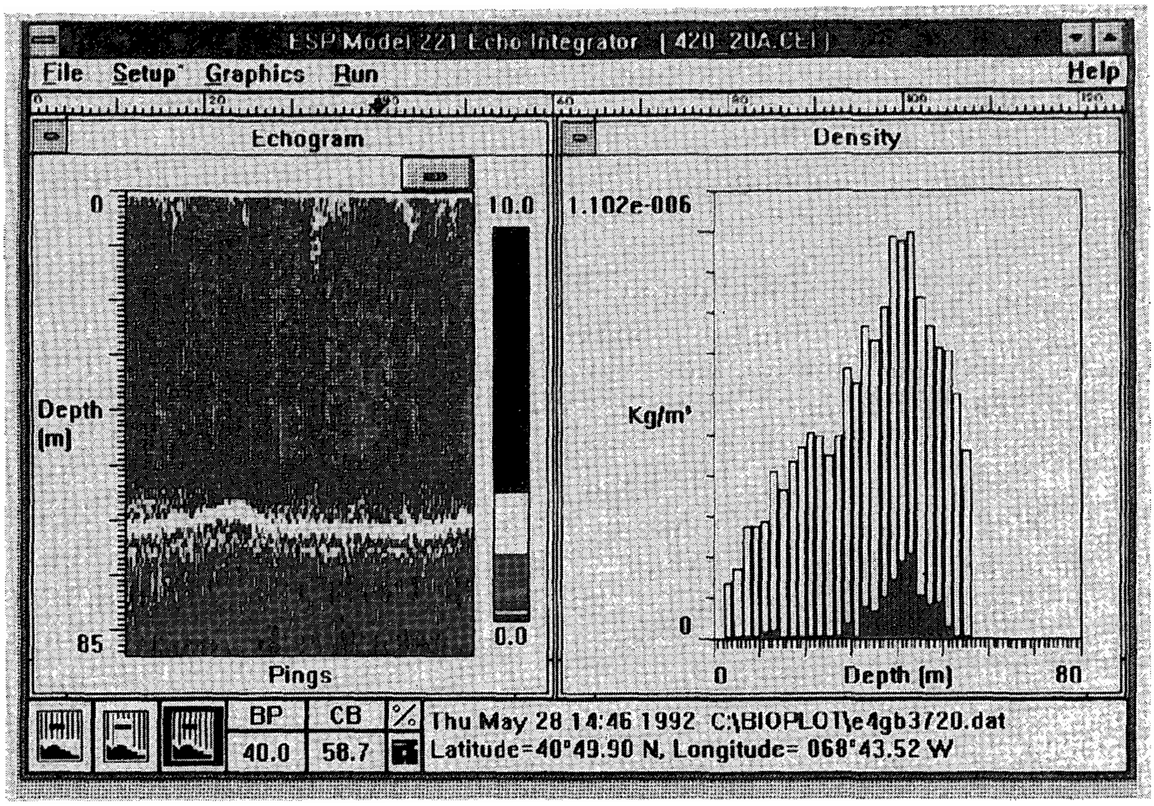

Fig. 10. *Vertical bands of zooplankton as revealed by a "snapshot" of the data being acquired by the 420 kHz echosounder deployed on the ENDECO towed body during the Great South Channel transect. The "snapshot" is representative of the structure observed during most of the 4.5 hour transect. Echogram (left) represents a 5-min recording period with the boat moving at two knots. The white band between 50 and 60 m is the bottom. Density plot (right) shows the vertical volume scattering profile (representing the vertical biomass distribution) averaged over the last 30-second sampling interval. The secondary (dark) histogram bars indicate depths where high intensity signals (dense patches or large fish) contributed significantly to the total volume backscattering.*

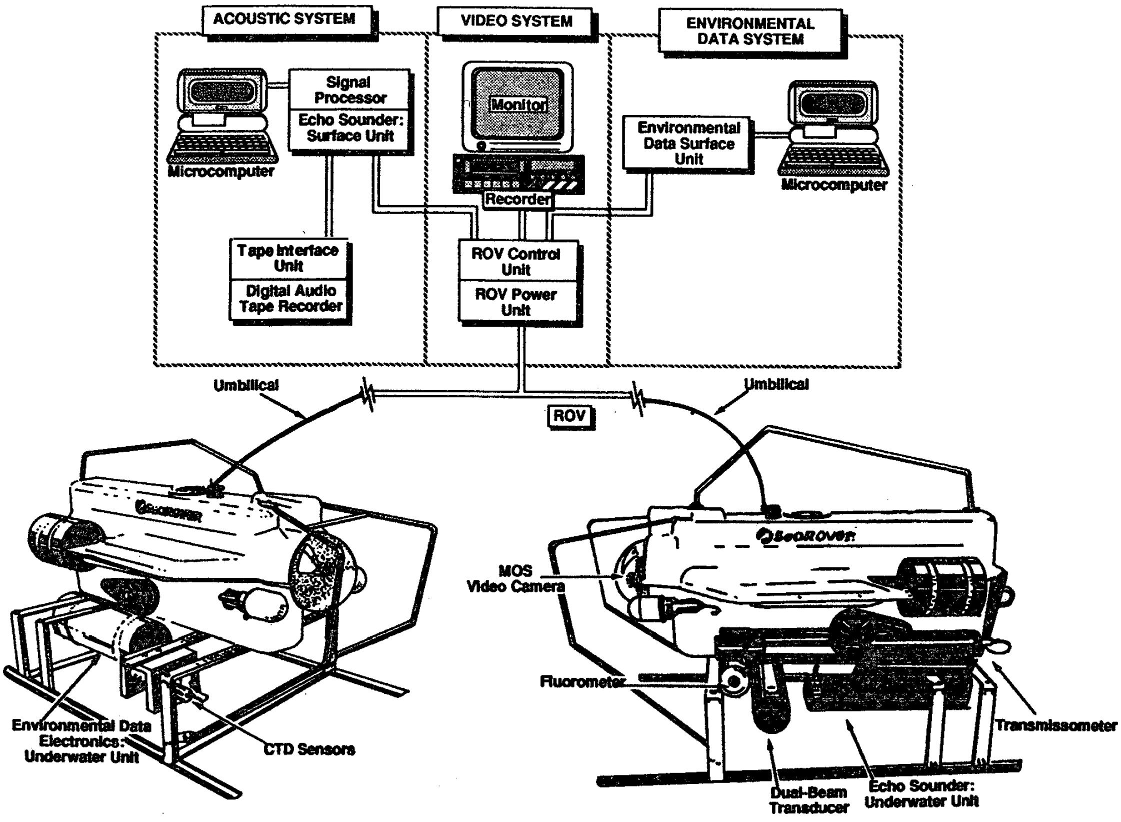

Fig. 11. Schematic drawing of the Benthos Sea Rover ROV with acoustic and environmental sensing equipment and the cabling to the computer processing, recording, and control systems.

anything we had observed previously on the cruise. Although the volume scattering increased along the transect, small-scale patchiness roughly 30 to 50 m persisted. A CTD-fluorometer towed along the track line was stopped for a seven min period about midway along the line and the unit was held at mid-depth. No significant variation in temperature or salinity was observed. However, a strong variation in the fluorescence signal was observed, which had a spatial pattern similar to the acoustical pattern. We are not yet able to suggest the driving force for this observed pattern. However, without the acoustic imagery, we would not have suspected that such pattern existed, nor would conventional sampling have enabled us to postulate its existence.

3.2. *ROV systems*

We have used the same basic acoustic and environmental sensing instrumentation on a Benthos Sea Rover (ROV–Fig. 11–Greene and Wiebe, 1990; Greene *et al.*, 1991). Both electronics packages and the sensors are located on the underside of the ROV. This system also is equipped with a low resolution video camera. The data processing is handled by two microcomputers, one for the acoustics data and one for the environmental data (Fig. 11). There are a monitor and recorder for the video information.

One place we used this ROV, was from an ice camp located to the northwest of Svalbard in the Fram Strait (83°N, 04°W–Fig. 12a). We used the

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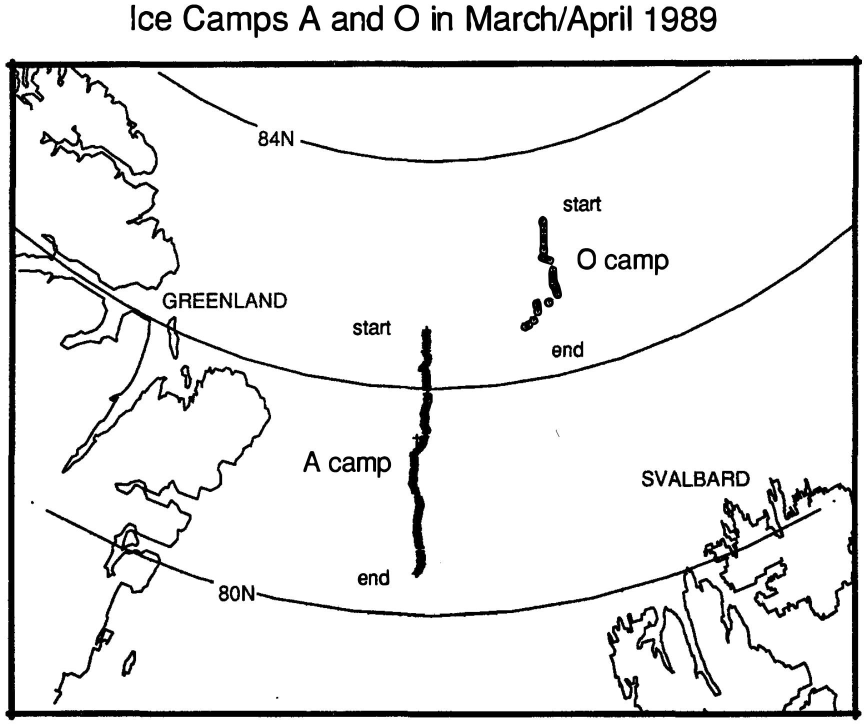

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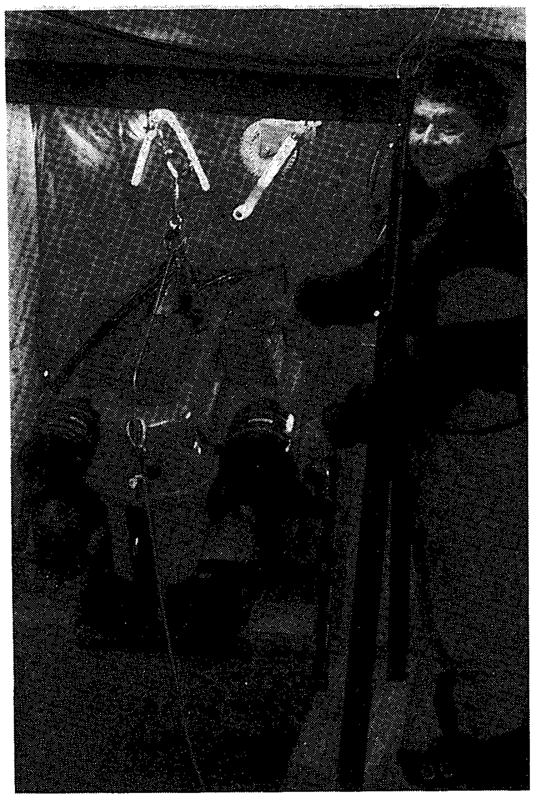

Fig. 12. *a) Location of Arctic Ice Camp A between Greenland and Svalbard at 82° N, 04° W where below ice bioacoustics work was undertaken in April, 1989. b) C. GREENE in the "Bug Hut" getting ready to deploy the Sea Rover ROV for under ice bio-acoustic studies of plankton.*

system to make acoustic measurements under the ice sheet at the A-camp. All of our equipment was located in a small hut (2.4 m wide×4.9 m long×2.1 m tall). At one end of the hut was a 0.9×1.5 m hole in the floor boards that was extended 5.5 m down to the open sea below the ice sheet. This hole was crafted using a University of Washington hole melter. The ROV was suspended over the hole from a small aluminum A-frame hoist (Fig. 12b). The ROV could be lowered into the water and powered down the hole to depths of 160 m. Profiles of water and acoustical properties were made using this system. Some of the data have been published (GREENE *et al.*, 1992).

3.3. Submersible applications

These same acoustical and environmental sensing instruments have also been deployed on two research submersibles, the Johnson-Sea-Link (Fig. 13) and Alvin. When using the JSL, one scientist sits in the forward sphere with a pilot and makes visual observations of the animals and points the transducer in desired directions, while the second scientist sits in the aft chamber where the data acquisition and processing computer equipment are located and operated. When using Alvin, one or two individuals will operate the equipment from the diving sphere. A series of dives has been made with this equipment on the Johnson-Sea-Link submersible in the submarine canyons south of New England (GREENE *et al.*, 1988, 1989a, b; GREENE and WIEBE, 1989) and in the Gulf of Maine (GREENE *et al.*, 1992; WIDDER *et al.*, 1992), as well as on the Alvin submersible over Fieberling Seamount.

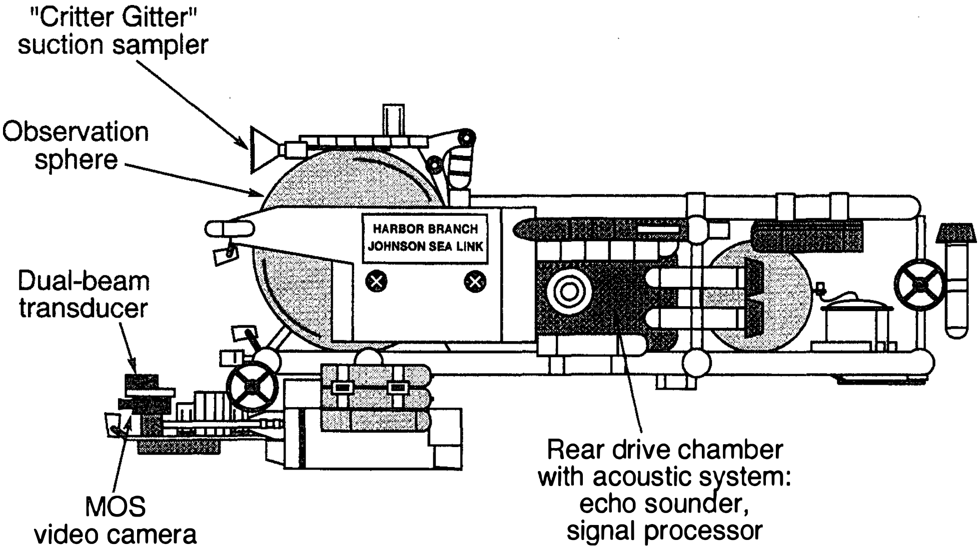

Fig. 13. Schematic drawing of the Johnson Sea Link submersible with dual-beam acoustical system deployed for operations in the Gulf of Maine and submarine canyons off southern New England.

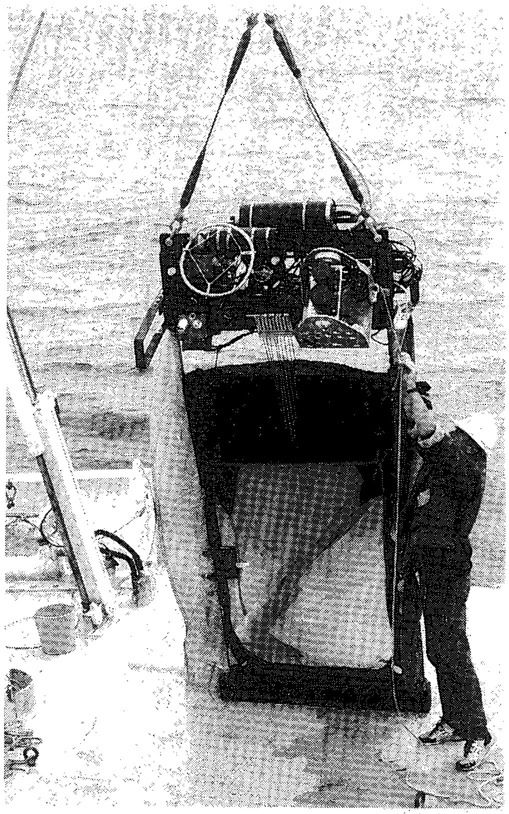

Fig. 14. The 1-m² MOCNESS equipped with a dual-beam echosounder and with a fiber-optic cable for data telemetry with the acoustical system during field trials in the Gulf of Maine aboard the RV ENDEAVOR *in August 1992.*

3.4. Towed net systems

We have adapted this same acoustical instrumentation for use with MOCNESS, but with an important new addition: a fiber optics telemetry system (Fig. 14). The use of a fiber-optic tow cable has opened up the bandwidth tremendously. There is now the possibility of acquiring substantially larger volumes of data from additional sensors and sensor packages. The first trial with this system was conducted in the Gulf of Maine in August 1992. A nine net 1-m^2 MOCNESS system was equipped with the dual-beam acoustics system and the MOCNESS environmental sensing package (temperature, conductivity, depth, fluorometry, beam transmittance, altitude [bottom finding pinger], flow, and net angle). The 420 kHz and 1 MHz were mounted in a training mechanism that had two driving motors (pitch and roll) to position the transducers so that they were oriented anywhere on a hemisphere looking forward of the net mouth. Positioning of the transducers was under computer control from the surface. The fiber-optic cable enabled the addition of a video system to the MOCNESS. An aluminum ring extending about 50 cm in front of the camera marked an area viewed by the camera and enabled quantitative counting of the organisms passing through the video field.

When the acoustical system is deployed on the net and the transducers are pointed forward into the net path, an individual organism's ability to avoid capture can be assessed by tracking its position as the net approaches. Target tracking is therefore an important additional computer computation that is needed to determine if avoidance behavior is occurring. With the transducers pointed perpendicular to the net mouth, the acoustical system can be used to assess the variability of the plankton populations in much higher resolution and encompassing a much larger field than that sampled by the net system itself. The net samples can then be used to calibrate and interpret the acoustical data along the net's trackline.

3.5. *Autonomous buoys*

Deploying acoustic gear from a wire on a ship or from a submersible has a significant deficiency; the acoustics data are only obtainable during the cruise. There is, however, a need for high quality acoustic measurements that can be made at reasonable temporal frequency for periods of months to years. This requires an acoustic system that can be deployed for autonomous data acquisition. Such a system, the BIOacoustic Sensing Platform And Relay (BIOSPAR) has been constructed (Ehrenberg *et al.*, 1989–Fig. 15).

BIOSPAR carries two down-looking dual-beam transducers, one operating at 420 kHz and the other operating at 120 kHz. Profiles of acoustic backscattering are obtained in one m depth intervals in the upper 100 m. The instrument is

Fig. 15. BIOSPAR being deployed in 80 m of water from the RV/Albatross IV at the Fixed Mooring Site on the southern flank of Georges Bank (see Fig. 9) in May1992.

currently programmed to collect data for one min every 15 min; for each frequency, these data consist of individual target strengths as a function of range, and average backscattering strength for each one meter range interval. All data are stored on an optical disk unit in the buoy for post processing. Reduced data in the form of a target strength histogram and integrated intensity for 10 depth intervals at each frequency are averaged over a specified interval, nominally two hours, for daily transmission to shore. Real-time VHF 1-way radio telemetry is also available.

BIOSPAR has the shape of a spar buoy–hence its name. A long cylindrical aluminum tube provides the casing for an instrument rack, 2.4 m long, upon which the BIOSPAR electronics circuitry is mounted. A mast carries a strobe light flasher, VHF radio circuitry in a PVC housing and antenna, and ARGOS satellite communication's circuitry in a PVC housing and antenna. Three solar panels are located on the top plate below the mast and provide power to recharge the buoy's batteries. Attached to the bottom end cap is an aluminum mounting bracket to which the 420 and 120 kHz transducers are attached. A cage extends below the mounting plate and protects the transducers without interfering with acoustic transmission or reception. Both transducers are built to survive a depth of 1000 m and operate with a 560 watt peak transmit power at a 10% duty cycle. Major components of the circuitry are the echo-sounder transmitter, receiver and digital signal processor, the controller, the ARGOS and VHF telemetry systems, and the power system.

BIOSPAR, as presently designed, can acoustically sample the upper 50 to 100 m water column and provide estimates of acoustic volume backscatter. The target strengths of individual zooplankton can be measured in near surface waters, while larger targets can be detected individually at greater depths. From this acoustic information, estimates can be made of zooplankton biomass and the size distribution of micronekton and nekton.

Results from the first field deployment of BIOSPAR: Time-series measurements were made from BIOSPAR that was tethered to an "S" mooring at a site on the southern flank of Georges Bank in approximately 80 m water depth (Fig. 16). BIOSPAR was deployed at the mooring site on 21 May 1992 and was recovered on 27 May. It operated successfully for the duration of the mooring period on the 120 kHz frequency. The tethered instrument provided volume backscattering and target strength information down to the bottom over the entire time the mooring was in place. Profiles of acoustic backscattering were obtained in one m depth intervals throughout the water column. The operating software was programmed to collect data for one min every 15 min; for each frequency the data consisted of individual target strengths as a function of range (six pings/frequency), and average backscattering strength (54 pings/frequency) for each one m range interval. Data were stored on an optical disk unit in the buoy for post-processing. Reduced data (in the form of minimum, maximum, and average target strength and integrated intensity for 10 depth intervals at each frequency) were transmitted to shore daily over a 4-day period *via* the ARGOS satellite. The full complement of data was transmitted in real-time by VHF radio

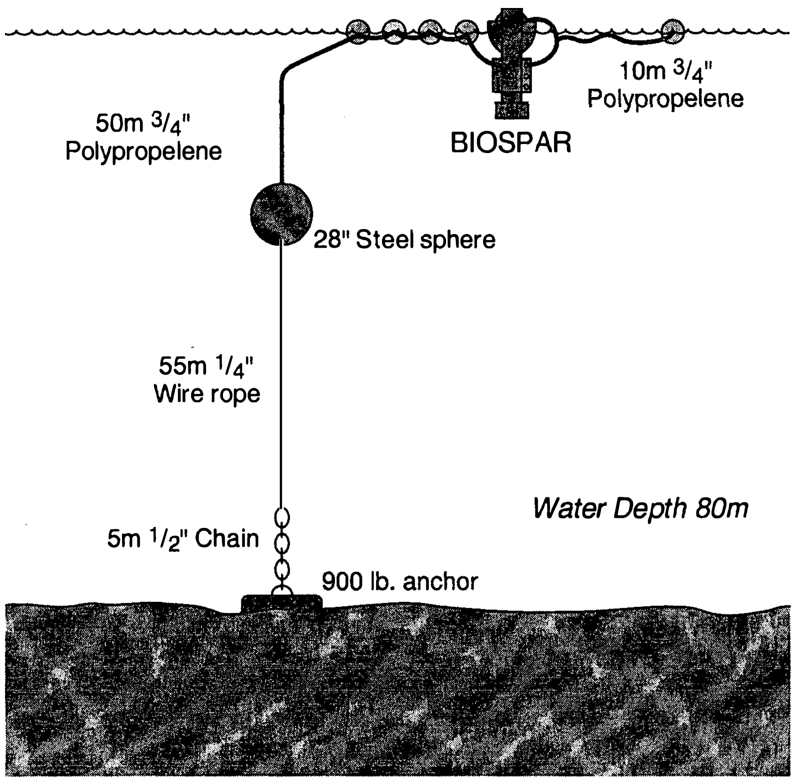

Fig. 16. Schematic drawing of BIOSPAR in the S-tethered configuration used during the Georges Bank experiment in May 1992.

telemetry to the ship when it was within five to 10 km of the buoy. These data were processed on board the ship to evaluate the echo sounder's technical engineering performance and to identify problems and modifications needed in the BIOSPAR software.

The data were also compared with measurements made from the ENDECO towed body to evaluate the buoy's acoustical performance with that of a known instrument. Data from this sounder were observed on an oscilloscope and computer processed in real-time; the analog signals from the echo sounder were recorded on a Sony DAT tape recorder for post-processing of data from selected grid studies and transect lines.

The BIOSPAR data acquired through the VHF telemetry link were converted into volume backscattering and plotted as vertical profiles *versus* time. A significant diel cycle was observed which consisted of a layer of high volume backscattering residing at mid-depths (~40 m) during the day and moving up into the surface layer at dusk (Fig. 17). Large transient targets, which may have been schools of herring or other larger fish, appeared from time to time at mid-depth to just above the bottom.

Two experiments were conducted to obtain ENDECO towed body 420 kHz echo integration data next to BIOSPAR. Both times the RV/Albatross IV maintained a position within 50 to 200 m of BIOSPAR for two to three hours while the two sounders were operating. Comparison of these data sets revealed that overall, the BIOSPAR 120 kHz system produced generally a factor of 10

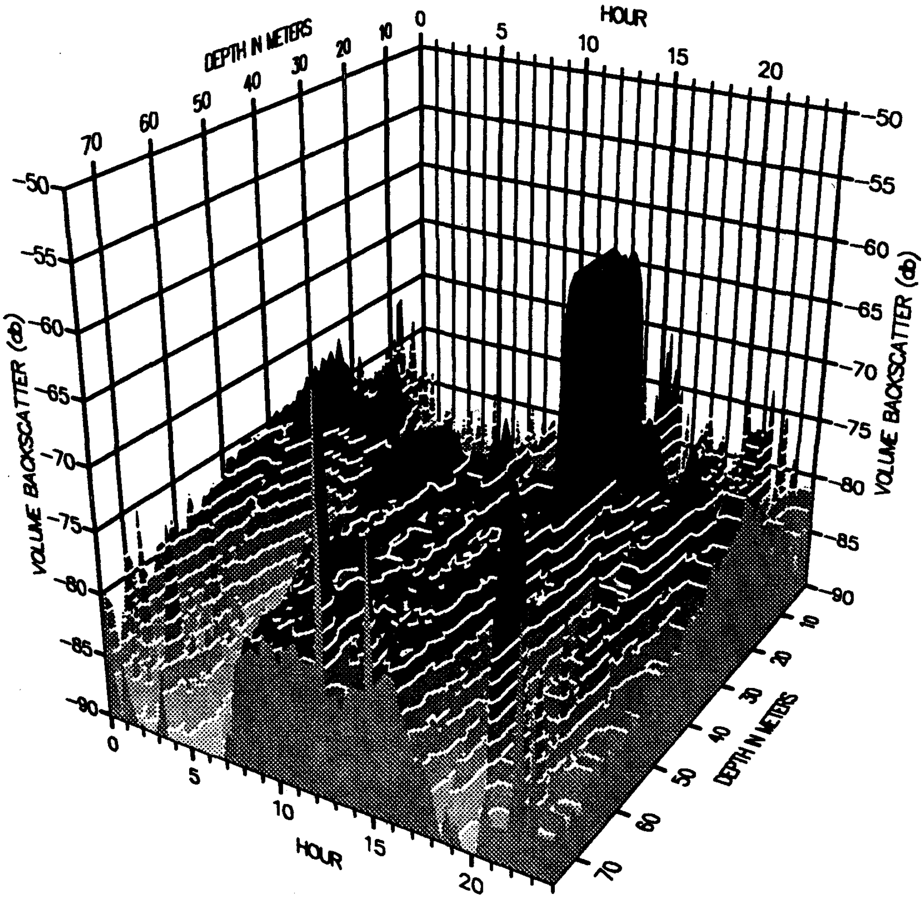

Fig. 17. BIOSPAR volume backscattering for 23 May 1992. The buoy was S-tethered anchored at the Fixed Mooring Site (see Fig. 9). Note large peak of volume back scatterers about 1500 hrs at 10–20 m. We speculate that it is a herring fish school which was also observed with the ENDECO towed body 420 kHz echosounder.

lower levels of volume backscattering than the 420 kHz sounder. This was expected because the abundance of targets detectable at 120 kHz (minimum detectable size ~10 mm) was significantly lower than the abundance of those detectable at 420 kHz (minimum detectable size ~4 mm). The 420 kHz sounder revealed a substantially different vertical distribution of the organisms in the water column. Heaviest volume backscatter was in the surface waters or at shallower subsurface depths, and much lower densities occurred at depths where the 120 kHz measured a pronounced peak. Our preliminary analysis suggests that the differences are real and reflect the difference in vertical distribution of the organisms detectable by the two frequencies. When a large fish school moved into the area, it was observed simultaneously by both BIOSPAR and the ENDECO towed body.

4. Problems to Be Addressed

A number of problems associated with using acoustics as a quantitative tool to determine the spatial distribution of plankton remain to be resolved. The following is a brief description of those that appear to be most pressing.

4.1. Technology based problems

The current state of hardware and software development still limits widespread and long-term use of acoustical systems. Some of the problems are: the high cost of most off-the-shelf systems, lack of sufficient data capacity in small low-power data storage devices, and the lack of availability of inexpensive multi-beam transducers that can be deployed to full ocean depth. In autonomous systems, there is a need for low power on-board computers, digital signal processors, echo sounders, and telemetry systems. The development of a standard data storage format for all acoustic systems would encourage and enable better software development both for data acquisition and for post-processing.

4.2. Biologically based problems

The relationships between target strength and zooplankton size, shape, body composition, and orientation are generally poorly known. More important, we need to know what the frequency response of target strength is to these parameters. Recent research has shown that because of modal variation, it is possible for an animal of small size to produce a target strength, at a particular frequency, which is larger than that produced by a larger individual (CHU *et al.*, 1992; STANTON *et al.*, 1993). The extent to which this process affects in situ field determinations of target strength distributions has not yet been resolved. Intercalibration studies comparing echo sounders operating with different frequencies and of different designs are needed.

Target tracking is also an essential element in future studies because a single echo from an individual is not sufficient to characterize its target strength (DAWSON and KARP, 1990; WIEBE *et al.*, 1990; GREENE *et al.*, 1992). The more pings, the better the estimate of the target strength of an individual. To some extent multiple pings on a single individual will reduce the errors associated with shape and orientation mentioned above. One problem associated with target tracking is determining that successive echoes are, in fact, from the same individual.

Three-dimensional visualization of volume scattering is also an increasingly important aspect of bioacoustical data processing (WIEBE *et al.*, 1992). For most research programs today, the development of an image of the spatial arrangement of organisms is but the first step in efforts to study and understand their relationships to each other and to their environment. Thus, there is a need for real-time 3-D images. When data are collected to create 3-D images, the information is commingled in space and time, since synoptic high-frequency acoustical images over large ocean areas are not yet feasible. One problem is that the fluid field that is being ensonified is moving (*i.e.,* there is current which is not necessarily uniform in space, *i.e.* it is often sheared flow). Techniques to track the water movements and to remove the effects of water motion while reconstructing the organism's 3-D distribution need considerable attention and effort.

Finally, the use of higher frequency sound to detect the presence of marine zooplankton may open the possibility of misinterpretation of the backscattering signal. Confounding sources of backscattering are the zooplankton and micronekton and the physical microstructure. This situation is a fundamental problem in bioacoustics rooted in the degree to which volume reverberation results from organism backscattering as opposed to ocean microstructure (STANTON, 1989a; GOODMAN, 1990). This problem is of particular concern to biologists interested in applying acoustical techniques to the study of micro-(<one m) and fine-scale (1's to 10's of m) distributions, behavior, and orientation of animals in vertically stratified or dynamically active physical situations. In most prior studies, it has been assumed that backscattering, even in strong gradients or turbulent flows, is due to reverberation from the particulates present in the water, most of which are biological in origin or biological entities themselves. There is evidence, however, that the physical structure of the water itself may be a source of reverberation especially in areas of intense activity such as in a breaking internal wave (GOODMAN, 1990; HAURY *et al.*, 1983: ORR and HESS, 1978; PRONI and APEL, 1975; MUNK and GARRETT, 1973). This is obviously a serious problem from the biological point of view, since any contribution to the backscattering that is not biological in origin is a source of error. It also is a problem for physicists using acoustics to visualize strong gradients and flow fields. Inaccuracies in the visualization will occur if the backscattering sources are variable in time and space. Reliable bioacoustical tools and techniques must be developed to discriminate physical/biological sources of backscatter, especially in regions of strong gradients where organisms tend to aggregate and important bio-physical interactions are believed to take place.

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