

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/240590768>

# Determination of zooplankton size and distribution with multifrequency acoustic technology

Article in ICES Journal of Marine Science · January 1989

DOI: 10.1093/icesjms/46.1.52

---

CITATIONS

120

---

READS

136

3 authors, including:



**Richard E Pieper**

University of Southern California

30 PUBLICATIONS 1,238 CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:



Thin Layer Dynamics [View project](#)

## Determination of zooplankton size and distribution with multifrequency acoustic technology

D. V. Holliday, R. E. Pieper, and G. S. Kleppel

Holliday, D. V., Pieper, R. E., and Kleppel, G. S. 1989. Determination of zooplankton size and distribution with multifrequency acoustic technology. - J. Cons. int. Explor. Mer, 46: 52-61.

The theoretical basis for using multiple acoustic frequencies in the assessment of the distributions of small zooplankton (ca. 0.1 mm to 10 mm in length) is discussed. One practical implementation of this theory is the Multifrequency Acoustic Profiling System (MAPS). The MAPS uses 21 discrete frequencies in the band between 100 kHz and 10 MHz. Acoustic data collected with this system are transformed to plots of zooplankton abundance versus size and depth for individual casts. Acoustic estimates of abundance versus size for individual casts are combined to illustrate two-dimensional spatial distribution and temporal variations. These patterns are compared with data collected at the same time for temperature, salinity, and chlorophyll fluorescence. Illustrations from several contrasting environments are included.

Nous discutons les raisons théoriques pour l'utilisation de fréquences acoustiques multiples pour l'évaluation des distributions de zooplancton (ca. 0.1 à 10 mm de longueur). Un usage pratique de cette théorie est le «Multifrequency Acoustic Profiling System» (MAPS). Le MAPS utilise 21 fréquences séparées dans la bande entre 100 kHz et 10 MHz. Nous transformons les données acoustiques récoltées avec ce système en graphes d'abondance de zooplancton contre leurs dimensions et contre la profondeur de mises-à-l'eau individuelles. Les estimations acoustiques d'abondance contre leurs dimensions pour les mises-à-l'eau individuelles sont combinées pour illustrer la distribution spatiale en deux dimensions et les variations temporelles. Ces résultats sont comparés avec les données de température, de salinité, et de fluorescence de la chlorophylle recueillies simultanément. Des exemples de plusieurs environnements différents sont inclus.

*D. V. Holliday: Tracor Applied Sciences, 9150 Chesapeake Drive, San Diego, California 92123, USA. R. E. Pieper: University of Southern California, 820 South Seaside Avenue, Terminal Island, California 90731, USA. G. S. Kleppel: Nova University, 800 N. Ocean Drive, Dania, Florida 33004, USA.*

### Introduction

Application of acoustic methods to the study of zooplankton is relatively new, compared with the use of acoustic technology in fisheries science. Nevertheless, substantial advances have been made during the last decade in applying acoustics to the detection and definition of spatial and temporal patterns in zooplankton. There are obvious similarities between acoustic instrumentation used to study zooplankton and fish. In this paper, however, it is our intention to focus on the differences in the technology which are essential to the detection and quantification of zooplankton, as opposed to nekton, and to point out subtle, but important, differences in the philosophical approach that appears to be evolving in the study of plankton with acoustic instrumentation.

The Multifrequency Acoustic Profiling System

(MAPS) is one of the more complex acoustic instruments currently in use for studying zooplankton. The MAPS incorporates many of the essential design features we have found to be necessary for the detection, estimation of abundance (with size discrimination), and description of zooplankton patterns in time and space in relation to the physical environment and the phytoplankton.

### Methods

#### Rationale for the MAPS

The evolution of the MAPS has been driven by a desire to understand the ecological relationships for plankton in the open ocean environment well enough to develop and validate predictive models. It was immediately recognized that such models would be most useful if they

incorporated heterogeneity on scales down to those which are important to individuals, i.e., temporal and spatial scales commensurate with ambit of an individual plankter. Conventional sampling technology, e.g., nets and pumps, were not adequate to the task. Sampling errors due to avoidance, size and species selectivity, the necessity to integrate over relatively long distances and times, and the time and costs associated with conventional processing of samples were identified as serious constraints.

Real-time feedback from data collected during a cruise is rarely used to adapt sampling strategies to account for the organisms present and their distribution. For example, selection of sampling gear (net, pump, mesh size, etc.) could be based on the characteristics of the organisms present when such data are available. Real-time adaptation of sampling effort in the vertical and horizontal to the spatial patterns encountered is not normally a part of a survey design in biological oceanography. Further, our limited ability to collect or process large numbers of samples by conventional techniques often leads us to resort to traditional methods of designing surveys in order to make the best possible gross estimates of mean abundance and variability. A sampling strategy designed in this way can blur or obscure patterns that could be extremely useful in the description of coherence between various biological distributions (phytoplankton, zooplankton, micro-nekton, and nekton) and physical variables (e.g., temperature, salinity, currents, light). The MAPS was designed to improve immediate information on the size and patchiness of organisms present. This allows the investigator to adapt the sampling strategy (places, times, and gear) to the character of the distribution and organisms present.

The use of optical fluorescence to estimate chlorophyll distributions in a rapid, continuous measurement had revealed useful pattern for phytoplankton ecologists (Platt, 1978). Similarly, the development of echosounder and echo-integrator technology in the fisheries assessment field, provided a pseudo-continuous coverage which allows definition of pattern for the nekton. It was apparent that an analogous tool for use in the determination of zooplankton distributions was desirable. The MAPS was developed to allow rapid, high-density spatial coverage. Two modes of operation, towing with dynamic depth control from the surface and casts at discrete locations and times, have been successfully used.

In order to achieve a high probability of detecting an object underwater with acoustics (in the absence of an associated gas bubble), it is desirable that the wavelength of the sound be on the order of, or shorter than, the size of the scattering object. This leads to a requirement for exceptionally high acoustic frequencies in an echo-ranging system designed for use in detecting small plankton. If we wish to study plankters of about 1 mm in length, and if the shape of the animal is similar to that

of a common calanoid copepod, then the acoustic measure of the size, the radius of a sphere of equivalent volume, is approximately 0.25 mm. The acoustic frequency which produces a wavelength of this size is about 6 MHz. Since sound is attenuated rapidly with distance at high frequencies, and there are physical constraints on the energy density one can transmit into the water, it is necessary that the acoustic instrument be placed within a few metres of the target organisms in order to achieve reliable detection.

This use of very high acoustic frequencies and the resulting constraint on the distance from the organisms at which one can operate represent significant deviations from the conventional fisheries-acoustics technology. For example, hull-mounted systems may be very limited in depth coverage. This limitation depends on the sizes of organisms one wishes to investigate. The larger zooplankton and fish larvae can often be detected with frequencies in the low 100s of kHz. Depending on the depth distribution of the organisms of interest, it is sometimes practical to work from a hull-mounted or towed transducer near the surface. For smaller plankton, this is usually not practical owing to the increased absorption of sound at high frequencies. The inclusion of larger, less abundant, but high-target-strength organisms in the relatively large sampling volumes (at depth) from a surface-mounted system also complicates the operation of acoustic systems designed to investigate small plankton from near-surface platforms.

Several acoustic approaches with decidedly different complexities and potential for the study of zooplankton have been previously identified. Greenlaw (1979) provides a good discussion of the options. In the simplest technique, a single acoustic frequency could be used to measure scattering from zooplankton. Biomass could then be estimated if the scattering was dominated by scattering from a single-size organism and its size was known. An extension of this single-frequency technique involves knowledge (either *a priori* or by *in situ* measurement) of the size spectra of the organisms in the study area and the existence of a validated mathematical model for acoustic scattering from these organisms. Several techniques, including the dual-beam and split-beam methods, have been developed to aid in obtaining the necessary scatterer size spectra. Operating within these assumptions, spatial pattern could then be obtained by an appropriate sensor deployment, e.g., casts, tow-yo, etc.

The more complex technique, involving the use of multiple acoustic frequencies, offered the potential for determination of zooplankton abundance by size. The multifrequency approach, which evolved into the current version of the MAPS, is briefly described below.

### Theoretical basis for the MAPS

The basis for the MAPS originates in the theoretical, experimentally validated, dependence of acoustic backscattering on the size and abundance of the zooplankters present in an ensonified volume. The scattering also depends on the frequency of the sound used and on the sound speed and density contrasts of the scattering organisms with surrounding water.

If one ensonifies an organism of size ( $a$ ) with a sound at frequency ( $f$ ), the amount of sound scattered directly back toward the original source of the sound can be described by a scalar quantity called the scattering cross-section  $s_{ij}$ , where  $i$  is the index for frequency and  $j$  is the index for size. Minimization of the vector expression,

$$\mathbf{S} - \mathbf{s}\mathbf{n},$$

where  $\mathbf{s}$  represents the matrix of scattering cross-sections  $s_{ij}$ , results in a solution for the vector  $\mathbf{n}$  whose elements  $n_j$  are the acoustically estimated numerical abundance of plankton at size  $j$ . The elements of vector  $\mathbf{S}$ ,  $S_i$ , are the measured volume scattering strengths at frequencies  $i$ , of a volume of water containing the organisms of interest. The solution vector  $\mathbf{n}$  can be written as

$$\mathbf{n} = (\mathbf{s}^T \mathbf{s})^{-1} \mathbf{S}.$$

Here,  $\mathbf{s}^T$  is the transpose of the matrix  $\mathbf{s}$ , and  $(\mathbf{s}^T \mathbf{s})^{-1}$  is the inverse of the matrix product  $\mathbf{s}^T \mathbf{s}$ . The vector  $\mathbf{n}$  can be considered the size spectrum for the organisms in the scattering volume. In practice, several uncertainties are introduced into the measurement of the vector  $\mathbf{S}$  and are also present in the elements of the scattering matrix  $\mathbf{s}$ . This complication can be resolved by adjoining a constraint matrix to  $\mathbf{s}$  and a null vector to the vector  $\mathbf{S}$ . The result is a nonlinear, non-negative least-squares (NNLS) problem which can be solved by several methods, one of which is due to Lawson and Hanson (1974). The result is a unique solution (Leih and Holliday, 1982) which provides the best possible estimate of the vector  $\mathbf{n}$  under the constraint that the abundance calculated for each size class be zero or greater. More detail on the necessity for the constrained solution can be found in Holliday (1977), and a good discussion of the inverse process is in Greenlaw and Johnson (1983).

In formulating the general problem, as illustrated above, we make no assumption regarding the character of the scattering organisms. The formalism has been successfully used for swimbladder-bearing epipelagic nekton (Holliday, 1980), for mesopelagic fish, principally myctophiids (Kalish *et al.*, 1986), and for small zooplankton, mostly copepods (Holliday, 1987). Both the frequency band and the experimental sampling volume in the MAPS are selected to maximize the probability that the scattering is dominated by small zooplankton. The acoustic model used for the current gen-

eration of the MAPS is a truncated version of the fluid-sphere scattering model developed by Anderson (1950). Additional detail on our use of this model is available in Pieper and Holliday (1984). While the robustness of the solution has not yet been experimentally validated for the case of a mixed population whose scattering cross-sections have significantly different dependencies on frequency and size, this generalization is mathematically rigorous (Holliday, 1977). In this latter case, solution of the inverse problem should result in a degree of target classification, partitioning the biomass into size spectra for each of the organism types represented by the scattering models included in the calculation.

There are subtle, but important, differences in the formulation of the problem of using acoustics to quantify fish and plankton distributions. At least three approaches are currently in use. The first involves measurement of the acoustic scattering from some range of depths, followed by an attempt to sample the organisms that were present at those depths. The organisms are then measured, the biomass is estimated, and a regression between biomass and acoustic scattering computed, providing an "intercalibration" between the acoustic scattering and the organisms thought to be responsible for the scattering.

The remaining approaches are more sophisticated, requiring a mathematical model to represent the relation between the scattering organism (usually parameterized with size, abundance, and acoustic frequency) and the volume scattering strength. The second approach utilizes an empirical model, and relies on an experimentally determined regression between acoustic target strength and organism size.

The third approach relies on models developed from first principles of physical acoustics, the morphology of the animal and the density and compressibility contrasts of the organisms with their local environment. The acoustic measures of scattering strength and the descriptors of the model parameters can be documented in absolute units, i.e., they are traceable to accepted, widely available standards. This allows comparison of results between different apparatus, investigators, times, and locations of surveys. Within the limits of current measurement and modeling technology, this approach has been the one we have attempted to follow for the MAPS and in our opinion offers the best long-term approach to quantification and classification of organisms without resort to direct sampling.

In those methodologies that use a comparison of acoustic backscattering and net or pump data, there are always identifiable error sources in the acoustic measurements (e.g., acoustic background noise, system noise). There are also inherent errors in the net or pump samples used as "ground truth" (e.g., avoidance, differences in sampled volume for the acoustic and direct samples). Thus, if one uses an "intercalibration" technique, the end result is often less accurate than the

direct sampling alone. Even so, experimental scenarios can be conceived in which the advantages of spatial and temporal resolution and the relative cost and speed of an acoustic approach outweigh the inaccuracies due to this kind of "calibration". This is especially the case when pattern, perhaps in relation to some physical oceanographic measure or topographic feature, is of primary interest.

The theoretical formulation developed for the MAPS can utilize an empirical estimation of the backscattering cross-sections needed to define the matrix  $s$ . This two-parameter matrix can be generalized to treat even more dimensions (e.g., frequency, size, organism depth, observation aspect angle, oil or fat content, time to moult, etc.). The practical difficulties of making a sufficient number of measurements to define a universally useful  $s$  empirically are overwhelming. The alternative is to develop analytic forms for  $s$ , based on fundamental principles of physical acoustics, with physical, taxonomic, and biological characteristics as independent parameters. It is, of course, mandatory that any model be subjected to a rigorous experimental validation.

For the MAPS, we have followed the strategy for computing  $s$ , in which the first two terms of a fluid-sphere model are used to describe the functional dependence of scattering on size and acoustic frequency (Pieper and Holliday, 1984). This approximation is conceptually based on the absence of sufficient symmetry in most zooplankton stages and species to offer consistent support for higher order spherical vibration modes. The density ( $g$ ) and sound speed contrast ( $h$ ) of the organisms and the surrounding fluid (sea water) also enter this formulation. In the ocean environments we have investigated with MAPS, small crustaceans, e.g., copepods, were the dominant scatterers. We determined values of  $g = 1.09$  and  $h = 1.12$  to be representative for this component of the zooplankton. These values were derived from measured values of  $g$  and  $h$  (by determination of bulk sound speed) for a variety of live zooplankton, increased slightly to account for the expected effects of an elastic carapace. The increase in each contrast, about 3%, was based on measurements of the target strengths of genera that are well represented in our pump and net samples. We have found that this approach results in acoustic estimates of size and abundance that are comparable to those obtained by simultaneous direct pump sampling at a distance of about 1 m, horizontally displaced from the acoustic sampling volume. The variance between the acoustic and pump samples is comparable to the variance between replicate one-minute pump samples collected sequentially (Costello *et al.*, 1989).

While various investigators have had some success in developing mathematical models for specific classes of zooplanktonic scatterers, e.g., bubble-bearing organisms, small zooplankton (nauplii and small copepods), and elongate zooplankton (euphausiids), interesting challenges remain. The development of realistic models

for zooplankton, even relatively simple ones, is already computationally non-trivial. Progress in this area should be accelerated as supercomputers become more accessible to scientists involved in this research effort. It should be noted, however, that added complexity in the models is not entirely sufficient to assure advances which make use of those second-order acoustic target characteristics on which classification and identification will ultimately depend. New developments in experimental technique and apparatus are also required to measure physical properties of parts of live animals, e.g., the density, compressibility, and elastic modulus of the material of the carapace. While the results we have obtained in systems dominated by crustaceans compare well with direct sampling, the indiscriminate use of the average values cited above in systems dominated by soft body scatterers (e.g., chaetognaths, doliolids, larvaceans) could lead to underestimates of abundance. The lack of adequate measurement techniques for determining the physical properties of live zooplankton parts remains a significant barrier in the advancement of this acoustic technology.

On the short term, for acoustic studies involving zooplankton, an important place may be found for those implementations of acoustic technology which depend on conventional, direct sampling for "intercalibration". Indeed, time and cost constraints and the relatively continuous acoustic estimates of biomass, which may illustrate pattern, may outweigh the fact that the acoustic result developed in this way may be in fact less accurate than data obtained by direct sampling with the same spatial or temporal resolution.

On the longer term, we believe that it is mandatory that basic research be devoted to analytic definition of acoustic scattering from zooplankton based on their size, shape, morphology, and material properties. This approach has the potential for stimulating an effort toward a quantitative understanding that may be lost in an empirical or measurement-based modeling approach.

### Characteristics of the MAPS

The MAPS described in Table 1 is three generations removed from the original concept. Those characteristics are listed which have been found most useful in the definition of zooplankton distribution, dynamics, and in directed sampling for feeding studies.

Data are initially displayed as plots of the various measured parameters as a function of depth. These parameters include abiotic (temperature, conductivity, salinity, sigma-t, buoyancy frequency, and downwelling light) and biotic (zooplankton size-abundance spectra, total zooplankton biovolume, fluorescence, and chlorophyll derived from fluorescence) measurements. If more than one profile is collected at different times or

Table 1. General specifications of the MAPS.

|                                             |                                                                                                                                          |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Frequency span                              | 100 kHz to 10 MHz                                                                                                                        |
| Number of frequencies                       | 21, log spacing                                                                                                                          |
| Pulse length                                | 50 $\mu$ sec, programmable                                                                                                               |
| Volume sampled                              | Ca. 0.01 m <sup>3</sup>                                                                                                                  |
| Pulse repetition rate                       | 21 frequencies in 21/30 sec                                                                                                              |
| Maximum operating depth                     | Cable limited at 135 m                                                                                                                   |
| Calibration technique                       | Self reciprocity                                                                                                                         |
| Vertical resolution                         | Normal: 2 m; maximum: 0.1 m                                                                                                              |
| Operating modes                             | Cast or towed                                                                                                                            |
| Ancillary measurements ( <i>in situ</i> )   | Depth, temperature, conductivity, downwelling light, fluorescence                                                                        |
| Ancillary measurements (as required)        | Three pumps (1", 2", and 3"-diameter hoses)                                                                                              |
| Active control of depth and list when towed |                                                                                                                                          |
| Data logging                                | Conversion to engineering units<br>Medium: floppy disks                                                                                  |
| Real-time data processing                   | Echo integration, ensemble averaging, depth binning                                                                                      |
| Displays (real time)                        | Data quality control, alarms (data sync, leak detection, etc.), binned volume scattering strengths vs depth, ancillary measures vs depth |

along a transect, sections or time series for any of the parameters discussed above can be formed from the individual profiles and displayed.

The entire data-acquisition and display process is controlled by two computers operating in parallel. One of these is used to interface to the user, control the programmable modes and timing in the underwater instrument package, and perform ping-to-ping integration, echo integration over the range gate, normally 1–2 m from the transducer package. This computer also formats the real-time data displays used for assur-

ing data quality, applies calibration constants to convert measurements to standard scientific units, records the "raw" data on floppy disks, and passes data to a second computer. The second computer is used to bin all of the data into (programmable, but typically) 2-m intervals and to display the result in a colour contour format. Between stations, this machine can be used to compute and display the data products listed under the last entry in Table 1.

A transducer, transmitter, and preamplifier are dedicated to each frequency. This approach, with an appropriate increase in software complexity, provides a degree of "graceful degradation". Should one or more hardware (frequency) channels fail, the system can be operated with an appropriately reduced resolution in the calculation of the size abundance spectra. The power amplifiers are digitally driven, operate in a switching mode, and use hexfet technology. The maximum electrical power provided for each channel is 100 watts, but the acoustic source level varies with the efficiency and directivity of each transducer. The receiving sensitivity and the source levels as well as the transmit and receiving directivity are measured by either a self-reciprocity method (Urick, 1967, or Bobber, 1970) or on occasion by comparison with a standard transducer/hydrophone.

The transducers are piezoelectric (barium titanate-lead zirconate) disks. The disk diameter at each frequency was selected to ensonify a common volume of about 0.01 cubic metres when echoes from a 50- $\mu$ sec pulse are gated into the receiver from a distance between one and two metres horizontally displaced from the transducers.

The receivers include a low noise gain stage, a transmit/receive switch, a baseband digital quadrature square law detector and a computer-controlled digital echo integrator for a programmed range gate.

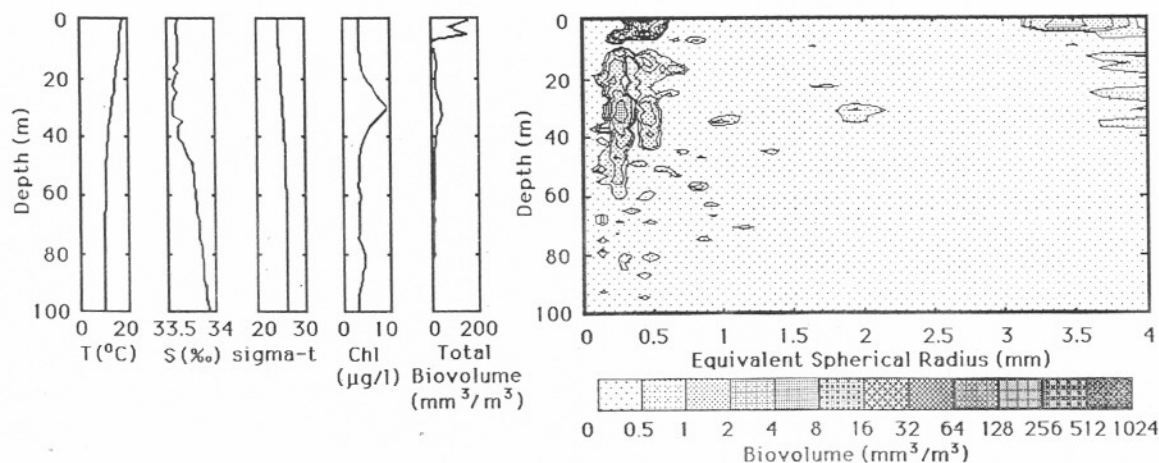


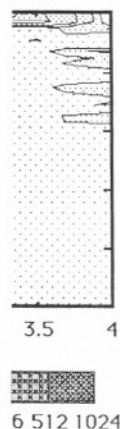
Figure 1. MAPS data from a station off Southern California. These data were collected aboard "Velero IV" in the San Pedro Basin (33°22.23'N 118°17.08'W) at 18:49 local time on 3 June 1985.

is to convert records the to a second in all of the -m intervals our format. to compute he last entry

ier are dedi- h an appro- vides a de- ne or more stem can be esolution in pectra. The perate in a . The maxi- annel is 100 ith the effi- he receiving the transmit ither a self- er, 1970) or transducer/

um titanate- at each fre- 1 volume of n a 50- $\mu$ sec distance be- placed from

age, a trans- quadrature olled digital ite.



ic San Pedro

## Results

Data are presented from four contrasting ocean environments to illustrate the resolution and type of data we can currently obtain with an acoustic system designed specifically to study small zooplankton in the marine environment. The data are from studies conducted in the San Pedro basin of the Southern California Bight, in the coastal transition zone off the northern California coast, at the northwest wall of the Gulf Stream near Cape Hatteras, North Carolina, and on the continental shelf near Cape Canaveral, Florida.

### Southern California Bight

The MAPS was used to determine zooplankton size spectra for the upper 100 m in the San Pedro basin on 3 June 1985. This is a continental borderland near the coast of Southern California. Water depths are over 600 m in the area, and the species are predominantly oceanic. The data illustrated (Fig. 1) are from one of a series of casts made hourly at the location of a drogus for a period of 24 hours. The biovolume, an analogue of biomass (similar to displacement volume), is displayed as shaded contours versus depth and the equivalent spherical radius (esr) of the plankters. Contours are spaced to indicate a doubling of the biomass between each pair of lines.

Most of the biomass was concentrated in three size groups in the seasonal upper mixed layer near the surface. These data were collected at 18:49 local time, and the diel vertical migration had not reached the surface. The vertical distribution of organisms near 0.25-mm size (esr) did not extend to the surface, and their upper limit is coincident with a shallow layer of water that had been warmed during the same day. The groups centred

near 0.45-mm and 3.5-mm esr extended to at least 0.5 m below the surface. While we did not attempt direct sampling at the time this cast was made, a hypothesis that the organisms greater than 3-mm esr included fish larvae would be consistent with our experience in this ocean area and season.

An assemblage of organisms centred near 0.25-mm esr was distributed from the upper limit of the pycnocline (ca. 10 m) to the lower boundary of the thermocline (ca. 60 m). The maximum concentration ( $13.1 \text{ mm}^3/\text{m}^3$ ) at about 35 m was coincident with the chlorophyll maximum. The size distribution centred near 0.48 mm was also bounded by the lower limit of the upper mixed layer, but the lower bound (ca. 44 m) coincided with a discontinuity in the halocline. Additional low biomass distributions were located throughout the depth-esr space. Two of these, near 1 mm and 2 mm, were also associated with the chlorophyll maximum.

### Coastal transition zone

The coastal transition zone (CTZ) is a complex oceanographic area located in deep water off the northern California coast. The surface manifestation of the circulation patterns in this area is a complex of "jets and/or squirts" and associated eddies. These features often contain relatively cold upwelled water which can be transported offshore, across the California Current, into the central Pacific Ocean.

The zooplankton size spectra versus depth for a station at the inshore end of a "jet" are similar in pattern to the data collected in Southern California. These data (Fig. 2) were collected on 30 July 1987 at 09:30 local time. The assemblage near the surface appeared to be more diverse, with at least six distinct size groups pre-

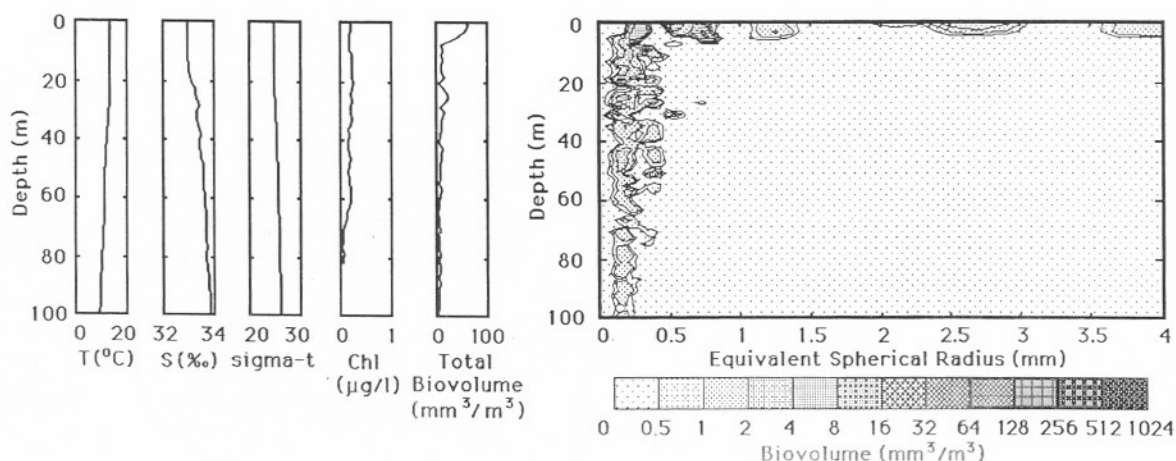


Figure 2. MAPS data from a station off Northern California. These data were collected aboard "Pt. Sur" in the coastal transition zone ( $38^{\circ}30.82'N$   $124^{\circ}05.52'W$ ) at 09:30 local time on 30 July 1987.

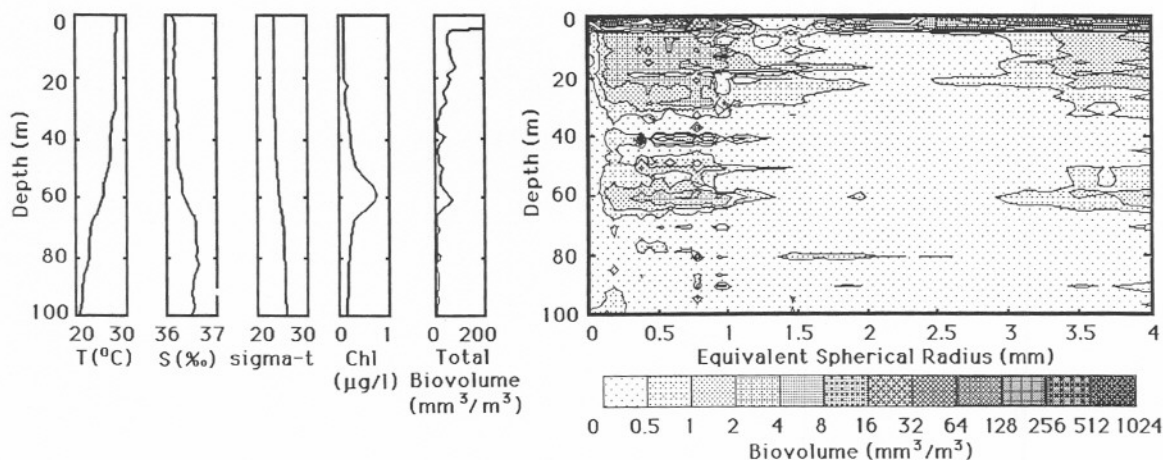


Figure 3. MAPS data from a station at the northwest wall of the Gulf Stream off Cape Hatteras, North Carolina (35°20'N 74°35'W). These data were collected at 11:35 local time on 12 August 1985.

sent. The total biomass in this surface assemblage is about one-half of that observed for the Southern California station discussed above.

Two size groups dominate the remainder of the biomass, one from about 0.1- to 0.2-mm and the other from about 0.25- to 0.45-mm esr. The smaller organisms were distributed with decreasing abundance from about 5 m to below 100 m. The chlorophyll concentrations (Fig. 2) were more than an order of magnitude lower than those measured in the San Pedro basin (Fig. 1). The phytoplankton present was also distributed in a relatively even manner over the upper 60 m. Nevertheless, the bounds of the larger size group are roughly delimited by the chlorophyll distribution. A break in the distribution of the smaller size group also occurred near the lower limit of the chlorophyll distribution. The filament sampled during our cruise was in the summer period. Values for both chlorophyll and zooplankton may be lower than samples from such a structure during the spring period.

#### Oceanic frontal zone

The northwest wall of the Gulf Stream is a major ocean boundary between water masses. Its physical structure is both complex and dynamic. The cast discussed here (Fig. 3) is from one of a series collected across the boundary. This station was occupied at 11:35 on 12 August 1985. Examination of the cross-sections formed from those data reveals that the Gulf Stream water extended to a depth of only about 35 m at this station (cross-section data not included here).

At this station, below about 60 m, the water was colder and more saline (slope water). There was a transition zone between the two water masses (35 m to 60 m). This transition zone was the location of the chlo-

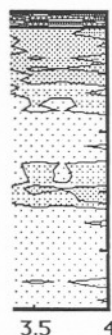
rophyll maximum. The acoustic estimate of the total biovolume (biovolume at each size class integrated over size) increased in the transition depth range. At this station, the increase was due to increases in both small and large plankton.

Most of the biomass at this station was in the upper 5 m. The total biovolume reached a value of 2768 mm<sup>3</sup>/m<sup>3</sup> at a depth of 1 m. With the exception of a small gap between 1.2-mm and 1.6-mm esr, all sizes within the range of our measurements were occupied in this near-surface zone.

#### Continental shelf

A station was occupied on 26 July 1985 at 07:20 local time on the continental shelf near Cape Canaveral, Florida. The water depth was 37 m, and our measurements were conducted about 60 hours after the passage of a hurricane. Sea conditions were exceptionally calm, and we were able to lower the MAPS to within about a metre of the bottom. An increase in acoustic scattering was observed near the bottom. Based on the very low scattering strengths for fine, suspended sediment (Holliday, 1987), it is likely that this layer was zooplankton rather than suspended sediment. While both larger and smaller size classes exhibited an increase at the bottom, much of the increase was due to a peak in the size spectra at 1 mm (27.5 mm<sup>3</sup>/m<sup>3</sup>). We have observed similar increases in biomass near the bottom at shallow-water coastal stations on the Pacific Coast of the United States.

Examination of the data in Figure 4 reveals a coherence between the shallow upper mixed layer (0–15 m) and organism abundance at both small and large sizes. The boundary of the well-mixed upper layer was correlated with the distribution of organisms between



5 512 1024

ina (35°20'N

of the total  
grated over  
ge. At this  
both small

1 the upper  
value of  
ception of a  
sr, all sizes  
occupied in

07:20 local  
Canaveral,  
ir measure-  
the passage  
nally calm,  
hin about a  
c scattering  
ie very low  
ient (Holli-  
oplankton  
larger and  
he bottom,  
in the size  
erved simi-  
at shallow-  
the United

ls a coher-  
(0-15 m)  
large sizes.  
was corre-  
s between

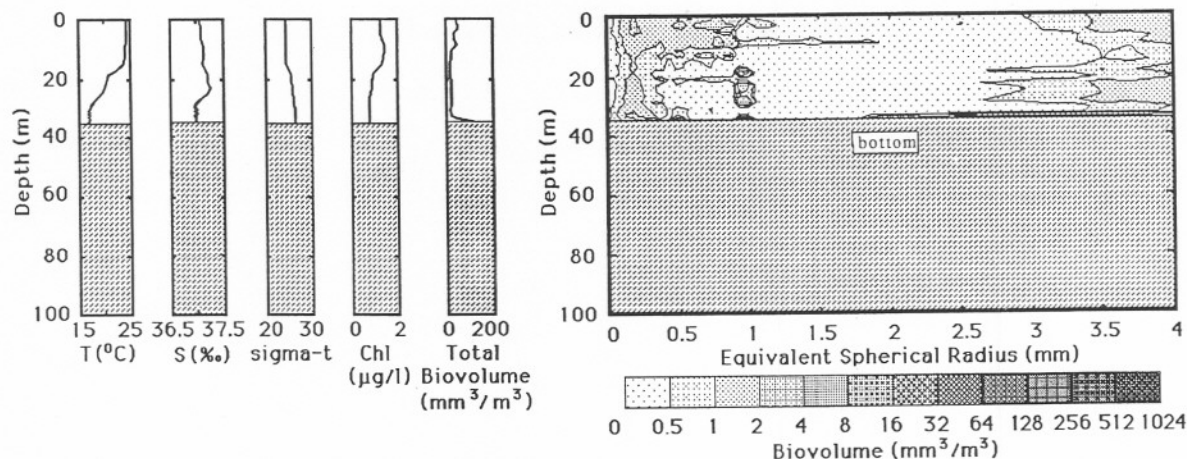


Figure 4. MAPS data from a station on the continental shelf at the western edge of the Gulf Stream off Cape Canaveral, Florida (28°13.7'N 80°12'W). These data were collected at 07:20 local time on 26 July 1985.

0.4-mm and 1.0-mm esr as well as those larger than 3.0-mm esr. A minimum in the vertical biomass distribution for the smaller organisms (ca. 0.05 mm to 0.45 mm) also occurs at the base of the upper mixed layer, but we did not collect organisms at this station, and are not able to ascertain the composition of the assemblage above and below this "boundary". The maximum chlorophyll values were also coincident with the upper mixed layer. The salinity maximum and the distribution of organisms between 18 and 30 m were coincident. A layer of organisms with sizes above about 2.75 mm was also located in the salinity maximum.

#### Continental shelf transect

Five stations were occupied on 26 July 1985, starting on the continental shelf off Cape Canaveral (see Fig. 4) at 07:20 and moving offshore. The last station was occupied at 22:10 local time. Sections of temperature, salinity, chlorophyll, and total biovolume versus depth are illustrated for this 48.9-km transect in Figure 5.

For temperatures greater than 26°C, the isotherms approach and intersect the surface at the inshore end of the transect (0 km). An isotherm elevation is evident below 10 m at a distance of 10 km from the west end (0 km) of the transect (Fig. 5a). In the region of the isotherm elevation, the isohalines exhibit a complex series of salinity reversals (Fig. 5b). Salinity increases with depth in Gulf Stream water, i.e., at the eastern edge of the transect (48.9 km). A high-salinity wedge appears to shoal from the Gulf Stream, shorewards, towards the region of the isotherm elevation. The chlorophyll section (Fig. 5c) shows a maximum in the upper 10 m over the isotherm elevation and salinity complex, possibly indicating a source of upwelling in this region. The illustration of total zooplankton biovolume

(Fig. 5d) indicates complexity in the zooplankton distribution as well. The highest values were found in the upper 10 m of the Gulf Stream (offshore). High values were also found in the upper 22 m at a distance of 22 km from Station 1, offset seaward from the region of the chlorophyll maximum and isotherm elevation.

#### Discussion and summary

When properly designed to match the assemblage of plankton (size, morphology, behaviour, etc.) and the environment one wishes to study, acoustic instrumentation can offer a rapid means of collecting detailed, quantitative information on the size, abundance, and spatial distribution of zooplankton in the marine environment. Enough is also now known to allow a low-risk extension of the technology to fresh water should this appear desirable. The experience gained with the MAPS may also allow the development of new, less complex instrumentation for specific organisms and environments.

Acoustic tools can be used in a "site specific" study, or to compare and contrast broader areas. As an example of the former type of study, multiple casts following a drogue for 24 hours revealed that the depths of the biomass peaks near 35 m (see Fig. 1) were vertically displaced by over 30 m during a 24-hour period by a tidally driven internal wave. This motion coincided with similar modulations of the thermocline and the chlorophyll maximum.

On a broader scale, comparison of the data from the Gulf Stream with those from the California Current reveals differences in the details of the size spectra. There are discrete sizes present in various layers throughout the water column in the California Current. In the Gulf Stream water, for the environments dis-

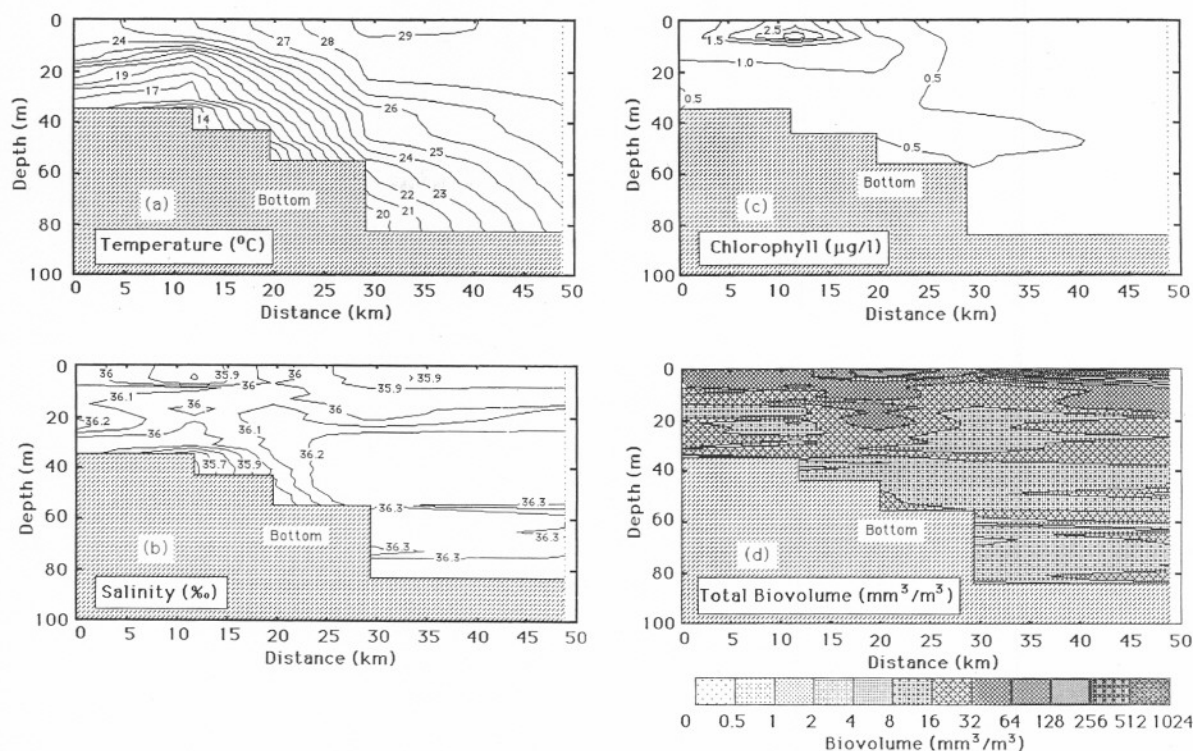


Figure 5. MAPS sections for temperature (a), salinity (b), chlorophyll (c), and biovolume (d) for a transect on the continental shelf off Cape Canaveral, Florida. The acoustically determined size spectra for the zooplankton at the western end (0 km) of the five station west-to-east transect are given in Figure 4. The total biovolume is derived by integrating over the size spectra between 0.025- and 4-mm esr. The western end of the 48.9-km transect was located near the normal position of the Gulf Stream core.

cussed, discrete peaks in the size spectra are present, but the biomass appears more evenly distributed in size.

The data set described highlights the importance of physical boundaries and gradients within the water column for zooplankton. Both maxima and minima are often observed in association with the bottom and the surface. It is also common to observe pattern in zooplankton abundance in relation to temperature, salinity, and chlorophyll maxima, minima, and gradients. While in some cases a zooplanktonic "preference" for water of a particular salinity, temperature, or phytoplankton distribution is likely, it is also probable that the coincidence of zooplankton biomass and these other water-column characteristics can be related to the origin and history of the water mass and its advected biological components.

While significant advances remain to be made in applying acoustic technology to the study of zooplankton, it is now time to ask new questions in zooplankton ecology – questions which it has not been practical to address with conventional sampling technology. Acoustic technology will almost certainly continue to advance. Today's challenges involve careful consideration of the scientific issues to be addressed with our new technologies and capabilities.

## Acknowledgements

Our appreciation is directed to the scientific and support staffs of Tracor Applied Sciences and the University of Southern California for their continuing support in the design and operation of the instrumentation used for data collection and in the analysis of that data. We also appreciate the special efforts of the captains and crews of the "Velero IV", the "Cape Florida", the "Gyre", and the "Pt. Sur". Steven Brandt, Clarence Clay, Gary Hitchcock, John Magnuson, Richard Nash, Peter Ortner, Mike Reeve, Sharon Smith, and Tim Stanton have all provided invaluable help at sea on some occasion. Special thanks are due John Dawson, David Doan, John Dmohowski, Peter Mull, Tom Boatright, Ed Houde, and Bernard Zahuranec. We should also like to thank an anonymous reviewer for a particularly careful and helpful review. This work was done under the sponsorship of the U.S. Office of Naval Research, Oceanic Biology Division, and the U.S. National Science Foundation, Ocean Sciences Division.



continental  
( km) of the  
tra between  
ream core.

c and sup-  
l the Uni-  
nuing sup-  
mentation  
that data.  
e captains  
rida", the  
Clarence  
ard Nash,  
and Tim  
at sea on  
Dawson,  
om Boat-  
We should  
r a partic-  
was done  
Naval Re-  
U.S. Na-  
ivision.

## References

- Anderson, V. C. 1950. Sound scattering from a fluid sphere. *J. Acoust. Soc. Am.*, 22: 426-431.
- Bobber, R. J. 1970. Underwater electroacoustic measurements. Naval Research Laboratory, Underwater Sound Reference Division, U.S. Govt. Printing Office Catalog No. D 210.2: UN2/2, pp. 27-43.
- Costello, J. H., Pieper, R. E., and Holliday, D. V. 1989. Comparison of acoustic and pump sampling techniques for the analysis of zooplankton distributions. *J. Plankton Res.* (in press).
- Greenlaw, C. F. 1979. Acoustical estimation of zooplankton populations. *Limnol. Oceanogr.*, 24(2): 226-242.
- Greenlaw, C. F., and Johnson, R. K. 1983. Multiple-frequency acoustical estimation. *Biol. Oceanogr.*, 2(2-3-4): 227-252.
- Holliday, D. V. 1977. Extracting biophysical information from the acoustic signatures of marine organisms. *In* *Oceanic sound scattering prediction*, pp. 619-624. Ed. by N. R. Anderson and B. J. Zahuranec. Plenum Press, New York.
- Holliday, D. V. 1980. Use of frequency diversity for marine biological measurements. *In* *Advanced concepts in ocean measurements for marine biology*, pp. 423-460. Ed. by F. P. Diemer *et al.* Belle Baruch Library in Marine Science, Number 10, University of South Carolina Press.
- Holliday, D. V. 1987. Acoustic determination of suspended particle size spectra. *In* *Coastal sediments '87*, pp. 260-272. WW Div./American Society of Civil Engineers (ASCE), New Orleans, Louisiana, May 12-14, 1987.
- Kalish, J. H., Greenlaw, C. F., Percy, W. G., and Holliday, D. V. 1986. The biological and acoustical structure of sound scattering layers off Oregon. *Deep-Sea Res.*, 33: 631-653.
- Lawson, C. L., and Hanson, R. J. 1974. Solving least squares problems. Prentice-Hall, Englewood Cliffs, New Jersey. 340 pp.
- Leih, T., and Holliday, D. V. 1982. Uniqueness of the non-negative least squares solution in the bioacoustic inverse problem. *Tracor Document No. T-81-SD-026-U*: 34 pp.
- Pieper, R. E., and Holliday, D. V. 1984. Acoustic measurements of zooplankton distributions in the sea. *J. Cons. int. Explor. Mer*, 41: 226-238.
- Platt, T. 1978. Spectra analysis of spatial structure in phytoplankton populations. *In* *Spatial pattern in plankton communities*, pp. 73-84. Ed. by J. H. Steele. NATO Conference Series IV: Marine Sciences, Vol. 3, Plenum Press, New York.
- Urick, R. J. 1967. Principles of underwater sound for engineers, pp. 37-39. McGraw-Hill, New York.