FOREWORD

A. R. MARGETTS
Symposium Convenor and Volume Editor

After World War 2 echo-sounders and sonar were developed rapidly and widely to become standard fishing vessel equipment for finding fish. Fisheries scientists, particularly in northern Europe, were soon looking into methods of using echo-sounders not only to find fish but to estimate the quantities of fish in an area. Their ideas and methods were developed very rapidly in the 1960s, so much so that by 1968 echo surveying with automated quantification of received fish echoes was in use as a method of fish abundance estimation. The methods were new, highly promising, but fraught with many sources of error.

Progress was reported regularly to the Gear and Behaviour Committee of the International Council for the Exploration of the Sea (ICES) at its annual Statutory Meetings. Through ICES and FAO, in March 1969 an Acoustic Training Course was held at Svolvaer in Norway, at which also the apparatus and methods developed separately in Norway, England, Scotland and the Netherlands were demonstrated and compared on research vessels at sea. The Svolvaer course was reported as FAO Fisheries Report No 78, 1969.


Acoustic assessment of fish stocks was just one, albeit then the outstandingly important one, of a wide range of uses of underwater acoustics being researched and developed at widely separated centres not only to improve detection of fish but also to provide new tools for research scientists. Their use was making possible new methods for assessing abundance of both adult and pre-recruit fish, for estimating the sizes of individual fish, for studying fish migrations and behaviour, and for investigating the performance of fishing gear and reactions of fish to gear.

ICES initiated, convened and organised a Symposium on Acoustic Methods in Fisheries Research, held in Bergen at the invitation of Norway, 19–22 June 1973. It was to provide a forum for the exchange of new research results, experience and ideas in this field between scientists from all parts of the world; specifically it did not include consideration either of the use and application of acoustic instruments in commercial fishing or of bioacoustics. FAO and the International Commission for the Northwest Atlantic Fisheries (ICNAF) collaborated with ICES in this Symposium and financially supported this publication.

Mr A. R. Margetts (Lowestoft, England), was convenor for the Symposium. He was assisted in the Scientific Planning Group by Mr L. A. Midttun (Bergen, Norway), Mr B. B. Parrish (Aberdeen, Scotland), Dr D. F. S. Raitt (FAO, Rome), Mr K. A. Smith (Woods Hole, USA) and Mr H. Tambs-Lyche (ICES).

Authors were invited to submit to the Symposium papers on acoustic methods applied to the topics set out as follows:

1 Fishing gear and topographical studies
2 Fish behaviour studies
3 Fish abundance estimation
4 Identification and sizing of echo targets
5 Novel instrumentation.

The Symposium was attended by 125 experts from 25 different countries throughout the world. An opening address was appropriately (because Norway was the host country and her scientists and technicians were amongst the pioneers of echo-sounder development) and kindly given by Mr K. Sunnanaa, Director General of Fisheries for Norway. He and all participants were welcomed by the President of ICES, M. R. Letaconnoux. Wherever possible, which, happily, was in the great majority of cases, papers were presented by their authors. Considerable and profitable discussion followed the presentation of papers, either individually or grouped according to topics. Altogether 50 papers were presented.

The first two programme sections, covering studies of fishing gear, topography, fish behaviour and migrations, illustrated the wide range of novel uses of underwater acoustic apparatus. High-resolution
sector scanning sonar had produced very impressive results in both fish behaviour and fishing gear investigations, particularly those concerning individual fish in the open sea while, in contrast, very long range low-frequency sonar provided a means of plotting fish shoals at a distance of many miles. A combination of two such systems could be invaluable to fisheries biologists. Acoustic transmitting and transponding tags were being used to follow fish movements and migrations, Doppler shift had been applied to the study of the dynamics of fish shoals and, in enclosed waters, a laid out range with hydrophones was being employed to track the detailed short-distance movement of acoustically tagged fish and the positions of towed gear. Now that data are collected by these methods at such an enormous rate, there is clearly a requirement for computerised methods of processing them: one computerized display of the direction and speed of movement of both fish and fishing gear during a fishing operation was presented.

The programme sections on fish abundance estimation and on fish target strength measurement and sizing provided very clear examples of how carefully thought-out and planned surveys using correctly designed and calibrated apparatus can quickly and comprehensively describe not only the distribution but also the quantity of pelagic fish in an area on a very large scale. No other method of such instantaneous assessment is comparably effective. But, inherent in the method are many sources of error. Together the presented papers and ensuing discussion showed that these were recognised and that various steps had already been taken, with varying but encouraging degrees of success, to eliminate or minimize biases and variances. The papers speak for themselves, but here it is to be noted firstly that, as yet, there is no acoustic method by which fish in the open sea or elsewhere can be identified so fish from which echoes are recorded must be sampled by some method such as fishing or photography, and, secondly, that thorough and correct calibration of acoustic apparatus is of paramount importance. Methods of calibration using live fish have proved reasonably successful; an elaborate experiment with simulated targets under large-scale laboratory conditions showed particularly how many serious and difficult to interpret inaccuracies can occur in an acoustic echo quantification system. The best measurements of target strengths so far have been with free-swimming fish on which large numbers of readings were taken to reduce variance. One major source of error in acoustic assessment lies with the shoaling patterns and packing density within the shoals of fish; much consideration was given to this and a number of ways of dealing with the problem, some very promising, were being developed though none was yet entirely satisfactory. Again, the collection of data at an enormous rate requires great attention being paid to suitable computerisation. Throughout the discussions on this programme section it was repeatedly emphasised that an understanding of the biology of the fish in the sea area investigated was fundamental; fish target echoes were not from inanimate objects and allowance must be made for this between theory and practical results.

This volume has been edited by Mr A. R. Margetts with assistance from Mr J. E. Ehrenberg on several of the papers. While the authors themselves are responsible for the technical content and presentation of the papers, it is possible that, especially with papers from USSR and Japan, some misrepresentation arising from translation difficulties may still be in this publication. Technical questions may be resolved directly with the authors. Of the 50 Symposium papers, several were either withdrawn from publication or omitted as being not properly within the stated scope of the Symposium. This volume contains 42 papers on subjects within the programme framework outlined above. Of these, three are concerned with fishing gear and topographic studies, six with fish behaviour and migrations, 32 with fish abundance, identification and sizing, and one with very recent or future possible developments. The papers are here arranged in an order broadly conforming to the main topic headings as above. In two instances two papers presented separately to the Symposium have been combined as one paper. The organizers of the Symposium herewith express their gratitude to Norway for providing the venue and excellent facilities for this Symposium at the Students Centre, Bergen, and to the Director and staff of the Fiskeridirektoratets Havforskningsinstitutt, Bergen, for their invaluable assistance in staging it. Thanks are also recorded here to the Scientific Planning Committee, to the Chairmen of the sessions at the Symposium, to the Secretariat of ICES, to the authors of contributed papers and to the participants at the Symposium; all of these together made for the acknowledged success of the Symposium.
A HYDROACUSTIC MEASUREMENT PROGRAM TO EXAMINE TARGET QUANTIFICATION METHODS

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The procedures and results of a basic hydroacoustic measurement experiment to quantify aggregations of targets are presented. Relevant theoretical and practical details of the experiment are discussed. Standard series production instrumentation was used wherever possible. The experiment employed a variable-density static random target array of 10 cm diameter spherical targets within a cylindrical volume 9.5 m in diameter and 2 m thick deployed in a water filled tank. Target densities of from 1.7 to 7 per m$^3$ were insonified by a pressure pulse at a carrier frequency of 122 kHz. The hydroacoustic transducer was positioned offset from the axis of symmetry of the tank and rotated in angular increments about this axis. The received echo signals from each hydroacoustic transmission at a specified transducer azimuth angle were recorded in analog form on magnetic tape, digitized and then processed in a digital computer algorithm to obtain an estimate of target density. The results of the experiment are not entirely consistent with the results predicted by prior theoretical investigations and those expected from standard hydroacoustic measurement techniques.

INTRODUCTION

The subject of this paper is an engineering investigation of the information regarding the number of targets contributing to an echo signal from an assembly of independent random scatterers.

Information in the received echo signal from a pulsed transmission of a specific carrier frequency and time duration may be contained in phase variations, amplitude, frequency and time duration. Also, the time delay between signal transmission and reception is an important source of information. For purposes of target quantification, the physics of sound propagation in water and the limited practical knowledge of acoustical scattering from targets such as fish inhibit the usefulness of phase processing. Therefore, the information concerning the number of targets which produce an echo signal may be contained in the remaining characteristics, e.g., amplitude, frequency, and time duration.

In order to conduct the investigation in a manner consistent with good engineering practice it was necessary to construct a physical model of a stationary hydroacoustic transducer positioned over a volume containing the targets of interest. The transducer emits a pressure pulse which after a certain period of time envelops or insonifies each of the targets. It is obvious that the positions of the targets within the volume affect the characteristics of the echo signal. For example, if the targets were all tightly packed about a certain point, the echo signal envelope could have a large amplitude, compared to a single target, and have a time duration of the order of the transmitted pulse duration. Conversely, if the targets were distributed uniformly within the volume the echo signal envelope could have a larger or smaller amplitude, compared to a single target, and a time duration considerably longer than the transmitted pulse, since the targets would be contributing to the echo signal at different times.

A reasonable physical model of the uniformly distributed targets is to position the individual targets according to a three-dimensional Poisson Probability Law. This allows the mathematics involving subsequent echo signal processing to be handled with well developed statistical theory. It is not clear that wild fish in an aggregation obey the Poisson law assumption, therefore, experimental verification of this situation is certainly in order.

The engineering investigation reported here is based on the concept of average target density as meaningful and applicable to most of the situations which may arise in aquatic animal abundance measurement. If this concept is acceptable, then the actual target distribution, Poisson or any other, would not influence an unbiased abundance estimate, based upon averaged effects. It must be noted, however, that the errors associated with any estimate are dependent upon the precise distribution of the targets.
OBJECTIVES

The overall objective of the MP-1 experiment was to examine the behaviour of a series of hydroacoustic signals propagated from a transducer to an array of targets, scattered by the array and returned to the transducer.

The specific objectives of the MP-1 experiment were to:

(i) investigate and verify the interaction between the complex factors inherent in the echo signals received from an aggregation of targets;
(ii) investigate and verify hydroacoustic echo-signal processing methods for technical validity and accuracy for target quantification;
(iii) provide technical information which may be used to formulate plans to examine the echo signals from live targets.

SCOPE

The scope of the MP-1 experiment was limited to include only efforts for which either there was no known precedent in fisheries research or the prior research was limited and considered to be inconclusive in relation to the stated objectives. The experiment was not performed to verify, in detail, the extant theories and practice of hydroacoustic propagation, scattering, and information processes for random independent scatterers. It was intended to establish a physical environment which would meet the specifications of existing theory and to provide a valid point of departure for the orderly engineering development, if possible, of a feasible method of measuring aquatic biomass employing hydroacoustic techniques.

The MP-1 experiment is a logical result of the theoretical investigation by Lozow and Suomala (1971). Similar theoretical work has been done elsewhere (Moose and Ehrenberg, 1971) and major efforts to confirm the validity of various echo signal processing methods have been carried out at sea with wild fish as the targets of interest (Midttun and Nakken, 1972; Bakken et al., 1972; Hylen and Smedstad, 1972). Despite these and many other similar at-sea activities, the validity or correlation between the received echo signal and the quantity of wild fish producing the echoes is the subject of considerable discussion and speculation in the fisheries research community. With the exception of the work by Truskanov and Shcherbina (1964), it appears that there have been few controlled physical environment measurements which could provide positive practical insight into the usefulness and accuracy of the application of hydroacoustic techniques for aquatic biomass measurements. The MP-1 experiment, therefore, appears to be unique in that it may represent a base-line from which to begin to examine the validity and effectiveness of previous attempts to quantify wild fish at sea and to provide guide lines for future efforts.

CONFIGURATION OF EXPERIMENT

The geometry of the experiment was a function of the tank size, the maximum transmitted hydroacoustic pulse length, and the spherical spreading characteristics of the emitted hydroacoustic pulse.

It is mandatory that any echo signals from the target array must be free of echoes from any other source, and the received echo from the target aggregation should have a time duration of at least five times that of the emitted or transmitted pulse. The reason for the factor of five is a consequence of the requirements for useful information from the echo signal envelope described by Lozow and Suomala (1971). By combining the pulse length requirement and the requirement to maintain a tank size of economic proportions, a time duration of 0.6 ms for the transmitted pulse was established.

The geometry of the tank, hydroacoustic transducer and the target array for the experiment is shown in Figure 95 which indicates the specified dimensions of importance relative to the working face of the transducer. The 2 m spacing between the mooring surface for the targets and the nearest targets in the array is...
to meet the 5 pulse length criterion mentioned earlier. In addition to the transducer and target array, three hydrophones were located as shown.

The function of the “A” hydrophone located on a swing arm was to provide a rapid and repeatable means of verifying the transducer directivity function and to measure the transmitted source level, and receiving voltage response of the hydroacoustic equipment. The “B” hydrophone was to assess the echo signal which was received by the transducer.

The “C” hydrophone was to examine the characteristics of the transmitted hydroacoustic pressure pulse after it had passed completely through the target array.

The tank configuration and general arrangement of the MP-1 experiment is shown in Figure 96. The detailed design, fabrication, erection and operational readiness of the physical test facility was performed by the NMFS Fisheries Engineering Laboratory, Bay St. Louis, Mississippi.

**TARGET ARRAY**

The target array was configured in a cylindrical volume 9.5 m in diameter and 2 m thick. The positions of the individual targets were in accordance with a three-dimensional Poisson Probability Law. The details of this situation have been discussed by Lozow and Suomalainen (1971).

A computer program was generated to provide a listing of the locations of 1000 targets in rectangular and polar coordinates scaled to the specified cylindrical volume. Each target was identified with a number and color. The color identification permits the changing of target densities, by removing or adding targets, without violating the three-dimensional Poisson probability location requirement. In the actual experiment, the highest density was deployed first.

A structural framework covered with a 10 cm stretched mesh nylon netting was employed to provide a mooring base for the targets. The individual target locations were tagged with the target number and color identification on the netting in order to facilitate release by diving personnel.

When the array was completely rigged with the target floats, the average of a series of measurements of the distance to the nearest target from 200 randomly specified targets was 0.31 m; this was in excellent agreement with the theoretical value of 0.3 m.
TARGETS

The selection of the 10 cm diameter spherical polystyrene target floats was a function of an acceptable scattering cross section, ease of handling, cost, and availability. Several candidate targets were examined including table tennis balls and 5 cm diameter plastic floats.

In discussions with NMFS personnel it was decided that the estimated target strength of the 10 cm floats, approximately —32 dB ref. 1 m, would be a reasonable target with which to conduct this initial experiment. A few of the selected target floats were obtained and target strength measurements were performed at the MASSA Division Laboratory. The maximum measured target strength was approximately —34 dB ref. 1 m. In addition, 20 floats were subjected to a hydrostatic test equivalent to 50 m water depth for 15 days. No leakage or structural failure of the floats was detected. Each float was contained in a large mesh netting bag made of light monofilament plastic line secured to a mooring line, also of small plastic line, terminated to a spring clip. The spring clips were attached to the target mooring grid at specified locations. The physical orientation of the targets in relation to the mooring lines was random, since the preliminary target strength measurements of the evaluation samples indicated that they did not exhibit isotropic scattering characteristics.

HYDROACOUSTICAL INSTRUMENTATION

It was decided early in the planning of the MP-1 experiment that, wherever possible, production instrumentation would be used in order to minimize costs, unless the experiment objectives would be compromised.

The selection of the transmitter carrier frequency was a function of the target size and transmitted pulse length. The target floats must, in order to meet the requirement of the applied theory, exhibit geometrical or optical scattering characteristics. The selected diameter of 10 cm placed the target floats conservatively within the geometric scattering region at a transmitted carrier frequency of 100 kHz or greater.

An examination of the specifications of several production echo-sounders was performed. The resulting selection of the Simrad EK 120 R was based upon the following considerations:

1. the EK 120 R is a standard series production unit;
2. it is currently used in commercial fishing and fisheries research throughout the world and is considered a reliable instrument;
3. the EK 120 R has transmitted power and transmitted pulse length selectability suitable for the experiment;
4. the circular aperture transducer normally supplied with the EK 120 instrument was expected to have
a directivity pattern which would be convenient to mathematically define in the estimator algorithm;

(5) the rack-mounted configuration provides excellent accessibility to various components for measurements and any modification or repairs which may be required.

DATA HANDLING

Figure 97 depicts the data-handling stages and data-verification steps involved in the MP-1 experiment.

DATA ACQUISITION

The transducer was offset 12 cm from the axis of symmetry of the tank and rotated about the axis. Figure 98 illustrates this geometry. In this situation the echo signal from each hydroacoustic transmission would be from a nearly identical target configuration. Consequently the variance of any resulting target quantity due to the ratio of the mean squared to the squared mean of the target strength and the ratio of the transducer function moments tends to be minimized, and the random phase contribution to the variance predominates.

The basic variables necessary for target quantity estimation are: time from the beginning of the transmitted pulse to the beginning of the echo return; the amplitude variations of the return echo with respect to time; time duration of the echo return.

The data were recorded on magnetic tape in analog form on an instrumentation tape recorder at a tape speed of 1.52 m/s to include all significant signal amplitude characteristics with less than 1 % amplitude distortion. The specified bandwidth of the Simrad EK 120 R was ± 5 kHz which at the 0-6 ms transmitted pulse time interval would pass approximately 95 % of the information contained in the received echo.

All signals of interest in the MP-1 experiment were acquired in an unmodified form except for broadband amplification, if required. The objective was to obtain as much of the original signal fidelity as possible in order that subsequent processing would allow all of the desired quantitative information to be extracted.

Table 24 lists the data name, recording methods, and function in the MP-1 experiment.

Figure 99 schematically depicts the data acquisition equipment and tank configuration in the MP-1 experiment.

DATA REDUCTION

The data reduction procedure is shown schematically in Stage III of Figure 97. The analog magnetic tapes were digitized via a program in a XDS-9300 hybrid computer. The resulting digital data from the XDS-9300, in punched-card form, was processed by an estimator algorithm program in a IBM 360 System 75 digital computer. The estimator algorithm is discussed in Appendix I.

IMPLEMENTATION OF EXPERIMENT

INITIAL TESTS AND MEASUREMENTS

In order to assure compatibility between the data acquisition facilities at the Fisheries Engineering Laboratory and MIT/CSDL, all of the test and hydroacoustical instrumentation was employed at MIT for initial tests, check-out and integration. Insofar as was possible, a complete end-to-end equipment calibration, test procedure development and verification, data ac-
acquisition, data reduction and analysis exercise was performed. An equipment configuration similar to that to be used at the test site was established. In addition to testing the echo sounder in air, hydroacoustic tests were performed in a small tank (3 m long, 2 m wide and 1.5 m deep) at CSDL. In addition various measurements of echo-sounder parameters were conducted at the MIT Oceanographic Facility in Boston Harbor.

Transmitter and transducer pulse characteristics were evaluated using wide-band calibrated hydrophones. Attempts to verify the specified source level and the transducer voltage response were not successful. The approximate value of the voltage response of the transducer was supplied by the manufacturer. The results of the tests in the tank showed that the source level was approximately 110 dB vs 119 dB/microbar/m specified. The same tests repeated in Boston Harbor gave nearly identical results. It was subsequently determined that the calibration data for the wide-band hydrophone employed in the tests was in error. Using the correct hydrophone calibration data the source level, using the data already obtained from the tank and the harbor tests, was computed to be 114.6 dB/microbar/m. Although the specified source level and receiving voltage response were not confirmed, the ability to measure these parameters precisely rather than accept the specified values was one of the most important criteria for the MP-1 experiment.

The integration and compatibility of the data acquisition and reduction equipment was initially tested by recording acoustic returns from the floor of the laboratory which were received by the transducer suspended from the ceiling. The acoustic echoes recorded on the tape recorder, allowed the first real data to be used to exercise the analog to digital digitization programs. Prior to this initial test the analog to digital programs were exercised by a simulation program, FISHSPY-II A, described by Lozow and Suomala (1971).

The transmitted acoustic pulse shape in the water was somewhat less than the square or "boxcar" shaped pulse specified by the current theory of information in the received echo from random independent scatterers. It was possible to improve the pulse shape somewhat by tuning the inductor in the EK 120 R. Although a number of different approaches were tried to further improve the pulse shape, none were found which would make the transmitted pulse "squarer" or give it a "flatter top".
Receiving amplifier characteristics were measured and found to be unacceptable for the MP-1 experiment. The most significant problem was that of clipping and nonlinear gain for large acoustic return signals. This was due to the short ranges and high target densities involved in the experiment. Analysis was performed which indicated that return amplitudes during the experiment would be in the nonlinear amplifier region. As a consequence we decided to use an adjustable gain wide-band amplifier to acquire the acoustic return signals and amplify them prior to recording.

During the initial air testing of the echo sounder, it was determined that the echo signal amplitude varied up to 30% while the input level to the transducer remained constant. This was later confirmed in the small water-filled tank. The cause of this variation was due to an intermittent contact in the transducer. A new transducer with its unique directivity data was supplied by the manufacturer and further tests verified the stability of the new transducer. Fisheries Engineering Laboratory personnel assisted in the systems integration, systems level testing, and test procedure development at MIT/CSDL.

TARGET STRENGTH MEASUREMENT

The target strength of 96 randomly selected targets was obtained. Six measurements of the target strength of each target in reference to a randomly oriented target coordinate reference system were taken and the data tabulated. This work was performed jointly by NMFS Pascagoula Laboratory and U.S. Navy Underwater Sound Reference Laboratory personnel at the U.S.N. facility. This work is reported by Kemmerer, Russell and Minkler (1972).

At the CSDL a computer program was employed to calculate the mean and standard deviation of the 576 measurements. The average target strength was 4.04 \times 10^{-4} or -33.9 dB ref. 1 m and standard deviation 3.55 \times 10^{-4}. The normalized standard deviation was 0.88. An examination of the target strength data in histogram form indicated that this data tended to follow a squared normal probability distribution.

FINAL TESTS AND MEASUREMENTS

After the initial tests were reviewed by Fisheries Engineering Laboratory and CSDL personnel, a review of the experiment calibration procedures was conducted. This review indicated that all procedures and techniques followed accepted hydroacoustical measurement and test engineering practices.

The following is a list of calibration and measurement procedures specified by MIT/CSDL which were developed and implemented by NMFS/FEL:

(1) water temperature
(2) water chemical analysis
(3) water turbulence
(4) air or gas bubble sources
(5) hydroacoustic transducer isolation
(6) transducer impedance
(7) transmitter output power
(8) transmitter pulse shape and length
(9) transmitted pulse shape and length
(10) transmitted carrier frequency
(11) hydroacoustic source level
(12) transducer receiving sensitivity
(13) transducer receiving bandwidth
(14) ambient noise
(15) transducer directivity function
(16) single target range and angle resolution

A detailed description of the MP-1 experiment environment monitoring, calibration, checkout and integration tests is given in a report prepared by NMFS/FEL (Anon. a).

EXPERIMENT DATA ACQUISITION

The experiment data acquisition was performed by NMFS/FEL personnel. A series of eight data tapes, each for a specific experiment configuration, was generated.

The following is a brief description of the sequence of steps followed for each configuration:

(1) Source level and voltage response measurement at all power levels and transmitted pulse lengths. In addition to log-book entries of all equipment settings and adjustments, the following oscilloscope photographs were obtained:
   a. Transmit pulse to transducer
   b. Transmit pulse from transducer received by "A" hydrophone
   c. Transmit pulse from transducer received by "C" hydrophone
   d. Signal generator pulse to "A" hydrophone
   e. Transmit pulse from "A" hydrophone received by transducer

(2) Position transducer and log orientation
(3) Trigger transmit pulse and log IRIG time
(4) Repeat Step 3 twice and obtain photograph of echo signal on C.R.T. oscilloscope, Annostate log-book sheet and photograph with EK 120 R power and pulse length, switch positions, transducer orientation and instrument scaling
(5) Repeat Step 1

Steps 2–4 in the above sequence were repeated for two transmitted pulse lengths at two transmitted power levels at transducer azimuth intervals of 5°. A series of
eight data tapes was generated according to the above which provided 72 unique data samples for estimation of a specific target density. In addition to the above sequence, all of the remaining procedures listed under "Final tests and measurements" except 2-6 and 15 and 16 were routinely implemented before and after each data acquisition activity.

**EXPERIMENT DATA REDUCTION**

Each data tape contained calibration voltage levels for each of the six data channels prior to and after each data run. The only data channel digitized in the MP-1 experiment data reduction was Channel 5, transducer echo signal. All data channels were examined at the test site via oscillogram recordings prior to shipment of the tapes to MIT/CSDL.

The data on the "B" hydrophone was not suitable for absolute analysis since they include dual mode harmonics.

**EXPERIMENT DATA ANALYSIS**

The target density estimator algorithm described in Appendix I utilizes three constant input parameters which account for: 1) the radiated hydroacoustic energy (transmitted source level); 2) the transducer receiving sensitivity (voltage response); 3) the average reflecting or scattering capabilities of the targets (target strength).

The value of average target strength was derived from the data of Kemmerer, Russell and Minkler (1972). For each hydroacoustic transmission, source level and voltage response were determined employing standard procedures. The method of employing the individual values of source level, voltage response and average target strength in the estimator algorithm processing of the data tapes resulted in consistently high estimates, by a factor of 4 to 5, compared with the actual density of the target array.

It was considered that a hydrophone calibration error could possibly be a factor causing the high density estimates. In order to circumvent this possibility and continue the data-acquisition activity, it was decided to employ a lumped parameter for the product of source level, voltage response, and target strength. This was accomplished as follows:

1. 200 target floats, selected at random from the target population, were located at a known depth and on the acoustic axis of the transducer;
2. each target was insonified by a single hydroacoustical transmission at the same power levels and pulse lengths as in the MP-1 data acquisition activity;
3. a CRT oscilloscope photograph of the raw echo signal for each transmission was obtained;
4. the average rms voltage level from each transmission was calculated from measurements of the photographs.

From the basic echo sounding equation given as Equation 4 in Lozow and Suomala (1971), it follows that the product of source level, voltage response and target strength for the MP-1 experiment can be written thus:

\[
(SL) (VR) (TS) = R^2 V_{rms}
\]

where

- \( R \) = range to target
- \( V_{rms} \) = average rms voltage of the received echo envelope

The results of the above sequence were tabulated for 95 trials, the results of which are given in Table 25. The degree of confidence of these values is high. The ratio of the standard deviation to the mean value (coefficient of variation) for both parameters is 0-8. A confidence interval calculated from Student's cumulative randomly distributed variable (Parzen, 1960) places both the true mean lumped parameters within 15% of the indicated value with a probability of 0-97. In other words, the true value of \( (SL) (VR) (TS) \) is very nearly certain to fall within \( \pm 15\% \) of the value derived from the 95 trials. This value is well within the limit adequate to satisfy the objectives of the MP-1 experiment.

The results of using the above mean lumped parameters in the estimator algorithm to process tapes 8–15 are presented in Tables 26 and 27. An examination of these results shows that the trend of the calculated densities is higher than the actual, in some cases by nearly 200%. Since each indicated density is the resulting average of 72 individual echo integrations at a particular source level, pulse length and target density, the magnitude and sense of the resulting errors is not consistent with the degree of accuracy expected. Only two tests have less than 15% relative error and three tests are out of a half or double range. The tests with the higher hydroacoustic source

<table>
<thead>
<tr>
<th>Transmitted power ratio</th>
<th>Transmitted pulse length (ms)</th>
<th>Averaged lumped parameter ( (SL) (VR) (TS) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1</td>
<td>0-6</td>
<td>3-09</td>
</tr>
<tr>
<td>1/10</td>
<td>0-6</td>
<td>0-646</td>
</tr>
</tbody>
</table>
level tended to give the greatest errors, and the average relative error for the high and low power tests was about 58%.

DISCUSSION AND ANALYSIS OF EXPERIMENT

An examination of the results of the MP-1 experiment data analysis suggests the possibility of uncertainty in the values of several parameters. The various parameters and analysis of their effects upon the results of the MP-1 experiment are discussed in the following paragraphs.

SELECTION OF STANDARD PARAMETERS

The standard parameters which were employed in the estimator algorithm are defined in Appendix I.

Acoustic source level

Two methods to derive the acoustic source level of the EK 120 R equipment were employed. The method employed at the Fisheries Engineering Laboratory was the standard hydroacoustic measurement technique of hydrophone peak-to-peak voltage and the time interval between the transmitted and received signal (Anon. b Reports of FEL and U.S. Navy Underwater Sound Ref. Div.). The method employed at MIT/CSDL is described in Appendix II. From a photograph of the hydrophone signal, the peak-to-peak amplitude of each cycle over the effective pulse length was measured, squared and integrated. The results of the two methods are given in Table 28.

From these, an average value for source level was derived. The source level constant parameter for the MP-1 experiment was:

1/1 Transmitted Power $SL = 113.3 \text{ dB/1 microbar ref. 1 m}$

1/10 Transmitted Power $SL = 105.6 \text{ dB/1 microbar ref. 1 m}$

Receiving voltage response

The measurement of receiving voltage response of the transducer was conducted in accordance with the method described in the Anon. b reports of FEL and independent verification using the available photographic data was performed at MIT/CSDL. From these measurements the receiving voltage response constant parameter for the MP-1 was $-80 \text{ dB/1 volt/microbar}$.

Table 28. Acoustic source level measurements

<table>
<thead>
<tr>
<th>Transmitted power</th>
<th>Transmitted pulse length</th>
<th>Measurement method</th>
<th>Source level dB/1 microbar ref. 1 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1</td>
<td>0-3</td>
<td>ref. Anon (a)</td>
<td>113-6</td>
</tr>
<tr>
<td>1/10</td>
<td>0-3</td>
<td>App. II</td>
<td>114-2</td>
</tr>
<tr>
<td></td>
<td>0-6</td>
<td>ref. Anon (a)</td>
<td>112-7</td>
</tr>
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<td></td>
<td>0-6</td>
<td>App. II</td>
<td>112-9</td>
</tr>
<tr>
<td></td>
<td>1/10</td>
<td>ref. Anon (a)</td>
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<td>0-3</td>
<td>App. II</td>
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<td></td>
<td>0-6</td>
<td>ref. Anon (a)</td>
<td>105-3</td>
</tr>
<tr>
<td></td>
<td>0-6</td>
<td>App. II</td>
<td>105-3</td>
</tr>
</tbody>
</table>
**Average target strength**

The data presented was used to obtain the mean, standard deviation, and normalized variance of the target strength of 576 unique measurements from 96 randomly selected targets. The constant parameter for average target strength was determined as $-33.9 \text{ dB ref. 1 m.}$

**Transmitted pulse length**

The transmitted pulse length was derived from the examination of the photographs of the hydrophone signal as in “Acoustic source level” above. The effective transmitted pulse lengths ($\tau$) were selected as 0.3 and 0.6 ms.

**Transducer directivity function**

The unique transducer directivity function data supplied by SIMRAD was employed to derive the estimator algorithm directivity function (see Appendix III). A comparison of the results of the transducer directivity function verification in the test tank and that employed in the algorithm showed that the variation between the tank measured directivity function at 1/10 power and the algorithm directivity function was less than ±10% over the major lobe and first minor lobes.

**RESULTS USING STANDARD PARAMETERS**

The $\hat{Q}$ estimators for echo-envelope sampling and echo-envelope integration were computed using the standard parameters described above. The results of the computer runs for echo-envelope integration are shown in Table 29. This shows that the values of the indicated target densities are consistently high, by a factor of 4 to 5, compared with the actual density in the array.

The received echo signal from each hydroacoustical transmission was for all practical purposes the result of insonifying the same target arrangement for each array density configuration. As a consequence, the average density from the estimator from 72 samples should be close to the array density. However, the estimate could be biased by the fact that the samples were not independent. Since this bias could, theoretically, have either a positive or negative value about the array density, the possible causes of the apparent large positive bias were examined in a number of ways.

**INVESTIGATION OF ESTIMATOR VALUES RESULTING FROM THE APPLICATION OF STANDARD VALUES**

**Estimator algorithm**

A thorough recheck of the digitization of the raw echo-signal envelope and the computer-generated plots produced negative results. Estimator-algorithm-computer data dumps also produced negative results. In addition, a manual method of echo-signal envelope sampling was devised (see Appendix IV). The checks via the manual method showed that the estimated target densities derived from the manual method varied from the densities derived from the estimator algorithm by approximately ±19%. A typical example of the density estimates derived from the manual method versus the estimator algorithm is listed in Table 30. It was concluded from the results of this investigation that the high target density estimates were not the result of any significant errors introduced in the digitization of the raw echo signal or subsequent processing in the estimator algorithm.

**Variance error**

Despite the high estimator values there was evidence that the precisions of the estimates were within reason, indicating that the random phase distribution of the

---

Table 29. Results using standard parameters

<table>
<thead>
<tr>
<th>Tape #</th>
<th>Power</th>
<th>Pulse length</th>
<th>Array density</th>
<th>Indicated density–$\hat{Q}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1/1</td>
<td>0.3</td>
<td>7.05</td>
<td>33.6</td>
</tr>
<tr>
<td>8</td>
<td>1/1</td>
<td>0.6</td>
<td>7.05</td>
<td>36.0</td>
</tr>
<tr>
<td>9</td>
<td>1/10</td>
<td>0.3</td>
<td>7.05</td>
<td>31.3</td>
</tr>
<tr>
<td>9</td>
<td>1/10</td>
<td>0.6</td>
<td>7.05</td>
<td>30.4</td>
</tr>
<tr>
<td>10</td>
<td>1/1</td>
<td>0.3</td>
<td>5.25</td>
<td>31.5</td>
</tr>
<tr>
<td>10</td>
<td>1/1</td>
<td>0.6</td>
<td>5.25</td>
<td>34.2</td>
</tr>
<tr>
<td>11</td>
<td>1/10</td>
<td>0.3</td>
<td>5.25</td>
<td>28.6</td>
</tr>
<tr>
<td>11</td>
<td>1/10</td>
<td>0.6</td>
<td>5.25</td>
<td>26.6</td>
</tr>
<tr>
<td>12</td>
<td>1/1</td>
<td>0.3</td>
<td>3.50</td>
<td>30.8</td>
</tr>
<tr>
<td>12</td>
<td>1/1</td>
<td>0.6</td>
<td>3.50</td>
<td>36.7</td>
</tr>
<tr>
<td>13</td>
<td>1/10</td>
<td>0.3</td>
<td>3.50</td>
<td>24.4</td>
</tr>
<tr>
<td>13</td>
<td>1/10</td>
<td>0.6</td>
<td>3.50</td>
<td>23.4</td>
</tr>
<tr>
<td>14</td>
<td>1/1</td>
<td>0.3</td>
<td>1.75</td>
<td>12.1</td>
</tr>
<tr>
<td>14</td>
<td>1/1</td>
<td>0.6</td>
<td>1.75</td>
<td>10.3</td>
</tr>
<tr>
<td>15</td>
<td>1/10</td>
<td>0.3</td>
<td>1.75</td>
<td>6.6</td>
</tr>
<tr>
<td>15</td>
<td>1/10</td>
<td>0.6</td>
<td>1.75</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Table 30. Results of manual echo signal processing

<table>
<thead>
<tr>
<th>Tape #8, PWR 1/1, 0.6ms pulse length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transducer azimuth</td>
</tr>
<tr>
<td>(degrees)</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>45</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>135</td>
</tr>
<tr>
<td>180</td>
</tr>
<tr>
<td>225</td>
</tr>
<tr>
<td>270</td>
</tr>
<tr>
<td>315</td>
</tr>
</tbody>
</table>
Table 31. Theoretical and measured variance

<table>
<thead>
<tr>
<th>Tape #</th>
<th>Pulse length</th>
<th>Normalized one sigma derived from estimator</th>
<th>Normalized one sigma derived from theory (random phases)</th>
<th>Normalized one sigma derived from theory (all sources)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0-3</td>
<td>0-45</td>
<td>0-30</td>
<td>0-66</td>
</tr>
<tr>
<td>8</td>
<td>0-6</td>
<td>0-44</td>
<td>0-48</td>
<td>0-56</td>
</tr>
<tr>
<td>9</td>
<td>0-3</td>
<td>0-46</td>
<td>0-30</td>
<td>0-66</td>
</tr>
<tr>
<td>9</td>
<td>0-6</td>
<td>0-42</td>
<td>0-48</td>
<td>0-56</td>
</tr>
<tr>
<td>10</td>
<td>0-3</td>
<td>0-33</td>
<td>0-30</td>
<td>0-68</td>
</tr>
<tr>
<td>10</td>
<td>0-6</td>
<td>0-44</td>
<td>0-48</td>
<td>0-53</td>
</tr>
<tr>
<td>11</td>
<td>0-3</td>
<td>0-33</td>
<td>0-30</td>
<td>0-68</td>
</tr>
<tr>
<td>11</td>
<td>0-6</td>
<td>0-44</td>
<td>0-48</td>
<td>0-53</td>
</tr>
<tr>
<td>12</td>
<td>0-3</td>
<td>0-47</td>
<td>0-30</td>
<td>0-72</td>
</tr>
<tr>
<td>12</td>
<td>0-6</td>
<td>0-49</td>
<td>0-48</td>
<td>0-63</td>
</tr>
<tr>
<td>13</td>
<td>0-3</td>
<td>0-45</td>
<td>0-30</td>
<td>0-72</td>
</tr>
<tr>
<td>13</td>
<td>0-6</td>
<td>0-48</td>
<td>0-48</td>
<td>0-63</td>
</tr>
<tr>
<td>14</td>
<td>0-3</td>
<td>0-38</td>
<td>0-30</td>
<td>0-82</td>
</tr>
<tr>
<td>14</td>
<td>0-6</td>
<td>0-35</td>
<td>0-48</td>
<td>0-73</td>
</tr>
<tr>
<td>15</td>
<td>0-3</td>
<td>0-30</td>
<td>0-30</td>
<td>0-82</td>
</tr>
<tr>
<td>15</td>
<td>0-6</td>
<td>0-36</td>
<td>0-48</td>
<td>0-73</td>
</tr>
</tbody>
</table>

received echoes were occurring as theory predicted. This can be illustrated by comparing the normalized one-sigma values (the square root of the variance divided by the mean target density is the normalized one-sigma value.) derived from a specific data set with those theoretically derived. Table 31 illustrates this relationship.

The theoretically derived normalized one-sigma values in Table 31 are the result of evaluating the equation for the variance error of the estimate (Equation 62 in Lozow and Suomala, 1971) using the appropriate values unique to the MP-1 experiment. In the MP-1 measurement configuration, the echo signal from each hydroacoustical transmission was from a nearly identical target configuration. In this case the variance due to the ratio of the mean squared to the squared mean of the target strengths and the ratio of transducer directivity function moments tends to be minimized and the random phase contribution to the variance predominates.

The result of this investigation suggested that the random phase distribution of the received echoes occurred as predicted and that the high estimates were due to other causes.

**Acoustic source level and receiving voltage response**

The possibility of hydrophone calibration errors which in turn could account for invalid SL and VR values being used in the estimator algorithm was considered. However, it was not feasible, within the existing time constraints, to continue the data acquisition activities of the MP-1 experiment to verify the hydrophone calibrations.

**Averaged lumped parameter**

The possibility of errors in the standard values of source level and receiving-voltage response was minimized by employing the artifice of a lumped parameter. The averaged lumped parameter is the product of source level, voltage response and average target strength. The results of this investigation are given earlier in Table 25.

**Average target strength**

The value of average target strength of the MP-1 target floats derived from the lumped parameter results was −28-4 dB ref. 1 m. This value was the result of using the standard values of source level and receiving voltage response.

This value of average target strength is 5-5 dB greater than the value obtained by the standard measurement techniques employed by Kemmerer, Russell and Minkler (1972). The 5-5 dB difference could account for a large portion of the high estimates of target density employing the standard parameters.

Subsequent calibration verification of the “B” and “C” hydrophones was obtained during tests at the U.S. Navy Underwater Sound Reference Division. The “A” hydrophone was damaged upon removal from the swing arm and calibration verification was not possible. The transmitting and receiving response characteristics of the MP-1 hydrophones is given in Table 32. The observed anomaly in the average target strength remains an open question at this time.

**Multiple scattering**

The possibility of multiple scattering of the hydroacoustical pressure pulse rather than independent scattering from the target floats was considered.

Theoretical considerations (Lozow and Suomala, 1971) indicate that multiple scattering is highly unlikely, but could not be completely ruled out as a possibility.
INVESTIGATION OF ESTIMATOR VALUES USING LUMPED PARAMETERS

Tables 26 and 27 show that the target densities indicated by the estimator algorithm tend to be higher than the actual average target density deployed in the tank. Specifically, the indicated densities at 1:1 transmitted power are greater than the actual densities in the tank. Also, the indicated densities at 0:3 ms pulse length are greater than those at 0:6 ms. Theoretically, there should be no increase in the algorithm calculated target density at higher transmitted acoustic power and the target density estimates should, on the average, be closer to the actual density in the tank than those at 0:6 ms.

Factors which could account for the observed results are the values of the average lumped parameter and of the transducer directivity function. The averaged lumped parameter employed at 0:3 ms may have been incorrect. The averaged lumped parameter derived at 0:6 ms was expected to be valid at 0:3 ms. Theoretically, there should be no difference in these values, but practical considerations may dictate otherwise.

The transducer directivity function used in the estimator algorithm was, for all practical purposes, identical to that of the actual transducer at 1/10 power. Theoretically, the transducer directivity should be constant and it was expected that the directivity function would not be affected by the range of power levels used in the MP-1 experiment. Practical considerations may, however, dictate otherwise.

In order to consider this situation it is convenient to introduce a concept called the quantification zone or detection zone of the hydroacoustical equipment. The zone of quantification is that portion of the insonified volume which, on the average, is the major contributor to the echo signal. Theoretically, it can be shown (see Appendix III) that the quantification zone may approximate closely to that volume described by the shape of the major lobe of the transducer bounded by the —10 dB points. In this situation the received echo from any targets outside the —10 dB points has a negligible effect upon the estimate of target density.

Table 33. Array density versus —10 dB quantification zone density

<table>
<thead>
<tr>
<th>Tape #</th>
<th>Array density</th>
<th>—10 dB quantification zone density</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/9</td>
<td>7.05</td>
<td>7.57</td>
</tr>
<tr>
<td>10/11</td>
<td>5.25</td>
<td>5.44</td>
</tr>
<tr>
<td>12/13</td>
<td>3.50</td>
<td>5.42</td>
</tr>
<tr>
<td>14/15</td>
<td>1.75</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Table 34. Relative error using —10 dB quantification zone

<table>
<thead>
<tr>
<th>Tape #</th>
<th>—10 dB quantification zone density</th>
<th>Indicated density</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>7.57</td>
<td>7.03</td>
<td>—0.07</td>
</tr>
<tr>
<td>11</td>
<td>5.44</td>
<td>6.15</td>
<td>+0.13</td>
</tr>
<tr>
<td>13</td>
<td>3.13</td>
<td>5.42</td>
<td>+0.73</td>
</tr>
<tr>
<td>15</td>
<td>1.89</td>
<td>1.37</td>
<td>—0.27</td>
</tr>
</tbody>
</table>

A detailed examination of the specified positions of the targets within the assumed —10 dB quantification zone was conducted. The results are summarized in Table 33. It can be seen that the target density in the assumed —10 dB quantification zone is close to the average density specified for the entire array.

As noted earlier, the value of the averaged lumped parameter was verified at a pulse length interval of 0:6 ms and the transducer directivity function was verified at 1/10 transmitter power. Using these parameters, the estimator output for the appropriate data tapes was evaluated and is shown in Table 34.

Examination of the relative error above indicates results which are within experimental error except for tape 12/13 which suggests an uncertainty not associated with the assumed zone of detection. It should be noted that the relative error given above compares closely with the data given in Table 27 for the same power and pulse length conditions except for tape number 12/13.

SUMMARY OF RESULTS

The MP-1 experiment employed a variable-density static target array in a tank environment insonified by a pressure pulse from a hydroacoustic transducer. The positions of the individual targets in the array were established in accordance with a three dimensional Poisson Probability Law. The transducer was positioned offset from the center line of the axis of symmetry of the tank and rotated in angular increments about this axis. The received echo signals from each pulsed hydroacoustic transmission at a specified transducer azimuth angle were recorded in analog form on magnetic tape, digitized, and processed in a digital computer algorithm to obtain an estimate of target density.

The current results of the experiment are not entirely consistent with the results predicted by the prior theoretical investigations of Lozow and Suomala (1971) and by standard hydroacoustic measurement techniques. The main findings, to date, are as follows:

1. The observed difference in average target strength of 3·5 to 1 between two independent but apparently technically valid measurement methods pre-
concludes a complete investigation and verification of the interactions between the complex factors inherent in the echo signals received from the target array.

(2) The digitization of the raw echo signal and subsequent algorithm processing functions as predicted and introduces no significant error in the resulting target density estimates.

(3) The quantification results of the estimator algorithm at low transmitter power and long pulse length appear consistent with those theoretically predicted, and are within the limits of experimental error except for one target density configuration.

(4) The quantification results of the estimator algorithm at low transmitter power and short pulse length are not consistent with those theoretically predicted.

(5) The quantification results of the estimator algorithm at high transmitter power and at both long and short pulse lengths are not consistent with theory.

(6) The precision of the estimates from the MP-1 experiment appear consistent with those theoretically predicted.

CONCLUSIONS

The MP-1 experiment was designed to model and examine an environment which is thought to be typical of that encountered in the process of aquatic biomass estimations employing hydroacoustic techniques. The model environment consisted of the basic elements from which any biomass estimation processes employing pulsed hydroacoustical instrumentation must begin, namely a single hydroacoustic transmission and the received echo signal.

All of the conclusions which may be drawn from the MP-1 experiment are not available at this time. However, the following conclusions, with relevant discussions, are put forward:

(1) It is feasible to estimate the density of a number of static targets in a static array from the received echo signals.

The density estimation can be achieved by echo envelope integration or echo envelope sampling (Lozow and Suomala, 1971). The latter method can also be performed by a simple, but somewhat tedious, manual method.

(2) It is feasible to estimate the precision of the target density according to theoretical statistical considerations and methods (Lozow and Suomala, 1971; Moose and Ehrenberg, 1971).

The echo signal processing schemes described by Lozow and Suomala (1971) will provide density estimates which will vary greatly even when the actual average target density is constant. The variations are caused by the random phasing of the individual target echo signal amplitudes, by differences in individual target strengths and by the absolute difference in the number of targets in one unit of volume versus another. The variations caused by phasing, and to some extent the differences in the individual target strengths, can be seen in the results of the MP-1 experiment. It should be noted however that the precision of the averaged density estimates does not necessarily imply the accuracy of the estimate.

(3) It is not feasible to verify the accuracy of the estimates due to various uncertainties associated with hydroacoustic measurement techniques and procedures.

The observed difference in the average target strength and the requirement to adopt the artifice of the averaged lumped parameter is a compromise of the goals set for the MP-1 experiment. It also illustrates the difficulty of assigning an accuracy criterion from a value of precision. It would appear that the adoption of the lumped parameter has reduced a source of bias in the MP-1 data. Until the differences in target-strength data are resolved, the verification of the accuracy of the density estimates is not feasible. Similarly, the possibilities of errors in the derived values of the lumped parameter and transducer directivity function inhibit accuracy verifications.

In terms of the possibilities of the estimation of the density of wild fish in the MP-1 test tank, similar difficulties and uncertainties associated with hydroacoustic measurements encountered in the MP-1 experiment will prevail, unless rectified. The complexities introduced by the addition of a biological element must be carefully examined so that the results of such a test will be meaningful.

In terms of the estimation of the density of wild fish in an open sea environment, it is reasonable to conclude that echo signal processing and statistical manipulation of the density estimates can be performed. This can be done in various degrees of complexity from a manual method with minimal instrumentation to a completely automated computer-aided device. This echo signal processing will yield an estimate of the insonified fish, and statistical manipulations of the density estimations will yield an estimate of the precision.

It is not clear whether the identification and evaluation of the uncertainties affecting the accuracy of the density estimation can be accomplished with the reliability achieved to date in the MP-1 experiment. There-
fore, in the light of the MP-1 experiment results, it is reasonable to conclude that in situ biomass estimates may be subjected to considerable uncertainty. This uncertainty will not only be due to the characteristics of the fish species of interest, but to ignorance of the true state of the hydroacoustical parameters involved.

ACKNOWLEDGEMENT

This report describes an engineering activity which was the result of the combined efforts of not only the CSDL and the authors, but a number of other individuals and organizations.

Individuals we would mention are: A. Kemmerer, W. Stevenson, W. Gandy, A. Stevenson and M. Russel of the NMFS; C. Cambell, T. Cobb, J. Anderson and J. Harrington at the MTF; also J. Garmil, formerly at CSDL; R. O'Connell, CSDL, for his support on the XDS 9300 and Beckman 2200 computers; H. Bodholt, SIMRAD A/S; and T. Pardy who assisted in the development of the calibration procedures.

To those people and organizations the authors express gratitude for their contributions.

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APPENDIX I

DESCRIPTION OF ESTIMATOR ALGORITHM

The MP-1 data reduction was accomplished by means of a computer program written in MAC 360 language.

The program accepted and stored a sequence of digitized data which represented discrete samples of the received echo signal envelope. The sampling rate was, in this case, equal to the transmitted carrier frequency. Other major inputs to the program were: 1) the lumped hydroacoustical environment parameters—source level, voltage response and target strength (SL VR TS), 2) the elapsed time between pulse transmission and echo reception, 3) the transmitted pulse length, and 4) a curve fit of the integrated transducer directivity function. A discussion of a method to determine the effective transmitted pulse length is given in Appendix II. Further, a discussion of the comparison of the actual and the theoretical transducer directivity functions and the resulting curve fit is given in Appendix III.

The program consisted of two separate, but similar algorithms which operated on the sampled voltages.

The expression for echo envelope integration is given by Equation 53 of Lozow and Suomala (1970)

\[
\hat{Q}_I = \frac{\pi c^4}{\delta TS I_0 VR^2} \int_{t_0}^{\infty} \frac{(t - \tau/2)^3 (t - t_0 \tau/2)}{V^2_{rms}(\tau)} \psi(\tau) \, d\tau
\]

which was approximated in the algorithm by the sum

\[
\hat{Q}_I \approx \frac{\pi c^4}{\delta TS I_0 VR^2} \frac{1}{\tau} \sum_{i} \frac{(t_1 - \tau/2)^3 (t_1 - t_0 - \tau/2)}{V^2_{rms}(\tau)} \psi(t_1) \Delta t.
\]

The expression for the echo-envelope sampling algorithm is given by Equation 44 of Lozow and Suomala (1971)

\[
\hat{Q}_S = \frac{\pi c^4 \tau}{\delta TS I_0 VR^2} \sum_{N} \frac{(N - 1/2) [t_0 + (N - 1/2) \tau/2]^3 (V^2_{rms})_N}{\psi N}
\]

The terms in the equations above are defined as

\[
\hat{Q}_I, \hat{Q}_S = \text{estimated number of targets in insonified volume for echo envelope integration and echo envelope sampling, respectively}
\]
Target quantification methods

\( c \) = velocity of sound in fresh water

\( \overline{TS} \) = average target strength of target floats

\( VR \) = transducer receiving voltage response

\( \tau \) = transmitted pulse time duration (length)

\( t_i \) = arrival time at transducer of \( \text{ith} \) voltage sample

\( t_0 \) = elapsed time (round trip) between start of hydroacoustic pulse transmission and start of received echo

\( V_{rms} (t_i), (V_{rms})_N \) = root mean squared value of sampled voltage

\( \delta \) = thickness of scattering layer

\( \psi (t_i), (\psi N) \) = integrated transducer directivity function

\( i, N \) = summation indices for echo envelope integration and echo sampling, respectively.

It will be noted that the summation representing the echo envelope integration occurs over all the data samples, but the summation representing echo envelope sampling occurs at data points that are separated by one pulse length.

The insonified volume for echo envelope integration is given by

\[
V_I = \pi/3 \cdot c^3/\delta \cdot (t_m - t_0) \cdot (t_0 + 2t_m)
\]

where

\( t_m = \text{arrival time of last data point used for integration} \)

The insonified volume for echo envelope sampling is given by

\[
V_S = \pi \cdot (ct)^2 R_N \cdot (N - 1/2)
\]

where

\( N = \text{nearest integer to the ratio of scattering layer thickness, } \delta, \text{ to } ct/2 \)

\( R_N = c t_0/2 + (N - 1/2) \cdot ct/2. \)

It will be noted that, in general, \( V_S \neq V_I \) unless the scattering layer thickness is equal to an integer \( \times ct/2 \).

There are, therefore, two scattering layer density estimates calculated, \( \bar{Q}_S/V_S \) and \( \bar{Q}_I/V_I \). In addition the running means and standard deviations of the density estimates for consecutive echo envelopes are calculated.

APPENDIX II

EFFECTIVE TRANSMITTED PULSE LENGTH

Expressions 44 and 53 in Lozow and Suomala (1971) include among other terms the variable, \( \tau \), which represents the time interval of a hypothetical rectangularly shaped hydroacoustical pulse. Practically, the pulse length, \( \tau \), is not generally precisely equal to the duration of the pulse emitted by the hydroacoustical instrument. For emitted pulses of long time duration \( \tau \) is very nearly equal to the theoretical rectangular model, but for emitted pulses the rectangular shape is distorted by bandwidth limiting of the transducer.

In order to handle the short pulse length in the MP-1 experiment the concept of effective pulse length was employed.

In essence a distorted pulse of duration \( Dt \) can be substituted by a rectangular pulse of amplitude \( A \) and effective length \( \tau_e \).

Let the distorted, non rectangular pulse be given by

\[ P(t) = E(t) \cdot \cos\omega t \]

where

\( E(t) = \text{pulse envelope} \)
\( \omega = \text{carrier frequency} \)
\( t = \text{time} \)

Further, let the amplitude, \( A \), be any given value that \( E(t) \) reaches of the duration \(Dt\).

From energy considerations it can be shown that \( P(t) \) may, for mathematical convenience, be substituted by \( \hat{P}(t) \) where

\[
\hat{P}(t) = \begin{cases} 
A \cos \omega t & 0 < t < \tau_e \\
0 & \text{elsewhere}
\end{cases}
\]

and

\[
\tau_e = 1/A^2 \int_0^{Dt} E^2(t) \, dt.
\]

The method of selecting the value \( A \) is not unique. It may be chosen as the maximum value \( E(t) \) becomes over \( Dt \), say \( A = E_{\text{max}} \) or an asymptotic level at which \( E(t) \) has reached after an initial overshoot in the pulse say \( A = E_{\infty} \). A convenient choice of \( A \) is to set \( \tau_e \) to a nominal value and perform the following integration

\[
A^2 = 1/\tau_e \int_0^{Dt} E^2(t) \, dt.
\]

Thus, if \( E(t) \) is an emitted pulse in microbars, \( A^2 \) equals an effective source level.
APPENDIX III
COMPARISON OF ACTUAL AND THEORETICAL TRANSUDER DIRECTIVITY FUNCTIONS

In Appendix I the terms, \( \psi(t) \) and \( \psi_N \) are definite integrals of the transducer directivity function \( G(\theta, \varphi) \).

The transducer employed in the MP-1 experiment is a circular aperture piston and the theoretical directivity function for this element is given by

\[
G(\varphi) = \frac{2 J_1(\pi d/\lambda \sin \varphi)^2}{\pi d/\lambda \sin \varphi}.
\] (1)

The actual directivity function of the physical transducer was determined from pattern measurements supplied from Simrad. This data consisted of polar plots of the directivity function in 5° intervals from \( \theta = 0° \rightarrow 180° \).

In order to make rapid comparisons between the actual and theoretical directivity functions a computer generated plot of Equation (1) was obtained.

The major lobe agreement was obtained by computing an effective diameter, \( d_e \), and substituting for \( d \) in expression (1).

The effective diameter for the actual transducer, \( d_e \), is given by

\[
d_e = 58.5/\theta \lambda,
\]

where \( \theta \) is the measured half power beam width (in angular degrees) and \( \lambda \) is the wavelength of the radiated sound. The physical diameter of the transducer employed in the MP-1 experiment is 10 cm. The wavelength is approximately 1.25 cm and the measured half power (-3 dB) beam width is 10°. Therefore, the effective diameter is

\[
d_e = 58.5/10 \times 1.25 = 7.3 \text{ cm}.
\]

It should be noted that the effective diameter is some 27% smaller than the physical diameter of the transducer.

It can be shown that a reasonable approximation to the major lobe expression is given by

\[
G(\varphi) = \left[ \frac{2 J_1(\pi d/\lambda \sin \varphi)^2}{\pi d/\lambda \sin \varphi} \right] e^{-1/4 (\pi d/\lambda)^3 \varphi^3}.
\]

The estimator algorithm required the integral of \( G(\varphi) \) thus

\[
\psi(\varphi) = \int_0^\varphi G^2 \sin \varphi \, d\varphi.
\]

By using an exponential approximation for \( G(\varphi) \) it follows that

\[
\psi(\varphi) \approx \int_0^\varphi e^{-1/2 (\pi d/\lambda)^3 \varphi^3} \, d\varphi = 2/\pi (\lambda/d)^2 \left[ 1 - e^{-1/2 (\pi d/\lambda)^3 \varphi^3} \right]
\] (2)

Figure 100. Integrated transducer directivity function, \( \psi \), against angle, \( \varphi \), from acoustic axis MP-1 experiment.

In addition to the above result, which for all practical purposes should be adequate for general use, digitized data from the actual directivity plots was integrated to give a curve of \( \psi \) vs. \( \varphi \).

The procedure followed to convert the polar plots of the transducer directivity function into digital form was somewhat cumbersome. However, since there was no requirement to repeat the process for various directivity functions, no effort was directed towards automating the processes. The process followed was:

1) the polar plots were digitized and the resulting data was obtained on punched paper tape in \( x, y \) coordinates;
2) a computer program in PL-1 language was generated at MIT/CSDL which read the paper tapes and processed the data into punched card form;
3) the cards were input to two MAC-360 programs, one plotted the data to compare with the initial digitization, the other provided the curve-fitting function.

The net result of the steps described above was that the integrated exponential function as in expression (2) differed by about +20% in minor lobe height from the \( \psi(\varphi) \) given by the rigorous digitization process. Therefore, it was decided to use the curve for \( \psi(\varphi) \) from the digitization process in the estimator algorithm, shown in Figure 100.

APPENDIX IV
MANUAL ECHO SIGNAL PROCESSING

It can be shown (Equation 40 of Lozow and Suomala, 1971) that the estimated density of an aggregation of randomly distributed targets is
Target quantification methods

\[ p = \frac{R^2_e c^2 \alpha R}{SL \overline{TS} \epsilon \tau \psi N} \overline{I} \]  

(1)

where

- \( R \) = average range to targets
- \( \alpha \) = sound attenuation loss due to the combined effects of scattering and absorption
- \( \overline{I} \) = randomly varying received sound intensity
- \( SL \) = transmitted acoustic source level
- \( \overline{TS} \) = average target strength
- \( c \) = sound propagation velocity
- \( \tau \) = time interval of transmitted pulse
- \( \psi \) = function of transducer directivity

The randomly varying sound intensity can be written in terms of a randomly varying voltage.

\[ \overline{I} = \langle V_{rms} \rangle / VR \]  

(2)

where \( VR \) = receiving voltage response of the hydroacoustical instrument.

The geometry of a hydroacoustical transducer in relation to the targets of interest is shown in Figure 101.

It is convenient to introduce the term, \( M \), at this time

\[ M = \delta / \epsilon \tau / 2, \text{ then } \epsilon \tau = 2 \delta / M \]

The average density, \( \bar{p} \), can be defined as

\[ \bar{p} = \left( \sum_{N=1}^{M} \frac{R^2_e c^2 \alpha R}{SL \overline{TS} VR \delta / M \psi N} \right) \]

(3)

Substituting (1) and (2) in (3) we have

\[ \bar{p} = \frac{1}{M} \sum_{N=1}^{M} \frac{R^2_e c^2 \alpha R}{SL \overline{TS} VR \delta / M \psi N} \]

(4)

and

\[ \bar{p} = \frac{R^2_e c^2 \alpha R}{8 SL \overline{TS} VR \delta \psi \infty} \sum_{N=1}^{M} (V_{rms}^2)N \]

(5)

or

\[ \bar{p} = \frac{R^2_e c^2 \alpha R}{8 SL \overline{TS} VR \delta \psi \infty} \sum_{N=1}^{M} (V_{rms}^2)N \]

(6)

where

\[ M = \delta / \epsilon \tau / 2. \]

By examining CRT photographs of the raw received echo signal, an estimate of the target density can be obtained.

The procedure is to measure the peak-to-peak voltage of the echo signal envelope at transmitted pulse length intervals. The number of pulse lengths is defined by \( M \), above. The summation of the squared peak-to-peak voltages multiplied by the constant values in (6) will give an estimate of the target density.

This technique is known as echo envelope sampling and is theoretically derived by Lozow and Suomalainen (1971).

The constant values for the MP-1 experiment are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_0 )</td>
<td>( \sim 4 \text{ m} ) Physical dimension</td>
</tr>
<tr>
<td>( \delta )</td>
<td>( \sim 2 \text{ m} ) Physical dimension</td>
</tr>
<tr>
<td>( \overline{R} )</td>
<td>( \sim 5 \text{ m} )</td>
</tr>
<tr>
<td>( \delta )</td>
<td>( \overline{R} = R_0 + \delta / 2 ) Small</td>
</tr>
<tr>
<td>( \psi \infty )</td>
<td>( 1.7 \times 10^{-2} ) Measurement*</td>
</tr>
<tr>
<td>( SL, VR, \overline{TS} )</td>
<td>Table 25 Measurement</td>
</tr>
<tr>
<td>( VR )</td>
<td>( 10^{-8} ) Measurement</td>
</tr>
</tbody>
</table>

* The half power beamwidth angle (HPBW°) of the circular aperture transducer was measured to be 10°. The angle \( \psi \infty \) was computed by the method described in Appendix III as \( 1.7 \times 10^{-4} \) (HPBW°).

By substitution of the appropriate parameter values in Equation (6) we have

<table>
<thead>
<tr>
<th>Transmitted power ratio</th>
<th>Transmitted pulse length ratio</th>
<th>( \bar{p} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/10</td>
<td>0.3</td>
<td>142.3 ( \sum \frac{9}{I} V_{rms}^2 )</td>
</tr>
<tr>
<td>1/10</td>
<td>0.6</td>
<td>29.7 ( \sum \frac{5}{I} V_{rms}^2 )</td>
</tr>
<tr>
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<td>0.6</td>
<td>142.3 ( \sum \frac{5}{I} V_{rms}^2 )</td>
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</table>