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RESEARCH ON ACOUSTIC METHODS OF RESOURCE ASSESSMENT

by

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INTRODUCTION

An interdisciplinary research and development program in marine acoustics has been conducted at the University of Washington since 1968 with financial support principally from the Sea Grant Program. The broad objective is the development and application of acoustic techniques to the study of biological populations, with emphasis on resource assessment. During the last two years, progress in the general program was accelerated by the application of knowledge gained in research projects funded by the National Marine Fisheries Service through the Fisheries Research Institute. The work done in the NMFS-funded project during 1972 is summarized in this report. Its major accomplishments were the cooperative development of techniques for automatic fish target strength measurement, improvements and additions to the Digital Data Acquisition and Processing System (DDAPS), further field testing of the DDAPS including duel-frequency surveys, and target strength studies. In addition to describing these results, a brief summary of the general marine acoustics program accomplishments during 1972 and a major Sea Grant-supported theoretical study of acoustic assessment techniques are appended.

(Part I) RESEARCH ON METHODS OF TARGET STRENGTH ESTIMATION

(1) Introduction

The two commonly used acoustic assessment techniques are echo counting and echo integration. Echo counting is generally effective only when fish can be resolved as individual targets and is of limited use when assessing most marine stocks. The estimate obtained with counters has a negative bias in high densities when the sound pulses reflected from adjacent fish overlap

(Ehrenberg, 1972). The echo integrator has a higher variance than the echo counter in low fish densities. However, unlike the counter, the integrator provides an accurate estimate in high densities (Ehrenberg, 1972). One disadvantage of the integrator is that the mean target strength of the surveyed fish population must be known or estimated before an absolute density estimate can be obtained. It is shown in Appendix A that

$$E(I) = K\lambda E(T)E(g^4(\theta,\phi)) \quad (1)$$

where E( ) is the expectation operator, λ is the fish density, T is the target strength, and g (θ,ϕ) is the directivity function of the transducer at angular cordinates (θ,ϕ), and K is a constant that can be determined from the system parameters. The expected value of the directivity function term, $E(g^4(\theta,\phi))$, can be calculated for a particular transducer and assumed spatial distribution of the fish. Love (1971) and others have made target strength measurements of various fish species in the laboratory and have found that the target strength is a function of size, but varies with species and angle of acoustic illumination. Because of this variability, it is difficult to select a value for the mean target strength, E (T), and it is felt that *in situ* target strength methods must be developed for absolute density estimation.

A method for obtaining an estimate of the target strength distribution from the echo level distribution has been proposed by Craig and Forbes (1969). Their method is physically motivated and implicitly assumes that the fish are uniformly distributed in space. Another solution to the problem is treated in the next section. The method is obtained from a probabilistic approach to the problem and can be applied to any spatial distribution. It has been evaluated by means of a Monte Carlo simulation, discussed in Section 3. The first step in any target strength estimation technique is to recover the echoes of those fish resolved as individuals from the received signal. Hardware for recognizing single targets has been built and is discussed in Section 4.

(2) Description of the System and Analysis

The estimate of the target strength density function is obtained in two steps. In the first step the density function of the single fish integrated squared echo is estimated. The echo density is then used to evaluate the target strength density. A block diagram of the hardware used to obtain the single fish integrated squared echo values is shown in Fig. 1.1.

The threshold device represents the inability of the single target recognition circuit to distinguish signals whose integrated squared echoes are smaller than a certain level, σ. If all single echoes could be distinguished, it would be possible to estimate $E(T)E(g^4(\theta,\phi))$ by the sample mean of the single fish integrated squared echoes. However, a large percentage of the total number of single echoes are from fish located in the low-gain portion of the beam pattern and fall below the threshold level.

The integrated squared echo from the i^{th} fish is

$$I_i = \begin{cases} CT_i\, g^4(\theta_i,\phi_i) & E_i \geq \sigma \\ 0 & E_i < \sigma \end{cases} \tag{2}$$

where C is a constant, σ is the threshold level, T_i is the target strength of the i^{th} fish and (θ_i,ϕ_i) specifies the angular location of the i^{th} fish in the beam pattern. In order to simplify notation, define the random variables A and B as

$$\begin{aligned} A &= CT \\ B &= g^4(\theta,\phi) \end{aligned} \tag{3}$$

with densities $p_A(a)$ and $p_B(b)$ respectively.

The relationship between the density functions of A and B and the density function of I can be found by the use of the elementary probability theory (Papoulis, 1965). The relationship is given by

$$P_I(i) = \begin{cases} C'\int_0^\infty \frac{1}{a} P_A(a)\, P_B(i/a)\,da & i \geq \sigma \\ 0 & i < \sigma \end{cases} \tag{4}$$

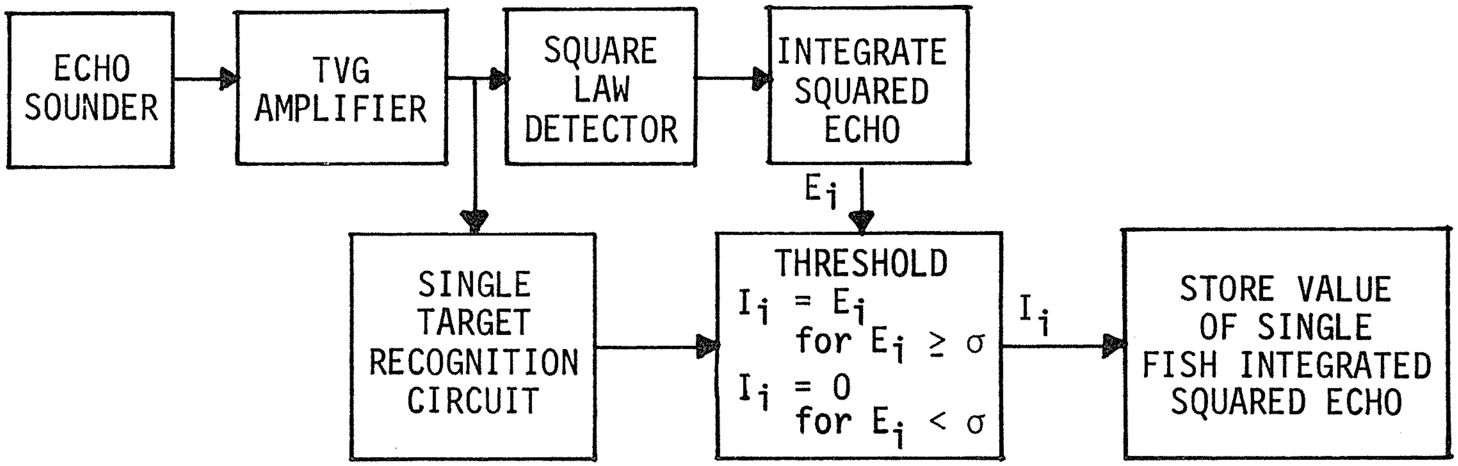

Fig. 1.1. Single echo recovery system.

where C', a constant that depends on the threshold level, σ, insures that $p_I(i)$ integrates to 1. The directivity function, $g(\theta,\phi)$, and consequently the random variable B is contained in the interval (0,1). The random variable proportional to the target strength, A, can be assumed to be contained in some finite interval (0, A_{max}). Using these intervals for A and B, one can rewrite Eq. (4) as

$$p_I(i) = \begin{cases} C'\int_i^{A_{max}} \frac{1}{a}\, p_A(a)\; p_B(i/a)da & i \geq \sigma \\ 0 & i < \sigma \end{cases} \qquad (5)$$

since $p_A(a)=0$ for $a>A_{max}$ and $p_B(b)=0$ for $b>1$. Equation (5) is a Volterra integral equation of the first kind for the unknown function $p_A(a)$. It can be shown that the integral equation has a unique solution within the class of positive functions.

The target strength density function estimate is obtained by numerically solving the integral equation, Eq. (5). The following procedure is one of the many methods that can be used to solve an integral equation. Some other techniques are described in Hildebrand (1965).

The estimate of the density function is written as an n^{th} degree polynomial,

$$\hat{p}_A(a) = \frac{1}{C'} \sum_{j=0}^{n} \alpha_j a^j. \qquad (6)$$

With this estimate for $p_A(a)$, the integral equation becomes

$$\hat{p}_I(i) = \sum_{j=0}^{n} \alpha_j\; \beta_j(i,A_{max}), \qquad (7)$$

where

$$\beta_j(i,A_{max}) = \int_i^{A_{max}} a^{j-i} \;\; p_B(i/a)da$$

and $\hat{p}_I(i)$ is an estimate of the density function for I. The maximum value of the target strength density, A_{max}, is not known *a priori*. It can be estimated by the greatest single fish integrated squared echo value. A Monte Carlo simulation has shown that the choice of A_{max} does not greatly affect the density estimate. The unknown coefficients, α_j, in Eq. (7) are evaluated by a least squares fit of the functions $\beta_j(i, A_{max})$ to the estimated echo density $\hat{p}_I(i)$. The normalizing coefficient, C', in Eq. (6) is chosen such that $\hat{p}_A(a)$ integrates to 1.

(3) Simulation

The procedure described in the previous section was investigated by means of a Monte Carlo simulation. Random variables, I, representing the integrated squared echo values were generated by taking the product of a beam pattern random variable, B, and a target strength random variable, A. The distribution for B was derived with the assumption of the use of a piston transducer and the existence of a uniform spatial distribution of the fish producing single echoes (Ehrenberg, 1972). The target strength density function was estimated by the method of Craig and Forbes (1969) and the method described in Section 2.

In the technique developed by Craig and Forbes, the data on echo level are divided into a number of cells and then manipulated to produce an estimate of the height of the target strength density function in each cell. The accuracy of the method is dependent on the cell size, the number of cells, the number of echoes and the true target strength distribution. For the case considered in the simulation, it was determined that the use of five cells each 4 db wide produced the best results.

For the method described in the previous section, the echo strength density function $p_I(i)$ was estimated by the derivative of a seventh-order least-squares polynomial approximation to the empirical distribution function of the echo value random variable, I.

Since little is known about the actual target strength distribution of a fish population, it was difficult to decide which density to use for $p_A(a)$. The target strength data that had been extracted by the use of the method of Craig and Forbes showed that the use of a normal distribution for target strength (in db) may be reasonable for some populations. When the target strength in db is assumed to be normal; then the random variables, A, should be lognormal, that is

$$A = e^{N(m,\sigma^2)} \qquad (9)$$

where $N(m,\sigma^2)$ is a normally distributed random variable with mean, m, and variance, σ^2. The results of the simulation for $m=3$, $\sigma^2 = .36$ are shown in Figs. 1.2 and 1.3. The curves in these figures were obtained from 300 and 1,000 samples, respectively.

The estimated density function can be used to obtain an estimate of the mean target strength, $\hat{m}_A$

$$\hat{m}_A = \int a \, \hat{P}_A(a) \, da \qquad (10)$$

A measure of the accuracy of this estimate is the relative error, defined as

$$\text{Relative error} = \frac{|\, \hat{m}_A - E(A) \,|}{E(A)}, \qquad (11)$$

where E(A) is the true mean target strength. The relative errors for the method of Craig and Forbes and the polynomial approximation technique are tabulated in Table 1 for a number of cases. In most cases the relative error in the mean target strength for the polynomial approximation to the density function was lower than the error produced by the method of Craig and Forbes. The accuracy of the estimate did not always improve with increasing sample size.

When the fish stock being surveyed is composed of two different year classes, the target strength density function may be bimodal. If an accurate target strength density function estimate could be obtained, it would provide a means of determining the relative abundances of the two year classes.

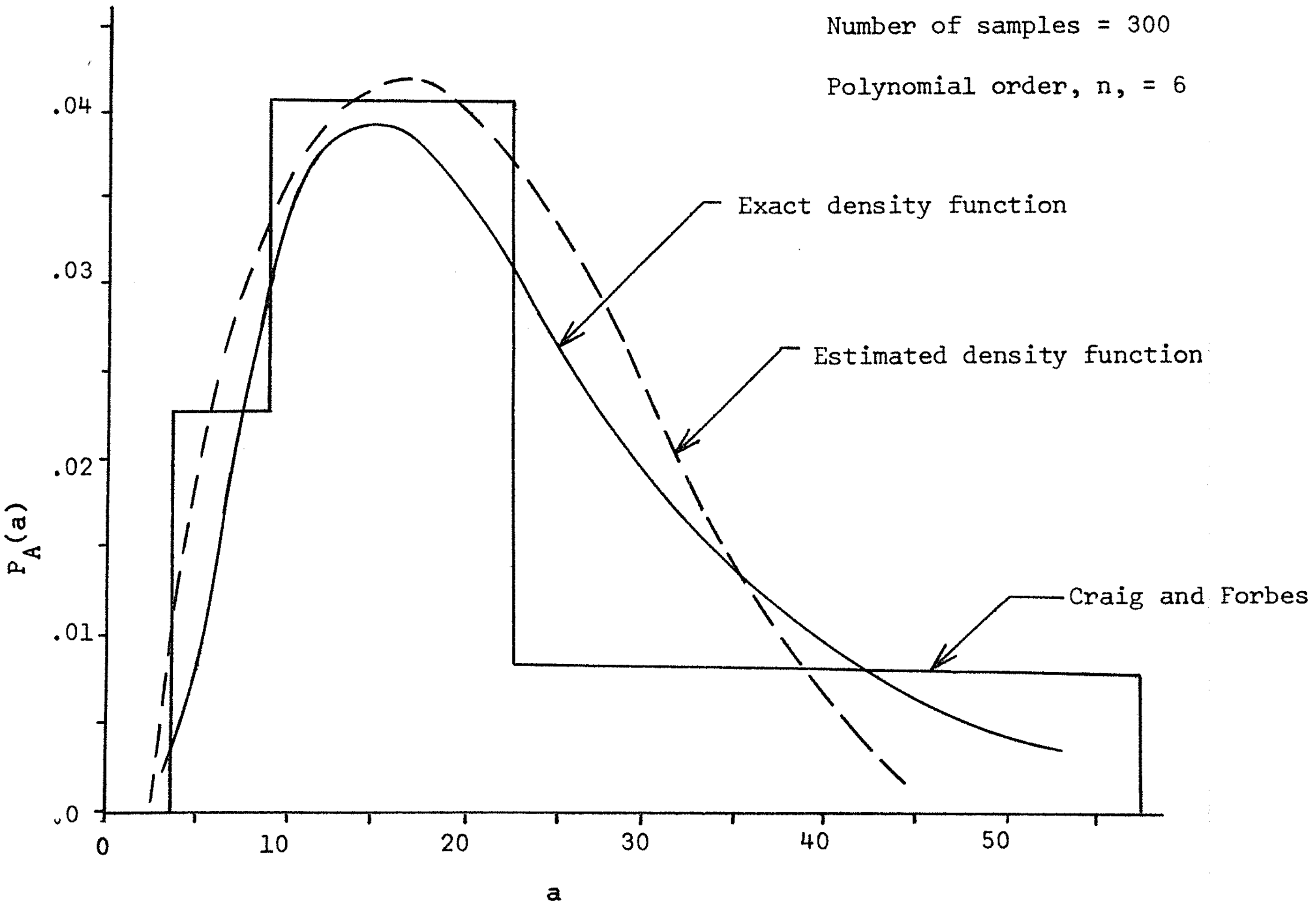

Fig. 1.2. Simulated density function estimate obtained with 300 samples.

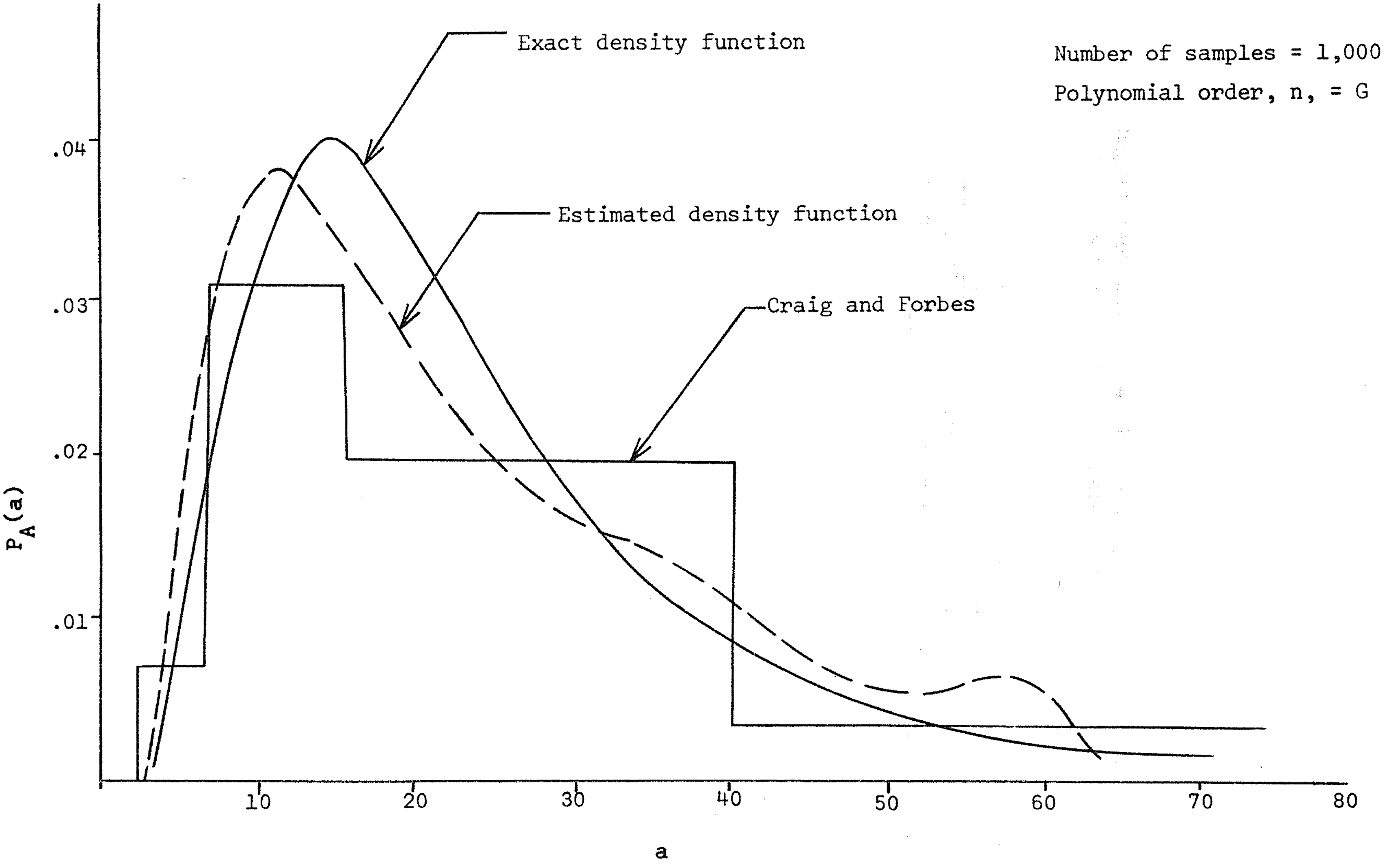

Fig. 1.3. Simulated density function estimate obtained with 1,000 samples.

Table 1. Relative errors in estimated mean target strength obtained by both estimation methods used

Distribution	Number of samples	Relative error Polynomial approximation	 Craig and Forbes
$A = e^{N(5.,1)}$	200	.104	.451
	300	.249	.576
	1000	.242	.594
$A = {}^{N(3.,.36)}$	200	.296	.160
	300	.212	.074
	1000	.019	.290

The results of the simulation for a population composed of two different log-normally distributed target strengths are shown in Fig. 1.4. The random variable A is given by

$$A = \begin{cases} e^{N(1,.2)} & \text{with probability } .5 \\ e^{N(2,.2} & \text{with probability } .5 \end{cases}$$

Both the method of Craig and Forbes and the polynomial approximation technique provided very poor estimates of the true density function.

From the results of the simulation it is apparent that neither the method of Craig and Forbes nor the method presented here provides the final solution to the target strength estimation problem. While the methods may provide good estimates of mean target strength for population estimates from integrated voltages, they are quite insensitive to the more detailed structure of target strength distribution in multimodal cases. In order to extract this type of information it may be necessary to utilize techniques that would extract target strength directly from individual echoes and be less sensitive to the shape of the target strength density or the spatial distribution of the fish.

(4) Single Target Recognition Circuit

The single target recognition hardware differentiates between an echo from a single target and overlapping echoes from two or more targets by measuring the length of the received echo. The hardware consists of a peak detector, a pulse width determination circuit, and a pulse length comparator (see Fig. 1.5). The peak detector circuit stores the maximum amplitude of the detected unfiltered signal. The peak detector is reset at the end of each input signal pulse. The pulse width determination circuit measures the width

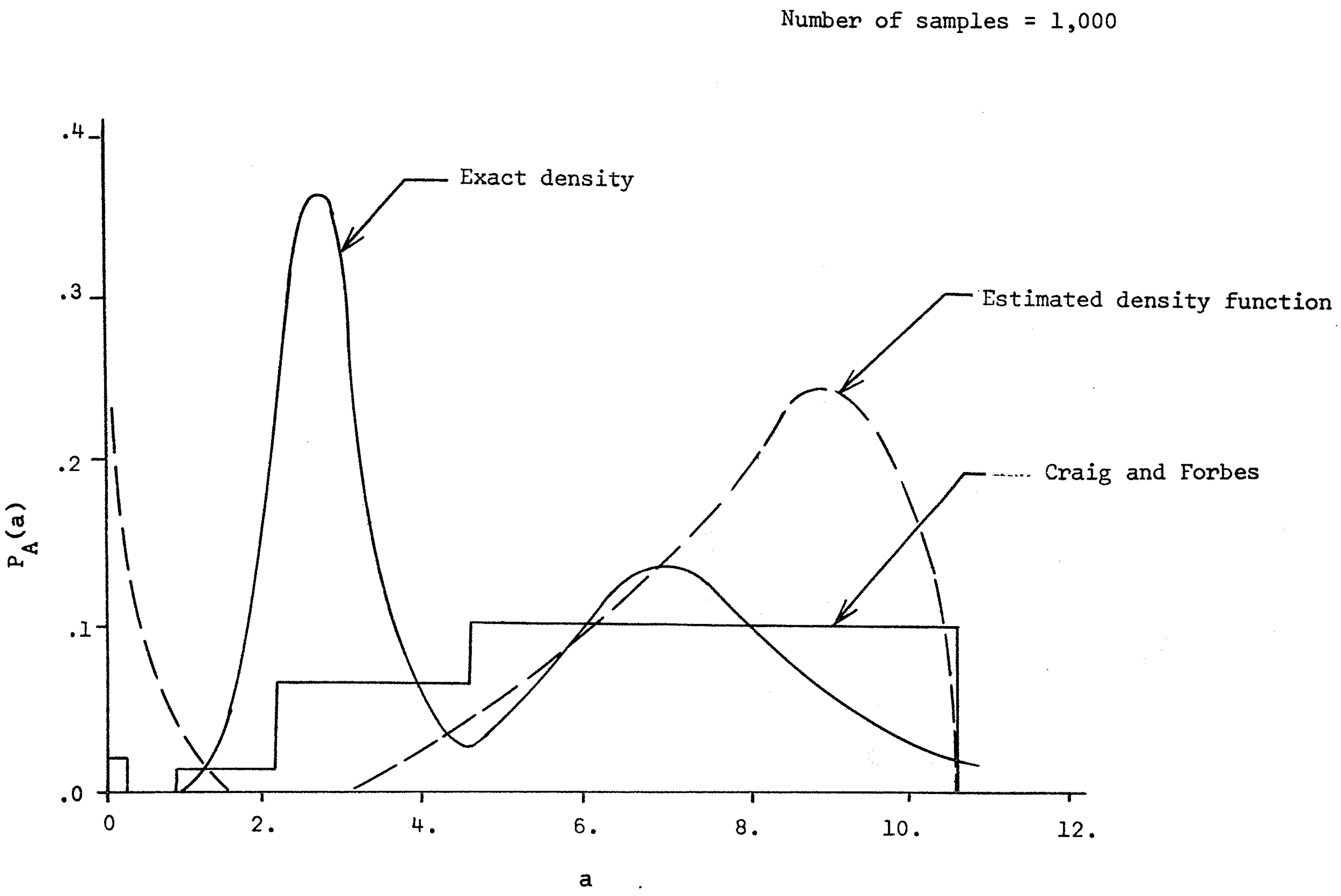

Fig. 1.4. Simulated density function estimate for a population with bimodal density.

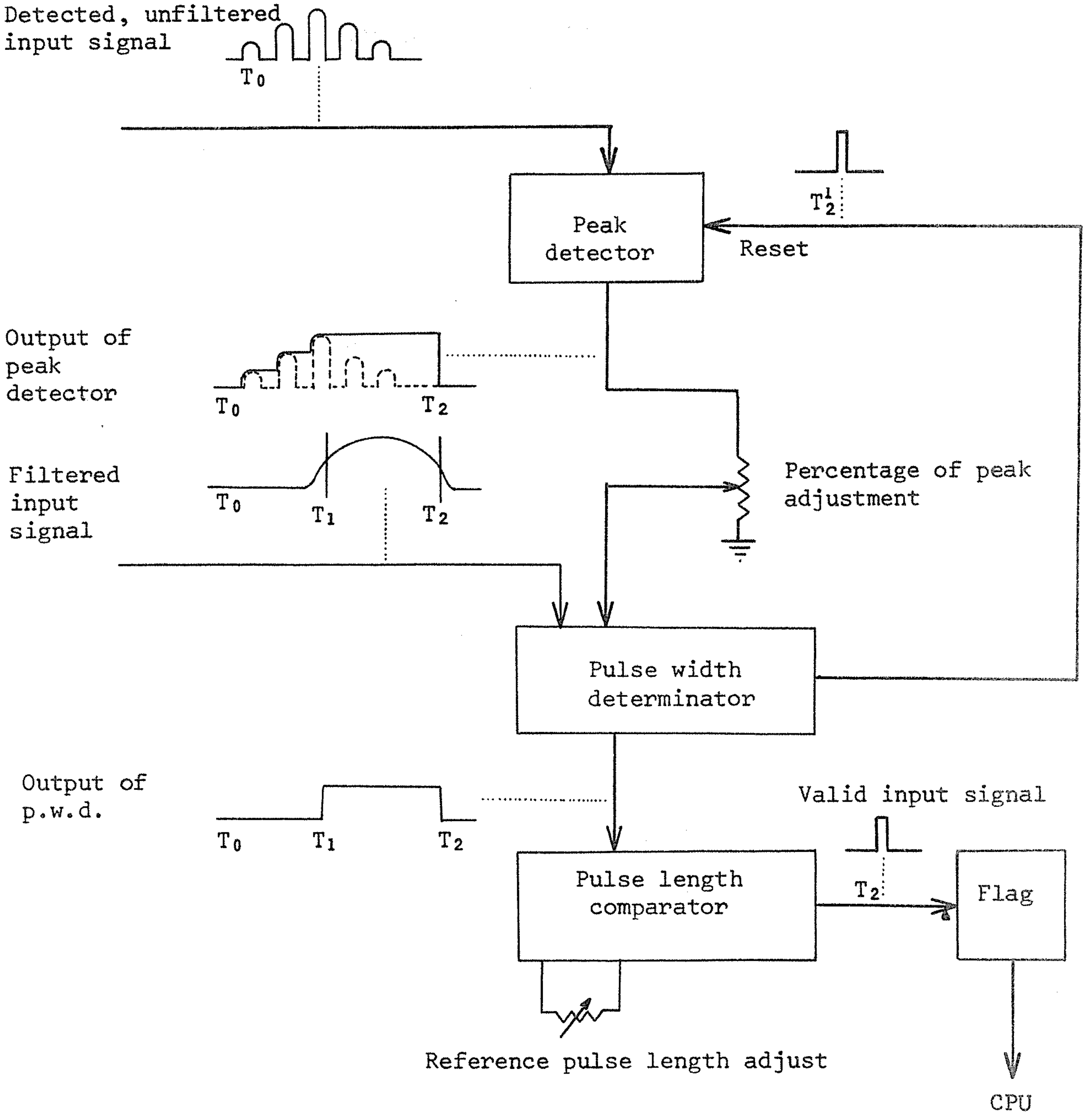

Fig. 1.5. Single target recognition circuit.

of the pulse at a height that is a preset percentage of the peak amplitude. The pulse length comparator checks the input pulse length to see whether it is within a specified tolerance of the expected pulse length. A flag is set for the computer at the end of each valid single target.

It is important to note that the single target recognition circuit is not useful only for the target strength estimation technique described in the previous section. All possible *in situ* target strength estimation techniques must have some method for extracting single targets.

(Part II) IMPROVEMENTS AND ADDITIONS TO THE DIGITAL DATA ACQUISITION AND PROCESSING SYSTEM

(1) Introduction

During the past year a number of improvements were made of the digital echo integration system (DDAPS) to expand the capability and utility of the system. The improvements are described briefly in the following sections. Detailed discussions can be found in the referenced documents.

(2) DDAPS Peripheral Storage

The most important modification of the hardware of the DDAPS system was the addition of a buffer core memory, tape storage unit, and tape controller. This work was done for a master's thesis and is described in detail in Shah (1972). The Central Processing Unit (CPU) of the PDP 8/L computer can use the buffer core memory as a high-performance extended storage for faster computations needing additional storage.

The tape unit can store operational programs for the system. The turnaround time for input/output (I/O) with use of the teletype is excessive.

For example, loading the DDAPS program via the teletype takes 17 min, whereas loading it from the tape unit takes 5 sec. Normally there are several users in a day, and several different programs are loaded into the computer. Thus loading the programs from the tape unit effects a great saving in time and greater use of the machine. When a user is testing a new program, the program frequently gets erased in the memory, and the user has to reload and modify the program. Where I/O is through the teletype only, several hours would be wasted in loading the program.

(3) Cross-Assembler Program

A number of changes in software have been made in the DDAPS system. One of the most useful products of the software development is the PAL/CDC cross-assembler. The purpose of the PAL/CDC cross-assembler is to allow the user to prepare programs to be run on a PDP-8 by submitting them to the cross-assembler on the CDC 6400. The cross-assembler accepts programs written in an extended version of the PAL assembly language, assembles and prints a copy of the assembled program, and outputs the object code on a variety of media.

The motivation behind the development of the cross-assembler was the difficulty of program preparation on the PDP-8 system. Most PDP-8's are dedicated systems using a teletype with a 10-character/second paper tape reader/punch for input/output; thus, preparation and modification of source programs is laboriously slow. The cross-assembler allows the use of standard punched-card input without the expense of adding a card reader to the PDP-8 system itself. In addition, with the standard PAL assembler the source program must be read three times, whereas the output tape of the PAL/CDC can be loaded directly. Further details of the cross-assembler are given in two documents by Clark (1972*a*; 1972*b*).

(4) Line Printer and Cathode Ray Tube Display

Operational experience with the DDAPS on shipboard and in the laboratory has shown a need for high-speed input and output peripherals to replace or supplement the teletype. Therefore, a small line printer and cathode ray tube (CRT) display terminal were purchased with Sea Grant funds and were added to the DDAPS during the last year. This addition has allowed an increase in data through -put and a corresponding decrease in operator workload.

The DDAPS system cannot acquire new acoustic data during the printing of results of a run. With the teletype, the time needed to print the results of a run is approximately 1 min. During this minute, it is not uncommon for the bottom depth to change enough to cause the bottom tracking algorithm to loose track. When this happens, the operator must reinitialize the tracking routine, and through -put rates of 50 per cent are not uncommon. The addition of the line printer has decreased the print-out time to approximately 6 sec. The resulting through -put rate is 95 per cent for 2-min runs. The CRT display terminal was incorporated as an input device in order to improve the reliability of the total system. In the past, nearly all the failures in the DDAPS were due to the teletype.

(Part III) DUEL-FREQUENCY SURVEYS

(1) Introduction

Additional data on Pacific hake were collected during March 27-28, 1972 and processed on DDAPS to examine the capability of the DDAPS to handle two-sounder inputs and to evaluate the advantages of two-sounder operation on acoustic surveys. The field data were also used to explore the reduction of variability in catch/integrated voltage relationships to be achieved by an extension of net haul duration from 10 to 15 min.

(2) Materials and Methods

Surveys were conducted on the hake stocks in Port Susan and Possession Sound, Washington, on the NMFS research vessel, *John N. Cobb*. A series of 9 transects were run in each area (Fig. 3.1). Acoustic data were collected on magnetic tape from a Ross 200A fineline sounder, 105 KHz, and a 38-KHz Simrad scientific sounder, modified to transmit synchronously. Then the data were analyzed by the DDAPS. It measured and integrated the squared echo voltages in various depth intervals from the two sounders and estimated the fish densities from input calibration data. The calibration relationships were determined from net haul catches as in previous surveys (Thorne, 1970; 1971; Thorne, Reeves, and Millikan, 1971) except that net haul durations were 15 min rather than 10 min.

(3) Results and Discussion

The relationships between net catch, in pounds, of hake per 15-min tow (45,000 m^3 swept) and integration from each of the two sounders are given in Figs. 3.2 and 3.3. They were highly linear for both sounders, although the intercepts were slightly positive, indicating that input signal levels were below optimal. If the regression model Y=bX is assumed, the relative errors of the beta coefficients would be 5.8 per cent for the Ross and 5.3 per cent for the Simrad. Both are less than that determined (9.6%) for the Ross sounder and 10-min hauls in earlier field tests (Thorne, 1971).

Fish densities during surveys were determined from the DDAPS integrated voltages by means of the generalized regression model Y=a+bX. The distributions of densities with depth along the various transects estimated with the two sounders are given in Tables 3.1 and 3.2. Population estimates were obtained by summing the products of the densities in the cells times the

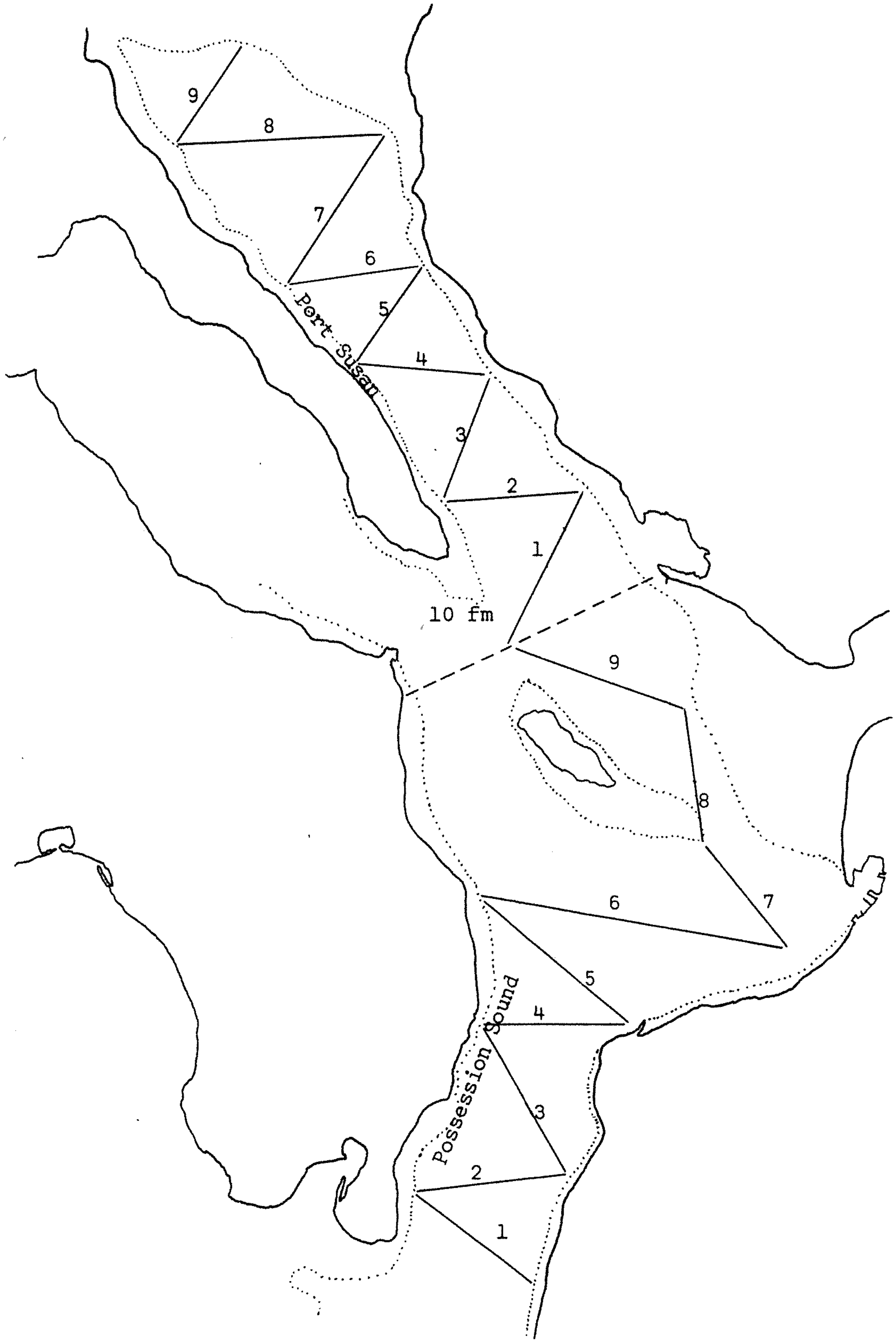

Fig. 3.1. Map of Port Susan and Possession Sound showing locations of transects.

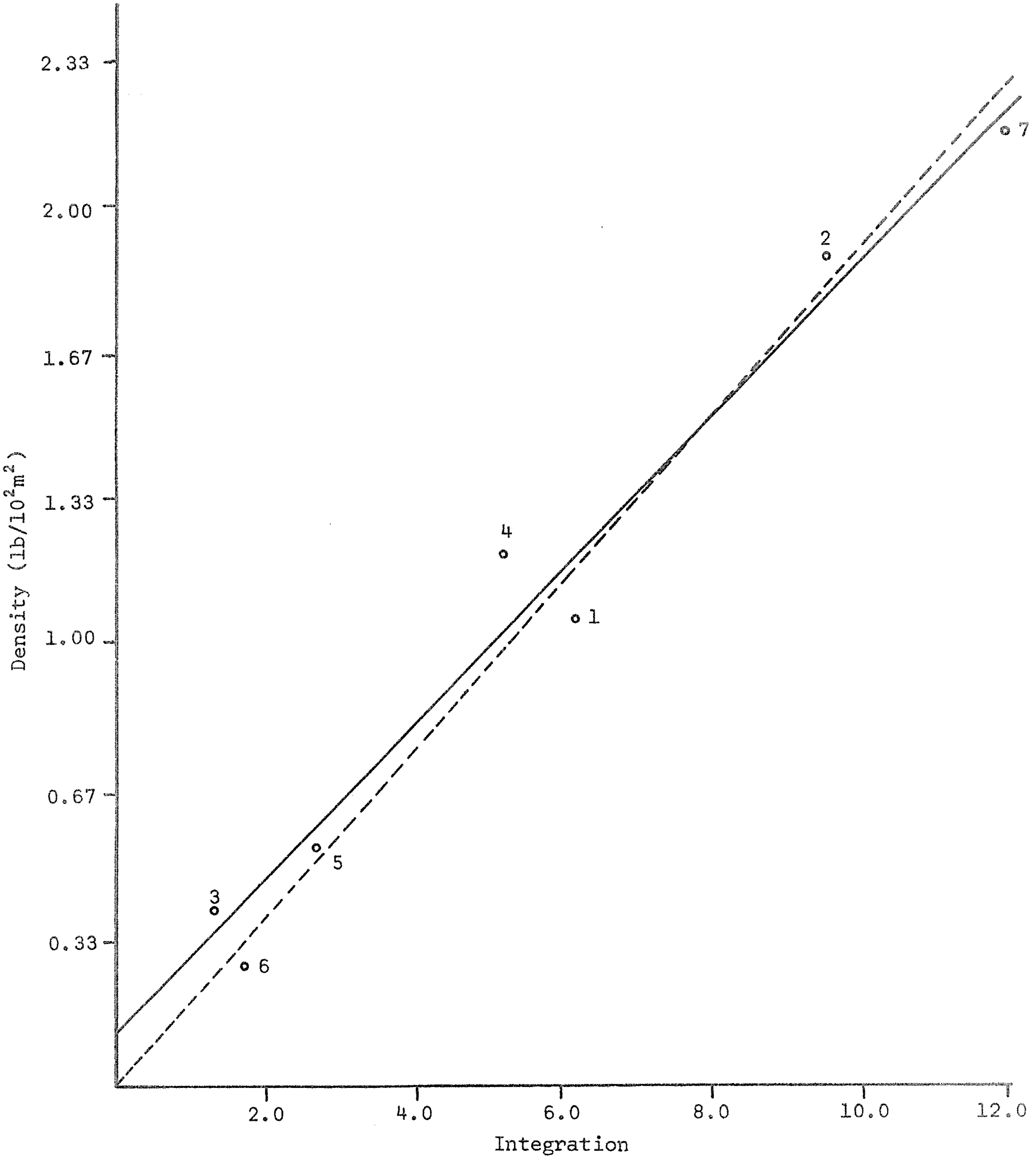

Fig. 3.2. Relation between density of fish and integration with Ross Sounder, Port Susan, 1972.

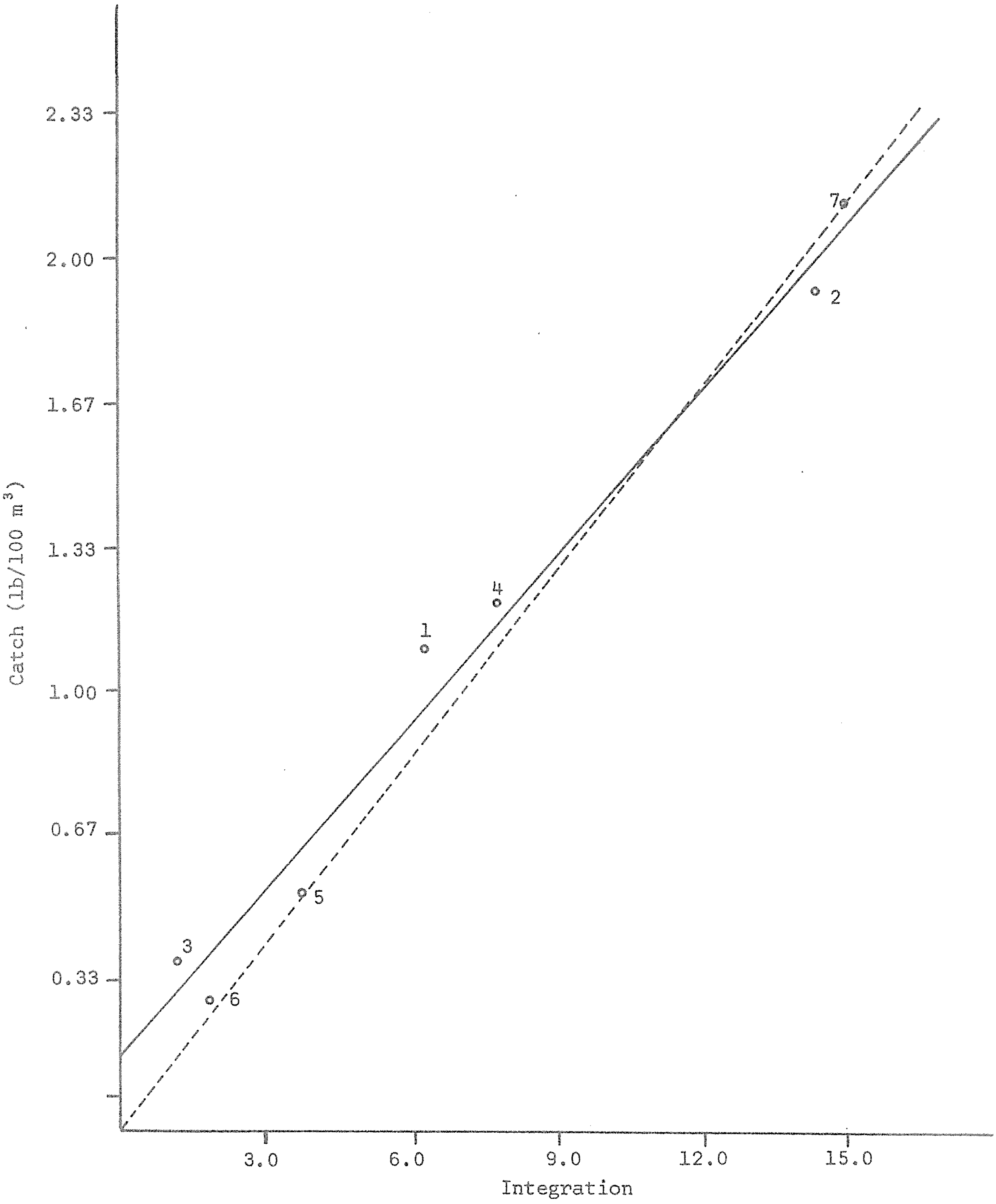

Fig. 3.3. Relation between fish density and integration with Simrad Sounder, Port Susan, 1972.

Table 3.1. Distribution of densities with depth along the various transects estimated with the Simrad sounder

	Possession Sound									
	1	2	3	4	5	6	7	8	9	Mean
60-70	0.20	0.20	0.19	0.21	0.23	0.25	0.48	0.44	0.38	0.287
70-80	0.21	0.27	0.26	0.32	0.51	0.32	0.68	0.53	0.66	0.418
80-90	0.33	(0.38)	0.42	0.57	0.87	0.44	0.75	1.00	1.84	0.733
90-100	0.37	(0.36)	0.36	0.60	0.62	0.39	1.11	1.88	2.11	0.867
100-120	0.25	(0.29)	0.33	0.47	0.79	0.35	1.21	0.00	1.91	0.700
Biomass (10^6 lb)	1.12	1.37	1.34	1.46	2.36	3.18	2.50	0.82	3.55	

	Port Susan									
	1	2	3	4	5	6	7	8	9	Mean
60-70	0.23	0.24	0.19	0.18	0.19	0.22	0.20	0.31	0.28	0.227
70-80	0.36	0.47	0.41	0.32	0.23	0.21	0.21	0.32	0.78	0.368
80-90	0.78	0.98	1.06	0.61	0.66	0.46	0.39	0.37	2.69	0.889
90-100	0.94	1.36	1.87	1.73	1.32	0.98	0.98	0.86	0.72	1.196
100-120	0.79	0.67	0.73	1.13	1.11	1.03	0.66	0.80	0.00	0.865
Biomass (10^6 lb)	1.71	1.99	1.84	1.86	1.23	0.89	1.36	0.96	0.97	

Table 3.2. Distribution of densities with depth along the various transects estimated with the Ross sounder

	Possession Sound								
	1	2	3	4	5	6	7	8	9
60-70	0.16	0.14	0.15	0.18	0.21	0.21	0.49	0.49	0.39
70-80	0.18	0.28	0.27	0.33	0.62	0.37	0.65	0.59	0.76
80-90	0.41	0.39	0.37	0.55	0.90	0.37	0.81	0.97	2.08
90-100	0.43	0.37	0.31	0.50	0.76	0.31	0.89	1.44	2.05
100-120	0.33	0.35	0.37	0.58	1.52	0.37	0.86	--	1.10
Area ($10^6 m^2$)	7.06	7.65	7.20	5.63	6.19	16.22	7.90	3.86	8.29
Biomass (10^6 lb)	1.28	1.44	1.30	1.50	3.42	2.91	2.24	0.80	3.56
Total volume	417	459	425	332	371	908	316	108	298

	Port Susan								
	1	2	3	4	5	6	7	8	9
60-70	0.38	0.30	0.22	0.19	0.22	0.32	0.19	0.40	0.26
70-80	0.51	0.70	0.68	0.42	0.31	0.26	0.19	0.40	1.07
80-90	1.20	1.42	1.62	0.81	1.13	0.58	0.46	0.48	4.26
90-100	1.17	1.58	2.26	2.09	2.70	1.10	1.00	1.04	1.00
100-120	1.27	0.82	0.91	1.61	1.44	1.17	0.44	0.78	--
Area ($10^6 m^2$)	7.40	5.80	4.40	4.50	3.30	3.90	6.80	6.60	6.80
Biomass (10^6 lb)	2.50	2.58	2.46	2.43	2.01	1.06	1.29	1.17	1.99
Total volume	296	278	229	234	172	164	299	218	156

associated volumes. The population estimates from the Ross sounder for Port Susan and Possession Sound were 17.5×10^6 lbs and 18.5×10^6 lbs, respectively. The corresponding estimates for the Simrad sounder were 12.8×10^6 lbs and 17.7×10^9 lbs.

An examination was made of the variability in the density estimates from the surveys so that variances could be obtained for the population estimates. The data from various cells were contoured into high and low density areas with the value of 0.61 lb/100 m^3 as the contour line. Exactly the same contours were obtained in Possession Sound from each sounder, whereas 3 values out of 45 were not in agreement in Port Susan (Tables 3.1 and 3.2). For each grouping a weighted mean density and its variance were calculated, with weighting proportional to the volume represented by each cell. Then the variances of the population estimates were determined from the relationship

$$\text{var } N_T = V_L^2 \bullet \text{var } D_l + V_H^2 \bullet \text{var } D_H$$

where N_T is the population estimate,

V_L is the volume associated with the low densities,

var D_l is the variance of the weighted mean low density,

V_H is the volume associated with the high density, and

var D_H is the variance of the weighted mean high density.

The variances of the biomass estimates for Port Susan and Possession Sound from the data from the Simrad and Ross sounders and from the combined-sounder operation are given in Table 3.3. Variance was lower for the Simrad sounder than for the Ross, possibly because of the greater sampling volume of the sounder beam (7° x 20° compared to 7.5° circular). Variance was decreased in all cases with the combined-sounder operation. The variances do not include those associated with the calibration relationships.

Table 3.3. Variances obtained for population estimates for hake in Possession Sound and Port Susan, obtained by Simrad, Ross, or combined sounder operation

Simrad		Ross		Combined	
Biomass (10^6 lb)	Variance (10^{12})	Biomass (10^6 lb)	Variance (10^{12})	Biomass (10^6 lb)	Variance (10^{12})
		Possession Sound			
17.7	1.325	18.5	1.413	18.1	0.69
		Port Susan			
12.8	0.807	17.5	3.33	15.2	0.786

It should be noted that the close agreement between the two sounders, the highly linear relationships between catch and integration, and the generally low variance, all confirm previous conclusions from Port Susan studies concerning the high precision possible with acoustic surveys, and in turn contrast with the conclusions of some limited theoretical and artificial target studies which imply extremely high variances. Evaluation of the precision of acoustic biomass estimates must take into account the sampling power of echo sounders. For example, at depths and densities encountered during this study the sounders were typically insonifying about 30 fish in the main beam within each 10 m interval, each pulse. Thus integration measurements associated with the 15-min net hauls typically represented about 50,000 highly independent echoes from fish, and each regression line was based on about 350,000 echoes on fish. The low observed variance is predictable from the extensive theoretical studies of Ehrenberg (1972).

(Part IV) FIELD STUDIES ON TARGET STRENGTH

(1) Introduction and Methods

Studies were conducted of the target strengths of two fish species, Pacific herring (*Clupea harengus pallasi*) and sockeye salmon (*Oncorhynchus nerka*), with two objectives: to examine the relationship between target strength and size and its variability and to provide background data for future application of the methods described in Part I.

Studies were conducted on herring in Carroll Inlet, Alaska, in January 1972 and on sockeye salmon in Lake Washington during September 1972. In both cases data were collected at night so that advantage could be taken of the dispersion of the fish, and the number of individual targets maximized.

Data were collected on magnetic tape from calibrated 105 KHz Ross 200 A sounders and analyzed with a storage oscilloscope. The oscilloscope was set on single trigger, and targets from a narrow depth range were randomly sampled by use of the reset switch. The data on echo strength were divided into decibel groups and the target strength distribution was calculated according to the method of Craig and Forbes (1969).

(2) Results and Discussion

The distribution of target strengths from 110 observations on herring is given in Fig. 4.1. Most of the herring were between 17 and 24 cm in length. The expected distribution of target strength was calculated from the length-frequency data on herring obtained from purse seine samples by use of the relationship between target strength and fish length given in Urick (1967). This distribution is also plotted in Fig. 4.1. The mean values are in good agreement, but the observed variability of target strengths is much greater than would be expected from variability in length.

The distributions of target strengths from 550 observations on sockeye salmon are shown in Fig. 4.2. Separate distributions are presented for south Lake Washington, where the majority of adult sockeye salmon were expected to occur, and for the remainder of the lake, which was occupied primarily by juveniles. The target strength distribution is clearly bimodal; one mode is associated with adults and the second with juveniles. The target strengths of the adults are estimated at -32 to -26 db. According to the relationship in Urick (1967), a target strength of about -25 db would be expected for fish between 50 and 60 cm. Target strengths of about -50 db would be expected from juveniles from 7 to 9 cm. The mean of the juvenile target strengths is difficult to estimate since target strengths less than -56 db were below the detection threshold.

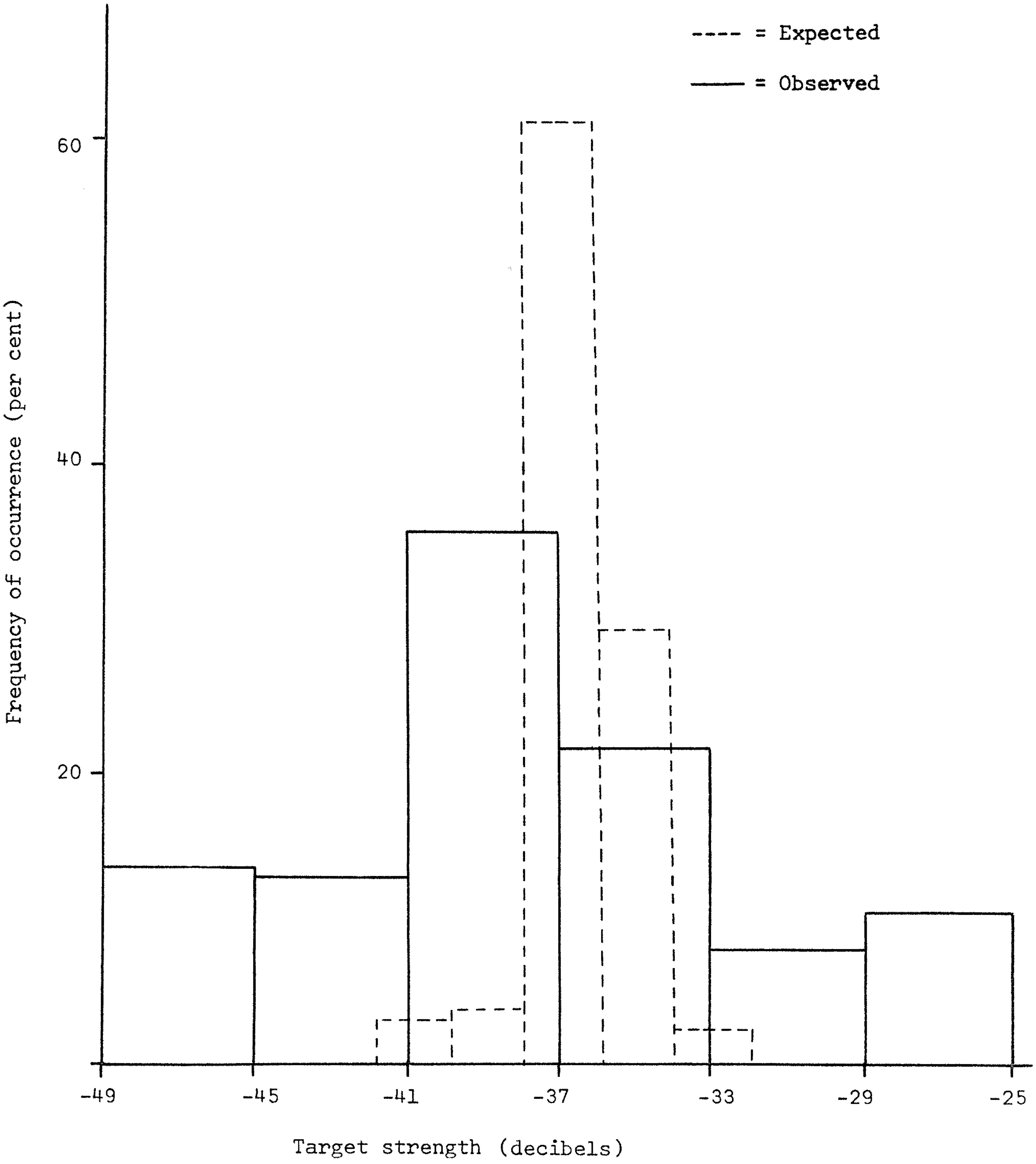

Fig. 4.1. Distribution of target strengths of herring in Carroll Inlet, Alaska, January 1972

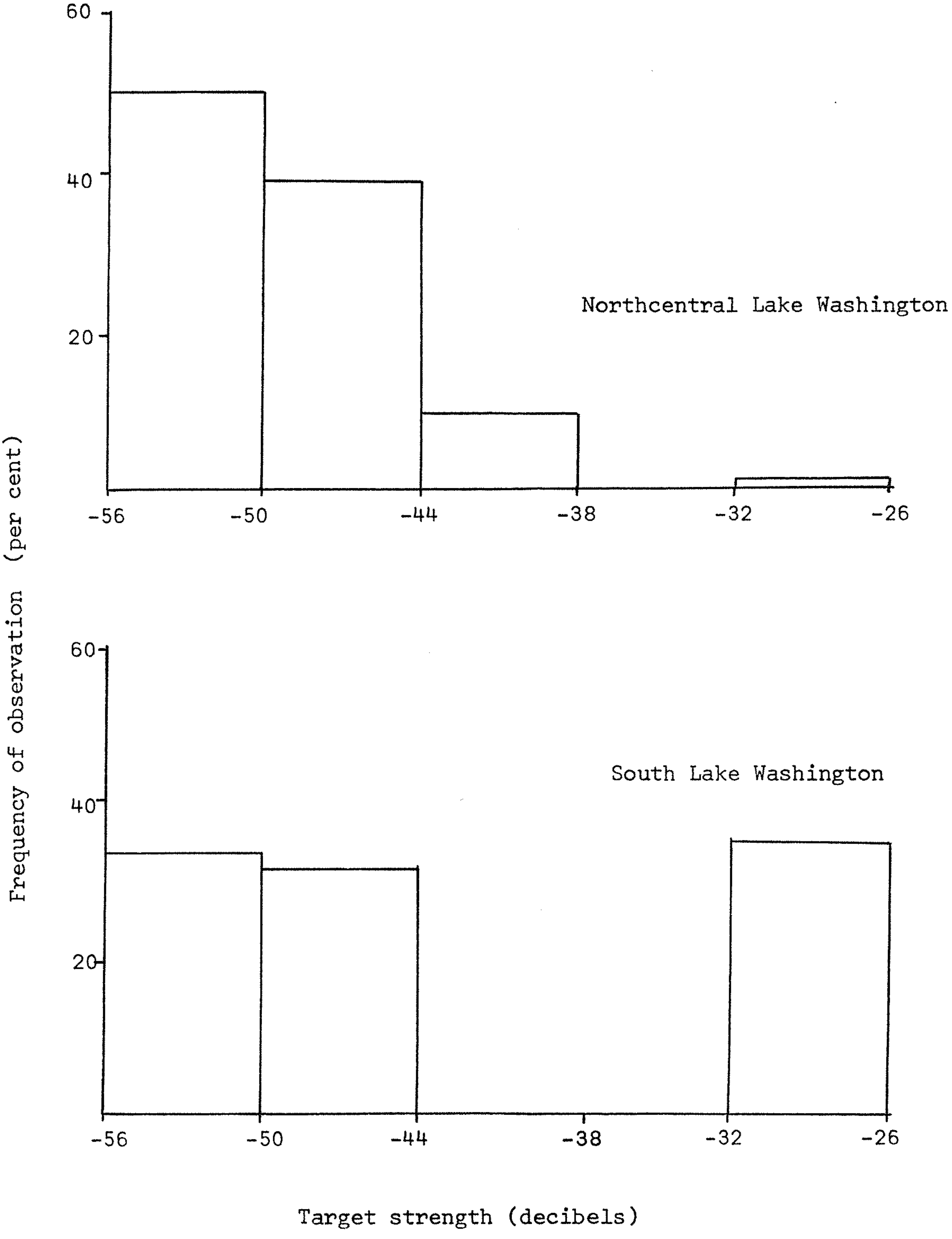

Fig. 4-2. Distribution of target strengths of sockeye salmon in Northcentral and South Lake Washington, September 1972.

Although the simulation studies indicate that the method of Craig and Forbes is insensitive for complex distributions, the above results do indicate that a bimodal distribution can be detected under conditions where two groups with a great difference in size occur.

SUMMARY AND CONCLUSIONS

A method for estimating target strengths was developed. The method was proven by simulation studies to be generally superior to the technique of Craig and Forbes. The method generally provides a good estimate of the mean target strength and reproduces well the detail of a target strength distribution with a single mode. However, like the method of Craig and Forbes, the method appears to be quite insensitive to more complex target strength distributions, and alternative approaches for extracting target strength information from multimodal populations should be explored.

Field studies were conducted on target strength of herring and sockeye salmon. The initial results showed target strengths in good agreement with those expected from early empirical studies of size and target strength, and two modes of target strength associated with adult and juvenile sockeye salmon, even though the variability in observed target strengths was large.

Extraction of target strength data by observation of echo strengths with a storage oscilloscope is very time-consuming. Hardware for recognizing single targets was completed. Used in combination with the DDAPS and the method for extracting the target strength distribution, it will allow automatic measurement of target strength. Considerable field testing is needed and much more information on the relationship between target strength and size and its variance for various species should be obtained.

Several improvements were made on the DDAPS, designed to increase its speed and versatility. Further field testing of the system was conducted, especially of its ability to handle two sounder inputs simultaneously. The system was also utilized extensively in a number of population studies (*See* Appendix B). While some additional minor refinements can be made, the limitations in the speed and storage of the system preclude major additional improvements in its total capability. Research was begun on larger and faster systems with other funding (*See* Appendix B).

Field studies with two-sounder operations showed very high correlation between density estimates obtained by the DDAPS from 105 KHz and 38 KHz sounders and demonstrated that major reductions in variances of population estimates can result from two-sounder operations. The possibility of reducing survey effort by multisounder operation should be further explored.

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APPENDIX A. MEAN INTEGRATOR OUTPUT

A block diagram of the basic echo integrator system is shown in Fig. A-1. The pressure wave received by the transducer is

$$P(t) = \sum_{i=i}^{N(t)} \frac{e^{-\alpha ct}}{(ct/2)^2} A_i g^2(\theta_i,\phi_i)X(t-\tau_i) \cos[w(t-\tau_i) + \psi_i] \qquad (A-1)$$

where C is the velocity of propagation in water, A_i, θ_i and ϕ_i are random variables representing the echo strength and angular coordinates of the i^{th} fish, $g(\theta,\phi)$ is the directivity function of the transducer at coordinates (θ,ϕ), $X(t-T_i)$ is the envelope of the i^{th} returned echo, and $n(t)$ is the number of fish in the ensonified volume. The propagation losses due to spreading and absorption are given by $e^{-\alpha ct}/(ct/2)^2$. The output of the integrator for a single acoustic pulse is

$$I = \int_{t_1}^{t_2} V^2(t)dt \qquad (A-2)$$

The expected value of the integrator output is

$$E(I) = \int_{t_1}^{t_2} v_x^2\, G^2(t)\frac{e^{-2\alpha ct}}{(ct/2)^4} \quad E[\{\sum_{i=i}^{N(t)} A_i g^2(\theta_i,\phi_i) x(t-T_i) \cos[W(t-T_i)+\psi_i]\}^2]dt \qquad (A-3)$$

where r_x is the pressure to voltage conversion constant of the transducer. When the squared sum in Equation (A-3) is rewritten the expression for E(I) becomes

$$E[I] = \int_{t_1}^{t_2} V_x^2\, G^2(t)\frac{e^{-\alpha ct}}{(ct/2)^4} \quad E[\sum_{i=1}^{N(t)} A_i^2 g^4(\theta_i,\phi_i) X^2.(t-\tau_i)\cos^2[w(t-\tau_i)+\psi_i] + \sum_{\substack{i=1\\ i\neq j}}^{N(t)} \sum_{j=1}^{N(t)} A_i A_j\, g^2(\theta_i,\phi_i)\, g^2(\theta_j,\phi_j) x(t-\tau_i)x(t-\tau_j) \cos[w(t-\tau_i)+\psi_i] \cos[w(t-\tau_j) + \psi_j] \qquad (A-4)$$

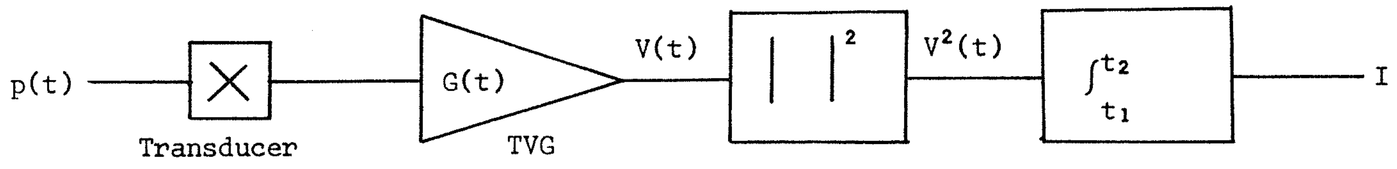

Fig. A-1. Echo integrator system.

The expectation of the double sum in Eq. (A-4) is equal to zero because of the random phase of the echoes from different fish. If one assumes independence of N(t), A, θ, ϕ, ψ, Eq. (A-4) becomes

$$E[I] = CE[A^2]E[g(\theta,\phi)] \tag{A-5}$$

where

$$C = \frac{x^2}{Z} \int_o^{T_p} x^2(t)dt \int_{t_1}^{t_2} \frac{G^2(t)e^{-\alpha ct}}{(ct/2)^2} \lambda(t)dt \tag{A-6}$$

and $\lambda(t)$ is the echo density at time t and T_p is the length of the echo envelope. In obtaining Equation (A-6), it was assumed that $G^2(t)e^{-\alpha ct}\lambda(t)/(ct/2)^2$ is almost constant over the duration of the pulse envelope. For some fish distributions (such as a layer of fish) the moments of $g(\theta,\phi)$ vary with time. In this case $E[g^4(\theta,\phi)]$ is defined as

$$E[g^4(\theta,\phi)] \doteq \frac{\int_{t_1}^{t_2} \frac{G^2(t)e^{-\alpha ct}}{(ct/2)^2} \lambda(t)E[g^4(\theta,\phi,t)]dt}{\int_{t_1}^{t_2} \frac{G^2(t)e^{-\alpha ct}}{(ct/2)^2} \lambda(t)dt} \tag{A-7}$$

The density function $\lambda(t)$ depends on the spatial distribution of the fish in the ensonified volume. In all cases, however, $\lambda(t)$ can be written as

$$\lambda(t) = \lambda f(t) \tag{A-8}$$

where λ is the density constant and f(t) is a deterministic function. For a uniform density

$$\lambda(t) = \lambda\frac{\pi c^3 t^2}{4} \tag{A-9}$$

In the general case, the mean integrator output is

$$E[I] = K\lambda E[T]\ E\ [g^4(\theta,\phi)] \tag{A-10}$$

where

$$K = \frac{r_x^2}{Z} \int_o^{T_p} x^2(t)dt \int_{t_1}^{t_2} \frac{G^2(t)\lambda(t)e^{-\alpha ct}}{(ct/2)^2} dt \tag{A-11}$$

APPENDIX B. SUMMARY OF PROGRESS IN MARINE ACOUSTICS PROGRAM IN 1972

Theoretical Studies

In addition to target strength studies reported here, a study was conducted for a Ph.D. Thesis by John Ehrenberg, entitled "Estimation of the intensity of a filtered Poisson process and its application to acoustic assessment of marine organisms." A copy of the thesis is appended (Appendix D). The thesis is also being prepared for publication as a Washington Sea Grant Publication.

Equipment Development

Additions and improvements to the DDAPS have been reported. Although the DDAPS represents a major advance over analog systems, it still has limitations of size and capacity, especially for large-scale surveys. The use of larger computer systems has been investigated. Work is presently underway on a larger acoustic assessment system for the National Science Foundation Coastal Upwelling Ecosystem Analysis Program using a PDP 11-45 computer.

Work was completed on a portable acoustic data acquisition system for use with small vessels. The system has its own internal calibration. It is described in detail in a new Washington Sea Grant Publication (Thorne, Nunnallee, and Green, 1972).

Field Studies

In addition to the field studies reported here, a number of population studies was conducted in 1972. These included studies of the hake in Puget Sound, part of which is described here, herring stocks in southeastern Alaska and Puget Sound, sockeye salmon in three Washington lakes (Washington, Quinault, and Wenatchee) and in Lake Iliamna, Alaska, and Lake Shuswap, British Columbia, trout populations in Ross Lake, and fish distribution in Lake Chelan.

Details of many of the Marine Acoustics Program studies can be obtained from the various publications of the Program, a list of which appears in Appendix C.

APPENDIX C. PUBLICATIONS AND THESES, MARINE ACOUSTICS PROGRAM

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Appendix D

ESTIMATION OF THE INTENSITY OF A FILTERED POISSON PROCESS AND ITS APPLICATION TO ACOUSTIC ASSESSMENT OF MARINE ORGANISMS

Ph.D. Thesis by

John E. Ehrenberg