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AN ACOUSTIC NAVIGATION SYSTEM

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TECHNICAL REPORT

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Approved for Distribution *Earl E. Hays*

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LIST OF ILLUSTRATIONS

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1. INTRODUCTION

This report describes a system for underwater acoustic navigation developed, and in use, at the Woods Hole Oceanographic Institution. It includes a brief discussion of the electronic components, operation, mathematical analysis, and available computer programs. There is a series of supplementary Technical Memoranda containing more information on various aspects of the system (see Appendix). We believe that this kind of documentation is more flexible and better meets the needs of potential users than including all technical details in one large volume. These are not final or definitive reports; acoustic navigation capabilities will continue to evolve at W.H.O.I. for some time.

Acoustic navigation provides a method of tracking a ship, and an underwater vehicle or instrument package ('fish'), in the deep ocean. Acoustic devices attached to the ship and fish measure the length of time it takes a sound pulse to travel to acoustic transponders moored on the ocean floor. If the transponder positions and the average speed of sound are known, the ship or fish position can be found.

Many people have contributed to the system development. The prime mover and coordinator has been William Marquet of the Deep Submergence Group. Marquet and Andrew Eliason from the ALVIN group, and Kenneth Peal from the Information Processing Center were responsible for the electronic development and interface between the various system components. Eliason designed the Timing Control Unit. Peal worked with Marquet and Eliason on system integration, and was responsible for the original at-sea checkout.

Marquet did the systems engineering, the preliminary mathematical analysis and program specifications; James Metzler and Andrew Singer also worked on the analysis of the system. Early in 1974, Woollcott Smith did a thorough mathematical analysis of the survey problem and developed a new scheme based on standard nonlinear regression results.

Most of the programming staff of the Information Processing Center has contributed to program development. Roger Goldsmith, Mary Hunt, Kenneth Peal, George Power, and Woollcott Smith have all made significant contributions.

Finally, throughout the development of all aspects of the system, William Schmitz has been very generous of his time and advice.

2. BRIEF HISTORY OF ACOUSTIC NAVIGATION

Early uses of underwater sound in navigation were limited to echo sounding, operational on U. S. naval vessels in 1922, and radio-acoustic ranging used by the Coast and Geodetic Survey in the 1930's. By the end of World War II the understanding of sound propagation, sound velocity variations, and ray tracing was sufficient for the development of more sophisticated applications. Naval and oceanographic communities channeled this new technology toward the use of underwater acoustics as a tool to study oceanic phenomena. During the late forties and early fifties, free-floating Swallow floats (Swallow, 1957) were tracked acoustically, and the height above the sea floor of towed cameras and oceanographic samplers was determined by monitoring the time delay between direct and bottom reflected pinger pulses.

Three dimensional positioning of instruments and vehicles requires a significant increase in the sophistication of techniques. Before 1960 two systems in use were: 1) the Missile Impact Location System (MILS) (Spiess, 1966) which used hydrophones monitoring the Sofar channel to pinpoint distant sound sources, and 2) the Three-D tracking range of the Applied Physics Laboratory of the University of Washington (University of Washington, 1958) which employed a transmitter and four bottom-mounted, rigidly spaced hydrophones to provide distance and bearing to vehicle-mounted transponders at short ranges. Both systems were coupled to the shore for control and signal processing.

For the past ten years emphasis has been on the development of precise relative navigation in two forms: range-bearing and range-range. Range-bearing methods use the difference in arrival times of timed pinger or transponder pulses at multiple hydrophones to position instruments or vehicles relative to a surface ship. An independent means of geographic navigation is required for the ship. Examples are: 1) the inverted Three-D system of APL-University of Washington (Van Wagenen et al., 1963), 2) the MIZAR system of the Naval Research Laboratory (Van Ness et al., 1966), 3) the W.H.O.I. system as used on the THRESHER search (Baxter, 1964), and 4) the system developed to position CUSS II of the Mohole project (Brown and Root, 1964) and improved upon for the Deep Sea Drilling Program aboard GLOMAR CHALLENGER. The bathyscaphe TRIESTE and the DSRV ALVIN have used a variation of the range-bearing theme to guide them to an underwater object (Spiess, 1966). A transponder mounted on the object was used to obtain range and a search sonar was used to obtain the bearing of the transponder.

The range-range method uses the elapsed time between an interrogation pulse and the reception of replies from more than one bottom-mounted transponder to calculate the position of the ship or lowered device relative to a network of transponders. Given the geographic position of the transponder network, this method provides precise limited area navigation relative to the sea floor. Principal users of this technique have been the U. S. Navy, the Marine Physical Laboratory (MPL) of Scripps Institute of Oceanography (SIO) (Boegeman et al., 1972), and the Woods Hole Oceanographic Institution. MPL has two systems designed for tracking a deep towed instrument package (Deep-Tow), one of which requires an electrical connection to the ship for the control and processing of navigation data for the towed package. The other MPL system and the W.H.O.I. system require no direct link to the ship. Basic to the differences between the two systems is the method of interrogation. The MPL system interrogates each transponder individually and each replies on the same frequency. The W.H.O.I. system interrogates the transponders collectively and each replies at a different frequency. Another application of the range-range method at W.H.O.I. has been the self tracking of a free-fall acoustic dropsonde to obtain a vertical profile of horizontal currents (Gould et al., 1974).

In general the accuracy of all systems is limited by the knowledge of instantaneous sounding velocity, by the ability to determine the relative spacings of hydrophones or transponders in networks, and by the motions of the ship.

The development of the W.H.O.I. acoustic range-range navigation systems began in 1967. The goal of the program was to provide a data acquisition system to be used aboard DSRV ALVIN to record scientific measurements and the necessary navigation information to make the scientific data meaningful. The first system was based on the precise timing of acoustic pulses. Two beacons were built that transmitted acoustic pulses at precise times. A master clock on board the submersible was synchronized to the beacons. Counters, started by this clock, were stopped by the reception of the acoustic pulses. Slant ranges to each beacon were presented, in meters, on digital displays and Precision Graphic Recorders. The system was used in 1968 to locate a downed F6F aircraft in 1600 meters of water. The loss of ALVIN in October, 1968 curtailed use of this system.

In 1970 a study of W.H.O.I. underwater tracking and navigation needs was conducted. The system described in this report was developed as a result of that study. In 1972 a prototype system was built. This system was funded by the Advanced Projects Research Agency (ARPA) and administered under ONR Contract N00014-71-C-0284. The system was designed to provide navigational tracking of DSRV ALVIN but also included provisions to track other types of submerged objects. Sea trials were conducted in the Gulf of Maine aboard the resurrected ALVIN.

In November, 1972, the equipment was placed aboard RV ATLANTIS II, then operating on the Mid-Atlantic Ridge, to obtain real time tracks of the ship and towed cameras and dredges.

Early in 1973, an informal group of investigators from the Departments of Ocean Engineering, Geology and Geophysics, and Physical Oceanography pooled resources to pursue the development of this system for general purpose acoustic navigation applications. William Marquet helped organize this group to expand the use of the ARPA/ALVIN system and to develop further system refinements, particularly in the area of computer programming.

A large portion of the support came from Contract APL/JHU, subcontract 372111, with the Applied Physics Laboratory of Johns Hopkins University, for the Internal Wave Experiment (IWEX). The scientists working on the project were Nick Fofonoff, Melbourne Briscoe, and Terence Joyce. On the technical side, Donald Moller was the project coordinator, and Thomas Aldrich acted as liaison between IWEX and the acoustic navigation development.

Another project involved in the development was NSF Grant GA 35979, for the French-American Mid-Ocean Undersea Study (FAMOUS). The scientists involved were Wilfred Bryan and Joseph Phillips.

Robert Spindel, under ONR Grant N00014-72-C-0205, also contributed to the development, for the purpose of tracking free-floating sonobuoys.

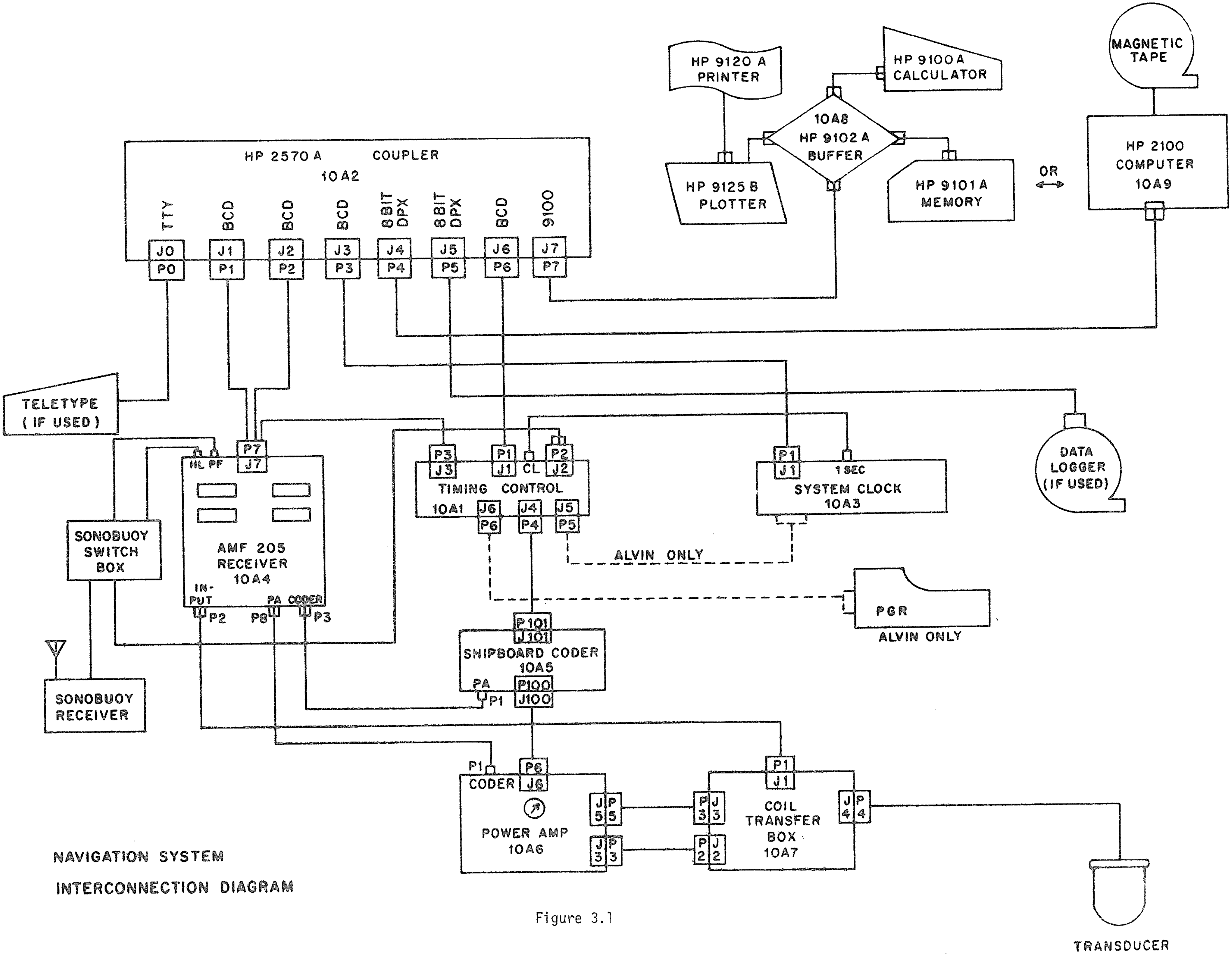
Three systems have been built. The first system was the ARPA/ALVIN system, called ALNAV (ALvin NAVigation). The second system, ANGUS (Acoustically Navigated Geological Underwater System), was built to support FAMOUS, and included a sonobuoy tracking capability. The third system, ANBUS (Acoustically Navigated Buoy Underwater System), was built to support the IWEX experiment. The acoustic parts of these systems are essentially identical. The ALNAV system uses a programmed desktop calculator to perform the calculations and the other systems use the standard W.H.O.I. shipboard computers (Hewlett-Packard 2116's).

3. SYSTEM DESCRIPTION

Proper use of the acoustic navigation system requires considerable electronic equipment. Details concerning the system hardware can be found in Technical Memorandum W.H.O.I. 4-74, Acoustic Navigation System Operating and Service Manual, by K. Peal. The shipboard electronics consists of three sections: control, acoustic, and processing (Figure 3.1). The control section consists of the Timing Control Unit and the system clock. It allows the operator to determine the mode of operation, and to select the length of time between observations. The Timing Control Unit also gives the operator the ability to communicate options and parameters to the processing section. Technical Memorandum W.H.O.I. 2-74, Timing Control Unit for the Acoustic Navigation System, by A. Eliason, contains a complete description of the Timing Control Unit.

The acoustic section consists of a 4-channel digital receiver, coder, power amplifier, coil box, and transducer. The transducer is fixed to the outside of the ship's hull and thus is a few meters below the sea surface. It transmits an acoustic signal (generated by the coder) at time intervals selected by the operator via the Timing Control Unit. The receiver measures the elapsed time between the transmission of the signal, and the reception of a reply at each of four frequencies.

The processing section consists of a coupler and (usually) a computer. The coupler is fed information from the Timing Control Unit, the clock, and the Digital Receiver, and in turn passes these data to the computer. If no computer is available, the coupler is connected to a data logger or teletype which collects data for analysis at a later time. A detailed description can be found in Technical Memorandum W.H.O.I. 3-74, Operation of the HP 2570A Coupler/Controller in the Acoustic Navigation System, by K. Peal.



NAVIGATION SYSTEM

INTERCONNECTION DIAGRAM

Figure 3.1

Figure 3.2 shows the ANBUS system as it was used by IWEX on RV KNORR cruise 34. On the far left are two 9-track magnetic tape drives (barely visible). Beside them is the front panel of the Hewlett-Packard 2116 computer. On the right, from top to bottom, are the system clock, the Dicom cassette unit, Timing Control Unit, computer terminal, and acoustic receiver.

In addition to the electronic hardware on the ship, the acoustic navigation system requires a network of at least two (preferably three) transponders, or beacons, moored on the ocean floor. Each beacon consists of an acoustic receiver, an acoustic transmitter, and processing and control circuitry. All these receivers are tuned to the same frequency, f_{ship}. Each of the transmitters sends a signal of a different frequency.

If tracking of an underwater vehicle, or 'fish' is to be done, a beacon must be attached to the vehicle. The receiver of this beacon is tuned to a different frequency, f_{fish}. Its transmitter sends signals of frequency f_{ship} to interrogate the bottom-moored transponders.

The navigation systems have been used to track a 'fish', both tethered and untethered, a submersible, and free drifting sonobuoys. Examples of the types of 'fish' that have been tracked include a camera sled, a rock dredge, a deep sea rock drill, and a free fall instrument package.

The two phases of the navigation, ship and 'non-ship', are performed as separate cycles, using different acoustic frequencies. Since the ship returns are necessary to solve for the non-ship vehicle, the sequence of navigation cycles is always: ship, non-ship, ship, non-ship, ...etc., where 'non-ship' can be fish, submarine, or sonobuoy. Following is a brief description of each of the four cycles which may be used.

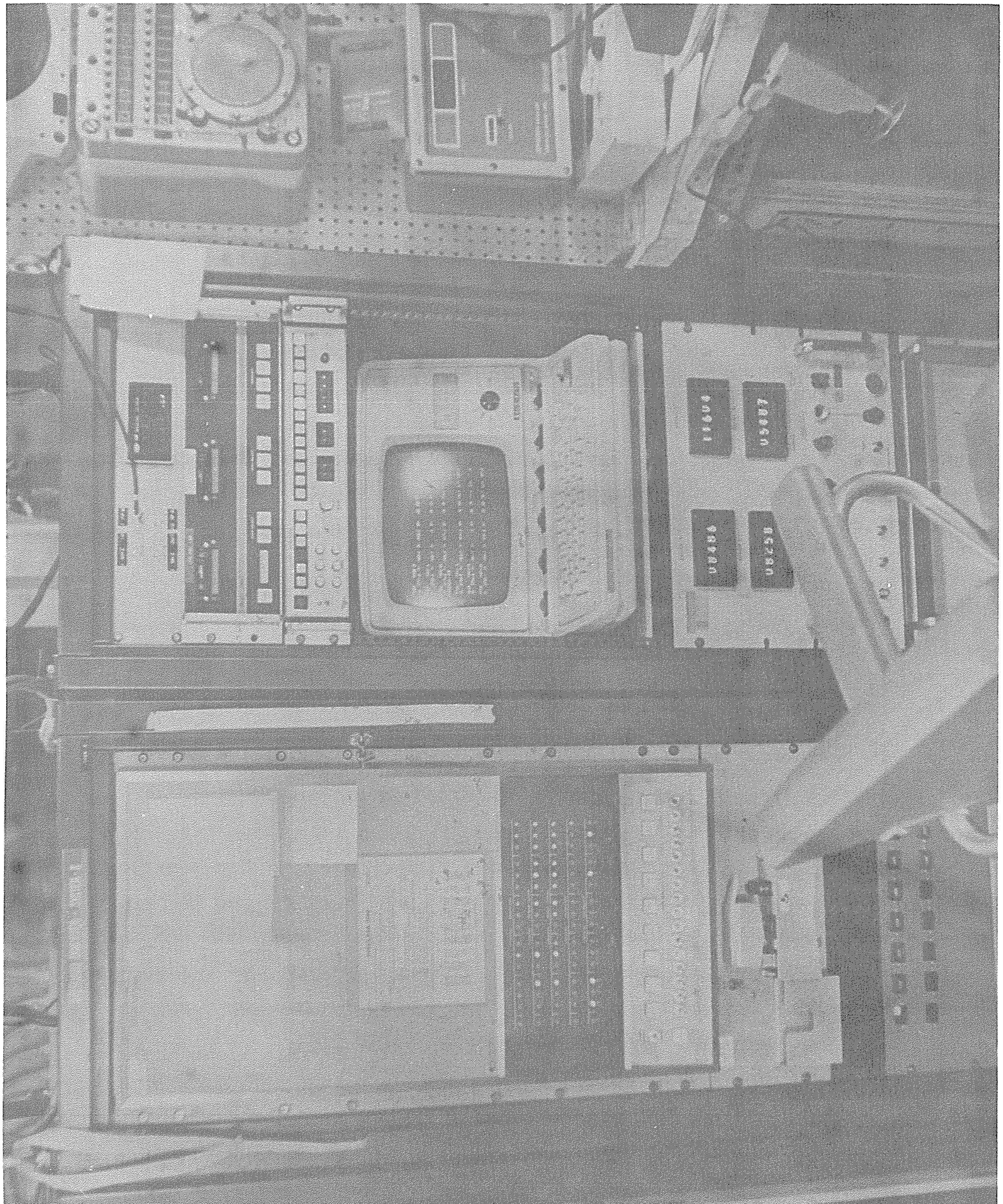


Figure 3.2. The ANBUS System Aboard R/V KNORR.

3.1 Ship Cycle (Figure 3.3)

At the start of a ship cycle, the acoustic system transmitter generates a pulse at a frequency f_{ship}. At the same time, digital counters in the receiver are reset to zero. The beacons in the network are all tuned to 'listen' at the frequency f_{ship}. When a signal at this frequency above a certain threshold is recognized, the beacon generates a reply pulse at a specific frequency. These are different for each beacon (f_{t1}, f_{t2}, f_{t3}). When one of these return pulses is detected by the shipboard receiver, the corresponding counter is stopped. This number is the round trip travel time, in milliseconds, between the ship and the respective beacon. From this, the distance from the ship to that beacon can be found. If two beacon returns are detected, solution for the ship position is possible.

3.2 Fish Cycle (Figure 3.4)

At the start of the fish cycle, the shipboard transmitter generates a pulse at a frequency f_{fish}, and again the counters are reset to zero. The fish beacon is the only one tuned to listen at this frequency. When it recognizes such a signal, it generates a reply pulse at frequency f_{ship}. One of the channels on the shipboard receiver is tuned to this frequency, and measures the round trip travel time between ship and fish. The bottom beacons also receive the f_{ship} signal generated by the fish beacon, causing them to reply on their particular frequencies. When one of these signals is detected by the ship receiver, the corresponding counter will contain the travel time from the ship to the fish to the respective bottom beacon and back to the ship. If two of these responses and the fish transmission are received, solution for the fish position is possible.

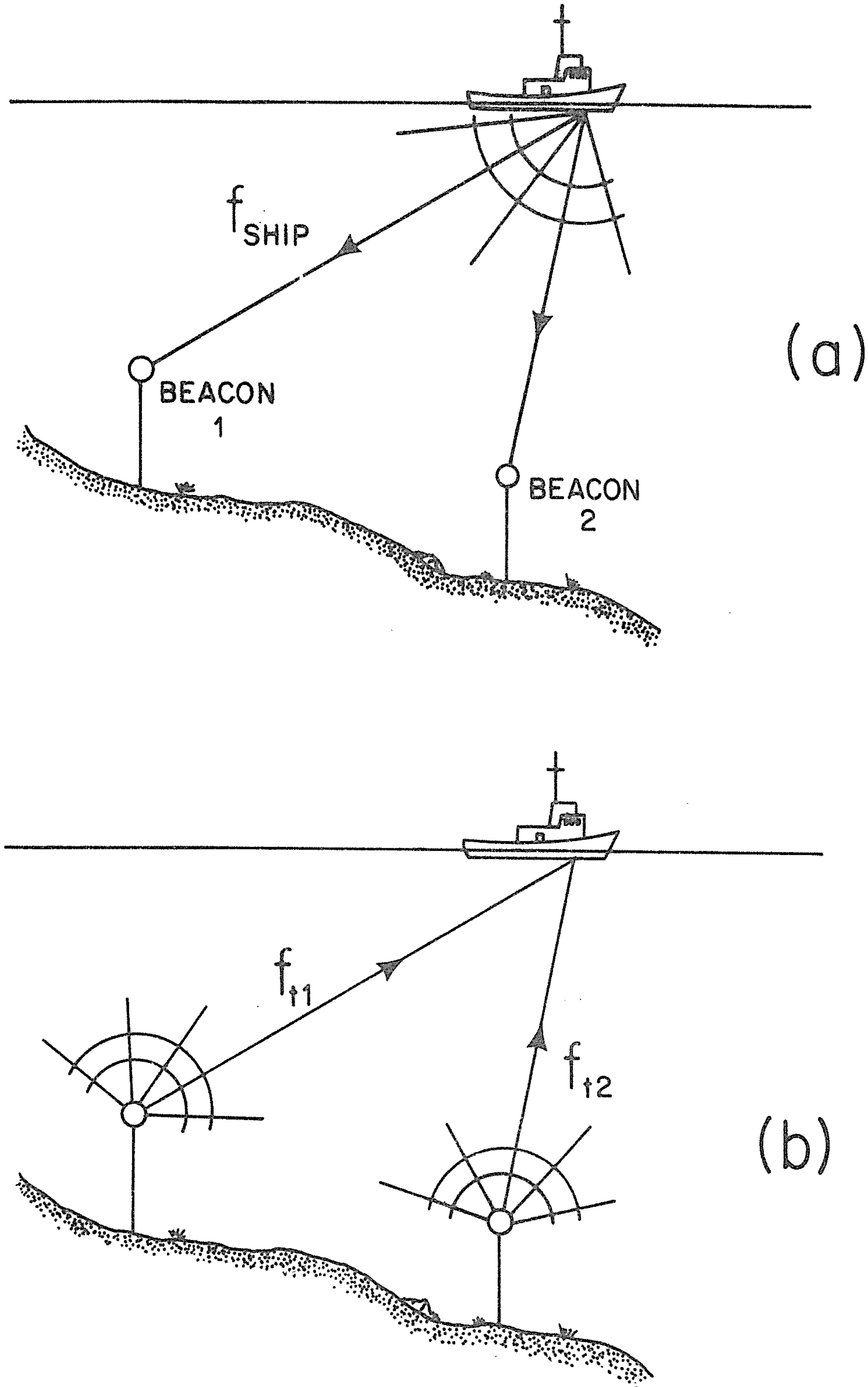


FIGURE 3.3
SHIP CYCLE

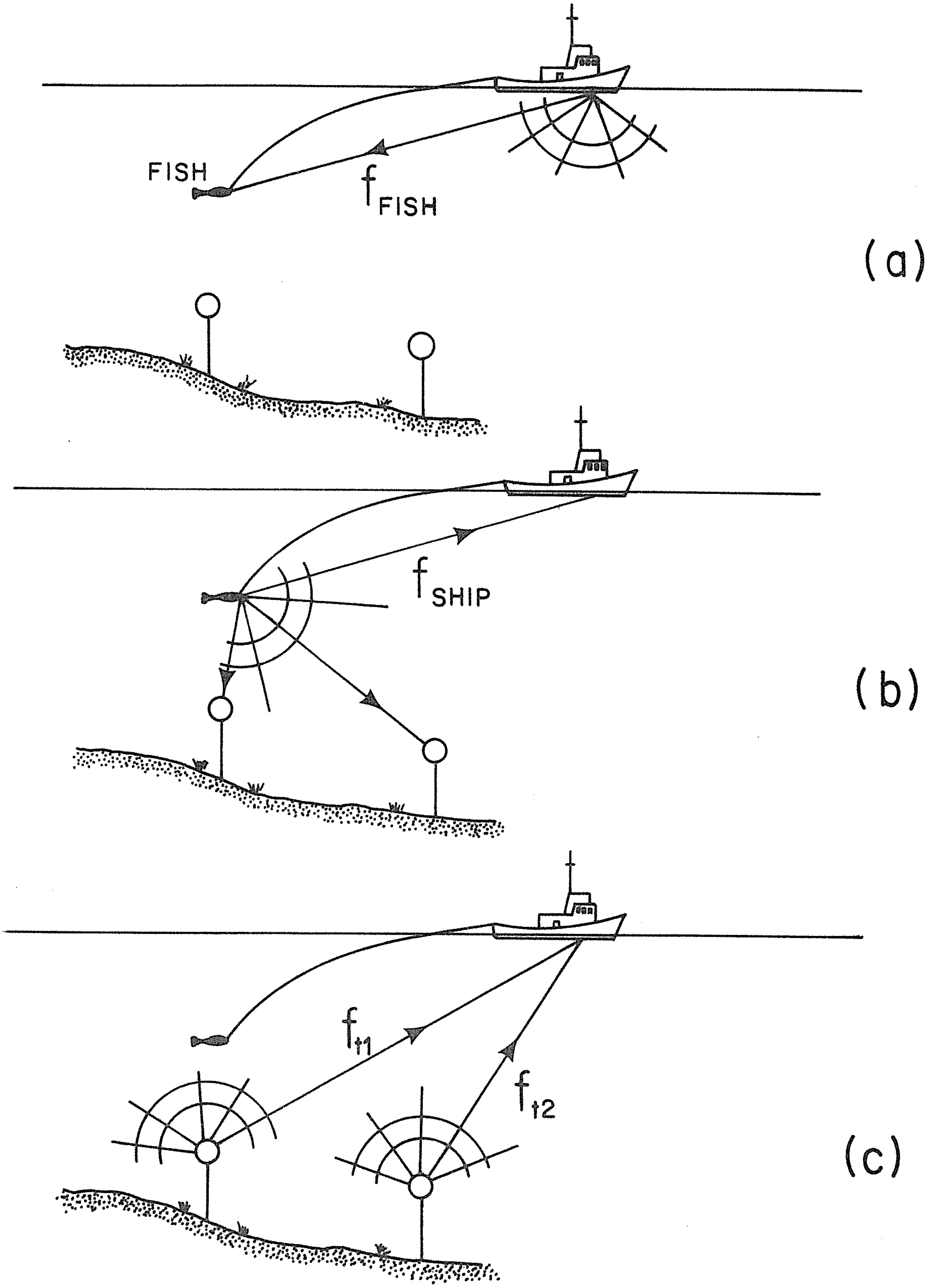


FIGURE 3.4
FISH CYCLE

3.3 Submarine Cycle (Figure 3.5)

When the underwater device is a submarine or submersible, a slightly different non-ship cycle occurs. Using the DSRV ALVIN as an example, it was known that when some vehicle systems were operating, sufficient acoustic noise was generated to prevent an acoustic receiver in the submersible from reliably recognizing the non-ship cycle interrogation from the tracking ship. To make the system independent of vehicle-generated noise, the acoustic receiver aboard the submersible has been replaced with a precision clock. Before launch of the submersible, the precision clocks aboard the tracking ship and the submersible are synchronized. For the non-ship cycle, the shipboard clock starts the shipboard counters but inhibits the ship interrogation. The submersible clock initiates a submersible transmission at frequency f_{ship} to interrogate the bottom-moored beacons. The beacon frequency counters of the shipboard receiver then give the submersible to beacon to ship acoustic travel times. With two of these returns plus the one way submersible to ship travel time, the submersible position can be calculated.

3.4 Sonobuoy Cycle (Figure 3.6)

When the non-ship cycle is a sonobuoy cycle, the ship transmitter generates a pulse at frequence f_{ship} (same as ship cycle). Again the counters of the shipboard receiver are reset. However, the replies from the bottom beacons at frequencies f_{t1}, f_{t2}, f_{t3} are picked up by the sonobuoy and transmitted (via radio) to the shipboard acoustic receiver. Assuming that the transmission time from the sonobuoy to the ship is negligible, the elapsed times from the counters are travel times from the ship to the respective bottom beacon to the sonobuoy. Two replies and the known depth of the sonobuoy hydrophone allow solution of the sonobuoy position.

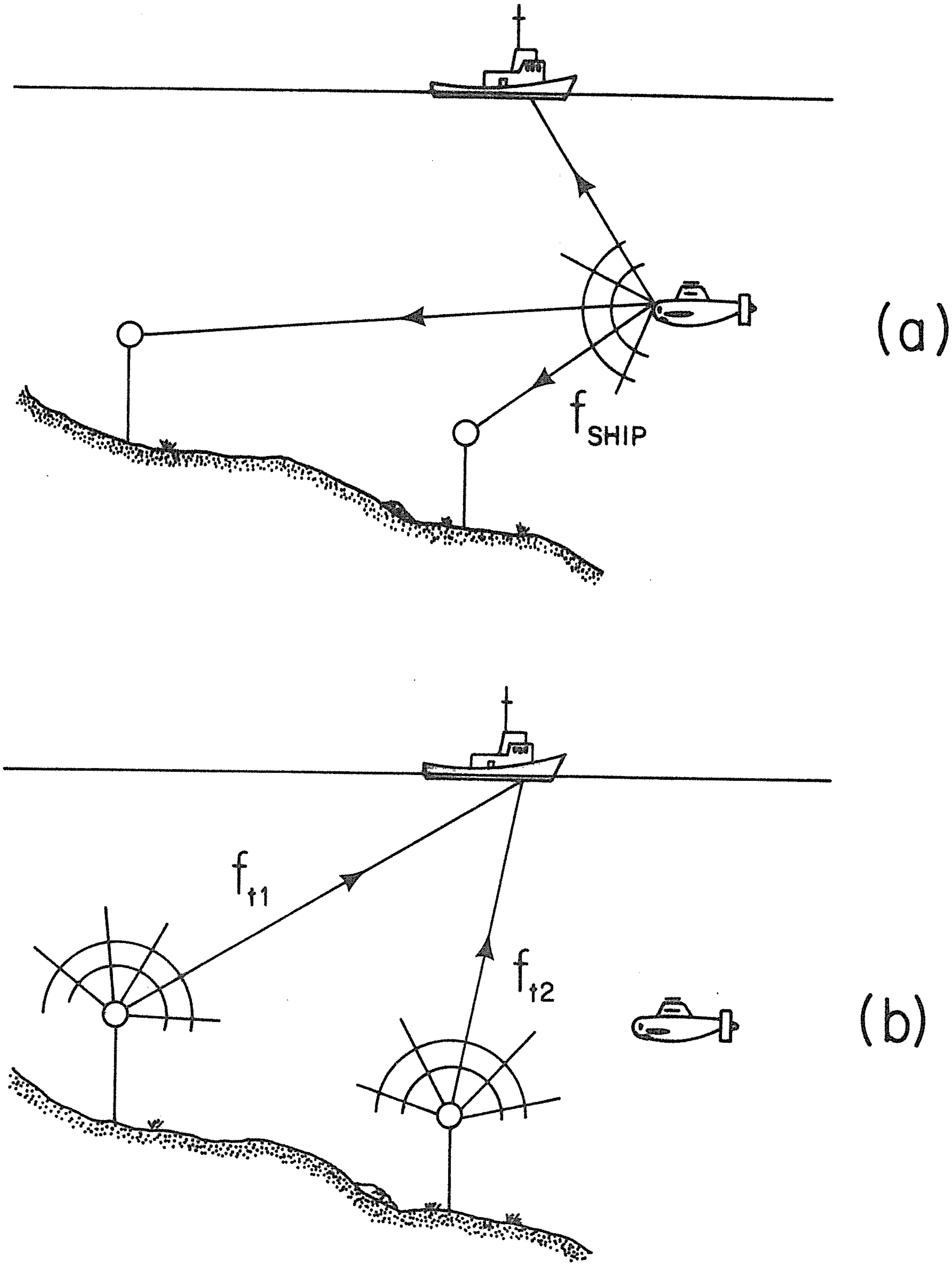


FIGURE 3.5
SUBMARINE CYCLE

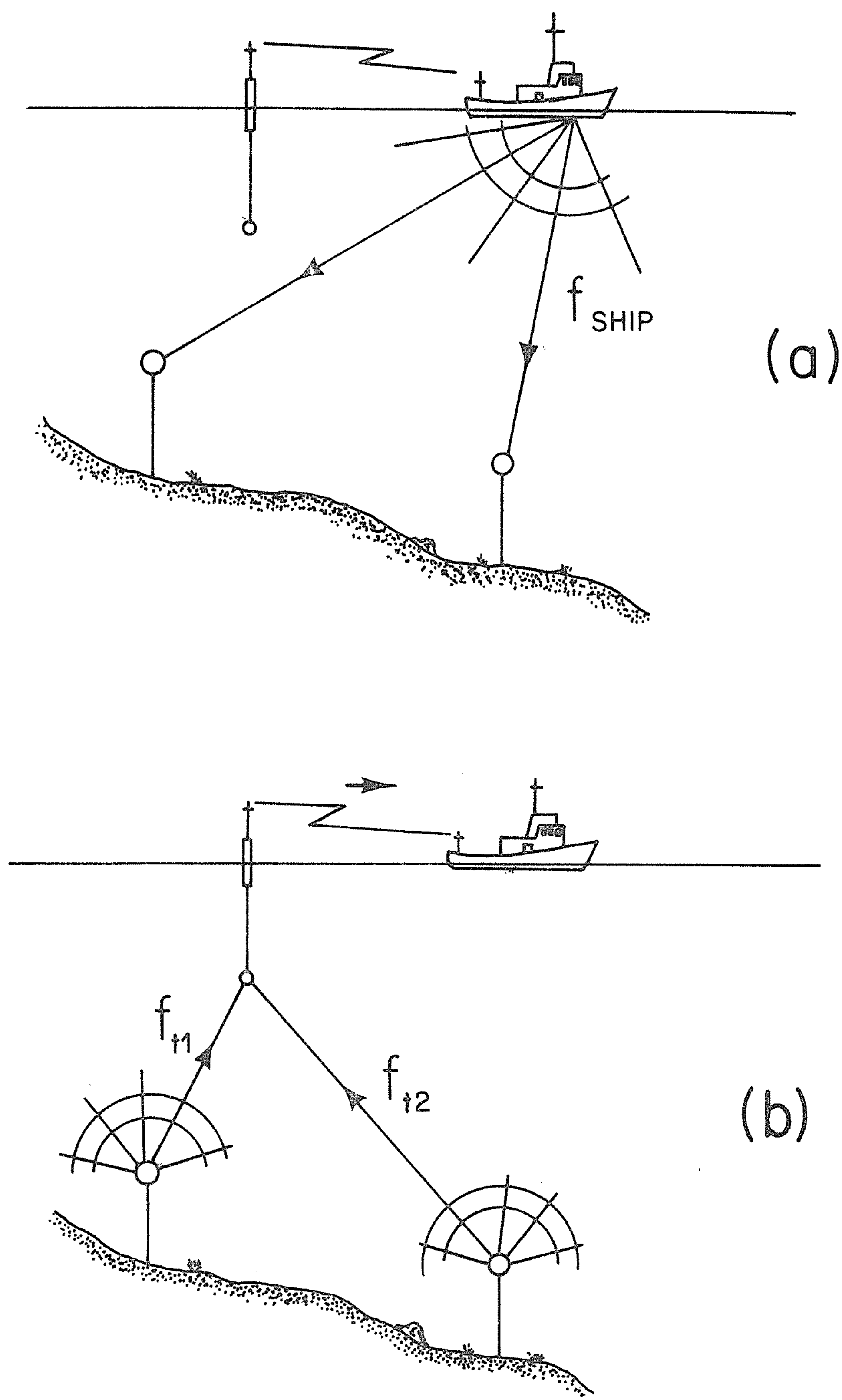


FIGURE 3.6
SONOBUOY CYCLE

4. MATHEMATICAL ANALYSIS

The acoustic navigation analysis is divided into three procedures: ray tracing, surveying, and navigation. The ray tracing procedure estimates, from the observed travel time to an acoustic beacon, the true slant range to that beacon. The survey procedure estimates, from a series of slant range observations, the relative positions of the beacons. Finally the navigation programs calculate, from known beacon positions and slant ranges, the position of the ship and/or instrument package. Since the navigation calculations are dependent on the particular configuration of ship and instrument package, we will not discuss these rather straightforward calculations here. In this section we give the analytic methods used in the implementation of the ray tracing and survey procedures.

4.1 Ray Tracing

Sound velocity in the ocean varies with pressure, temperature, and salinity. Because of this, a sound ray in the ocean does not follow a straight line. Thus, the travel time to an acoustic beacon is not strictly proportional to the geometric slant range. The general problem of finding the correct relationship between travel times of sound and the geometric slant range is discussed in Officer (1958) and Eby (1967). Here we outline the assumptions and numerical calculations used in the present system.

Following Eby's (1967) exposition of ray paths in a planar ocean, we assume that the sound velocity is a function of depth only. Let $c(z)$ denote the velocity of sound at depth z. A ray departing from depth z_o at an angle θ_o from the perpendicular will have traveled, at depth z, a horizontal distance

$$x = \int_{z_o}^{z} \frac{c(z)}{\left[c_V^2 - c(z)^2\right]^{1/2}} \, dz', \tag{1}$$

in a time

$$t = \int_{z_o}^{z} \frac{c_V}{c(z) \left[c_V^2 - c(z)^2\right]^{1/2}} \, dz', \tag{2}$$

where

$$c_V = \frac{c\ (z_o)}{\sin\ (\theta_o)}$$

The problem then is to find a slant range to the beacon given by

$$sr = \left[x^2 + (z-z_o)^2\right]^{1/2}$$

as a function of the travel time given by equation (2). The navigation system finds an approximate solution to this problem in two steps. First, for a set of N departure angles, $\theta_o^{(1)}$, $\theta_o^{(2)}$, ..., $\theta_o^{(N)}$, travel times and slant ranges are found by numerical integration of equations (1) and (2). The second step is to use the N values of travel times and slant ranges ($t^{(1)}$, $sr^{(1)}$), ..., ($t^{(N)}$, $sr^{(N)}$) to find a polynomial of the form

$$sr^* = (a_o + a_1 r + a_2 r^2)\, r \; , \qquad (3)$$

where r is just a first approximation of the slant range using the average sound velocity: $r = \bar{c}t$. This polynomial function is then used to approximate the relationship between slant range and observed travel time. The coefficients of equation (3) are found by using standard least squares techniques. Both these steps are carried out in Program SETUP. The coefficients are then passed to the survey and navigation programs for estimating the slant ranges.

The integration of equations (1) and (2) is illustrated in Figure 4.1. The sound velocity profile is approximated by a function with M linear pieces. Each piece can be integrated exactly (Officer, 1957, page 59). For segment i from depth z_i to z_{i+1} with gradient

$$g_i = \frac{c(z_{i+1}) - c(z_i)}{z_{i+1} - z_i} \; ,$$

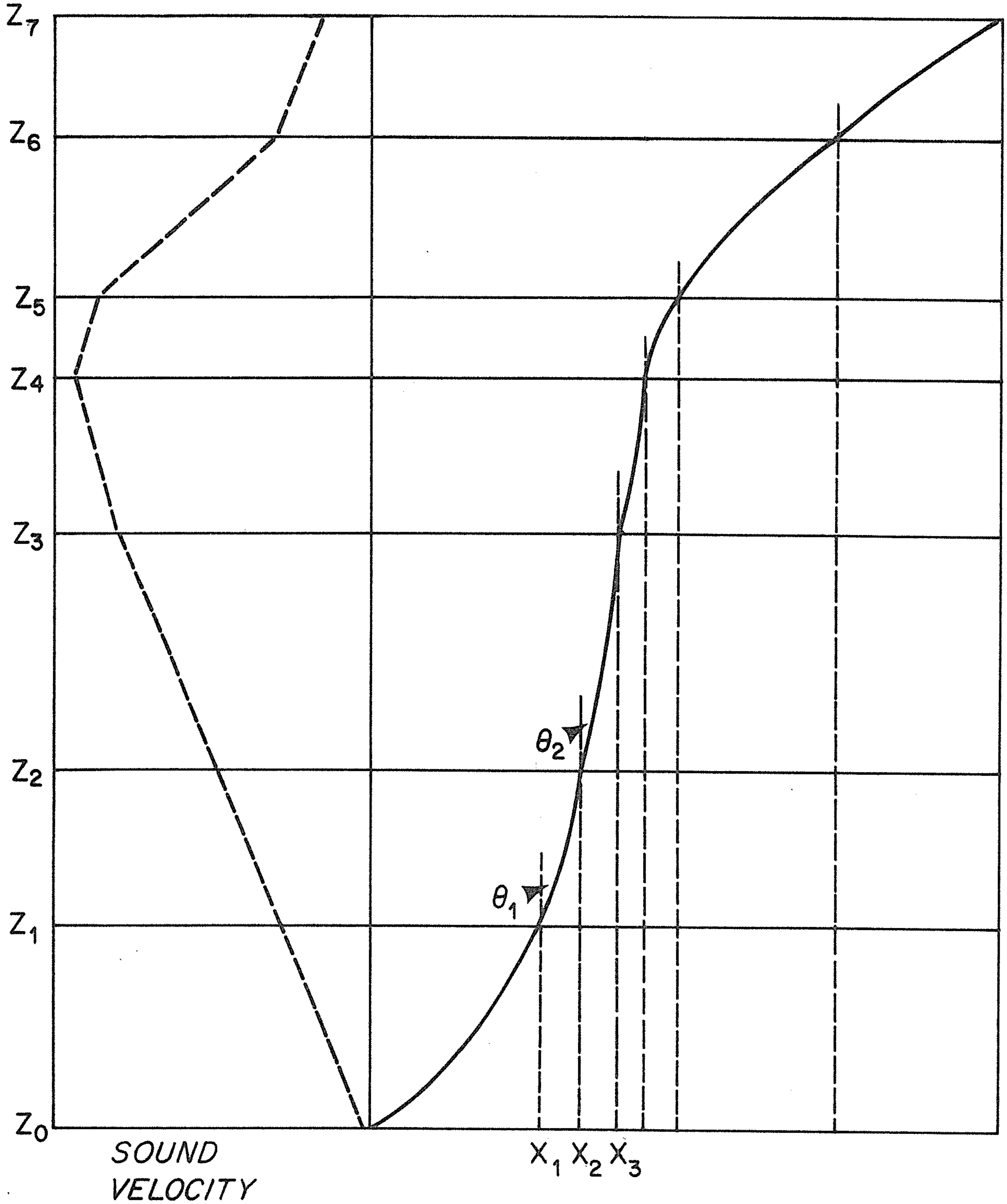


FIGURE 4.1
RAY TRACING

the angle of departure from the i'th layer is

$$\theta_{i+1} = \sin^{-1}\left[\frac{z_{i+1}-z_i}{c(z_i)} \sin\theta_i + \sin\theta_i\right] ,$$

the horizontal distance traveled in the i'th layer is

$$\Delta x_i = \frac{c(z_i)}{g_i}\left[\frac{\cos\theta_i - \cos\theta_{i+1}}{\sin\theta_i}\right] ,$$

and the time spent in the i'th layer

$$\Delta t_i = \frac{1}{g_i} \ln\left[\frac{\tan\frac{\theta_{i+1}}{2}}{\tan\frac{\theta_i}{2}}\right] .$$

To reach depth z_M the ray will travel a horizontal distance

$$x_M = \sum_{i=0}^{M-1} \Delta x_i$$

in a time

$$t_M = \sum_{i=0}^{M-1} \Delta t_i$$

4.2 Survey Analysis and Design

The relative positions of three sonar beacons can be determined from slant range observation taken by a ship at a series of survey points. From these slant range observations the beacon positions can be estimated using non-linear least squares (Lowenstein, 1965; and McKeown, 1972).

In this section we discuss the least squares estimation procedure and also give some new analytical techniques for determining the errors in estimating the beacon positions, and for finding the configuration of survey points that gives the most accurate estimates of the beacon positions.

The statistical methods developed in this section come under the general heading of non-linear regression. A good presentation of the general theory is given in Box and Lucas (1962) and Draper and Smith (1970).

The mathematical notation in this section is of necessity rather complex. For the general reader the numerical results given in section 5 might best summarize the new error analysis and design methods developed here.

4.3 Least Squares Estimates

For clarity we will consider here only the 3-beacon survey problem although this method can easily be extended to more than three beacons. Figure 4.2 describes the three-beacon situation: the beacons are positioned at $(0, 0, z_1)$, $(x_2, 0, z_2)$, and (x_3, y_3, z_3). The ship's transducer at constant depth, zs, near the surface measures the slant ranges to the beacon positions at a set of n survey points, (xs_i, ys_i, zs), $i = 1,2,\ldots,n$. Let $\underline{S}_i' = (S_{i,1}, S_{i,2}, S_{i,3})$, $i = 1,2,\ldots n$, denote the vector of observed slant ranges at point (xs_i, ys_i, zs). Let $sr_{i,j}$, $j = 1\ldots3$, denote the exact geometrical slant range to the jth beacon at survey point i,

$$sr_{i,j} = ((xs_i-x_j)^2 + (ys_i-y_j)^2 + (zs-z_j)^2)^{1/2}$$

where $x_1 = y_1 = y_2 = 0$.

For convenience we will place all coordinates of the survey in a single vector. Let $\underline{\theta}_1$ denote the column vector of survey coordinates for the n survey points. Its transpose, $\underline{\theta}_1'$, is the row vector $(xs_1, ys_1, xs_2, ys_2, \ldots xs_n, ys_n)$. Similarly let $\underline{\theta}_2$ denote the column vector of beacon coordinates, $\underline{\theta}_2' = (x_2, x_3, y_3, z_1, z_2, z_3)$. Finally let $\underline{\theta}$ denote the column vector of the 2n+6 parameters of the system, $\underline{\theta}' = (\underline{\theta}_1', \underline{\theta}_2')$. We denote the vector of slant ranges from a survey point i to the three beacons by $\underline{sr}_i'(\underline{\theta}) = (sr_{i,1}(\underline{\theta}), sr_{i,2}(\underline{\theta}), sr_{i,3}(\underline{\theta}))$ and the slant range vector for all n survey points by

$$\underline{sr}'(\underline{\theta}) = (\underline{sr}_1'(\theta), \underline{sr}_2'(\theta), \ldots, \underline{sr}_n'(\theta)).$$

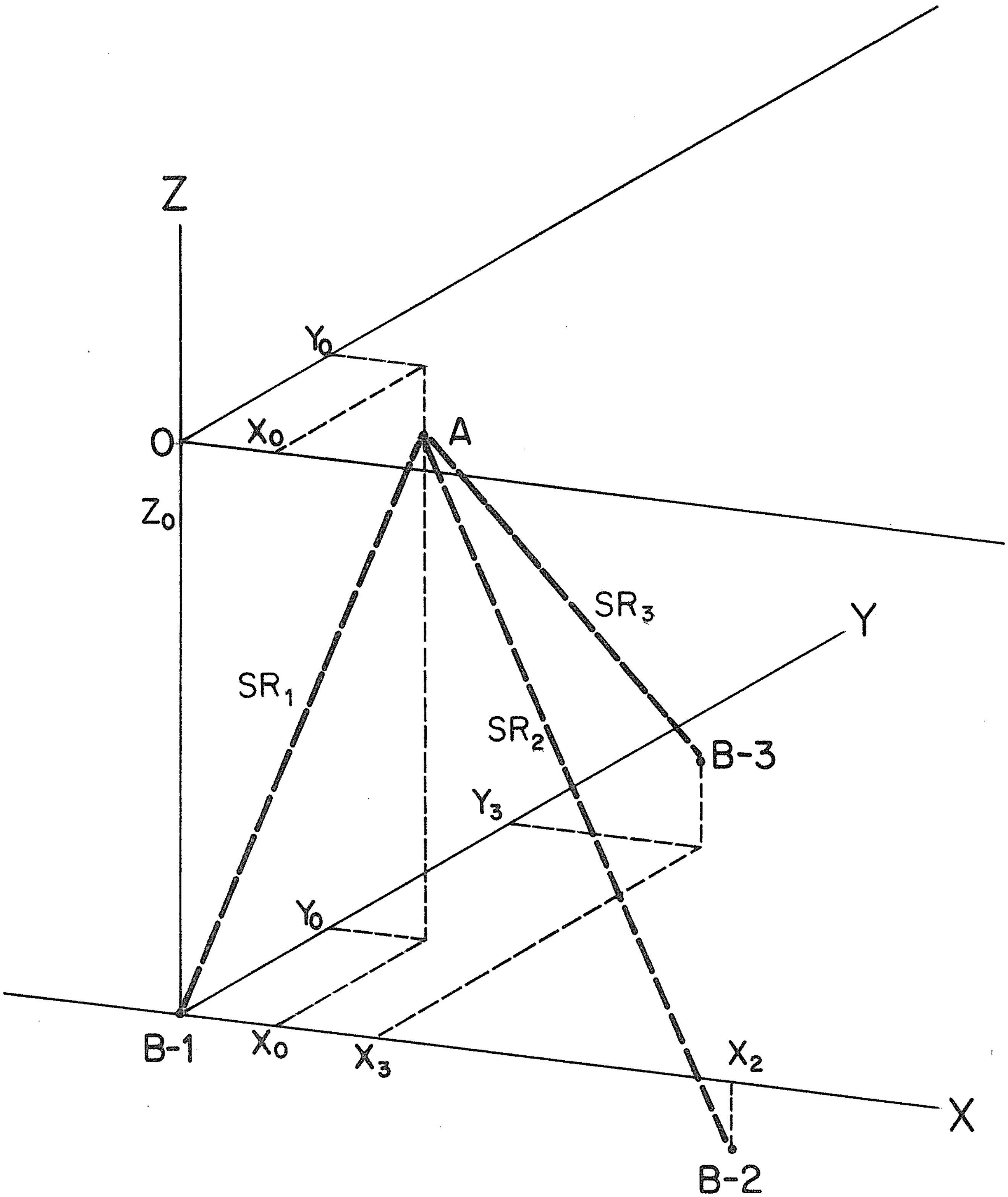


FIGURE 4.2
3 BEACON GEOMETRY

We assume that the observed slant range $S_{i,j}$ can be defined by,

$$S_{i,j} = sr_{i,j}(\underline{\theta}) + \varepsilon_{i,j}$$

where the $\varepsilon_{i,j}$ are independent identically distributed normal random variables with mean 0 and variance,

$$\sigma^2 = \text{var}[\varepsilon_{i,j}]$$

Under these assumptions the maximum likelihood estimate is just the $\underline{\hat{\theta}}$ that minimizes the sum of squared errors,

$$SS(\underline{\hat{\theta}}) = \min_{\underline{\theta}} \sum_{i=1}^{n} \sum_{j=1}^{3} (S_{ij} - sr_{ij}(\underline{\theta}))^2 \tag{4}$$

The problem of finding the $\underline{\theta}$ that minimizes (4) has already been investigated by Lowenstein (1965) and McKeown (1972).

We have adopted a slightly different minimization procedure based on the use of the Gauss-Newton procedure to update the survey coordinates within a Fletcher, Powell (1963) minimization algorithm. However, for the purposes of this discussion we assume that $\hat{\theta}$ has been found and we wish to estimate the error in finding the beacon coordinates.

4.4 Error Covariance Matrix for Beacon Positions

The covariance matrix for the parameter estimates can be approximated by finding a Taylor series expansion for the slant ranges in terms of the parameters, $\underline{\theta}$. For small changes in $\underline{\theta}$ denoted by $\underline{\Delta\theta}$ we can represent $\underline{sr}(\underline{\theta}+\underline{\Delta\theta})$ by a Taylor series expansion

$$\underline{sr}\ (\underline{\theta} + \underline{\Delta\theta}) \approx \underline{sr}\ (\underline{\theta}) + \underline{X}\ \underline{\Delta\theta}$$

where X is the 3n by 2n+6 matrix of the derivatives of the slant ranges with respect to the parameters $\underline{\theta}$. For the survey problem the matrix X has the special form

$$\underline{X} = \begin{bmatrix} \underline{B}_1 & & & & & \underline{A}_1 \\ & \underline{B}_2 & & \bigcirc & & \underline{A}_2 \\ & & \cdot & & & \cdot \\ & & & \cdot & & \cdot \\ & \bigcirc & & & \cdot & \cdot \\ & & & \underline{B}_{n-1} & & \underline{A}_{n-1} \\ & & & & \underline{B}_n & \underline{A}_n \end{bmatrix}$$

where B_i is a 3 by 2 matrix of derivatives of the slant ranges at survey point i with respect to the coordinates of survey point i,

$B_i = [b_{j,k}^{(i)}]$ for j = 1,2,3, and k = 1,2, where

$$b_{j,k}^{(i)} = \frac{\partial \; sr_{i,j}(\underline{\theta})}{\partial \; \theta_{2i-2+k}}$$

The 3 by 6 matrix A_i is the matrix of derivatives of the slant ranges at the i'th survey point with respect to the beacon coordinates, $\underline{\theta}_2$, $A_i = [a_{j,k}]$, for j = 1,2,3, k = 1,2..,6

where

$$a_{j,k} = \frac{\partial \; sr_{i,j}(\underline{\theta})}{\partial \; \theta_{2n+k}}$$

Only six elements of the A_1 matrix are non-zero, since the position parameters for beacon j only enter into the slant ranges to beacon j.

With the Taylor series representation for the slant ranges, one can apply standard linear regression theory (Draper and Smith, 1970) to determine an approximate error covariance matrix, Σ, for $(\hat{\underline{\theta}}_1', \hat{\underline{\theta}}_2')$, yielding,

$$\Sigma = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix} \simeq \sigma^2 [\underline{X}'\underline{X}]^{-1}$$

where σ^2 is the variance of the slant range errors.

Now we are primarily interested in the 6 by 6 lower right-hand submatrix, Σ_{22}, that describes the covariance of beacon parameters estimates, $\hat{\theta}_2$. Fortunately because of the special structure of the $\underline{X}$ matrix, we can evaluate Σ_{22} without inverting the entire 2n+6 by 2n+6 matrix. This can be done by standard procedures for operating on submatrices (see Rao, 1965, page 29). Σ_{22} is then

$$\Sigma_{22} = \sigma^2 \left[\sum_{i=1}^{n} \underline{A}_i' \, [\underline{I} - \underline{B}_i (\underline{B}_i' \underline{B}_i)^{-1} \underline{B}_i'] \, \underline{A}_i \right]^{-1} \tag{5}$$

Equation (5) can easily be implemented on small computer systems, since it requires only the inversion of a single 6 x 6 matrix.

To estimate the covariance matrix from the survey data, one substitutes $\hat{\underline{\theta}}$, $\hat{\sigma}^2$ for $\underline{\theta}$ and σ^2 in equation (5).

$$\hat{\sigma}^2 = \frac{1}{n-6} \text{ SS } (\hat{\underline{\theta}}) \text{ ,}$$

where $SS(\hat{\underline{\theta}})$ is defined in (4). To estimate σ^2, $SS(\hat{\underline{\theta}})$ is divided by its number of degrees of freedom (i.e., the total number of slant range observations, 3n, less the number of parameters estimated, 2n+6).

4.5 Survey Design

The position of the survey points relative to the beacons is important in determining the size of errors in the beacon position estimates. By evaluating Σ_{22} defined in equation (5) for different sets of survey points, one can determine a survey design that minimizes these errors. Of course, both the positions at the beacons and the survey points are unknown; however, in practice one can obtain approximate positions by using other navigation systems.

A measure of the size of the error in the survey is the sum of the variances of the beacon position estimates;

$$C = \sum_{k=1}^{6} \text{Var}\ (\hat{\theta}_{2n+k}).$$

It can be shown that C is just the sum of the Eigenvalues of the matrix Σ_{22}.

The approximate covariance matrix given in (5) is a function of two independent effects: slant range measurement error (i.e., σ^2), and the position of the survey points.

In section 5.3, eight examples of survey patterns are discussed and the survey error is calculated for each pattern. These examples show that careful planning of a survey can reduce both estimation error and the ship time taken to survey the beacons.

5. SHIP SURVEYS OF A THREE TRANSPONDER NET

The results given in Section 4 can be used for both the evaluation of actual survey data and for the planning of surveys to minimize the overall survey error. The problem of an accurate survey of three transponders has been shown to consist of two independent parts, slant range measurement and survey geometry. In this section we give some operational methods and geometrical survey patterns that can reduce both measurement error and survey estimation error.

5.1 Slant Ranges

The need for accurate slant range measurements has long been recognized. To obtain this goal, signal to noise ratios should be high, a good sound velocity profile is necessary, and the depth of the shipboard transducer must be accurately known. To minimize the distortion of travel time measurements, the ship should be stationary when collecting survey data, or the raw data should be corrected for the motion of the ship.

In evaluating the accuracy of the slant range measurements, there are two considerations. First, how accurate are the measurements as a whole? And second, are there any bad data points which are clearly inconsistent with the rest of the data? The first question is answered by the slant range standard error. There is approximately a 2/3 chance that each slant range measurement differs from the 'true' value by no more than one standard error.

To improve the editing of survey data, an error term is computed for each survey point. This error term can aid in the recognition of survey points with bad slant range data caused by instrument malfunction or other transient events.

5.2 Survey Geometry

Navigation problems in general are sensitive to geometry. Given relatively good range measurements but poor geometry, one cannot expect to obtain accurate transponder locations. The second part of the survey problem is to create favorable survey geometry.

The variables in the survey problem are the number and locations of the ship survey points relative to the transponder net. Since the geometry of any transponder net varies with the water depth and the distance between the transponders, it is not possible to define a universal solution to optimum ship survey points. We can say positively, however, that a set of survey points which form a conic section should be avoided. The solutions in this case are not unique.

There are six unknown transponder coordinates to be estimated in the three transponder survey problem. From the number and location of the survey points, Program SWURV (using equation 5) evaluates a geometry error magnification term for each of these six unknown coordinates. The sum of the squares of these six error magnification terms is called the survey error and is useful as a single index to compare one survey geometry with another.

5.3 Survey Examples

To illustrate the usefulness of this method, and to provide some guidelines in designing a ship survey, eight examples will be discussed. These examples were taken from the SWURV program report which is included in the W.H.O.I. Technical Memorandum 5-74. The geometry for the sample surveys are shown in Figures 5.1 through 5.8. In each case, the transponder depths are approximately equal to the distance between transponder A and transponder B. The results of the geometry error analysis are listed in Table 5.1. The eight sample surveys are discussed in order of improving survey error.

Survey #1 (Figure 5.1) illustrates very unfavorable survey geometry. The error magnification terms for the unknowns in the horizontal plane range from 13.73 to 23.81. For example, if the slant range standard error is 2 meters, the errors in the horizontal transponder coordinates would be 2 times the error magnification terms, or approximately 30 to 40 meters. The six survey points almost form a circle around the transponders. As mentioned previously, survey points that form a conic section must be avoided.

The 'Y' pattern in Survey #2 (Figure 5.2) is composed of 24 survey points instead of the minimum of six. Eleven of the data sets are outside the triangle formed by the three transponders. The analysis of this survey pattern gave large geometry magnification terms ranging from 4.00 to 11.90. The 'Y' survey pattern is not recommended.

Survey #3 (Figure 5.3) is very efficient in terms of ship survey time and consists of six survey points. The geometry error magnification terms for the depths of the transponders are favorable, each having a value of 1.00. The terms for the horizontal unknowns are relatively larger, ranging from 3.59 to 6.04. It should be noted that if many survey points were taken in each of the six locations indicated, the slant range measurement error might be reduced by eliminating questionable ranges, but little or no improvement in the geometry errors could be expected.

Survey #4 (Figure 5.4) consists of 17 survey points with a large number offset to one side of the transponder net. A majority of the survey points are outside the triangle formed by the transponders.

The geometry error magnification terms for this survey range from 0.64 to 4.90.

Survey #5 (Figure 5.5) is similar to survey #3 in that it also consists of six survey points, and is a practical pattern for a ship to run. The points are symmetrical relative to the transponder net and are all outside the net. The individual geometry error magnification terms range from 0.98 to 2.41 which is quite an improvement over survey #3.

Survey #6 (Figure 5.6) is the result of a computer program which was designed to answer the question, " If only six survey points are to be used, what is the most favorable geometry to minimize the survey error?" The computer program did not consider the practical problem of how far one can actually signal accurately. The six geometry error magnification terms range from 1.11 to 1.74.

One would expect that if more than six survey points were used, the survey error would be smaller. Survey #7 (Figure 5.7) uses twelve survey points and is patterned after survey #5 with the extra points being added without increasing the total ship track. The individual geometry error magnification terms range from 0.72 to 1.82 which are favorable.

Survey #8 (Figure 5.8) is a further amplification of survey #7 in that 4 extra points are added. The individual geometry error magnification terms are very favorable, ranging from 0.51 to 1.46.

Survey pattern #7 is currently being recommended to W.H.O.I. navigation system users. Ten to twelve distinct ship locations along this track, with six to eight sets of good consistent data from each station should be taken. If additional ship survey time is available, or if maximum accuracy is required, extra ship data stations should be added as shown in survey #8. Also, every effort should be made to minimize the slant range measurement errors with particular attention to a good sound velocity profile and an accurate knowledge of the depth of the ship's transducer.

Survey No.	No. of Survey Points	Geometry Error Magnification Terms X2	X3	Y3	Z1	Z2	Z3	Geometry Survey Error
1	6	23.81	13.73	18.83	4.01	5.30	4.39	1173.58
2	24	6.95	11.90	5.71	4.15	4.33	4.00	274.41
3	6	4.24	6.04	3.59	1.00	1.00	1.00	70.34
4	17	4.65	4.90	2.22	0.77	0.84	0.64	52.30
5	6	1.94	2.41	1.61	0.98	0.98	0.98	15.01
6	6	1.35	1.74	1.20	1.15	1.11	1.09	10.05
7	12	1.62	1.82	1.40	0.72	0.71	0.72	9.41
8	16	1.16	1.46	1.10	0.57	0.57	0.51	5.59

TABLE 5.1

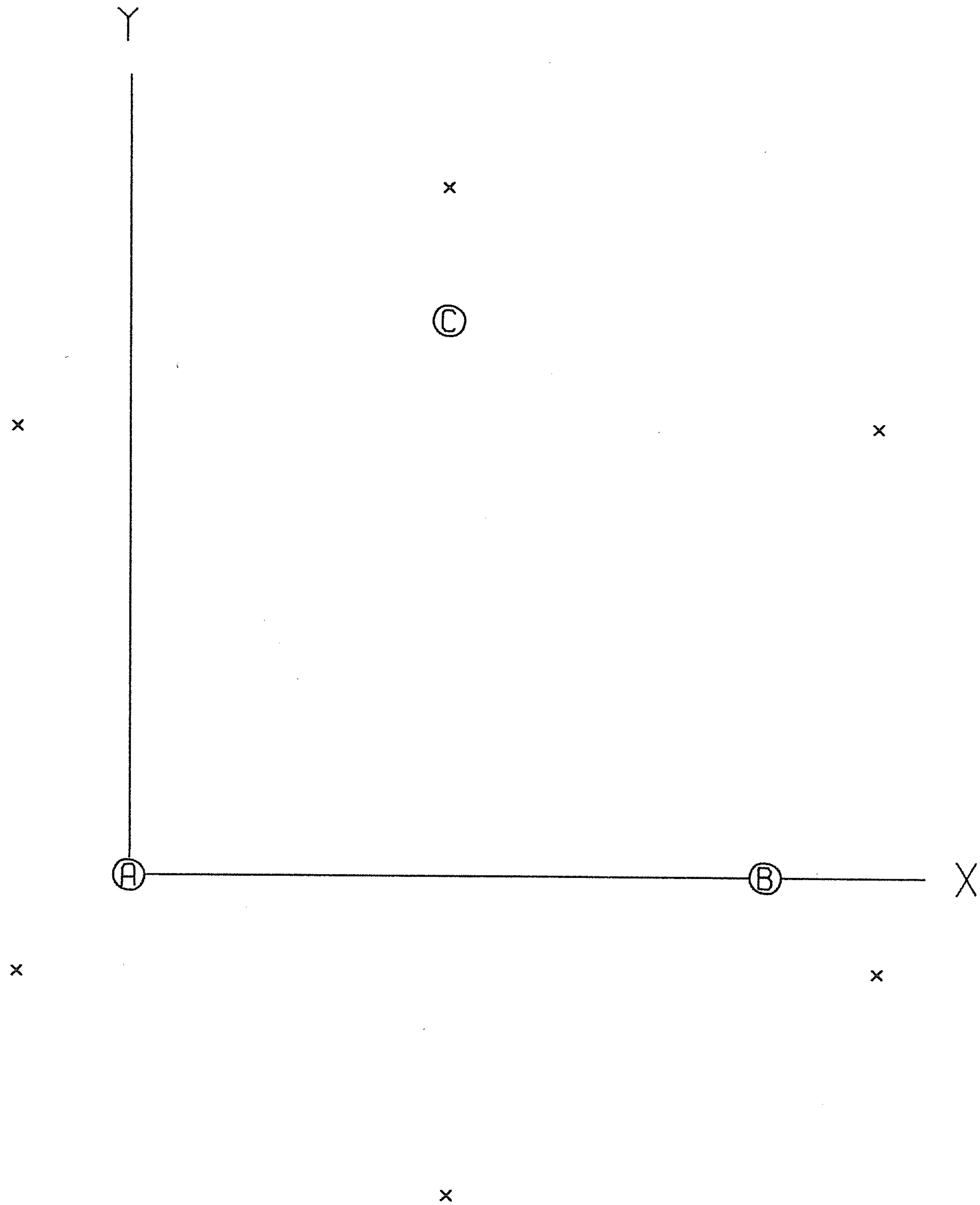


FIGURE 5.1
SURVEY 1

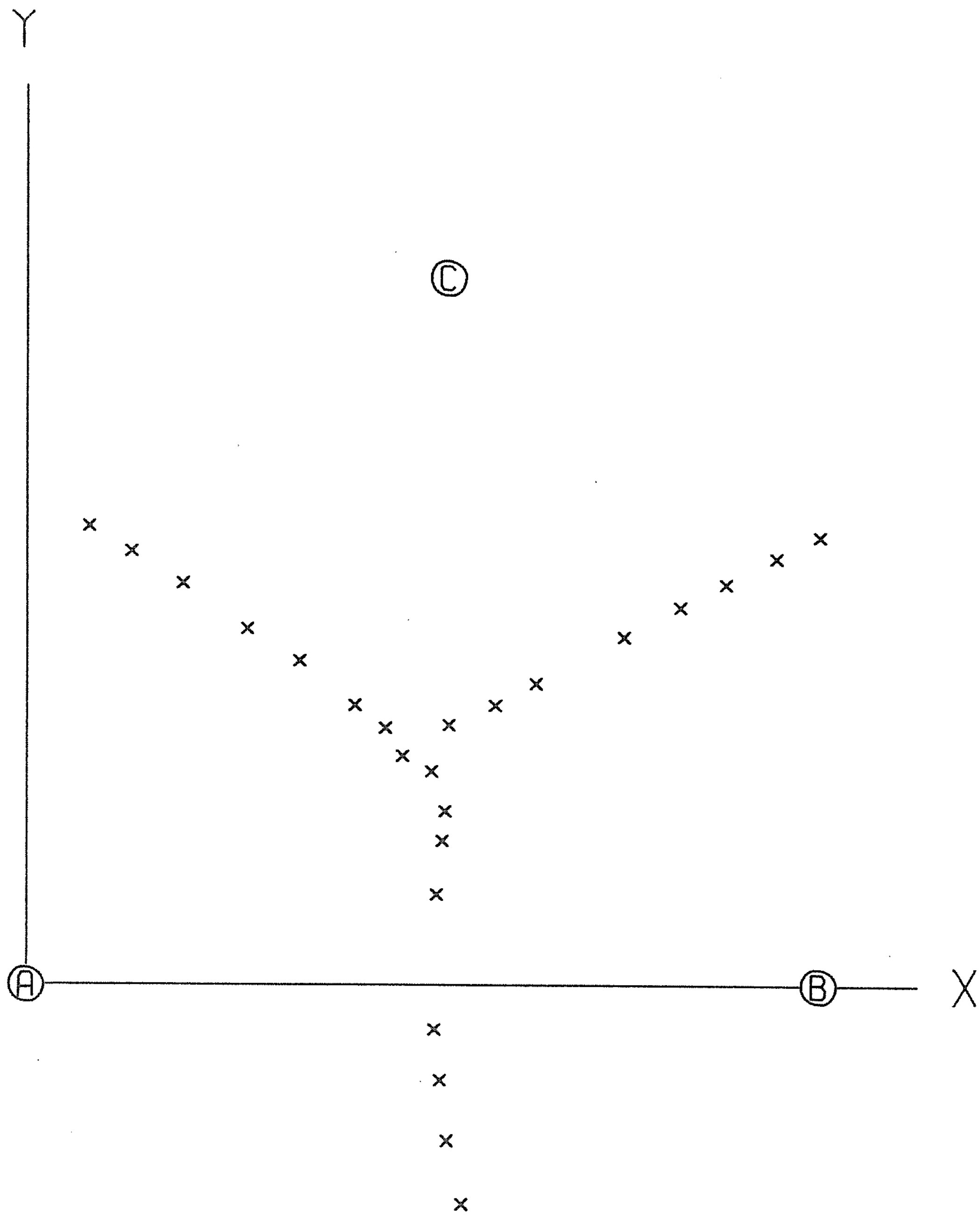


FIGURE 5.2
SURVEY 2

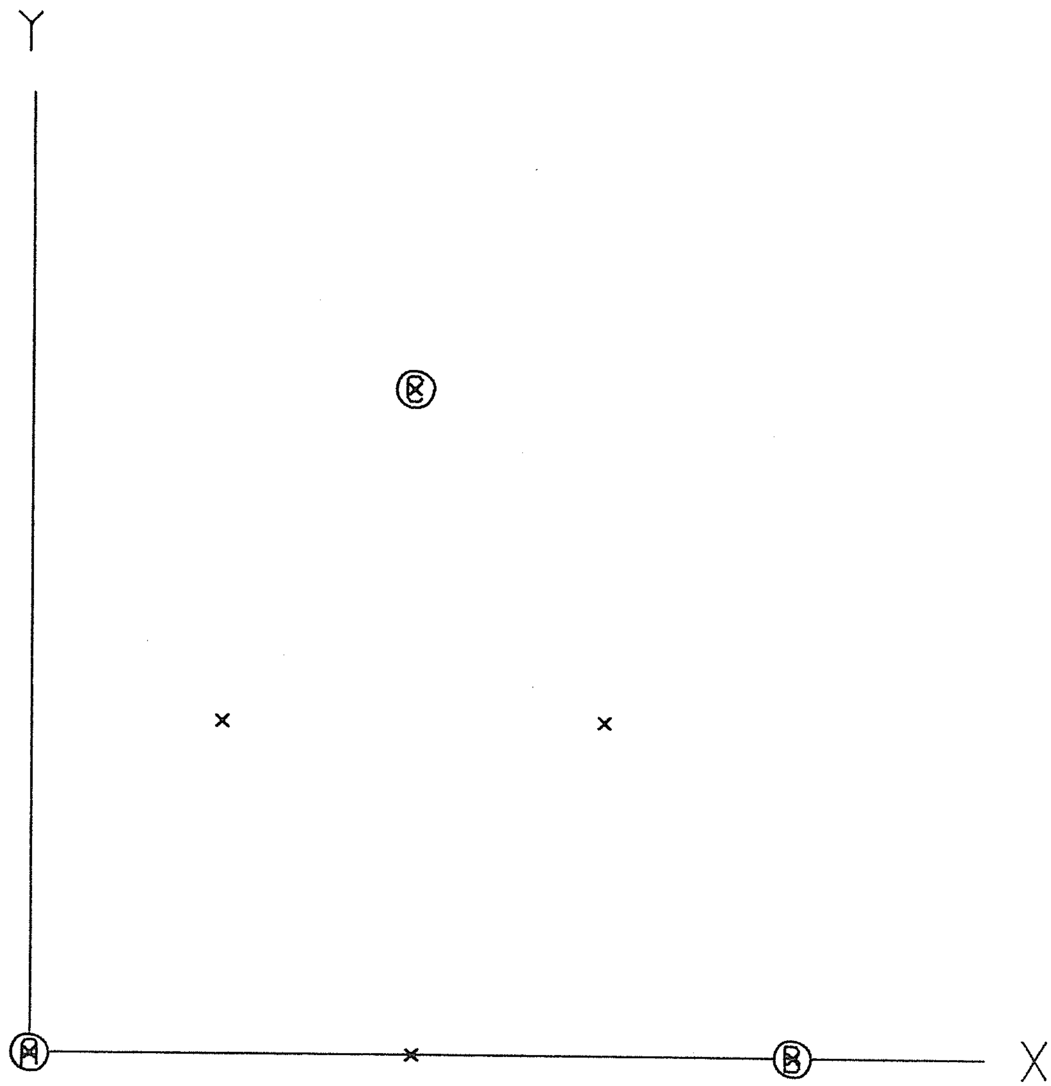


FIGURE 5.3
SURVEY 3

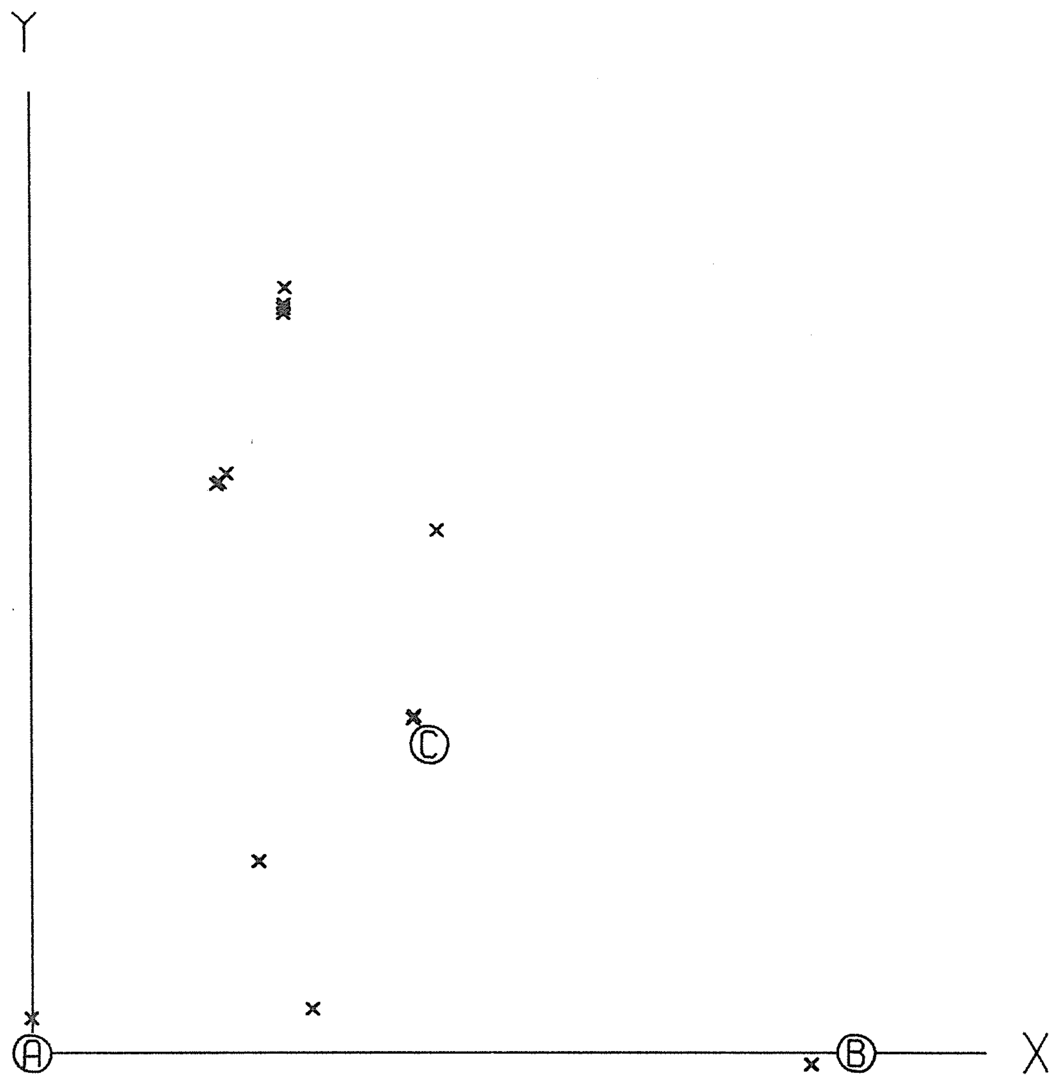


FIGURE 5.4
SURVEY 4

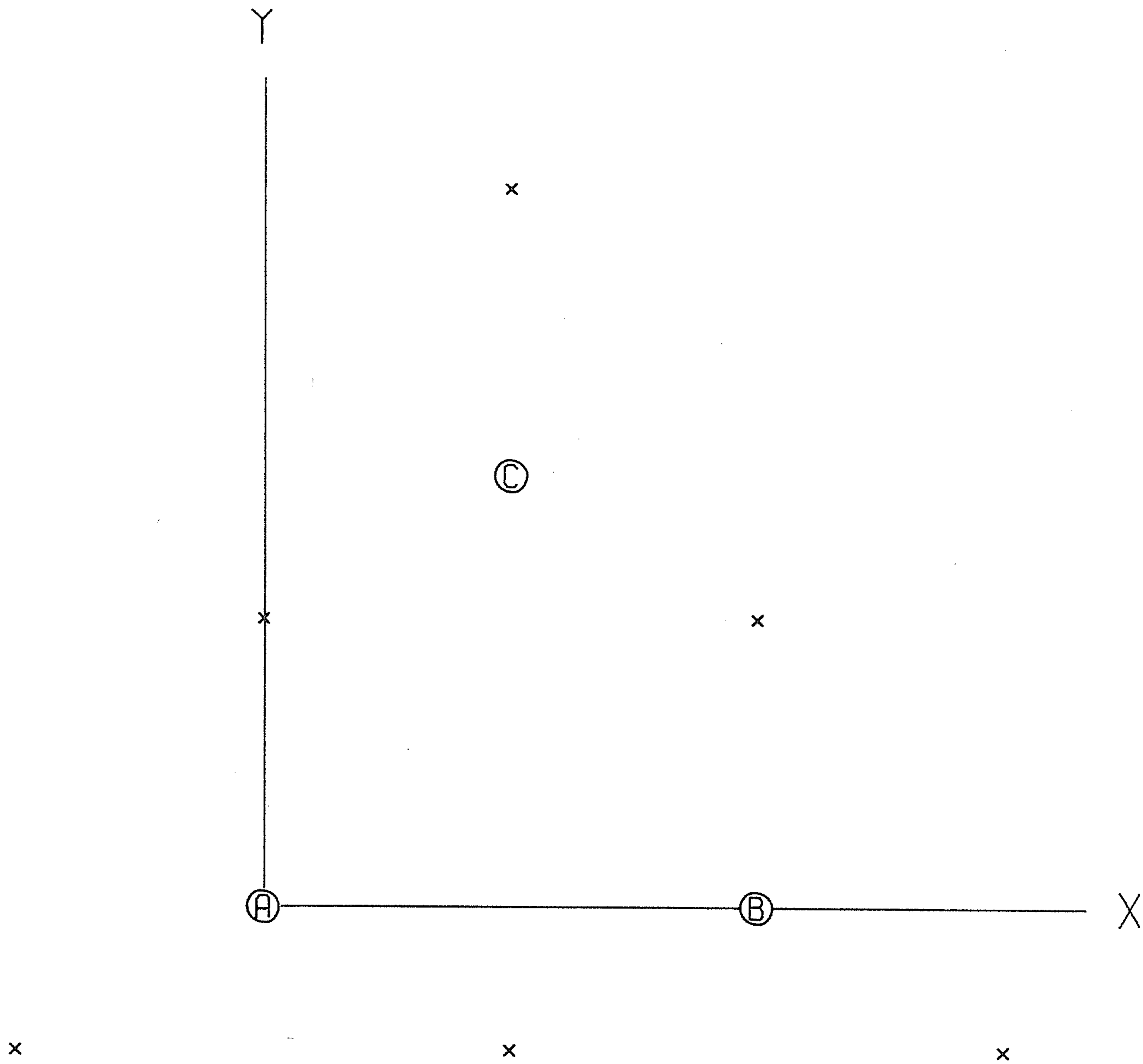


FIGURE 5.5
SURVEY 5

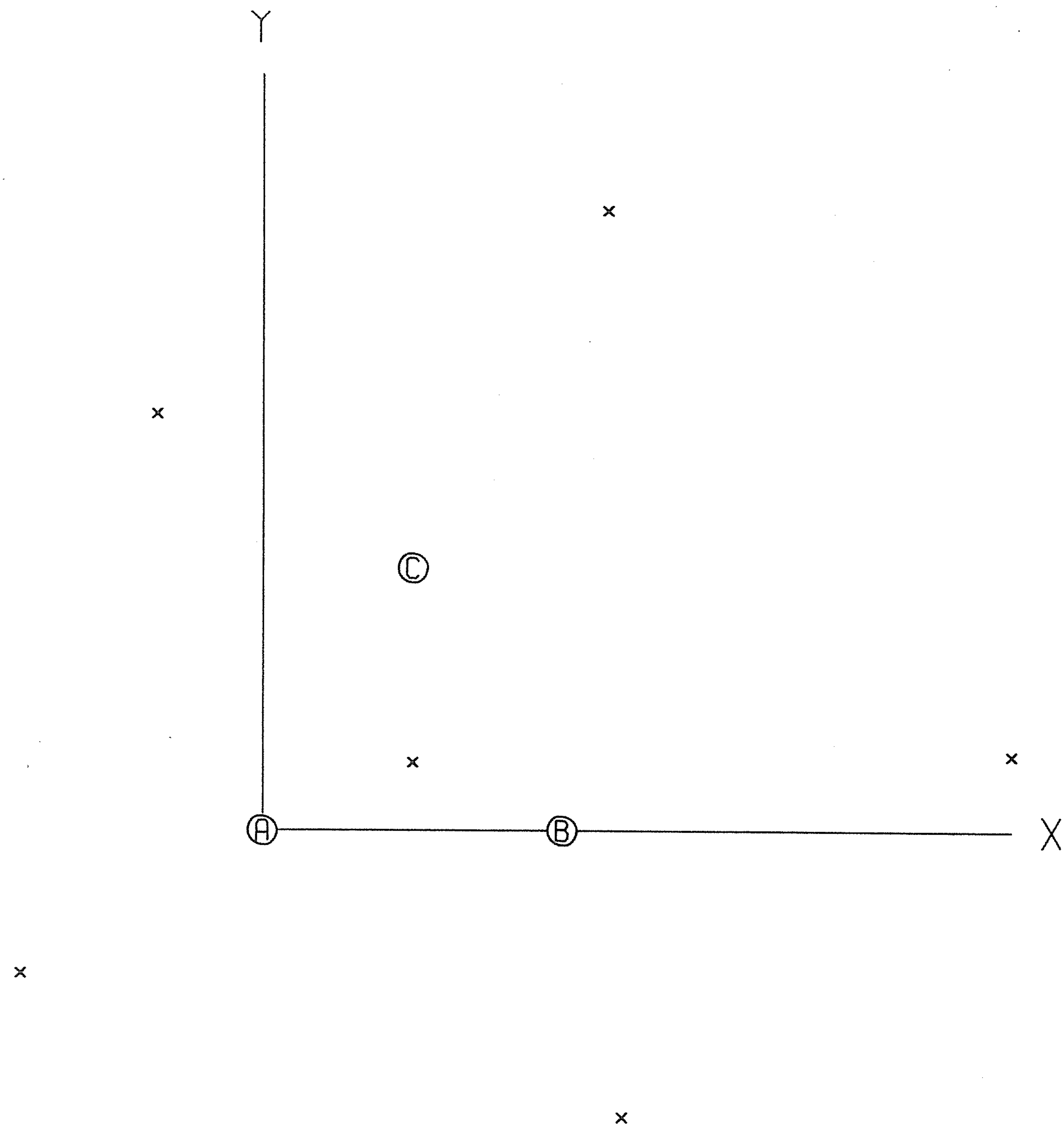


FIGURE 5.6
SURVEY 6

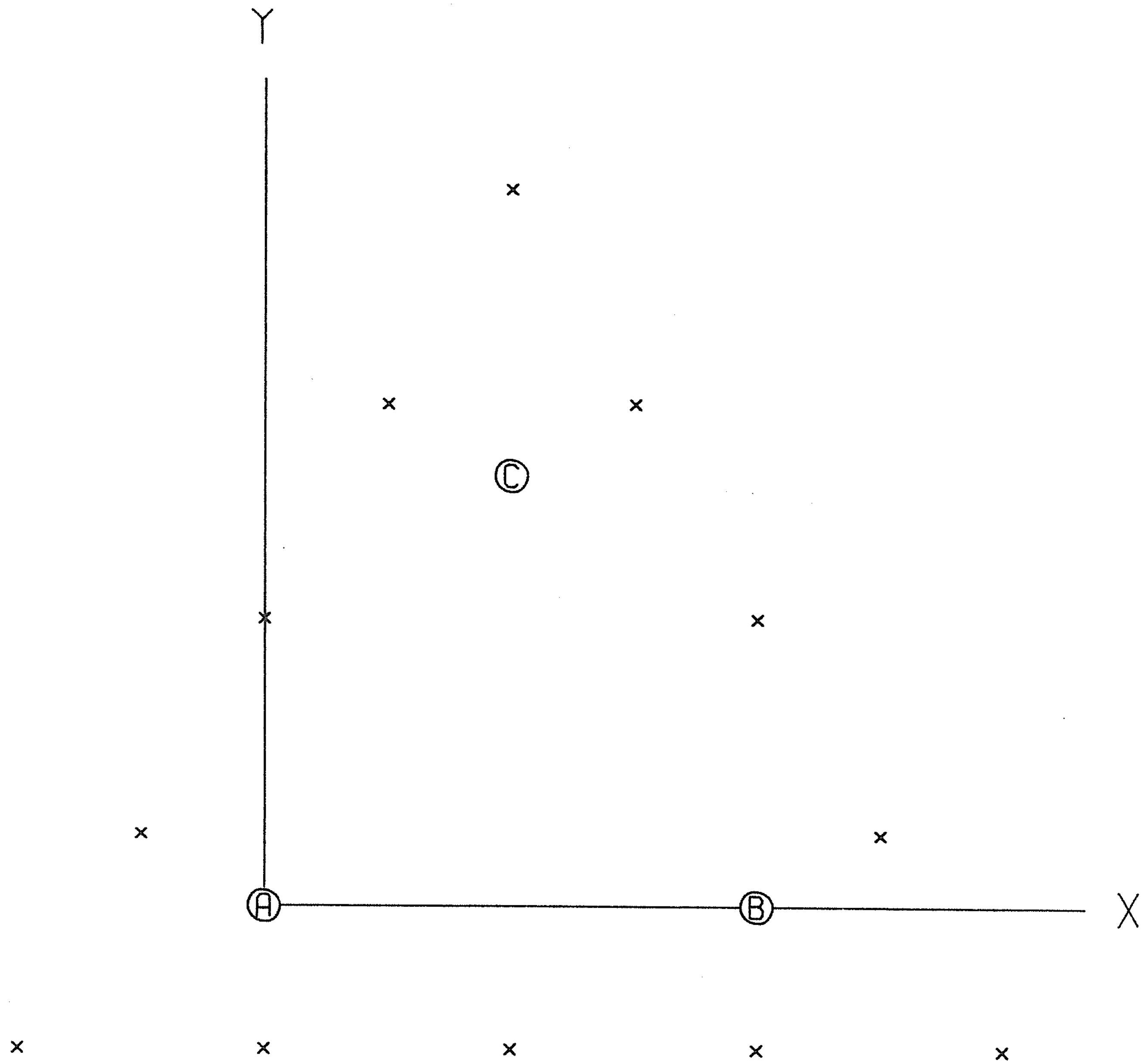


FIGURE 5.7
SURVEY 7

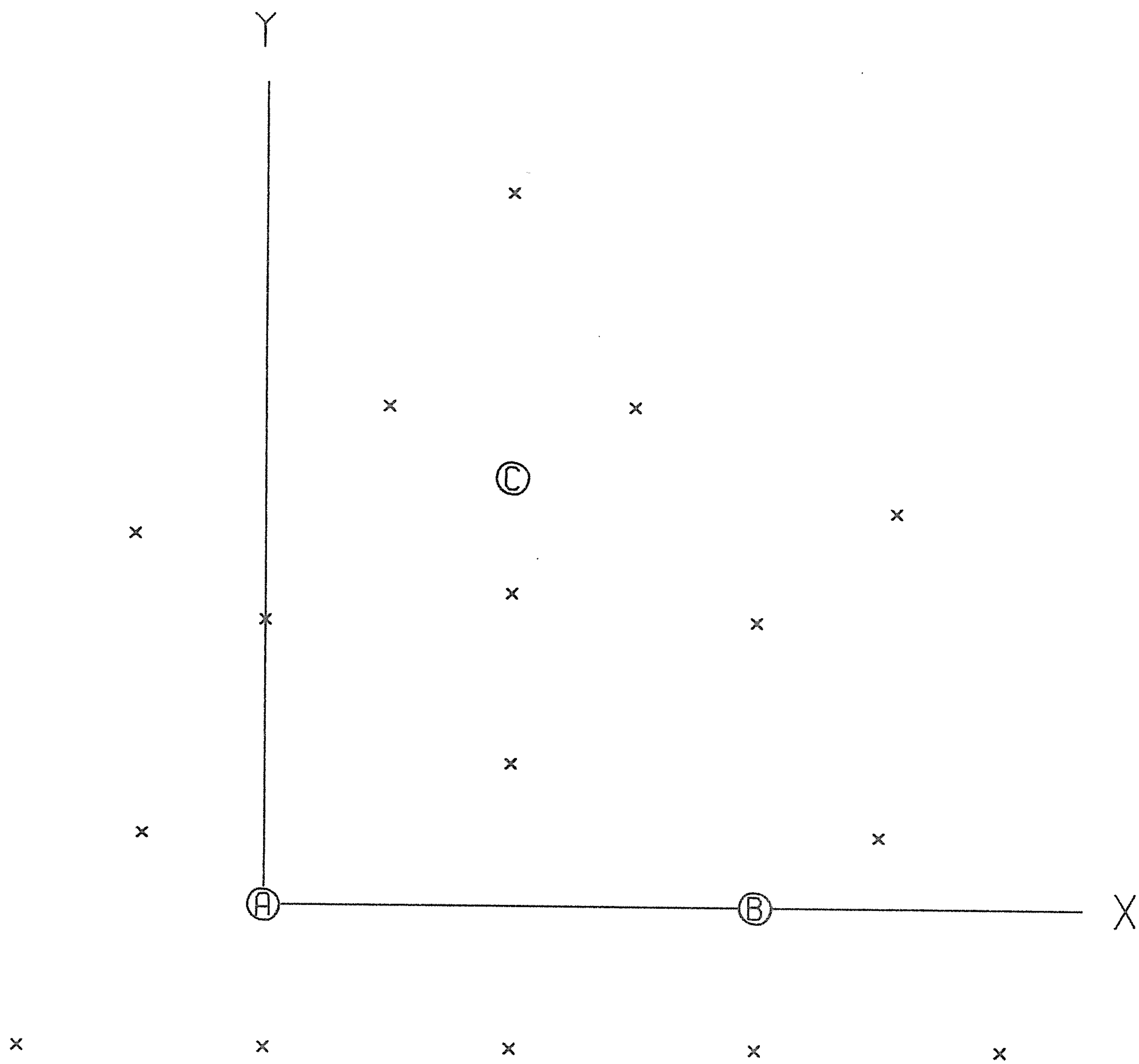


FIGURE 5.8
SURVEY 8

6. PROGRAMS

The acoustic navigation software package consists of three programs: SETUP finds ray-bending coefficients, SWURV finds the beacon positions, and ACNAV does real-time navigation. These programs were all written for the Hewlett Packard 2116 shipboard computer system. Also, there are versions of each available for the Xerox Sigam 7. The logical relationship between the three programs is shown in Figure 6.1. Complete program reports can be found in Technical Memorandum WHOI-5-74, Acoustic Navigation System Programs, by Mary Hunt.

6.1 Program SETUP

The first program to be run in any application is Program SETUP. The ray-bending coefficients computed by SETUP are used to convert travel times to distances. To find the ray-bending coefficients, it is necessary either to know the sound velocity profile, or to have the raw data from which it can be computed. Also required are the approximate depth of the beacon array, and the depth of the ship transducer. Program SETUP creates a paper tape containing the sound velocity profile and ray-bending coefficients. This tape is used as input to Program SWURV and Program ACNAV.

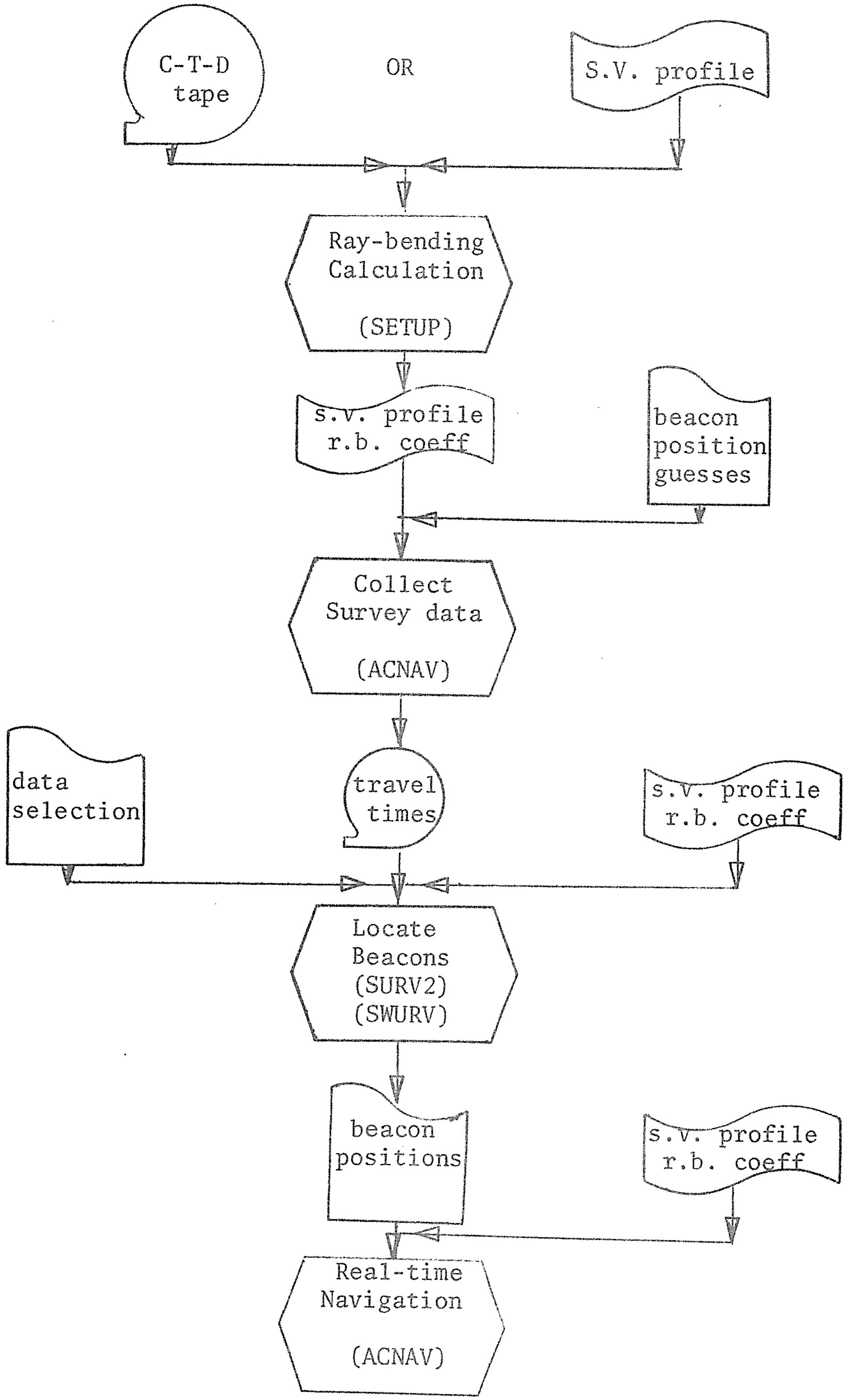


Figure 6.1

SYSTEM FLOW DIAGRAM

6.2 Survey Programs

The next logical step is to determine the depths and relative positions of the beacons. The survey program, using travel time observations from the ship transducer to each of the beacons, modifies the initial estimated beacon positions until it finds positions which best fit the observed data.

Previous survey schemes have defined 'best fit' as that solution which minimizes the sum of the differences between the transducer depth calculated from each of the data points and the true transducer depth. The present program, SWURV, uses the least-squares techniques described in section 4. This procedure also gives an estimate of the errors in determining the beacon positions.

Program SWURV is used when there are three beacons. The two-beacon program, SURV2, requires that the ship collect travel times while steaming back and forth across the baseline. At least three baseline crossings must be made.

6.3 Program ACNAV

Program ACNAV can be used for real-time navigation, for data acquisition, or for processing data collected on a previous run. When operating in real-time, ACNAV accepts input, consisting of travel times and selected options, from the coupler, and computes the ship (or fish) position.

There are two slightly different versions of ACNAV; one used by FAMOUS, and one used by IWEX. The main differences are in the options included, and the type of displays available. Both versions include a display, on either TEKTRONIX or CALCOMP, of the positions of the ship and 'fish' relative to the beacon positions. The FAMOUS version also includes computation of sonobuoy positions, automatic correction for surface bounce during the fish cycle, and a display of bottom depth and depth of the 'fish' plotted against time. The IWEX version includes two different methods of displaying fish depth.

Figure 6.2 shows Thomas Crook (computer technician), D. Moller, M. Briscoe, and T. Aldrich studying a Calcomp display of fish position during KNORR cruise 34.

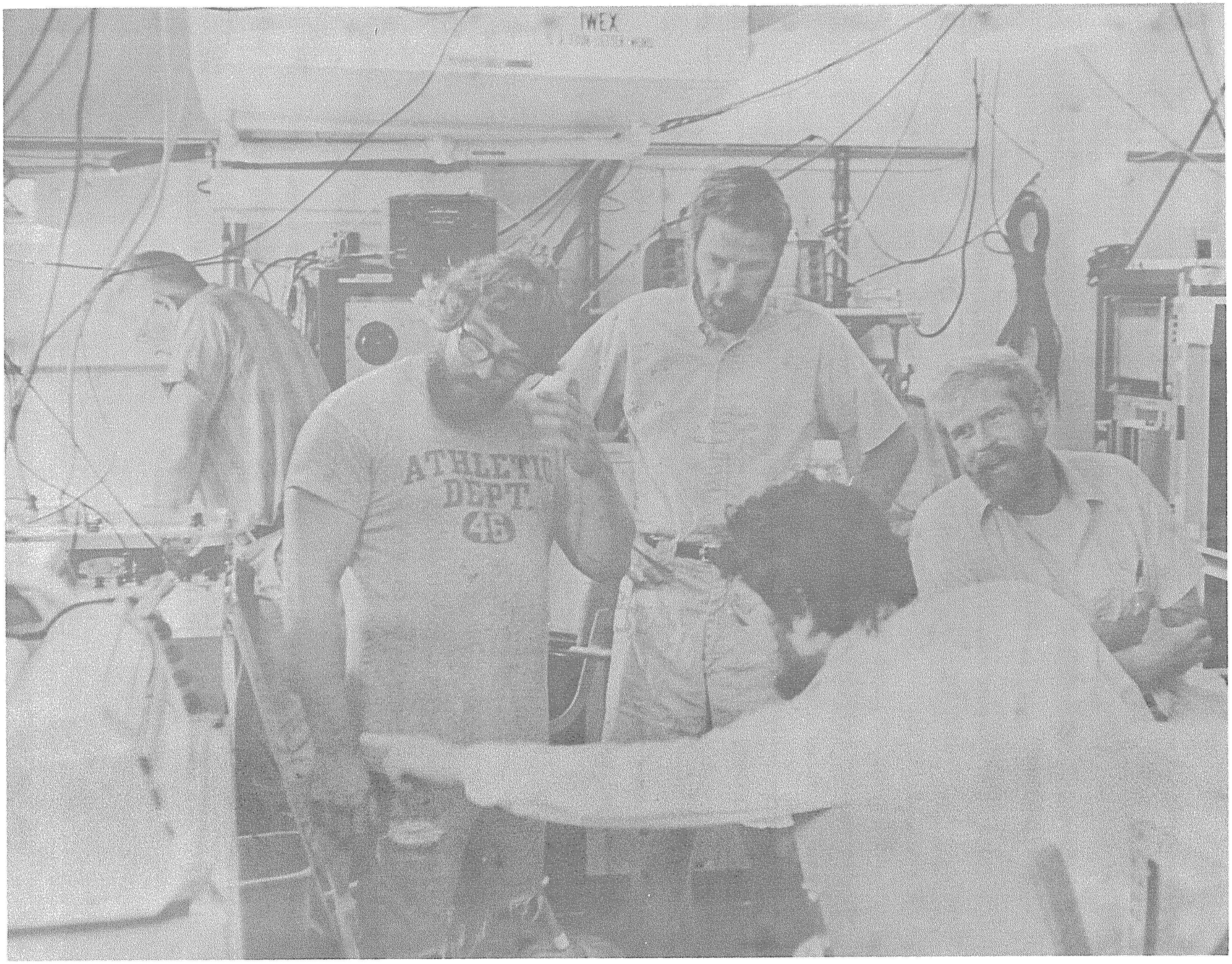


Figure 6.2. T. Crook, D. Moller, M. Briscoe, and T. Aldrich Conferring During KNORR Cruise 34.

7. RESULTS

7.1 Project FAMOUS - August, 1973

The ANGUS system was first taken to sea by Project FAMOUS (French American Mid-Ocean Undersea Study) in August, 1973 on RV ATLANTIS II, cruise 77. Three networks of beacons were set, one consisting of three beacons, and the others of two beacons. Real-time ship navigation was carried on for about ten days. Figure 7.1 shows a plot of the ship track. In addition, navigation data were collected for the lowered instrument (camera, dredge, or heat flow probe) for 30 stations, many of which included sonobuoy data.

Difficulty was experienced in real-time processing of the 'fish' data, partly because of the unusually rough terrain. If the direct path from the fish to a beacon is blocked, the signal received by the beacon is a reflection of the sound pulse from the ocean surface. An observer watching the travel times displayed by the receiver would notice a substantial increase in the time from the corresponding channel. This 'surface bounce' signal path is illustrated in Figure 7.2. The signal path to an imaginary transponder at depth $-D_T$, directly over the real transponder, is also shown.

Although this 'surface bounce' had been anticipated for operations with DSRV ALVIN, the necessary computations had not been included in the version of ACNAV which was taken to sea. On return to Woods Hole, the program was modified to include this capability. In reprocessing, about 80 per cent of the returns yielded fish positions which appeared valid.

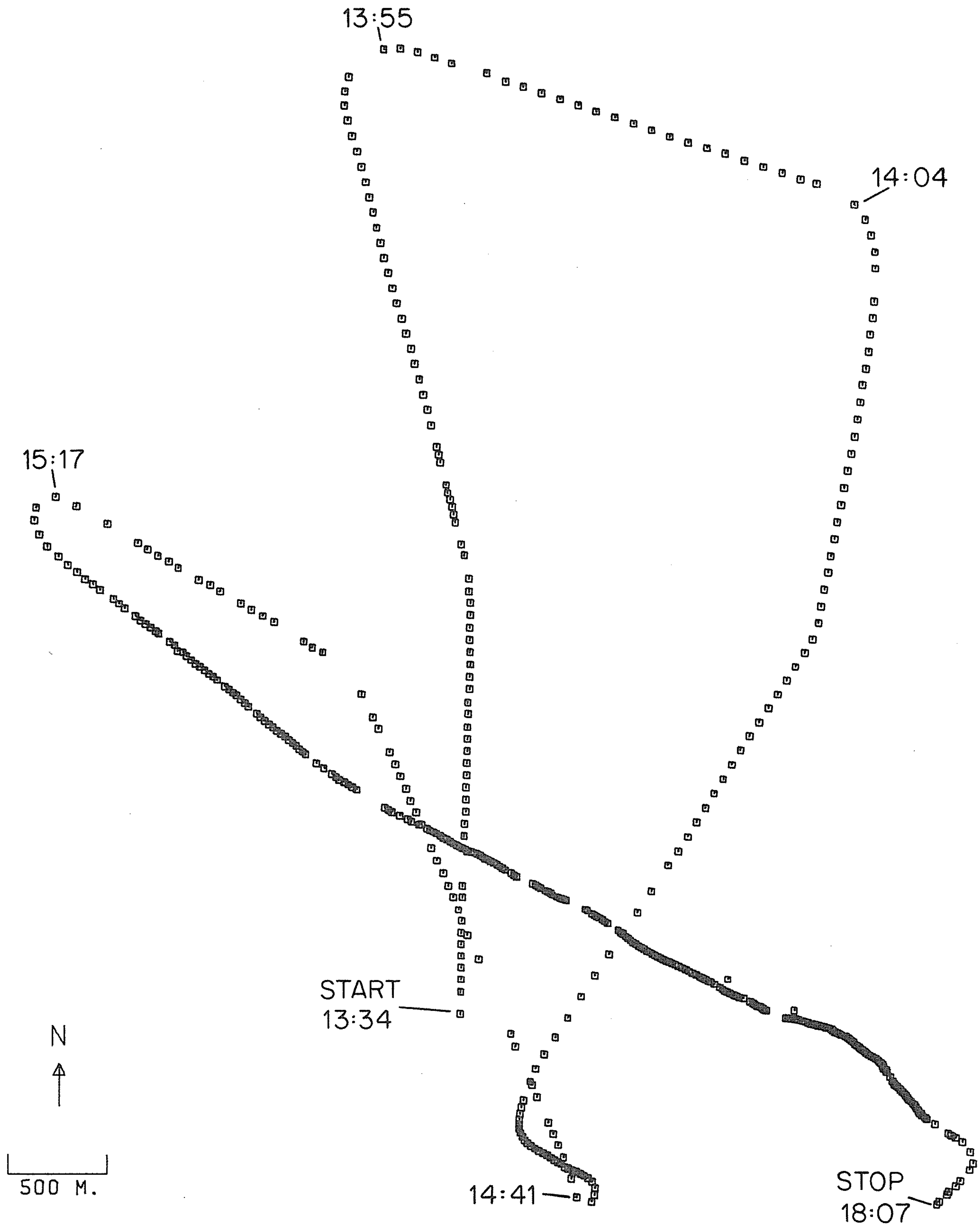


FIGURE 7.1

SHIP TRACK, AUGUST 23, 1973

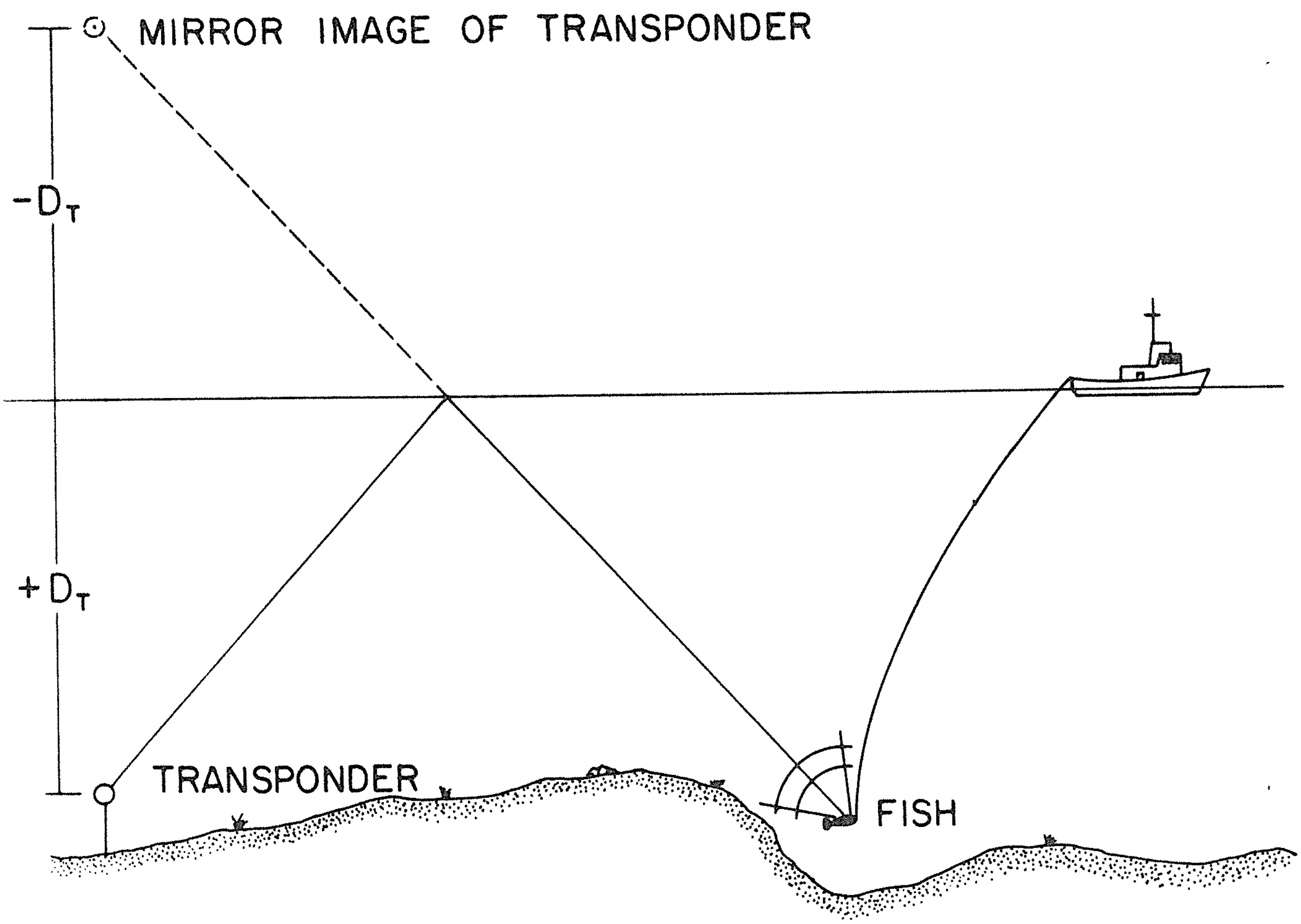


FIGURE 7.2
INTERROGATION OF A BOTTOM TRANSPONDER
VIA SURFACE BOUNCE

Tracking of three sonobuoys, in conjunction with ship and fish tracking, was successful. Tracks of the sonobuoys for a period of about three hours are shown in Figure 7.3.

7.2 Project IWEX - October, 1973

The ANBUS system was taken to sea in October, 1973 on RV KNORR, cruise 34, to initiate the Internal Wave Experiment (IWEX). The navigation system was used to place the three legs of a tripod mooring in a pre-determined configuration, at a depth of about 5 kilometers. It was desired to position the anchors to form an equilateral triangle, each leg about six kilometers long. In addition, each of the three anchors had to follow a specific path while being lowered, to avoid tangling the various lines and cables. Controls for maneuvering the ship were installed in the main laboratory of the KNORR, beside the Tektronix 4010 display. Figure 7.4 shows D. Moller operating these controls.

The navigation system worked well and the anchor deployment was successful. It is not known exactly how accurately the anchors were positioned, but the final depth of the apex float was within a few meters of the intended depth. Figure 7.5 shows a plot of the 'glide path' of the first anchor as it was being lowered.

In an effort to minimize the interference of ship noise with the acoustic navigation (the KNORR is very noisy), the transducer was lowered into the water attached to a weighted line, boomed out away from the ship. The resulting transducer position was 15 meters away from the side of the ship, and about 50 meters deep. Despite these precautions, the KNORR proved to be too noisy in all but special operating conditions. Satisfactory acoustic conditions were obtained by lowering the ship's main engine speed from 330 rpm to 250 rpm, and using only minimal thrust and low ship speed.

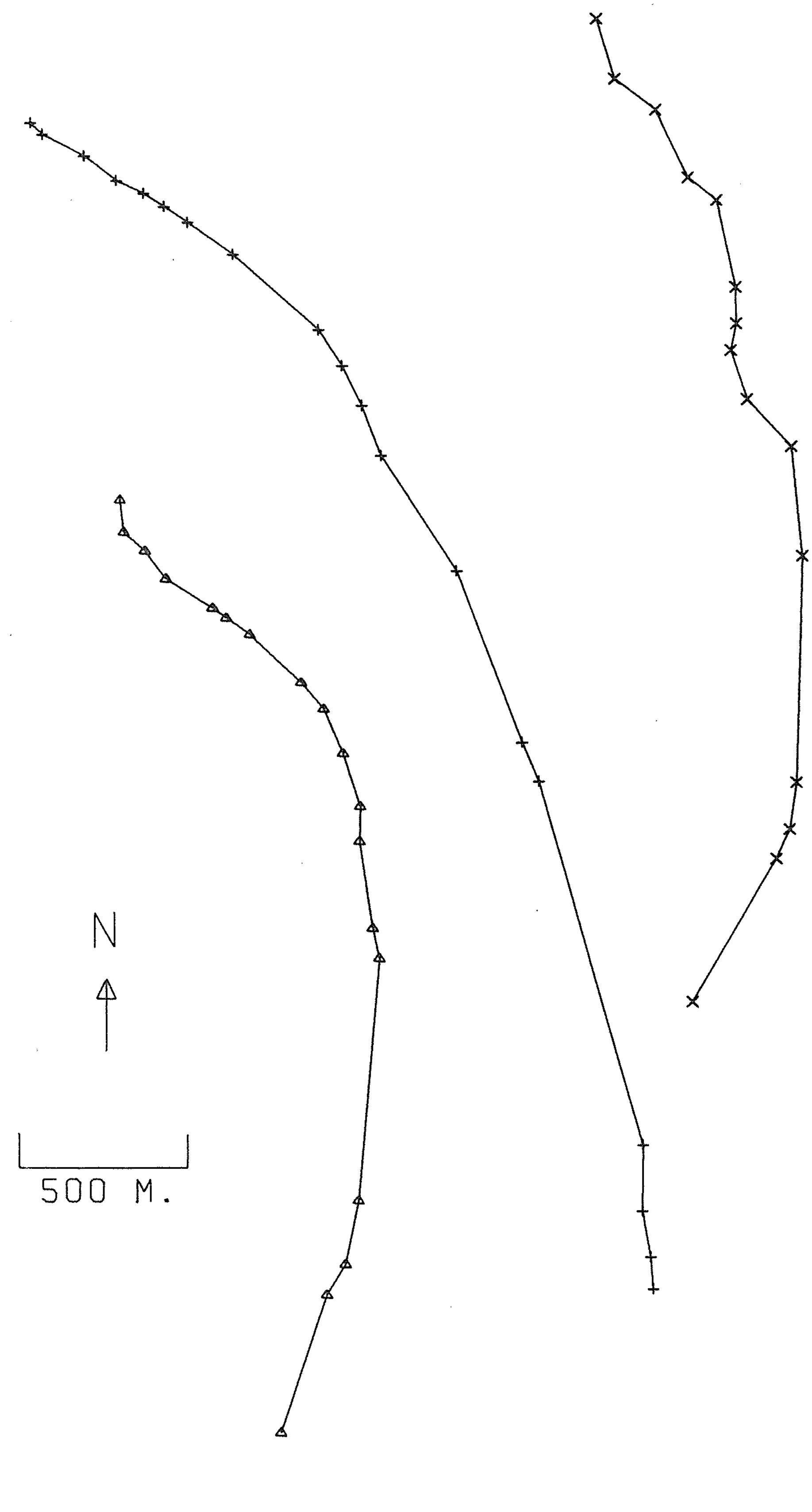


FIGURE 7.3
SONOBUOY TRACKING

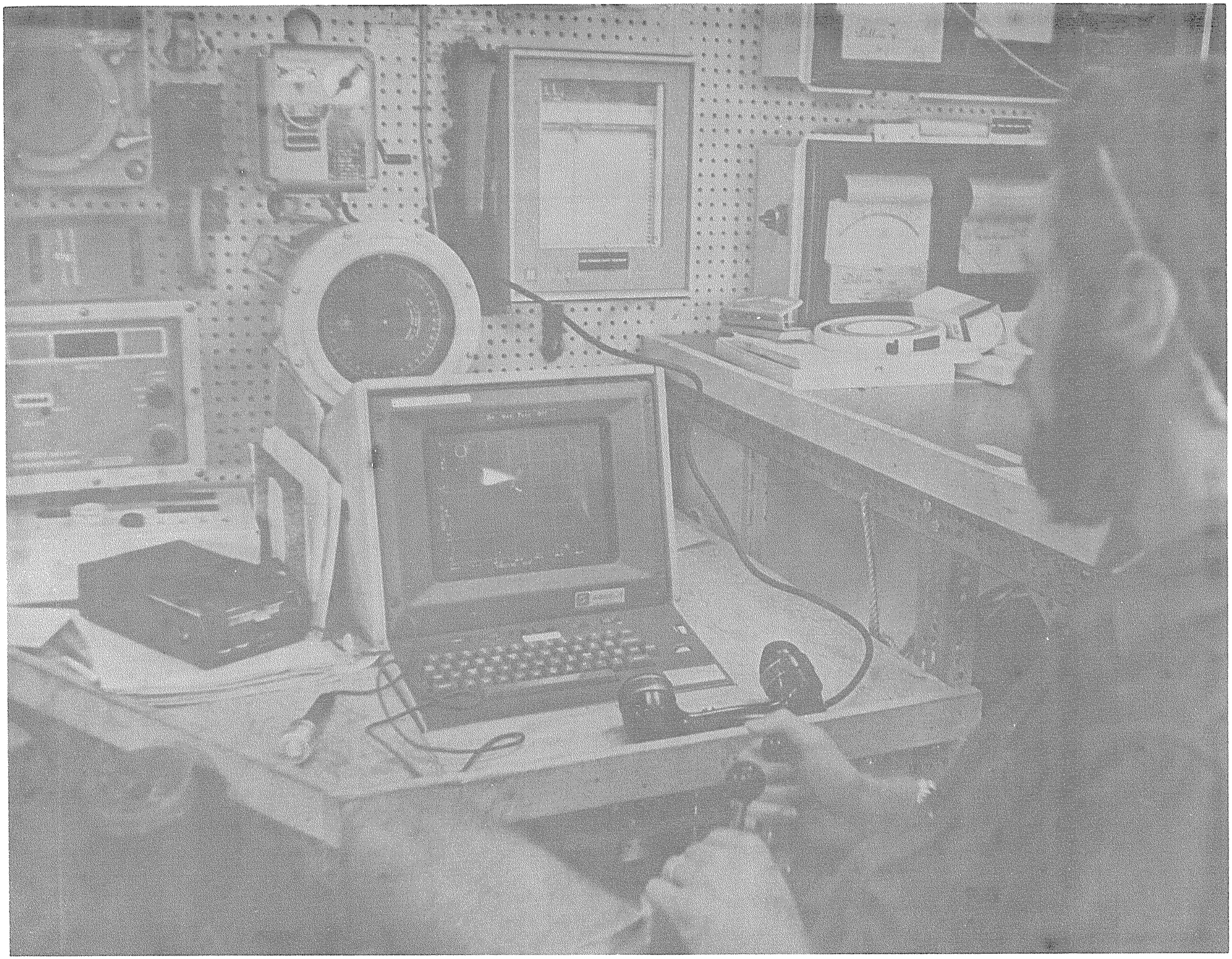


Figure 7.4. D. Moller Operating KNORR From the Main Laboratory.

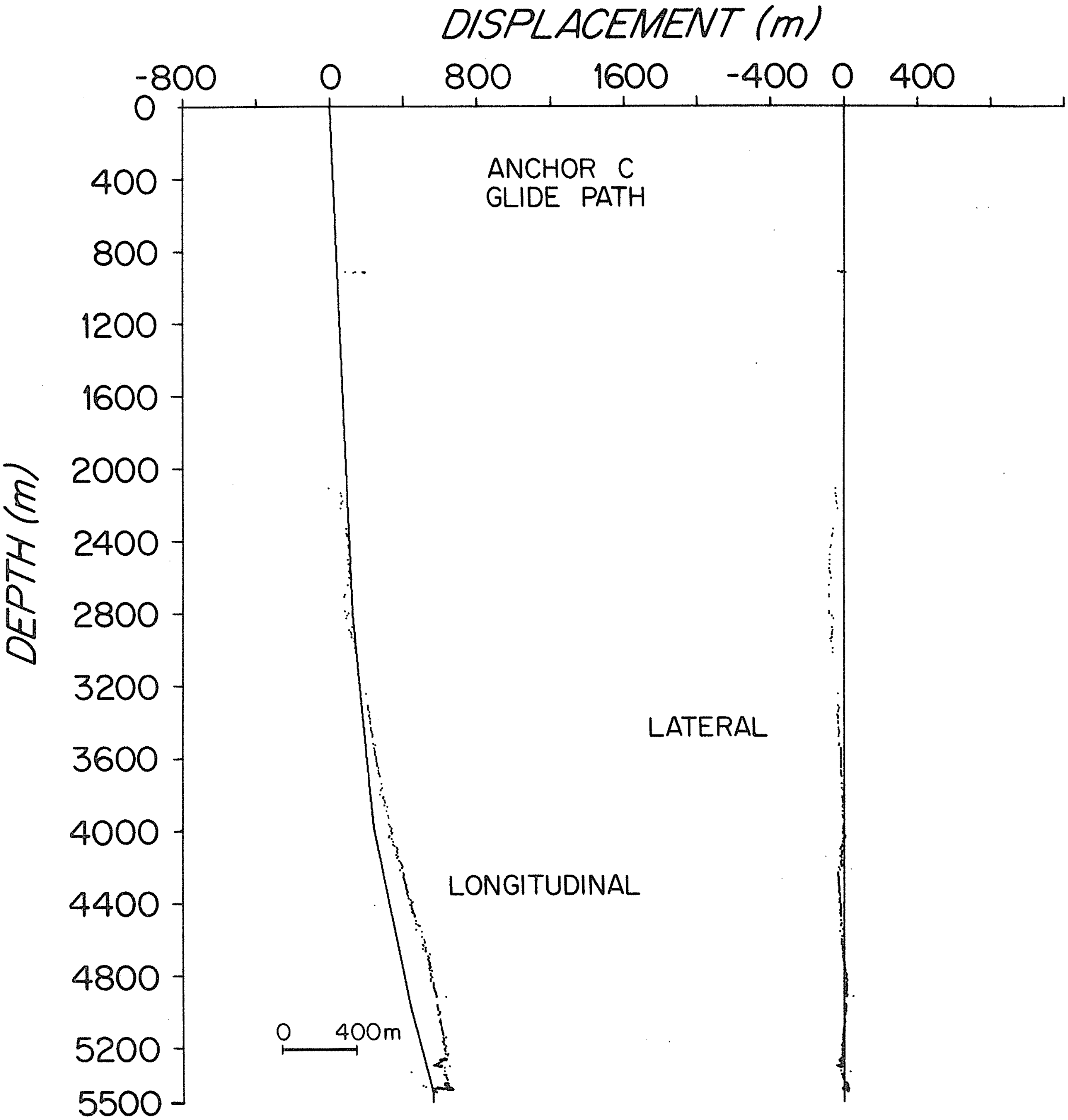


Figure 7.5. Plot of Anchor Glide Path

The transducer hanging over the side was also a problem for maneuverability of the vessel. The ship operator had to be careful not to move the ship rapidly in the direction of the transducer for fear of damage to the cable and transducer. Because of the drag on the transducer, weights and cable, its depth was difficult to determine, as it varied with speed. Only when the ship was stopped did we know the transducer depth accurately. This parameter is critical to precise navigation and was perhaps one of the most severe limiting factors to high precision. All things considered, the over-the-side transducer scheme is not a satisfactory one and would not have worked had more thrust from the cycloids been demanded.

7.3 DSRV ALVIN - February, 1974

The final at-sea developmental trials of the ARPA/ALNAV system were conducted in February, 1974 in the Tongue-of-the-Ocean. During these exercises it was found that when the submersible was operating on the bottom, the direct path between ALVIN and the bottom-moored transponders was often obstructed by intervening topography. As had happened the previous summer with the ANGUS system, the sound pulse was reflected from the ocean surface. This surface bounce had been expected, but the reliability and usefulness of this signal path had not been fully proven. It was found that, when the direct path between ALVIN and a transponder was blocked, the transition to the surface bounce path was sharp and reliable. The jitter in the measured surface bounce travel times was greater than for direct path signaling, but useful ALVIN positions could be calculated.

The programs for the ALNAV HP 9100 calculating system were re-written to include an operator-selectable surface bounce option. The program assumes that two bottom-moored reference transponders (A and B) are to be used. Under these conditions four ALVIN-to-transponder signal combinations are possible.

a) Direct path to both A and B transponders.

b) Direct path to A transponder and surface bounce to B transponder.

c) Surface bounce to A transponder and direct path to B transponder.

d) Surface bounce to both A and B transponders.

In the surface bounce mode of operation, the program calculates the depth of ALVIN for each of the four cases given above. The operator inputs the approximate depth of ALVIN via thumbwheels on the Timing Control Unit. The program selects the combination of signal paths that gives the calculated depth of ALVIN nearest to the operator input depth, and then proceeds to complete the position calculations. The ALVIN positions are automatically plotted and a printout is made which includes a code to indicate which of the four possible signal path combinations was used in the calculations.

Using a coordinate system with the origin at the ocean surface, these calculations were not difficult to incorporate in the program. Assume that the signal path from ALVIN to the "A" transponder is via surface bounce and that the signal path from ALVIN to the "B" transponder is via the direct path. To calculate the ALVIN position the depth of the "A" transponder stored in the calculator memory is changed from plus to minus and the depth of the "B" transponder is left as plus (see Figure 7.2). This simple change is all that is required to obtain the correct solution for the position of ALVIN.

7.4 Project FAMOUS - Summer, 1974

The ARPA/ALNAV system was used to track ALVIN during the FAMOUS submersible operations during the summer of 1974. These operations were conducted in the area of the Mid-Atlantic Ridge at depths of 8,000 to 10,000 feet. Underwater mountains posed several problems in successful submersible navigation. A reference net of five transponders was used, with each transponder moored 100 meters above the sea floor. The distance between transponders was typically 3,000 meters. The transponders were surveyed from the KNORR using the ANGUS system, and the ALVIN tracking was conducted from the RV LULU using the ALNAV system. The surface bounce mode of operation proved to be both necessary and invaluable during the time ALVIN was operating on the bottom. The topography was such that ALVIN spent a major part of her bottom time in areas where the direct path from the submersible to the transponders was blocked. The automatic surface bounce mode of operation permitted ALVIN tracking to continue thus avoiding gross holidays in the vehicle bottom tracks.

In addition to providing tracking of ALVIN while she was on the bottom, the ALNAV system was used to guide ALVIN during her descent to the bottom. Each ALVIN bottom track was planned to start at a particular location. The navigation system was used daily to measure the drift of the LULU during the twenty minutes that it takes to launch ALVIN. With this information, the launch of ALVIN was started offset from the target point on the bottom. When ALVIN had descended to approximately 1,000 meters, LULU took up her tracking position directly above ALVIN and gave ALVIN the range and heading of the bottom target point. The launch control plus this mid-descent correction permitted ALVIN to consistently arrive on the bottom within approximately 50 meters of the desired location.

8. FUTURE DEVELOPMENTS

The preceding sections have described a high precision, pulsed, acoustic navigation system. It has been accepted by this oceanographic research community as a basic and necessary tool for precise geographical navigation at sea. In its concept and execution the system incorporates engineering and computational techniques that contribute to state-of-the-art pulse navigation performance. The various requirements of a diverse group of users have led not only to an assortment of operational conveniences, but have helped to ensure a continuing program of system improvement. For example, the special survey requirements of a group involved in mooring deep-water instruments have resulted in improved survey techniques and programs. ALVIN navigation requirements have led to careful analysis of acoustic ray-bending effects. Acoustic engineers concerned with hydrophone array element motion have modified the system to include the capability of navigating free-drifting sonobuoys. In the near future it is expected that modifications, improvements and extensions will continue to be applied to the basic pulse system; such changes being driven primarily by user requirements.

With good signal to noise conditions and an accurate sound velocity profile, the pulsed navigation system provides typical accuracies of ten meters. Position determination requires the measurement of acoustic round trip travel time from a platform (ship, submersible, buoy, etc.) to a datum (transponder), and subsequent conversion of acoustic travel time to slant range. Precision of the travel time measurement is proportional to the signal-to-noise ratio and bandwidth of the received acoustic pulse. A typical system bandwidth of 200 Hz limits time measurements to several msec. Thus 2-3 meter errors are unavoidable even assuming large signal-to-noise ratios and perfect conversion to slant range. In fact, conversion to slant range is less than perfect due to unknown sound velocity variations, and signal-to-noise ratios can be so low that an accuracy of 20 meters might be more typical. The pulse system is further constrained by relatively low data rates. The time between fixes is limited to the maximum round trip travel time from platform to most distant datum (usually 15 to 30 seconds).

Although incremental reductions in these sources of error can be achieved (and indeed, constitute a continuing program of system improvement), scientists and engineers at W.H.O.I. are pursuing the development of an alternative navigation scheme that, when coupled with the present system, promises to offer ultimate accuracies of centimeter proportions. This technique is based on the Doppler principle; it obtains motion information by observing the velocity induced Doppler shift of an acoustic tone. The system employs beacons (rather than transponders) which serve as highly stable, continuous wave, acoustic sources. Platform velocity, v, along the beacon-receiver vector is directly proportional to measured Doppler shift since,

$$f_d = vf_b/c$$

where f_d is the Doppler shift, f_b is the beacon frequency and c is the speed of sound. Platform translation is obtained by integration of velocity.

The system, as currently implemented, employs beacons in the 12-13 kHz region (Porter, Spindel, Jaffee, 1973). Doppler frequency is not measured directly, rather departures from 12 kHz (f_d) are measured in phase cycles; $\Theta_d = 2\pi f_d t$. Each cycle corresponds to translation of a full wavelength at 12 kHz, approximately 12.5 cm. Measurement to a quarter cycle yields range resolution of about 3 cm. The accuracy of the measurement is proportional to the signal-to-noise ratio in the narrow band that encompasses the maximum Doppler shift. At 10 knots the Doppler band is 40 Hz compared with the 200 Hz figure for the pulse system. Slower speeds yield even more favorable comparisons. In fact, the slowly varying narrowband signal can be tracked by a signal conditioner with a bandwidth as small as 1 Hz. Thus in addition to providing one to two orders of magnitude improvement in system performance, an immediate gain of 23 dB in signal-to-noise ratio is achieved. Moreover, the data rate for a Doppler system is high compared with the pulsed system, typically 60 to 120 fixes per minute, compared with one every 15-30 seconds.

The Doppler navigation system, although capable of very precise relative (fix to fix) navigation, is difficult to calibrate. The system does not readily provide an origin for accumulation of Doppler shift information. Straightforward measurement of beacon to receiver range is highly ambiguous because many thousands of wavelengths can be encompassed in a several kilometer transmission path. This shortcoming, however, is complimented by the ease with which a pulsed system accomplishes this requirement.

A development program in the Department of Ocean Engineering is currently underway to combine the best features of the pulse and Doppler navigation concepts. It is anticipated that an order of magnitude improvement will be achieved in fix accuracy and in survey precision, and that fixes will be obtained at greatly increased rates. The program is being pursued under the sponsorship of the Advanced Research Projects Agency and the Office of Naval Research.

APPENDIX: Associated Documentation

The supplementary Technical Memoranda are:

1. Timing Control Unit for the Acoustic Navigation System, by A. Eliason, W.H.O.I. 2-74.

2. Operation of the HP 2570 Coupler/Controller in the Acoustic Navigation System, by K. Peal, W.H.O.I. 3-74.

3. Acoustic Navigation System Operating and Service Manual, by K. Peal, W.H.O.I. 4-74.

4. Acoustic Navigation System Programs, by M. Hunt, W.H.O.I. 5-74.

Invididual manuals are available as follows:

AMF MODEL 205 RECEIVER - Operation and Maintenance Manual

AMF MODEL 200 SHIPBOARD EQUIPMENT - Operation and Maintenance Manual

HP 2570A COUPLER/CONTROLLER - Operating and Service Manual

DATUM MODEL 9100-506 DIGITAL CLOCK - Instruction Manual

ERC MODEL 2402 DIGITAL CLOCK - Instruction Manual

ATEC MODEL IC19 DIGITAL CLOCK - Instruction Manual

HP 9100 COMPUTING CALCULATOR - System Documentation (ALVIN group)

HP 2100 COMPUTER - System Documentation (SCS group)

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Bendix-Pacific Division, Bendix Corporation (1964) "Acoustic Navigation Systems".

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2. Underwater Vehicle Tracking
3. Acoustic Array Survey Design
4. Real Time Navigation
5. Hydrophone Network

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Acoustic navigation provides a method of tracking a ship, and an underwater vehicle or instrument package ('fish') in the deep ocean. Acoustic devices attached to the ship and fish measure the length of time it takes a sound pulse to travel to acoustic transponders moored on the ocean floor. When the transponder positions and the average speed of sound are known, the ship and fish position can be found. This report describes a system for real time acoustic navigation developed, and in use, at the Woods Hole Oceanographic Institution. It includes a brief discussion of the electronic components.

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