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THESIS

(6) PROPOSAL FOR A REAL TIME AUTOMATED
CLOSE COASTAL AND HARBOR NAVIGATION SYSTEM.

by

(10) Timothy Martin Grabski

(9) Master's thesis,

(11) Dece~~mber 1~~977 (12) 82p.

Thesis Advisor: G. D. Ewing

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This thesis is a proposal for an automated, real time navigation system which will be used in a close coastal and harbor navigation environment. Special consideration was given to designing the system in such a manner that the present system of navigation would be retained — no personnel would be either added or removed from the ship's complement, all logs and records would be retained in their current form,

(20. ABSTRACT Continued)

and the piloting routine would not be changed. When the system is functioning as designed, real time navigational data will be generated which will be verified by the slower manual plotting method. Should mechanical failure occur, the manual plot already being maintained will take over.

The system design calls for installation of a commercially available desk-top microcomputer with CRT display devices located in remote locations for dissemination of data. The cost of the complete system is less than $4000, and repair is effected by replacement of modules drawn from onboard spares. Considerable flexibility is retained for later changes and additions to the system should such be desirable.

Proposal for a Real Time Automated Close Coastal and Harbor Navigation System

by

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Lieutenant, United States Navy
B.S., Miami University, 1972

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

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ABSTRACT

The thesis is a proposal for an automated, real time navigation system which will be used in a close coastal and harbor navigation environment. Special consideration was given to designing the system in such a manner that the present system of navigation would be retained – no personnel would be either added or removed from the ship's complement, all logs and records would be retained in their current form, and the piloting routine would not be changed. When the system is functioning as designed, real time navigational data will be generated which will be verified by the slower manual plotting method. Should mechanical failure occur, the manual plot already being maintained will take over.

The system design calls for installation of a commercially available desk-top microcomputer with CRT display devices located in remote locations for dissemination of data. The cost of the complete system is less than $4000, and repair is effected by replacement of modules drawn from onboard spares. Considerable flexibility is retained for later changes and additions to the system should such be desirable.

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I. INTRODUCTION

"I think I can get us there by seaman's eye, Captain." These words are all too often heard on the bridges of Navy ships. With all the sophistication of equipment aboard ships in the Navy, and with the marvels of this electronic age available to assist man in navigating his ships safely in restricted waters, it is curious that this common exercise is still executed as if the ships are still made of wood and the men of steel.

One of the reasons why the "Seaman's eye" is still used is the sometimes questionable accuracy of information provided by the Navigator to the conn of the ship. Even more frustrating is the fact that the geographical information can be very precise, but due to the delay inherent in the present system of piloting, it is not timely. This is particularly true when in a pressure situation such as the approach to an anchorage or navigation in a narrow channel under heavy traffic conditions and/or low visibility. Even the best navigation team cannot be expected to provide a complete and, more importantly, comprehended set of position information in anything less than thirty seconds. Typically the time required for obtaining the fix, processing the information, and then relaying this information to the conn takes from forty to sixty seconds. A ship transiting a channel at the modest speed of twelve knots can travel from 270 to 400 yards in this period of time, a considerable distance when the nearest navigational hazard may only be 300 yards away!

There must be a better way, and the subject of this thesis is a proposal for just such a system.

A. BACKGROUND

Before plunging headlong into the proposal for the system, it is important that a needs assessment be made concerning the type of system to be employed. In as tradition-bound an organization as the Navy it is sometimes dangerous to make proposals for radical change in methods which have become almost classical in their application, particularly when the safety of hundreds of men and millions of dollars of government equipment may be at stake. Thus, before making the proposal, the system presently used aboard ship will be described.

The piloting team aboard most ships in the Navy usually consists of the Navigator and four or more other personnel. While the number of people may vary, the functional positions they must fill do not. There must be a plotter, a bearing recorder, bearing taker(s), a radar operator, and a fathometer operator. In addition there are usually phone talkers for the distribution of information between the conn, the Navigator, and the Combat Information Center (CIC).

The navigator is in overall charge of the piloting team. He may, in some cases, also do the plotting, but most navigators prefer to assign one of the senior petty officers on the team as plotter. This allows the navigator to be free to observe the shipping situation, weather, and the other factors which may affect the ship's movements while also being available for consultation with the conning officer and Captain. As should be evident, an unreliable or inexperienced plotter can adversely affect the navigator's efficiency in dealing with the tactical situation.

The bearing recorder serves as director of the piloting team. He is positioned alongside the navigator and plotter and is in direct communication with the other members of the team via sound-powered phones. Through him, the navigator designates which objects shall be used for obtaining the lines of position (LOP's) to the bearing takers. When a round of bearings is taken, the bearing takers report the bearing of their assigned objects to the bearing recorder who records them in the Bearing Book. He also simultaneously reports the bearings to the navigator and plotter. A depth sounding is also taken at this time and recorded for comparison with the charted depth.

On small ships there may only be one bearing taker. However, the ship's superstructure usually prevents this on larger ships so that there are usually two bearing takers, one on the port side and one to starboard. He is usually assigned one or two objects to "shoot", and when a round of bearings is called for, he first shoots the most rapidly changing bearing and "remembers" it, then swings to the next object, and so forth. He then reports the bearing to his assigned objects when called for by the bearing recorder.

A radar operator may or may not be used, depending on the situation. This radar range information is generally used to supplement the information obtained visually. The range to an object can be used when some ambiguity exists as to the common crossing point of the LOP's obtained visually. Typically, a redundant plot of ship's position is maintained in the CIC using radar ranges. This information is constantly being compared with that obtained visually and, ideally, the fixes obtained by the two methods should compare quite favorably. Another reason for maintaining the two different plots is that, should the visibility deteriorate, the CIC team is generally much better able to efficiently operate the radar and obtain the maximum information available from it. Thus, for efficiency in transferring from one plot to the other, a continuous plot is maintained.

A separate fathometer operator may or may not be required. The necessity of this member of the team is dictated by the location of the fathometer recorder.

1. The Piloting Team Routine

Fixes under conditions of normal visibility are established through the use of bearings obtained on objects which are designated by the navigator. These objects are then located on the chart of the area and the bearing lines to these points are then drawn. Each line is called a line of position (LOP), and the crossing point of these lines is the probable position of the ship. Of course, many times these lines do not all cross at a common position, but rather usually form a (hopefully) small triangle. It is then up to the navigator to use his judgment to determine the most probable position of the ship given the information he has at hand.

The frequency of obtaining fixes varies with the situation, the desires of the navigator, and the wishes of the Captain and OOD. In most cases, when piloting a rather narrow channel, the maximum fix frequency which is tolerable is two minutes. Under less arduous conditions this frequency might be decreased to every three minutes. Also, as the situation becomes more critical, such as the final approach to an anchorage, the frequency may be increased to one minute.

As the time for obtaining the fix approaches, the bearing taker alerts the other members of the team of this fact, and then at the exact time says "mark"m at which time the bearing takers "shoot" their bearings to their assigned objects. When called for by the bearing taker, these bearings are passed to the navigation plot via sound powered phones and are recorded in the Bearing Book. In order to simplify the book-keeping of this information, the objects are usually designated by letters of the alphabet and are referred to as such. Finally, the fathometer reading is also called for and any radar ranges which are being obtained are also recorded. The plotter then uses this information to establish the fix by drawing the lines of position on the chart. The navigator then examines the fix and reports the position of the ship relative to the predesignated track. He also reports the proximity of the nearest navigational hazard, the range and time of the next change in ship's status (turn point, anchorage, range to pier, etc.). He also reports how the charted depth at the fix point obtained compares with the fathometer reading. Finally, he reports the comparability of his fix with that obtained in the independent plot being maintained in CIC. In the time remaining between the completion of this report and the calling for the next fix, the navigator examines the tactical situation, attempts to eliminate any ambiguities which may have been evident in the last fix, such as a bad LOP, redesignates objects to be shot as necessary, and proposes any changes to ship's course and/or speed. Also, he must determine the set and drift information which shall be reported as soon as it is determined. This procedure is repeated until the ship reaches its designation.

As is evident, the safe and routine navigation of a ship requires a considerable amount of coordination and teamwork. If all goes well, and if the team is experienced and efficient, the information concerning a particular fix can be delivered to the conn in about forty seconds. In some cases, though, this information is not received by the conn in anything less than sixty seconds. Also, in many cases, the conn does not really "receive" the information, since the tactical situation may require the conning officer's undivided attention at the time that the navigational information is being relayed to him. Additionally, the information may be inconclusive and no fix may be obtained. Not only does this require that the navigator call for the next fix prematurely, but in the event that this next fix also proves to be unreliable, he may need to do a little problem solving in order to determine what it is that is causing the difficulty. Should the visibility deteriorate, the navigator may be forced to rely on the plot being maintained in CIC and a smooth and orderly transition to this plot must be effected. Equipment malfunctions can occur, such as the loss of the gyrocompass, or of the radar or the fathometer. The ship might be forced to maneuver in order to avoid shipping, and instead of the nice orderly transit along the predesignated track, the navigator must now insure that the ship does not transit into a hazardous area, and then must determine the best course to use in order to get back on track after the maneuver has been completed.

As should be apparent, piloting in restricted waters can be a very tense and potentially hazardous operation. If the processing of a routine fix is taking one minute of the navigator's time, and if the fix frequency is at the rather routine two minute interval, the navigator and his team have a mere one minute period of time in which to perform all these other functions. In many cases, there just is not time enough, and that is where the art-form of navigation takes over, and the "Seaman's eye" reigns supreme. Any time that the navigator can buy is useful and can lead to increased safety and a higher degree of confidence on the part of the OOD and the Captain. The proposal contained in this thesis is for a system which automatically processes the information obtained by the bearing takers and radar operators and, by means of a display device located in the area near the conning station, disseminates this information. In this way, the navigator can use all of his time in evaluating and advising, and the conning officer and the Captain can receive the routine information when they want it, not when it is being delivered by someone who may not be aware of tactical considerations.

B. SYSTEM CHARACTERISTICS

Before the design proposal of the system was formalized, due regard was given to the general characteristics of the system. Just what was it that the system should accomplish?

It was desired that the system should replace as many of the manual operations as possible and yet that the system retain enough redundancy so that, should mechanical failure occur, the safe transit of the ship would not be jeopardized.

The inputs to the system must still be obtained by human operators. Clearly, designing a machine which can discriminate between a church steeple and a smoke stack would not be practical. Thus, the bearing takers must remain.

Next is the navigation plot. This is the area in which considerable automation can be introduced with the concomitant savings in time. Just how much automation is acceptable was a question which required considerable thought.

Total elimination of the human factor in the plotting and evaluation phase is technologically possible. A minicomputer can take the inputs of bearings, ranges, and ship's characteristics and, from this, calculate ship's position, course and speed made good, range to turn, range to anchorage or pier, etc., and by means of an automatic plotter the system could even plot the position of the ship. At first, this was thought to be the desirable system. Further thought, however, caused removal of the automatic plotter as part of the system. The reasons for this removal were several.

As was stated previously, acceptance of the system is a major obstacle. Redundancy is an aspect of the system which will go far in gaining acceptance of the proposal. Should the system be fully automatic, mechanical failure could cause serious problems. Should such failure occur, the navigation would be carried out manually as has been done in the past and as described in the previous section. The problem with the automatic system is one of transition and of expertise. With an automatic system, the piloting team would get very little practice in harbor navigation. It is probable that the transition from the automatic plotter to a manual routine would be slow and uncertain. While it is not possible to prove this claim since the system does not exist, the author's experience in the conduct of seldom-occuring drills led to the conclusion that a fully automated system would be difficult to sell to the Naval community. Also, the fully automatic system would not have a built-in safeguard against a system error which might be generating erroneous information and yet seemingly be functioning as designed.

Further, the automatic plotter, since it would be rather large in order to use existing charts, would also be very susceptible to damage by bumping, rough handling, or tampering. Finally, the cost of the plotter was found to be significant, particularly since it would have had to be designed specifically for this purpose and could not be bought "off the shelf". Further comment about the automatic plotter will be made later in this thesis.

The use of a micro-computer for processing of navigational information remained. The specific design characteristics of this computer comprise a major part of this proposal. This leads to the next major consideration, that of cost. Much press and intraprofessional discussion has been witnessed concerning the limited funds available for military expenditure. While a very fine system would doubtless result from a ground-up design of the system, costs would no escalate considerably. Hence, every effort was made to minimize costs and yet maintain reliability, repairability, and flexibility. Requiring special charts for the system would cause tremendous upheaval in the Oceanographic Office. Costly, complex equipment would mean that special training in the repair of the equipment would be necessary since the ship would not be likely to be able to afford a back-up system. Installation of the system can be effected by existing shipboard personnel. Personnel can be trained to use the system with little expenditure of time or funds, and this training could be designed to be conducted onboard. Other than the computer and remote display devices, no other equipment is needed nor is there a necessity for modification of any existing equipment onboard.

The computer and its associated display devices was designed to process input navigational information and to display, in real time and without human interaction except for input, navigational information as to ship's position, course and speed made good, range and time to turn or other maneuver, set and drift, recommended correcting and compensating course, error in crossing points of LOP's, proximity of nearest navigational hazard, comparability of the fix obtained visually with that obtained by the CIC, and other information as may be designated by the navigator. So as not to be "Hard-wired" into accepting the program of some shore-based designer, the system should have several program options and this progamming should be easily done by personnel who have minimal training in computer science. A keyboard programmable unit was felt to be ideal.

Repairability must be routine and rapidly accomplishable. By maintaining low cost, it was felt feasible to completely replace any unit in the system with an onboard spare. The faulty piece of gear could then be turned in to a repair facility should the repair be beyond the capability of onboard personnel.

The display devices (there are several options as discussed later) must be readable under any lighting conditions and from oblique angles. The devices must be insensitive to changes in temperature, rain, salt, and any other of the arduous conditions associated with a shipboard environment. Several display devices are necessary so that the navigational information is available wherever the conning officer is likely to be while performing his duties.

In summary, the system should have built-in redundancy. It should provide all normally deisred navigational information when provided with the same information as is currently used in manual plotting. The check on system performance will be accomplished by the manually m aintained plot. This plot, however, will not delay the dissemination of navigational information nor in any way consume the navigator's time, since all that it will provide is a confirmation of the information generated by the computer. The navigator will only examine the manually generated plot in order to determine whether or not its agrees within acceptable tolerance with the computer-generated information. The system must be small, easy to install, easy to operate, require no additional personnel for operation or maintainance. It must be rugged, amply protected from the elements, and "Sailor-proof." The display devices must be low-cost as there will be several, easily installed, readable under any conditions, and easily replaced in the event of failure. Finally, the system must be self-sufficient. No changes or additions to peripheral equipment should be required. The system must "sneak in and take over" and should be designed in such a manner that it will be enthusiastically received rather than being viewed with apprehension.

II. PROCEDURE

The procedure which was used in arriving at a specific design for the system was determined primarily by studying the information required by the navigational situations which were likely to be encountered and by the mathematical methods for providing a solution. The microcomputer must be able to process a minimum number of inputs into the navigational information desired in an expeditious manner. It must then display the results of the calculations made to the various display devices. There must also be sufficient flexibility in the computer capabilities to provide for possible changes in the program in the event that future requirements may change or if it is found that there is a better way to compute the desired information.

Before selecting a specific computer design for the system, it was felt to be paramount that the type of calculations to be made should be known. Thus, a mathematical method for computing the information to be obtained was developed. In developing this mathematical algorithm, regard was given to maintaining mathematical simplicity so that operator understanding would be assured. The number of inputs to the computer must be as small as possible for simplicity sake and in an effort to minimize sources for error. The output must be given in a manner which is readable and understandable to a person who may know nothing about computers or computer language. Communication with the computer should be in the language of the man and not of the machine.

After developing, testing, and refining the algorithm, the next step was the selection of the type of computer which would be used. Several companies were contacted and their proposals were examined prior to making the final recommendations for the system. The quality of the equipment, its ability to perform the required functions quickly and reliably, adaptability of the computer for use in other applications aboard ship, ease of programming, repairability, sensitivity to the shipboard environment, ease of interfacing with display devices, simplicity of operation, compactness, and lowest possible cost were some of the factors which came into play in the selection procedure.

Next the display devices were studied. First, the most desirable type of display device had to be chosen. The display device must be readable from a variety of viewing angles. It must be insensitive to the harsh environmental conditions to which it will be subjected. It must be readable in a variety of lighting conditions, varying from darkness to bright sunlight. Installation should be quick and easy and must be readily accomplishable by shipboard personnel. The display device must be easily replacable in the event of failure, and since there are several, it must be of low cost.

Finally, future changes to the system had to be anticipated. It was felt that an automatic plotter should not be included. However, it is possible that the addition of one might later prove to be desirable. Thus, the system must be designed in such a manner that one could be added without major modification to the system as it has been proposed. Modifications to the program had to be accomplishable by shipboard personnel. There should be sufficient computer memory to handle any additional computing tasks which may be found to be necessary to perform with this computer. It certainly was desirable that extra memory could be added externally in the event that the computer might be used for celestial or electronic navigation in the future. The system had to be one which would be immediately useful and which could be later modified to the level of sophistication which might be desired.

A. THE MATHEMATICS OF THE PROBLEM

A variety of information must be calculated from the bearings provided by the bearing takers during a navigational exercise. Mathematical methods for computing the relationship of the ship's position to the proposed track, range and time to turn, proximity of the nearest navigational hazard, course and speed made good, and set and drift information. The navigator may also wish to display information concerning the type of navigational hazard at hand, any recommended course changes, what the next course will be, the turn bearing for a maneuver, concurrence of non-concurrence with the manual plot and/or the plot in CIC, or virtually any other bit of information which he feels the conning officer might need. Some of this information is calculable, while the rest is from observation, intuition, or some other non-mathematical source. This section deals with the formulation of a method which could be used to calculate the information needed during a piloting exercise.

Triangulation provides a means to determine the present position of the ship in a mathematically simple and accurate manner. The known factors in the problem are the positions of the objects which are being "shot", and the true bearing of these objects from the ship. It is relatively simple to determine the unknown ship's position from this information since straight-forward calculations provide two angles and the included side of the triangle formed by two objects and the ship. Figure 1 shows a geometric representation of the type of transit typically encountered in a piloting exercise. Note the labeling of the points to which bearing lines will be taken, the proposed track, the turn points, the navigational hazards which must be avoided, and the slide line which is used for determining the turning point.

Figure 2 shows the triangulation problem which must be solved in order to determine the current position of the ship using just two of the points which are being shot. The exact positions of points A and B are known. From their positions, it is a simple matter to determine the distance

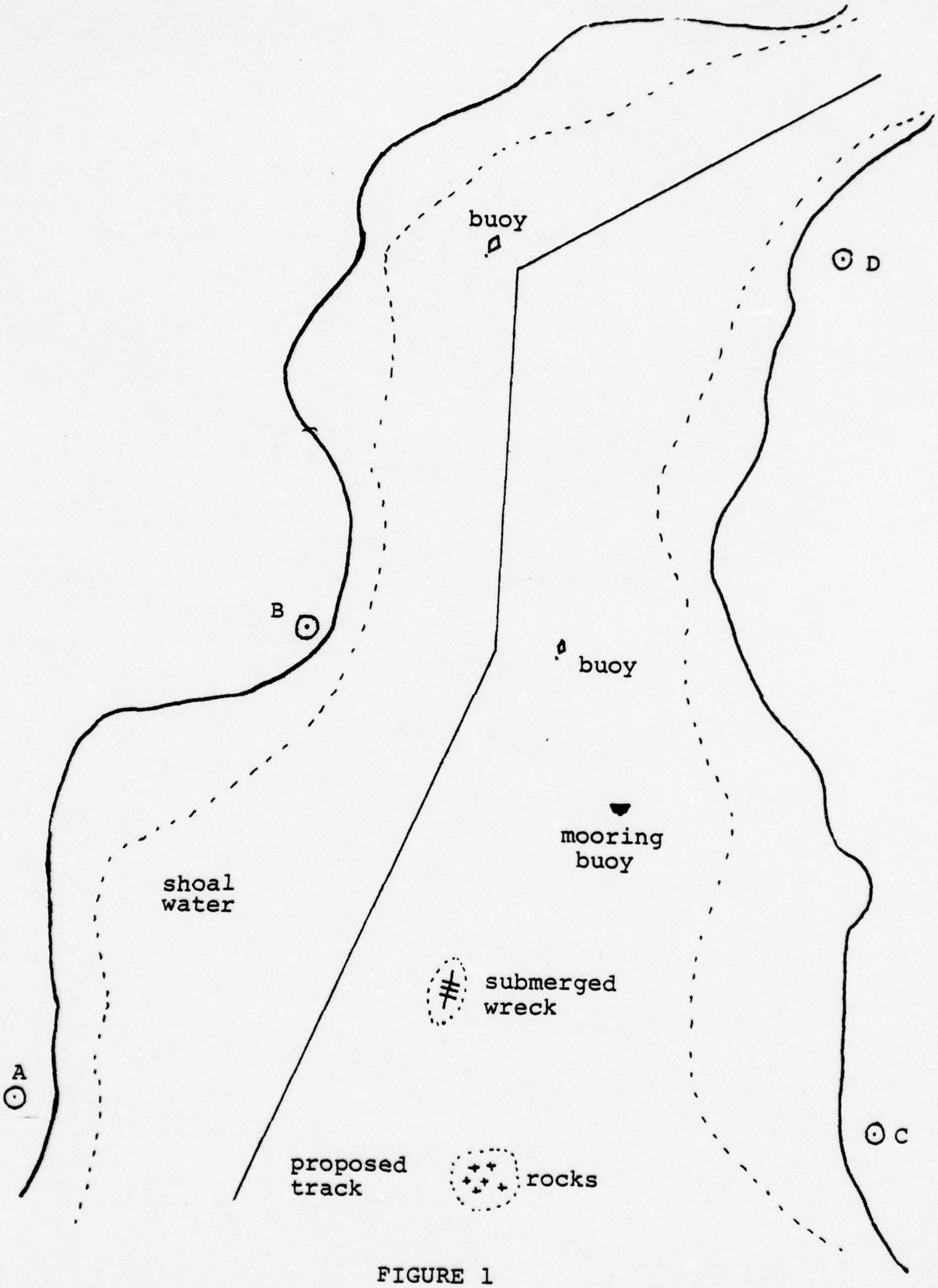

buoy
D
B
buoy
mooring buoy
shoal water
submerged wreck
A
C
proposed track
rocks

FIGURE 1

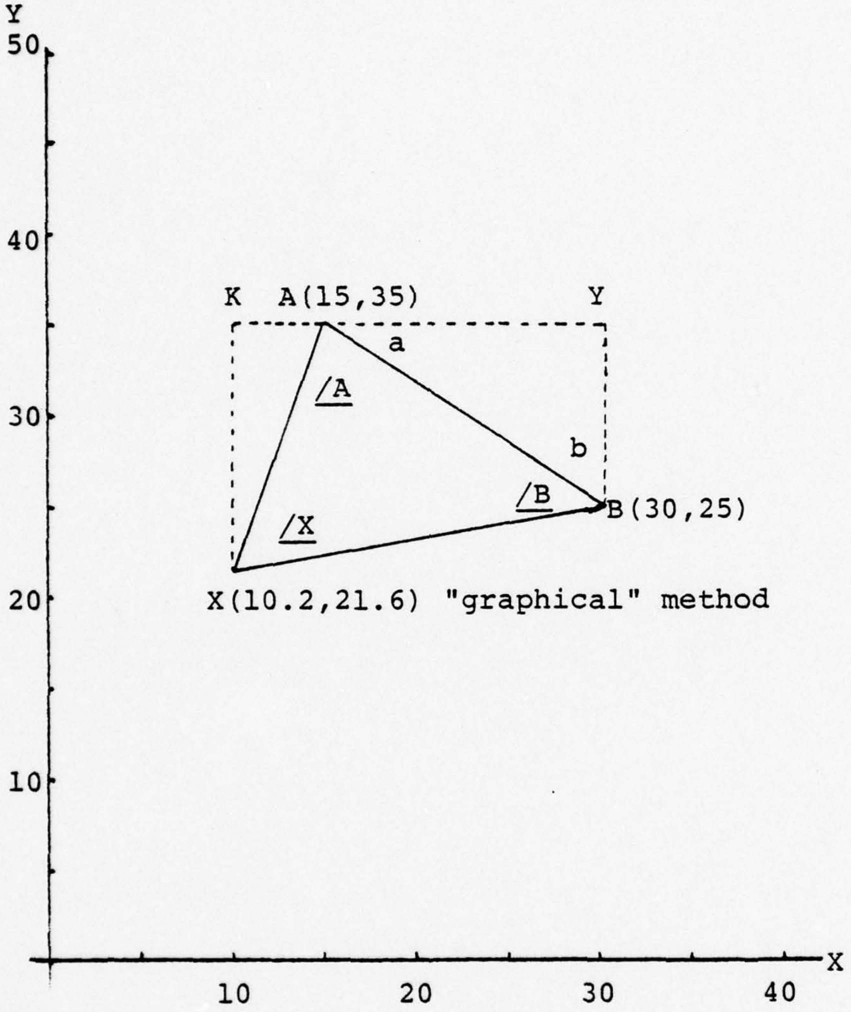

Y
50
40
30
20
10
K
A(15,35)
Y
a
/A
b
/B
B(30,25)
/X
X(10.2,21.6) "graphical" method
X
10
20
30
40

FIGURE 2

between these points, and hence one side of the triangle is known. From the true bearings to these points, the angles at points A and B on this triangle can be determined. Once these angles are known, the angle at the fix point, X, is known. Now that all three angles and a side are known, by application of the appropriate mathematical formulae, the unknown sides $\overline{AX}$ and $\overline{BX}$ can be found. Finally, by applying further formulae, the position of point X is determined.

The formulae which are necessary and the method of calculating ship's position can be best demonstrated by solving for ship's position as indicated in figure 2. In this example, the bearing takers have reported the following bearings to points A and B:

Bearing to point A 020 deg True
Bearing to point B 080 deg True

The exact geographic position of points A and B can be found in latitude and longitude from the chart. The computer could be programmed to operate in this coordinate system, but for reasons which are given later, it was felt that the use of simple X-Y coordinates were more desirable. Using a template, the navigator determined that the coordinates of point A were (15,35) and those of point B were (30,25).

Graphically, the information provided thus far describes a triangle as shown in figure 2. Point X is the ship's position determined graphically by plotting. In order to arrive at a computer solution to this triangle, the angles A, B, and X must be determined, as well as the length of side $\overline{AB}$. From the coordinates of points A and B, the angle made by side $\overline{AB}$ relative to true north can be readily determined. The triangle ABY as shown in figure 2 is used for this purpose. The cosine of angle a is

$$\cos a = \frac{(x_B - x_A)}{\overline{AB}}$$

thus

$$a = \cos^{-1} \left[\frac{(x_B - x_A)}{\overline{AB}}\right]$$

and

$$b = 90° - a$$

here

$$a = \cos^{-1} \left[\frac{30 - 15}{\overline{AB}}\right]$$

$$\overline{AB} = [(x_B - x_A)^2 + (y_B - y_A)^2]^{1/2}$$

$$= [(30 - 15)^2 + (25 - 35)^2]^{1/2}$$

$$= 18.03$$

Thus

$$a = \cos^{-1}\left[\frac{15}{18.03}\right]$$

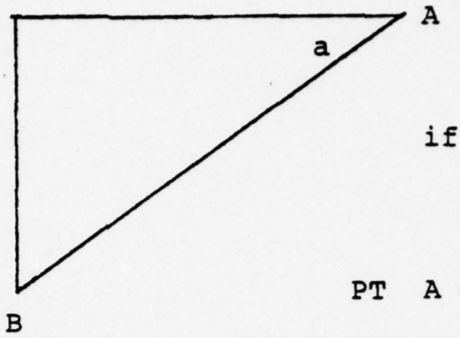
$$a = 33.69°$$

and

$$b = 90° - 33.69° = 56.31°$$

In general, if the x-coordinate, x_A is less than x_B and y_B is greater than y_A, the angle of $\overline{AB}$ relative to true north is simply the angle a. If, however, x_A is less than x_B and y_B is less than y_A as is the case in this example, the angle of $\overline{AB}$ relative to true north if 90° + a, or 123.69° for this case. The angle of $\overline{AB}$ relative to true north at the respective vertices of the triangle will be called the point angle at that point, here point angle A or PT ANG B. Thus, in this example, point angle A is 123.69°, and PT ANG B is 180° + PT ANG A, or 303.69°. The other two possible orientations of points A and B are shown in figure 3 along with the formulae necessary for determining the respective point angles.

Now triangle ABX can be solved. First, the angle at A must be determined. The bearing takers have given the angle of point A from the ship as 020° T. Clearly, then, the ship is at an angle of 180° + 020° or 200° T from point A.

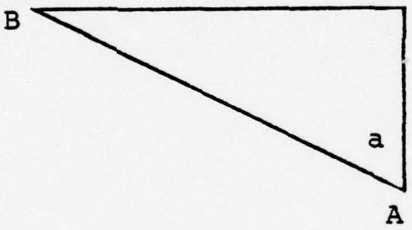


if $x_A > x_B$

and $y_A > y_B$,

PT A = 270°-a

PT B = 90°-a



if $x_A > x_B$

and $y_A < y_B$

PT A = 360°-a

PT B = 180°-a

FIGURE 3

The angle at A is thus:

$$180° + TB_A - PT\ ANG\ A$$

where TB_A is the true bearing to point A. In a similar manner, the angle at B is determined. Here,

$$B = |180° + TBA - PT\ ANG\ B|$$

If the result of this calculation is greater than 180°, then subtract 360° and take the absolute value of this result and this is the angle at B. If the result of the above calculation was less than 180°, then this is the angle at B.

In the general case, the calculation as described here for the angle at B is done for all cases. Thus, in the example of figure 2, using the general method to solve, the angle at A is given by:

$$A = |180 + TB_A - PT\ ANG\ A|$$

$$= 76.31°$$

which is less than 180°.

$$B = |180 + TB_B - PT\ ANG\ A|$$

$$= 43.69°$$

It should be noted that PT ANG A is the only one of the point angles used here, since PT ANG B is determined from this point angle and thus the calculation of the angle at B can include this determination. That is,

$$\text{PT ANG B} = 180° + \text{PT ANG A}$$

$$\begin{aligned} B &= \text{PT ANG B} - TB_B \\ &= 180° + |\text{PT ANG A} - TB_B| \\ &= 180° + |TB_B - \text{PT ANG A}| \\ &= |180° + TB_B - \text{PT ANG A}| \end{aligned}$$

Now, angles A and B and side $\overline{AB}$ are known, and from this sides $\overline{AX}$ and $\overline{BX}$ can be found as well as the angle at X.

$$X = 180° - A - B \approx 180 - 76.31 - 43.69 = 60.00°$$

From any table of mathematical formulae, it is found that given two angles and the included side, here angles A and B and side $\overline{AB}$,

$$\overline{AX} = \frac{\overline{AB} \sin B}{\sin X}$$

$$\overline{BX} = \frac{\overline{AB} \sin A}{\sin X}$$

Thus,

$$\overline{AX} = \frac{18.03 \sin 43.69°}{\sin 60.00°} = 14.38 \text{ units}$$

$$\overline{BX} = \frac{18.03 \sin 76.31°}{\sin 60.00°} = 20.23 \text{ units}$$

All that remains now is to find the coordinates of point X. It can be seen that in figure 2, triangle AKX, we know side $\overline{AX}$ and the angle at A.

$$\text{angle at X} = TB_A$$

$$\overline{AK} = x_A - x_X = \overline{AX} \sin TB_A$$

$$x_X = x_A - \overline{AX} \sin TB_A$$

and

$$y_A - y_X = \overline{AX} \cos TB_A$$

$$y_X = y_A - \overline{AX} \cos TB_A$$

For this example,

$$x_X = 10.08$$

$$y_X = 21.49$$

This final calculation completes the problem of solving for ship's position. Again, the orientation of the points A, B, and X above can vary, but it should be clear that computer branching with appropriate mathematical variation to the above method will produce the desired result. One distinct advantage of using this mathematical method for computing ship's position is the minimization of error it provides relative to manual plotting. The only inputs to the computer were the bearings obtained by the bearing takers and the grid positions of the points A and B. With careful reading of the grid the latter will be negligible. The bearing error from the bearing takers exists no matter what system is used and can be minimized to some extent by practice. Of the two sources for error in this system, the bearing taker error is certianly dominant.

Manual plotting, on the other hand, not only has the bearing error to contend with, but also other human-generated problems. The plotter is often quite rushed and as such the setting of the plotting protractor (called the parallel motion protractor or PMP) is hurried and frequently not precise. Also, there is often some wobble in the arm which by itself can cause error in spite of the care exerted by the plotter. The plotting error is most significant when the crossing angles of the LOP's is either very small or very large. In plotting, care must be taken to avoid these angles, but in some cases this is not possible. Much of the ambiguity which is apparent when using several LOP's rather than just two results from these small or large angles.

To illustrate the magnitude of this potential error, consider a crossing angle of 10°. Using this angle as one angle in a right triangle as shown in figure 4, line $\overline{AC}$ is 10° from the horizontal, while line $\overline{AC'}$ is 10.5° from the horizontal, representing a 1/2 degree error in setting the PMP arm. If $\overline{AB}$ is 4 units long and angle C is 10°, then

$$\overline{AB} = \overline{AC} \sin C$$

$$\overline{AC} = \frac{\overline{AB}}{\sin C} = \frac{4}{\sin 10°} = 23.04 \text{ units}$$

Thus,

$$\overline{BC} = (\overline{AC}^2 - \overline{AB}^2)^{1/2} = (23.04^2 - 4^2)^{1/2}$$

$$= 22.69 \text{ units}$$

Now, if C' = 10.5°

$$\overline{AB} = \overline{AC'} \sin C'$$

$$\overline{AC'} = \frac{\overline{AB}}{\sin C'} = \frac{4}{\sin 10.5°}$$

$$= 21.95 \text{ units}$$

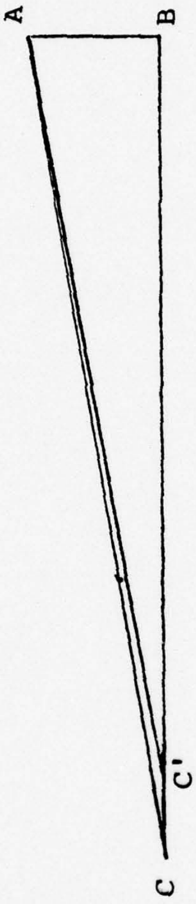


FIGURE 4

and

$$\overline{BC}' = (\overline{AC}'^2 - \overline{AB}^2) = (21.95^2 - 4^2)^{1/2}$$

$$= 21.58 \text{ units}$$

This is an error of 1.11 units. Clearly, if $\overline{AB}$ is longer, the error is even greater. In fact, the error increases in direct proportion to increases in length of $\overline{AB}$. Commonly, in plotting, lines are drawn which are 1 or 2 feet in length. A chart scale of 400 yards per inch, which is not a small scale in plotting, can result in large errors if the lines are of average length. For example, if $\overline{AB}$ is 2 inches long, and thus $\overline{AC}$ is 11.52 inches long, the potential error would be 0.56 inches or some 220 yards! In a piloting situation, a 25 yard accuracy is considered to be paramount. Additionally, when several LOP's are being used, such a large error most probably would cause widely separated crossing points and thus considerable doubt would exist as to the correct ship's position. The graphical error inherent in manual plotting is eliminated by the system proposed here and a strong argument for improved navigational safety can be presented to the prospective user.

Next, a method for determining the position of the ship relative to ship's proposed track was developed. Since the planned movement of the ship through the restricted waters was discussed prior to the maneuver, this information, expressed as distance either right or left of track, gives the conning officer a mental image of how much good water is available in the direction he may be contemplating taking.

If the track is expressed as an equation of a straight line of the form

$$Ax + By + C = 0$$

the mathematical tables may once again be consulted to provide a means if finding the distance from the fix point obtained to the line formed by the ship's track. It was found that the distance from a point to a line is given by

$$\frac{Ax + By + C}{\pm(A^2 + B^2)^{1/2}}$$

where A, B, and C are the values of the constants in the equation of the straight line given previously and x and y are the coordinates of the fix point P(x,y).

$- \frac{A}{B}$ = slope = m of track line

$a = -\frac{C}{A}$ the x-intercept

$b = -\frac{C}{B}$ the y-intercept

Thus, when laying out the proposed track, if the navigator enters the x-y coordinates of the various turn points, the computer will generate the equation of the line for use in the formula above.

The equation of the track line can be found if either intercept is known and the slope is known. If in figure 5, the navigator enters the points I and II, (16,8) and (41,30) respectively, the slope is then found from

$$m = \frac{\Delta y}{\Delta x} = \frac{22}{25} = 0.88$$

The intercept of the x-axis is seen to be at $x \cong 7.2$. Mathematically, the y-intercept is found to be

$$\text{y-intercept} = b = y - mx$$

here, using I as a reference point

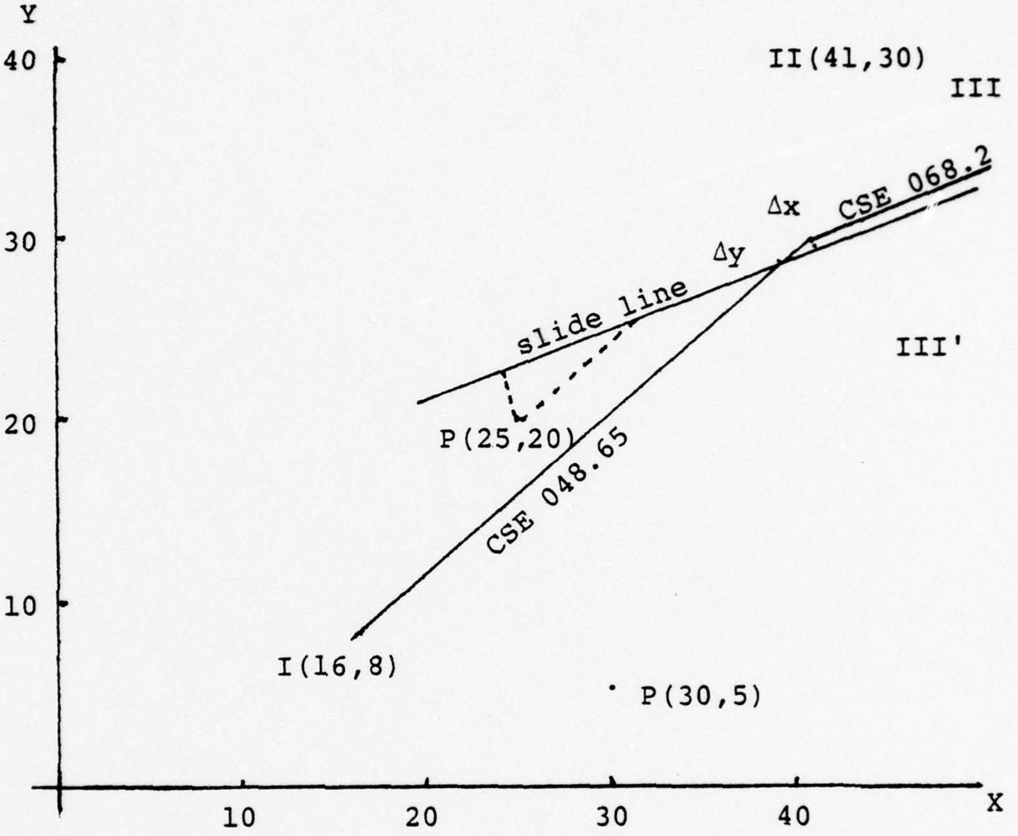
$$b = 8 - 0.88(16)$$

$$b = -6.08$$

The x-intercept is at $y = 0$, or

$$0 = 0.88x - 6.08$$

$$x = \frac{6.08}{0.88} = 6.91$$



Y
40
30
20
10
II(41,30)
III
CSE 068.2
Δx
Δy
slide line
III'
P(25,20)
CSE 048.65
I(16,8)
P(30,5)
10
20
30
40
X

FIGURE 5

Now the slope is known as well as the x and y intercepts. Converting the slope-intercept form of the equation of a straight lint into the form $Ax + By + C = 0$,

$$y = mx + b$$

$$y - mx - b = 0$$

and thus

$$A = -m, \quad B = 1, \quad C = -b$$

For this example,

$$A = -0.88$$

$$B = 1$$

$$C = 6.08$$

therefore,

$$-0.88x + y + 6.08 = 0$$

To find the distance from point P(25,20) to the track previously defined,

$$\text{distance} = \frac{-0.88(25) + 1(20) + 6.08}{\pm\ \overline{(-0.88)^2 + 1^2}}$$

$$= 3.06 \text{ units}$$

To further demonstrate, let the P be P(30,5). Then,

$$\text{distance} = \frac{-0.88(20) + 1(5) + 6.08}{\overline{(-0.88)^2 + 1^2}}$$

$$= -11.5 \text{ units}$$

It is noted that the algebraic sign of the distance can be either (+) or (-). If the sign is (-), the ship is below proposed track. In this case, this means right of track for left to right motion on the chart. The (+) sign indicates that the ship is left of track.

Next, a method for finding the range to turn was determined. The same formula which was used to find the distance right or left of track is used in the process of finding the range to turn. Again referring to figure 5, the navigator has predetermined the track he wishes the ship to follow. In this example, the ship will proceed along a track on course 048.65° initially, and then will change course to 068.2°. In order to account for advance and transfer of the ship during a turn, advance and transfer tables may be consulted. From these tables, a "slide line" is developed which is based on the ship's characteristics at the speed of advance and the magnitude of the turn, as well as the direction of the turn. Most navigators eventually develop a "feeling" for the slide line distance necessary in a given maneuver but, strictly speaking, this distance is determined by using the more cumbersome and time-consuming method of advance and transfer calculations. The computer can be programmed to compute the slide line distance. See figure 6 for a pictorial representation of the advance and transfer problem.

Returning to the example, the slide line changes the coordinates of point I by two units in the opposite direction of the current track. By knowing the course of the track, the x-y coordinates of point P' can be found by

$$\Delta x = R \cos(90 - \text{cse})$$

$$\Delta y = R \sin(90 - \text{cse})$$

Here the course is 048.65°. Therefore,

$$\Delta x = 2 \cos(041.35) = 1.50$$

$$\Delta y = 2 \sin(041.35) = 1.32$$

Thus, point II' is (41 - 1.5,30-1.32) = (39.5,28.68). In order to find the equation for the slide line, the point III must also be redefined at III'. In this case, however, only

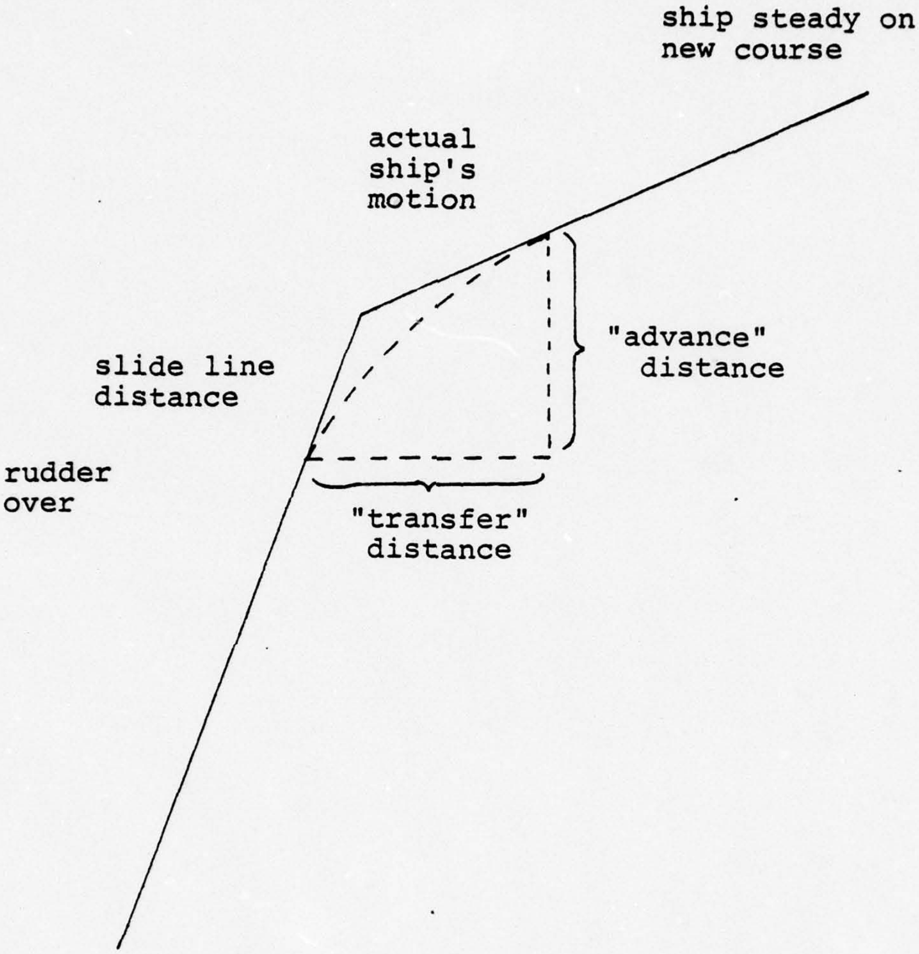

ship steady on new course
actual ship's motion
slide line distance
rudder over
"advance" distance
"transfer" distance

FIGURE 6

the y-coordinate need be changed, since the choice of this point is somewhat arbitrary and is only being used here to determine the equation of the slide line. Here, the geometry of the problem yields

$$2 \sin(19.55) = R' \cos(19.55)$$

where 19.55° is the difference angle made at the turn (068.2 - 048.65). Therefore,

$$R' = \frac{2 \sin 19.55°}{\cos 19.55°} = 0.71$$

and thus point III' is (46,32 - 0.71) = (46, 31.29). Next, the equation of the slide line is found.

$$y = mx + b$$

$$m = \frac{31.29 - 28.68}{46 - 39.5} = 0.40$$

and, at II',

$$28.68 = 0.40(39.5) + b$$

$$b = 12.82 \quad \text{the y-intercept}$$

Thus, the equation of the slide line is

$$y = 0.40x + 12.82$$

$$-0.40x + y - 12.82 = 0$$

Here, this equation is of the form necessary for finding the distance from a point to a straight line.

$$A = -0.40, \quad B = 1, \quad C = -12.82$$

Using point P(25,20), the distance to the sline line can be found as

$$\text{distance} = \frac{-0.40(25) + 20 - 12.82}{\sqrt{0.4^2 + 1^2}}$$

$$= 2.62 \text{ units}$$

Clearly, this is not yet the range to turn. It is only the distance of a perpendicular line to the extension of the slide line nearest the point. Once again, by the geometry of the situation, the range to turn can be found by finding the distance R indicated in figure 5.

$$R = \text{range to turn} = \frac{2.62}{\sin 19.55°} = 7.83 \text{ units}$$

Once again, it should be noted that plotting errors are avoided and increased accuracy of range to turn data should be realized.

A similar problem in finding range exists for the determination of the range to the nearest hazard to navigation. A complicated problem is eveident if the navigator wishes to find the distance to shoal water as this hazard usually follows a curve which would be virtually impossible to define by equation. Figure 7 shows a typical example of the type of hazards present in a harbor. It is suggested that the navigator designate the hazards by straight line approximations to them as shown in figure 7 and enter the end points into the computer memory prior to the exercise. The hazards would further be designated by labels, such as H_1, H_2, etc. During the exercise, the navigator would designate the hazard for which he wishes the data generated, and as the ship transits, he would change to the other hazards as they become of concern to the ship. While it is possible to program the computer to make this selection process, the large number of hazrds which are typically present would require that considerable branching take place in order to report only those distances which are of importance at the time. More specifically, the hazards as shown in figure 7 can be represented by a piecewise continuout plot as indicated. However, this requires that the end points be the limit on each portion of the hazard. Given the equation of a line, there is no way for the computer

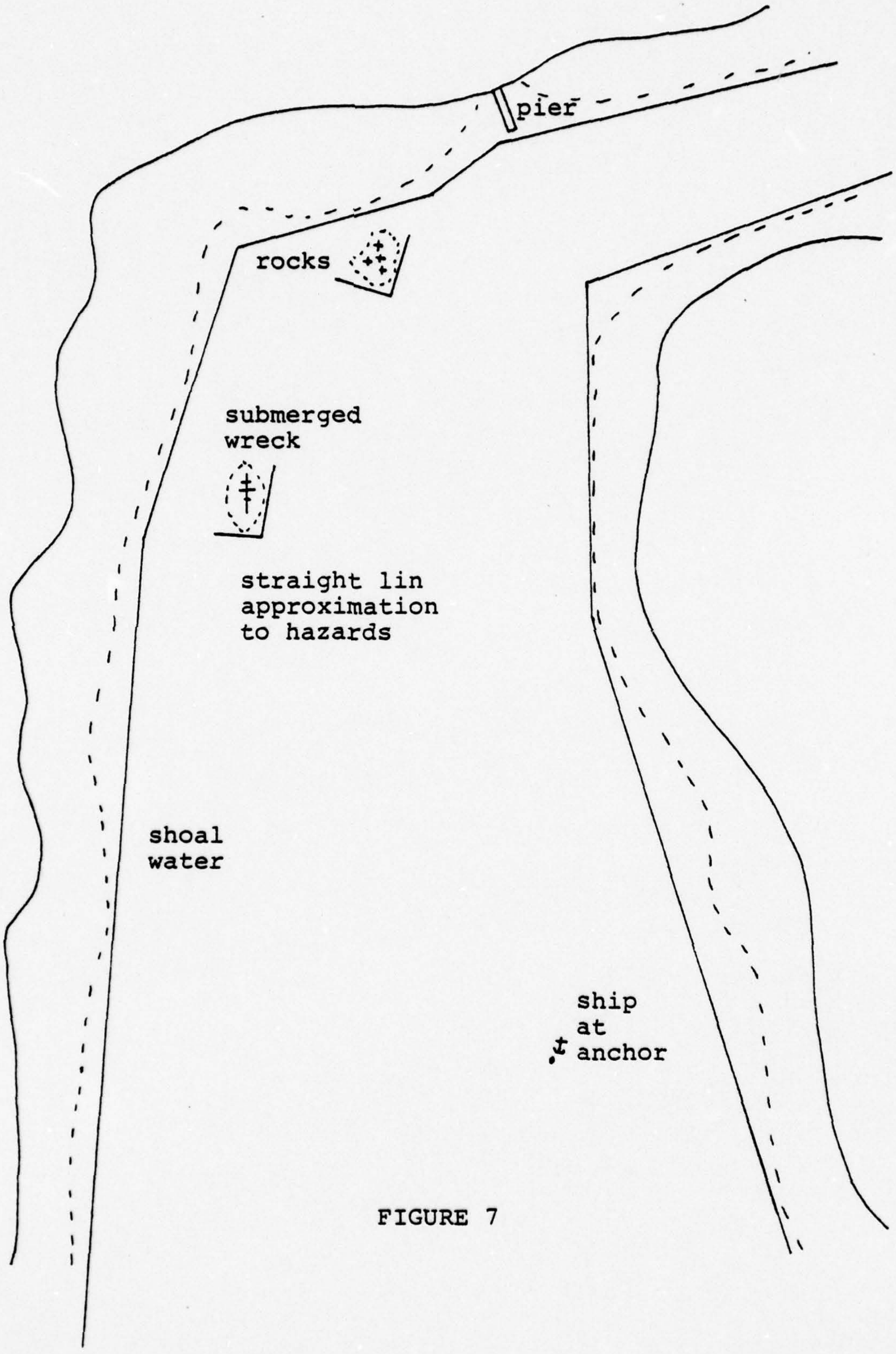

pier
rocks
submerged
wreck
straight lin
approximation
to hazards
shoal
water
ship
at
anchor

FIGURE 7

to know whether a point on that infinitely long line is contained on one which is limited by the end points specified in establishing the shoal water without testing the point of intersection of the perpendicular line to the shoal water line in question. For each fix, data would be generated as to the distance to the line representing the shaol water, regardless of whether or not the line exists as defined by the piecewise continuous nature of the shoal water plot at the point of intersection with the perpendicular drawn from the fix point to the line. Then, the existence of this point would be tested. If the test fails, this distance is not reported or stored. If, however, the point does exist, then the distance value must be stored and the next line is then processed in the same manner, and so on until all of the portions of the hazard lines have been similarly processed. Finally, the stored values would be compared, and the computer would report the smallest value found and the nature of the hazard and its relative location with respect to the ship. This is a very time consuming procedure and, it is felt, an unnecessary one.

Using a method where the navigator designates the hazards as the ship transits would not require more than a few seconds time from the navigator for each change, and doing so would also force the navigator and his team to continually monitor the progress of the ship through the myriad of hazards which exist along the track. Also, some tactical situation may dictate that the range to a hazard which is not necessarily the closest one at the time should be reported. This could be readily accomplished by only entering the hazard designator for this one area. Finally, keeping the man involved while letting the machine tend to the routine is felt to be desirable for safety sake, and also for the sake of gaining the acceptance of this system by the users.

Another requirement at each fix is to report the course and speed made good. This is a simple calculation, since all that needs be done is to store a predetermined number of fixes and then generate the equation of the best straight line through these points. The method which is proposed for use is the method of least squares. The equation to be determined should be of the form

$$y = mx + b$$

Given a set of points (x_i, y_i), where $i = 1,2,\ldots,n$, the stored values are then processed by the following formulae:

$$m = \frac{[\Sigma xy - \frac{\Sigma x \Sigma y}{n}]}{\Sigma x^2 - \frac{(\Sigma x)^2}{n}}$$

$$b = \overline{y} - m\overline{x}$$

where

$$\bar{y} = \frac{\Sigma y}{n}$$

and

$$\bar{x} = \frac{\Sigma x}{n}$$

Further, the coefficient of determination can be found, which is a number between 0 and 1 which indicates how closely the equation fits the experimental data: the closer the coefficient of determination is to 1, the better the fit. To find the coefficient of determination, r^2,

$$r^2 = \frac{[\Sigma xy - \frac{\Sigma x \Sigma y}{n}]^2}{[\Sigma x^2 - \frac{(\Sigma x)^2}{n}][\Sigma y^2 - \frac{(\Sigma y)^2}{n}]}$$

The navigator can choose how many points he wishes to be used, since there are times when very small course changes are made of the order of a degree or two during a transit and he may wish to use only a few points once and a larger number later. Once a number designating the number of points to be used is entered, the computer will generate a course and speed made good from the fixes obtained most recently which correspond to that number of points. To do this given that the computer has calculated the equation of the line as indicated above, the next step is to find the angle relative to true north which is made by this line. This can be accomplished by using the value of the slope, m, and taking the inverse tangent of this value. In order to eliminate the ambiguity which exists between the angles contained in the first and third quadrants and the second and fourth quadrants, appropriate branching should be implemented to determine the proper course direction.

The speed made good can be readily determined by simply calculating the distance traveled between the earliest and latest points used to determine the course made good and dividing by the time. Then this distance would be converted to knots and the solution is completed.

Another problem which must be solved is the determination of the set and drift information. Set and drift is given as a direction (in true coordinates) and a speed. It indicates the resultant effect of outside factors such as wind, current, swells, etc., and how these factors are affecting the intended motion of the ship.

For example, assume that the ship is to proceed on a course of 045° T at a speed of 12 knots. After a three minute period, it is found that the ship has, in fact, made a course of 042° T and a speed of 10.5 knots. A pictorial representation is shown in figure 8.

The set and drift is simply the vector which connects the intended position with the actual position attained. Here it is a vector in the direction 249° T with a velocity of 1.5 knots. Typically, the navigator will attempt to

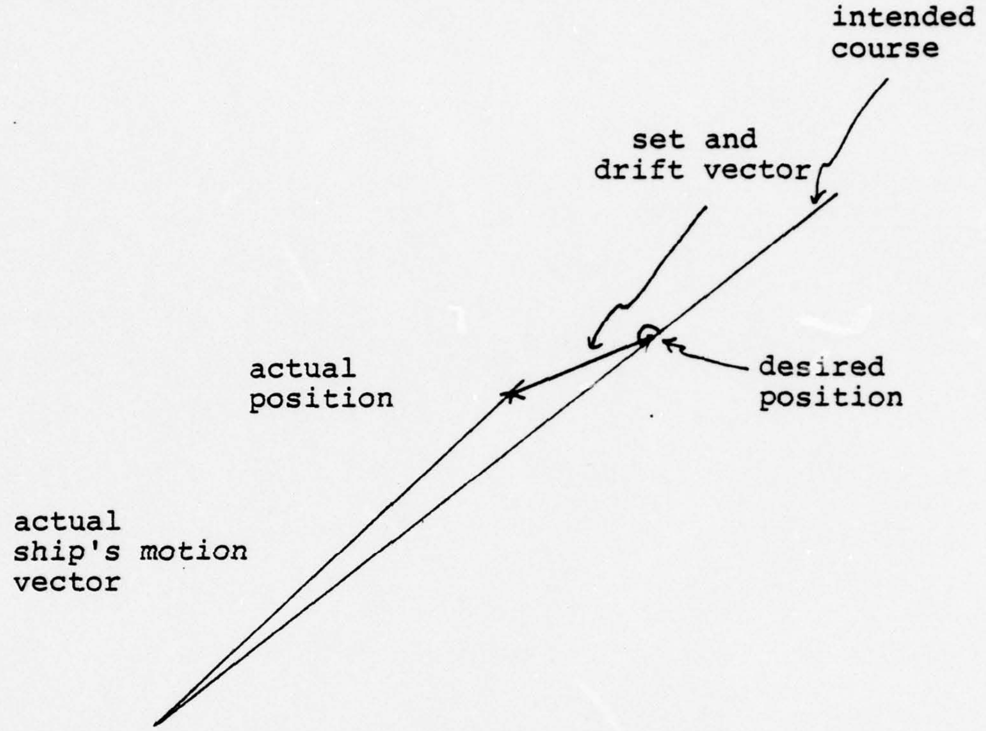
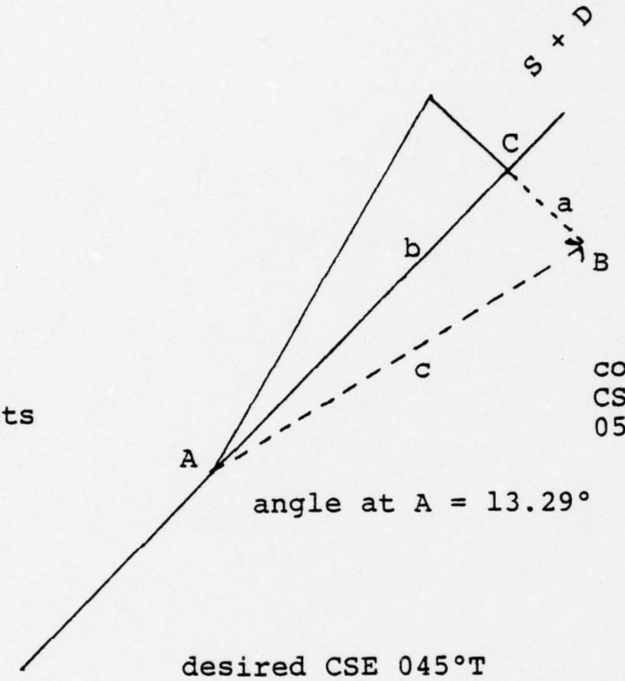

intended course
set and drift vector
actual position
desired position
actual ship's motion vector

FIGURE 8

compensate for this set and drift by steering a compensating course and speed. In some cases, where adherence to the proposed track is necessary, he will also first take a correcting course, followed by the compensating course once the correcting course has brought the ship back to the proposed track. Clearly, any course which will ultimately bring the ship back to the proposed track may be termed a correcting course. Normally, the navigator chooses a time interval within which he wishes to regain the track and sets his course accordingly.

Selecting these various courses is simply a matter of vector algebra. Given the two fixed quantities, here the known set and drift and the desired course and speed, the third quantity can easily be found graphically. To demonstrate a mathematical method which may be used. Consider another example where the angles are larger than in figure 8. Assume, as shown in figure 9, that the desired course and speed is as before, 045°T at 12 knots. The set and drift was found to be 305°T at 3 knots. Graphically, the compensating course was found to be 058°T at 13 knots. Mathematically, this course and speed may be found by triangulation. Using relative bearings, it is clear that the angle made between the desired course line and the set and drift is

$$045° + (360° - 305°) = 100°$$



actual
ship's
motion
031°T, 12.5 kts

compensating
CSE/SPD
058°T, 13 kts

angle at A = 13.29°

desired CSE 045°T
SPD 12 kts

FIGURE 9

We now know two sides and the included angle. Then, by the law of cosines,

$$c^2 = a^2 + b^2 - 2ab \cos C$$

and, here,

$$c^2 = 3^2 + 12^2 - 2(3)(12) \cos 100°$$

$$c = 12.86 = \text{compensating speed in knots}$$

further,

$$a^2 = b^2 + c^2 - 2bc(\cos A)$$

$$A = \cos^{-1} \frac{b^2 + c^2 - a^2}{2bc}$$

$$A = 13.29°$$

and

$$A + \text{desired cse} = \text{compensating cse}$$

$$= 058.29°\text{T}$$

For general use, the algorithm would be

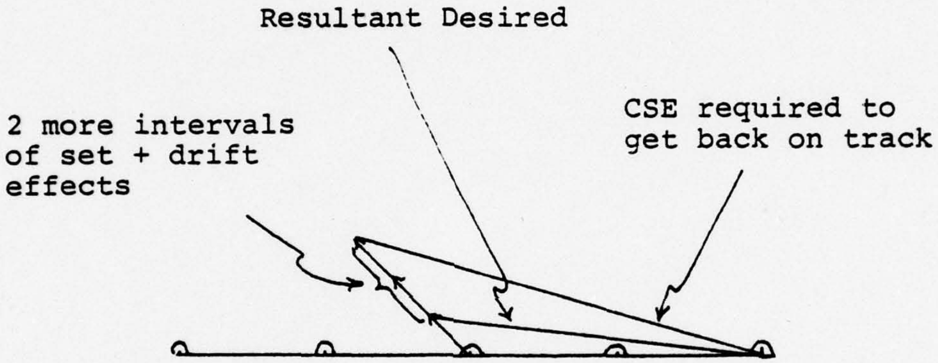
$$|(\text{set direction}) - (\text{desired cse})| = C$$

$$\text{if } 0 > 180^\circ\text{, then use}$$

$$360^\circ - (\text{set direction}) + (\text{desired cse}) = C$$

where C is the angle C shown in figure 9. Then, compute the set and drift as was done in the preceding example.

In order to derive a correcting course one must deal with distances, since this course will depend upon the time interval allowed for getting back on track. This problem can be avoided by using a method involving similar triangles. It is desired that the ship proceed on a course and speed that will bring the ship back on track in, say, six minutes. From the current position point a line is drawn indicating the resultant direction desired. Since, over a six minute interval, the set and drift will affect the ship twice, we then draw in a vector in the same direction as the set but at twice the magnitude. This is illustrated in figure 10. The unknown vector will yield the correcting course to be steered. The correcting velocity is simply half the magnitude of this vector. For example, assume the desired course and speed is 090°T at 5 knots. The set and drift was found to be 315°T at 3 knots. This problem is illustrated in figure 10. Graphical solution of thsi problem yields that the co-recting course is 111°T at a speed of 8.7 knots, in order to get back of track in six minutes. It is normally only desired that the ship get back on the track line, but



Desired CSE/SPD
is 090°T, 5 kts

Correcting CSE/SPD
is 111°T, 8.7 kts

FIGURE 10

not necessarily at the precise point on the track as determined by the pre-transit planning. In such a case, the resultant direction and velocity are not known. Instead, the velocity of the set and drift and the correcting velocity are known. This situation is illustrated in figure 11. Mathematically,

$$A = 90 - A'$$

thus

$$A' = 90 - A$$

$$\cos(90-A) = \frac{a'}{b}$$

and

$$90 - A = \cos^{-1}(a'/b)$$

$$A = \cos^{-1}(a'/b)$$

The other parameters in the triangle are found by

$$a' = a \sin(180 - B)$$

and since the correcting belocity, b, is known,

$$A = 90 - \cos^{-1}(a'/b)$$

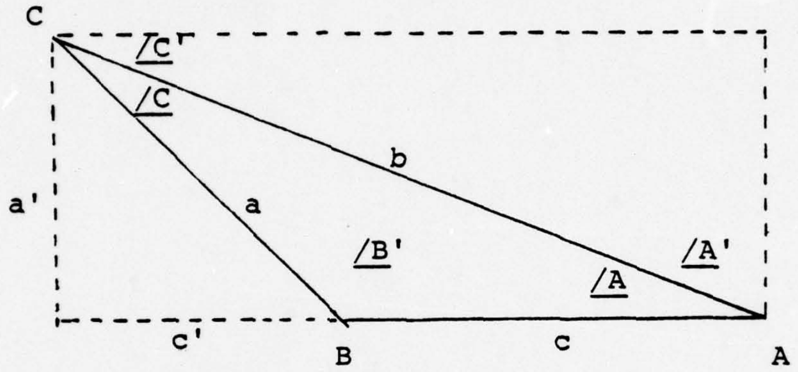


FIGURE 11

$$C = 180 - A - B$$

and

$$c = (a^2 + b^2 - ab(\cos C))^{1/2}$$

Thus, if the desired speed is known, the time to get back on track is specified, and the set and drift is known, the course to be taken to correct can be found by

$$(1 + \frac{\text{time in minutes}}{3})(\text{drift}) = a$$

$$\frac{\text{time in minutes}}{3}(\text{speed}) = b$$

$$B = \text{set} \quad (\text{relative to ship's head})$$

To find B,

$$B' = 360° - \text{set} + \text{cse}$$

$$\text{If } B' < 180°, \text{ then } B = B'$$

$$\text{If } B' > 180°, \text{ then } B = |B' - 360°|$$

Then, knowing the values of a' and A' as given above,

$$C' = 90 - A'$$

$$\text{correcting cse} = \text{desired cse} + C'$$

The above mathematics presupposes that the ship os off course due to the effects of just one three minute interval of set and drift effects.

In the completely general situation, the navigator finds himself off track by some distance which does not correspond to three minutes of set and drift effects, but rather some distance greater than that. This problem can be solved in the manner described for the three minute effects with appropriate adjustment to the values of a and b in figure 11. For this case,

$$a = \frac{\text{(no. min set and drift eff)} + 6}{3}\ \text{(drift)}$$

$$b = \frac{\text{(time in minutes)}}{3}\ \text{(speed)}$$

In the above equations, (no. min set and drift eff.) is a value arrived at by finding how many minutes it would take the set and drift present to cause the ship to be off track by the amount found. This quantity can be readily obtained by solving a right triangle with one angle corresponding to the set, and one side representing the distance the ship is off track. The length of the hypotenuse of this triangle, when converted to yards, is then divided by drift. The result is then divided by 100, and this result yields the number of three minutes intervals of set and drift effects.

Then, multiplying by 3 gives the number of minutes of set and drift effects. Also in the above equations, (drift) is the drift in knots, (speed) is the ship's speed to be used in correcting, and (time in minutes) is the time in which the navigator wishes to get back on track.

After the values of a and b above are found, the remainder of the solution uses the equations previously developed. If the course which results from these calculations is too radical a course change, a different time interval can be used.

This completes the list of navigational information which is routinely reported at each fix. Since the display of this information will be nearly instantaneous, the computer can be called upon to provide other information which might be useful. For example, it might be desirable to inform the conn of the probable error in the fix. This error is pictorially evident when more than two LOP's are used to determine the ship's position. If three LOP's are used, except in rare instances, a (hopefully) small triangle is formed by the intersection of the lines. In order to arrive at a computer-generated position given these various crossing points, it is suggested that the x and y coordinates found for the crossing points be averaged and the average values reported. The maximum deviation could then be displayed, or some other parameter of the navigator's choosing could be reported.

Another item of interest could be the estimated time of arrival at the destination based on the speed made good. The correcting speed necessary to arrive on time could also be determined and displayed. However, care must be taken so as not to clutter the display with so much information that it becomes unreadable.

The treatment up to this point concerned a routine channel transit. Frequently, the ultimate objective of a channel transit is to reach an anchorage. Clearly, an anchorage approach subroutine should be included and is easily developed. In fact, the mathematics are so simple that the detail will be left out. All that is required is to report the distance and direction to a point from the current position, which is obviously a simple problem to solve.

B. THE EQUIPMENT

Not only did the previous section demonstrate that the navigational information can be found mathematically, but also provided knowledge of the type of calculations which the computer must perform. This section deals with the equipment options which were found to be the most desirable for this system.

Several computer systems were found which could be used very satisfactorily to provide the required data. In fact, the decision as to which company should be selected to provide the equipment will most likely be based on the price, a favorable situation in view of the normal military procurement system. Certainly, the minimum requirement was that the system could perform the calculations necessary to generate the navigational data which is required. Other major considerations which were used in selecting acceptable systems for inclusion in this report were:

1. East of installation
2. Availability of peripheral devices
3. Compatibility with equipment from other manufacturers
4. Size
5. Price

Availability of peripheral devices and compatibility with equipment from other manufacturers eliminated the Apple II microcomputer from consideration. This otherwise attractie system does not currently have floppy disc memory available and, when developed, it will require a design of unique properties which will only be sold by Apple Computer Inc. The Cromemco Z-2 Computer System was not considered because of its rather large size and the relatively high cost.

The three systems which will be discussed here are those manufactured by IMSAI Manufacturing Corporation, Processor Technology Corporation, and PolyMorphic Systems. It was found that, while differences certainly exist between the computers, these differences were not of consequence for the system as it is proposed. Each system uses the Intel 8080 microprocessor chip, which is the most widely used chip on the market of its type. Each has a wide range of peripherals available, with system design options already existing which exceed any probable future requirements for the system. All three computers are small in size and attractive, easily installed by inexperienced personnel, comparable in price, and are compatible with equipment from other manufacturers.

The IMSAI system which would be proposed for use would consist of the I-8080 computer, RAM 4A-4K memory, PROM 4-4 memory for 4K-byte BASIC, software consisting of BASIC 4A PROM-programmed 4K BASIC and DOC-6 BASIC User's Manual, and for input-output the CRT-2480A Video Display/Keyboard Terminal, and the SIO 2-1 Serial I/O Interface board. Total cost of the system as described would be almost $3700 based on current retail price catalogues, fo which $1595 is for just the video monitor and keyboard. It is possible to purchase just a keyboard for $275, and then provide a monitor procured from a different source for about $100, thus effecting a savings of some $1220, bringing the cost of the IMSAI system down to a manageable $2480. In fact, in each case being considered, it is wise to purchase the monitor from a supplier other than the computer manufacturer, since the prices for the monitors always seemed higher than was necessary for the quality of equipment required. In the IMSAI case, as is the case with other manufacturers, the video terminal and keyboard is combined into one chassis to form a compact and attractive unit, but the cost is very high, and the repairability is certainly compromised. It is felt that one important feature of the system should be the relative ease with which the system may be kept operational by simply exchanging the bad component for a good one and giving the faulty piece of equipment to a facility ashore for repair at a later date.

The I-8080 features a front panel control board which contains 16 address/data switches, 16 LED address indicators, 8 LED data bus indicators, 8 LED prog-ammed output bit indicators, 6 control function switches, and 8 LED status indicators (including control indicators for INTERRUPT, ENABLED, RUN, WAIT and HOLD). If this front panel is not used, the slot may be used to expand the size of the Mother Board. The Mother Board which is standard is a 4-slot one, and the chassis is capable of accepting up to a 22-slot Mother Board. The system uses a 2-MHz clock, more speed than should ever be required or used for the intended application. The power supply provides 28 amperes at a +7V dc minimum, and 3 amperes each at +15.8V and -15.8V minimum. This supply operates from 120V, 50-60 Hz power.

The basic memory is provided by the 4K Random Access Memory (RAM 4A-4). This board stores 4096 bytes of changeable information, either programs or data. Information may come from a computer program, a peripheral device, or the front panel switches. It has a memory write-protect feature which protects 1K-byte blocks of data under program or front panel control. The program can test for protect status os any 1K-byte block, and an interrupt is generated when a protected block is illegally accessed.

The system amkes up to 64K-bytes of memory directly accessible with a basic machine cycle of 0.5 microseconds, and as many as 256 I/O ports accessible. It is backed by a family of options and peripheral devices and interfaces to do just about any job. Peripheral memory includes a floppy-disk system, with each disk capable of storing up to 243K bytes of data, with an average access time of 330 milliseconds. This expandable memory allows for possible future use in celestial or electronic navigation. Other peripheral devices available include serial and line printers, with the line printer capable of printing up to 314 lines of 80-column material per minute. The price for this highly capable line printer is a relatively modest $2610. The complete list of interfaces and peripherals already available is extensive and certainly would ensure that the system would not be subject to obsolescence or unadaptability to future needs.

The next system to be discussed is the Sol-20, which is manufactured by Processor Technology Corporation. This INtel 8080-based system is relatively new on the market and shows great promise. The system is designed with simplicity in mind, since the main marketing thrust for the system is directed at users with little or no familiarity with computers. The system is supported in depth by extensive software and peripherals.

General characteristics include a 1024-character video display (16 64-character lines with upward scrolling if overloaded), 1024 words of static RAM for program storage, an 85-key solid-state upper and lower case keyboard with cursor keys and arithmetic keypad, an audio cassette interface capable of controlling two recorders at 1200 bits per second, both parallel and serial standardized interfaces with connectors on a card, power supply, case, software including a PROM and a cassette with BASIC-5 language, a design compatible with all S-100 bus products (a very common bus in the computer industry), and a back plane capable of accepting five expansion modules. All of this is available at a retail cost of $2129. This price includes the Sol-20 described above along with an 8192-byte RAM memory, the SOLOS module (a form of PROM), the PT-872 monitor, and the RQ-413A cassette recorder. The monitor for this system is manufactured by Pansonic and sells for $199. Again, as was the case with the IMSAI system, the monitor could be procured separately at lower cost.

Operating characteristics of the Sol system are similar to the IMSAI, and the available peripherals and interfaces are comparable. A disk drive is also available for the SOL providing 386,000 bytes per disk with an average access time of 0.3 seconds. The number of peripherals for the Sol system is not as extensive as the IMSAI list, but the list of peripherals is solid where it counts. Various memory options are available, interface modules can be purchased as needed, and due to the S-100 bus, the system can be expanded using peripherals of other manufacturers with S-100 compatibility such as IMSAI, Altair, and the PolyMorphic system discussed next. Due to the oeprational simplicity of the system and the emphasis which the manufacturer has placed on expandability, not to mention the relatively low cost of the fully functional system, the Sol system must be considered a strong candidate to implementation.

The final system to be discussed is the POLY 88 which is manufactured by PolyMorphic Systems. ONce again, the system is Intel 8080 based and it too utilizes the S-100 bus. The basic system considered was the POLY 88 System 16. This system includes the cassette based System 16 with CPU card, 1K of ROM, a video card, cassette interface, 16K of RAM, chassis, five slot backplane, power supply, keyboard with cables, monitor with cables, and a cassette recorder. 11K BASIC and Assembler are included. The price for this capable system is $2250. Once again, the video interface provides for 1024 characters on the display (64 characters per line with 16 lines). The overall operating characteristics of this system are comparable to the two systems discussed previously.

The list of peripherals available is adequate and once again the S-100 bus compatability provides for interchange of components between various manufacturers. Again, disk and additional RAM memory are available, with the cost of this add-on being about half that of the IMSAI or the Sol at a retail price of $1095.

While it is clear that more data was given for the IMSAI than for the other two systems, this does not mean that the IMSAI was found to be more desirable than the others. Rather, the characteristics of the Sol and PolyMorphic systems were so similar to the IMSAI that it was not felt necessary to duplicate this information. In general all three systems were found to be more than adequate for the intended purpose in this proposal. It is certain that several other systems from other manufacturers would also be acceptable. The purpose in outlining the systems selected for inclusion in this proposal was to provide examples of off-the-shelf equipment which could be used to perform the calculations required of the navigation system which is being advocated.

Another equipment consideration was that concerning the type of display device. The standard I/O devices available for the computer systems discussed were paper tape, teletype, serial and line printers, and video display using a television monitor. The use of LED or liquid crystal displays was considered, but cost factors and lack of availability of the necessary type of displays caused devices of this type to be eliminated.

Of the remaining types of devices, the television monitor was chosen as the best display device for several reasons. First, the manufacturers of the microcomputers of the type being considered for use in the system all have video interfaces available at low cost. In fact, the systems have been designed with the video display as the primary display device assumed. Aslo, interfaces are available for slaving several monitors to the computer at low cost, thus accomplishing one of the important requirements of the system, that of providing several remote displays for the conning officer. Additionally, the video monitors can be very low cost items, since any black and white television can be modified easily and inexpensively to serve as a display device. If properly enclosed inside weather-resistant cases and with proper mounting, these devices should be relatively sturdy and, with the use of non-glare glass on the picture. tube, and due to the nature of a television display, the monitors should be readable under most conditions during a channel transit. Because of the low cost and the ease of replacement, several spares can be carried onboard so that, should a monitor fail, module replacement can provide for minimization of system repair time in the event of display device failure. Should a permanent record of the information displayed be deemed desirable, a line printer or some other form of permanent display device could be located in a protected location and the data could then be retrieved upon completion of the exercise.

It was previously mentioned that the inclusion of an automatic plotter was considered. The large size of navigational charts requires that such a system be designed to specifically meet the needs of the system, and such an effort could prove to be costly. Additionally, the vulnerability of the system to mishandling and abuse would in all probability cause the plotter to be the weak link in the system. Finally, the plotter was felt to introduce an undesirable reliance of man on the machine, and should failure occur, the transition back to a manual plot was felt to be compromised due to the ensuing lack of navigation team practice in harbor navigation due to the total automation of the system. However, should such a feature be deemed desirable by the user, each of the computer systems proposed for use can be equipped with a digital-to-analog and/or analog to digital converter. An x-y plotter could then be designed which would provide full chart coverage, and a real time plot could then be generated.

The mathematics have been developed, the computer options have been reviewed, and the display device has been selected. What remains is the selection of the final system design. This is the subject of the next chapter.

III. CONCLUSIONS

The first and most important conclusion is that the system can do what is required of it. The mathematical development demonstrated a possible method for computing all of the navigational information currently required and desired during close coastal and harbor navigation. Computer systems were found to be available which would handle the types of calculations to be performed by the system, and display devices were found to be available at low cost which were highly readable under the normal conditions encountered during a harbor navigation situation.

The system which is proposed consists of a microcomputer with features comparable to those found to be shared by the IMSAI, Sol, and PolyMorphic offerings discussed in the previous chapter. The selection as to the specific computer to be purchased should be made with primary consideration given to the cost of the computer system, with due regard being given to the compatibility of the system to the addition of peripherals and the resistance of the system to obsolescence. The displays should be very low cost television monitors located in positions which are likely to be close to the conning officer during the navigational exercise. A minimum of four displays is felt to be necessary, these being located at the plotting station in the pilot house, one on each bridge wing, and one inside the pilot house near the Captain's chair, but readable by other bridge personnel. Other possible monitor locations might be the CIC, and the flying bridge. The precise location of the monitors should be left to the individual command.

It is further proposed that in the equipment selection procedure, careful thought be given to the ease of installation of the equipment. It is felt to be highly desirable that the personnel support for the system be minimized. Ideally, it is felt feasible that the system could be implemented without necessitating the addition of any personnel in direct support of the equipment and with a minimum of impact on the training funds and man hours available for training. This goal can be achieved by maintaining low cost features and modular construction so that modular replacement can take the place of on-station repair of equipment.

One aspect of the system design which has not yet been discussed is the addition of CIC as a remote imput station to the system. Navigational information could be generated in a manner analogous to that developed from visual input data with the development of an algorithm for the processing of radar range information into position information. Once the ship's position was determined, the remainder of the information would be provided by the same method used for the processing of visual data. A priority interrupt interface module would be added to the main computer, and a remote intelligent keyboard and video monitor would be installed in CIC for I/O. The algorithm would then include a provision for comparison of navigational data between the visual and the radar plots providing a check on the probable accuracy of the data being obtained independently and, more importantly, would provide a smooth transition to the radar plot should the visibility deteriorate. Additionally, the CIC plot would then also be a real time plot, a matter of some importance in improving the reliability of information and increasing the safety of navigation in a low-visibility environment.

It was previously mentioned that the system could be programmed to plot in latitude-longitude coordinates. However, due to the variations in the relationship between distance and degrees of longitude depending on the location of the ship, this was felt to be a somewhat more difficult system to manage. Additionally, providing locations of objects and fix positions in a latitude-longitude system can be a rather time-consuming process. Rather, it was decided that a grid system in x-y coordinates be used. Location of objects would be determined by placing a template over the chart. The origin of the template would be in the lower left hand corner of the chart. The template could take the form of either a large overlay which could be placed over the chart as needed, or a smaller template which could be used to locate an object inside a smaller rectangle which would be drawn on the chart prior to the start of the exercise. The latter alternative is the one which is proposed for use. The navigator would carefully draw lines on the chart corresponding to major intervals on the x and y axes, resulting in squares of several inches on a side. These lines would be labeled in a manner analagous to that used in graphing. Then, a small template would be provided which would fit the larger square. This smaller template would be ruled to provide for a high degree of accuracy in establishing the location of the point in question. A drawing of the template design is shown in figure 12.

A system of the type proposed here could be purchased at retail prices for under $4000 installed. Such a system would be comprised of the microcomputer system at a cost of approximately $2300 (including keyboard and monitor), a second keyboard for use in CIC at a price of about $230, 7 video monitors providing for five remote locations and 2 on-hand spares for a total cost of about $1000 including interfaces, the template, and the associated software for the system. For an additional cost of under $2000 a spare terminal computer could also be purchased, making the system completely redundant.

The navigation team procedure would be changed by implementation of the system. Instead of the system previously described in the introductory chapter, the following system would be used to process navigational information. All personnel on the team would continue to obtain and process information as was previously done except that the bearings to the assigned objects as obtained by the bearing

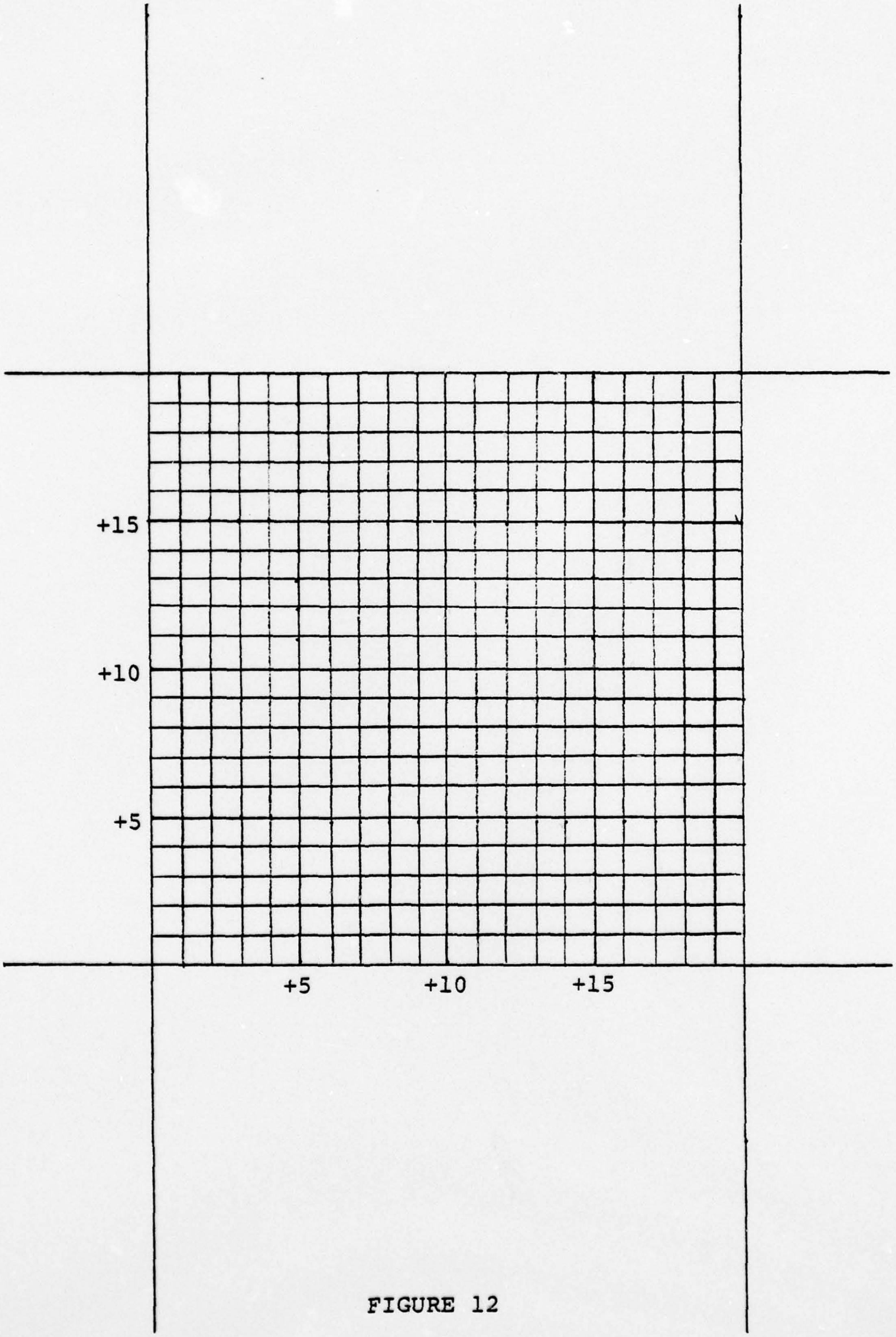


FIGURE 12

takers would be entered into the computer by the team plotter as they were recorded in the navigation log appropriate for this use. The computer would then process this information and instantaneously display the desired information. The plotter would then plot the information in the customary fashion and, upon completion of the plot, would compare the data found manually with that displayed on the computer display. Up until this time, the display would have some sort of indication that the information was not yet compared against the manually generated fix such as the word "Pending" in the lower right hand corner of the screen. When the positions are compared and concurrence established by the navigator, he would then tell the computer that the solution was accepted and the "Pending" status would be changed to "Concur". The display would then be held until the next set of data was to be entered. The display would be cleared by the entering of "TIME ____", with the blank being filled in by the time at which the next round of bearings would be taken. This would provide the time data to the computer and also signal the computer to prepare for a new set of data. As can be seen, the only information necessary for the computer to generate the fix information is that which was required for visual plotting. The designation of the hazards, track, points, etc., would have already been entered when preparing for the exercise. Any changes required during the transit could be easily entered as required.

The nature of the hazards would be identified to the computer when the hazard lines were entered. These designations would be such things as shoal water, wreck, rock, etc., and this descriptive information would be displayed along with the range to the hazard and its location relative to the ship's bow, such as port/starboard bow, dead ahead, port/starboard beam. Fix information as to reliability would be displayed as EXCELLENT, GOOD, FAIR, or POOR depending on the magnitude of the average variation from the established position of the crossing points of the LOP's.

Should failure of equipment occur, the shift to the manual plot would be instantaneous and smooth, since this plot was never abandoned. In the event that a display device became inoperative, the phone talker would then relay navigational information from the plot to the conning officer. Also, should the conning officer find that he cannot see a display device or did not wish to remove his attention from some other visually important object or event, the phone talker could read the information on the display to him. Thus, redundancy is assured and tradition and proven methods have been retained.

The information display would be in line by line format. The display for a hypothetical fix might appear as follows:

TIME	1003
POSIT	32 YDS RIGHT OF TRACK
NEAREST HAZARD	SHOAL WATER 600 YDS STBD BOW
CSE/SPD MADE GOOD	258 AT 12.3 KTS

RANGE TO TURN	2700 YDS
TIME TO TURN	1009 AND 35 SEC
SET/DRIFT	085/2.5 KTS
COMP CSE/SPD	256/13 KTS
CORR CSE/SPD	254/13 KTS BACK ON TRACK IN 6 MIN
VIS/CIC COMP	30 YD DIFFERENCE
FIX QUALITY	EXCELLENT
ETA DESTINATION	1045, 5 MIN LATE ***PENDING***

For final anchorage approach, the navigator would alert the computer to change to the anchorage approach format. The same information would be displayed except that immediately after the time, the distance to center of anchorage would be displayed.

This competes the proposal for the system. The only work remaining involves the selection of the individual equipments and the writing of the program in the language of the computer system selected. It is felt that the system is one which would be welcomed by commanders and operators alike and one which would have a minimal impact on the limited funds available to the Navy. Its acceptance is encouraged.

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