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6345
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Date: 8 June 1956

Project Whirlwind
Servomechanisms Laboratory
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Cambridge, Massachusetts

SUBJECT: INFORMATION SYSTEM OF INTERCONNECTED DIGITAL COMPUTERS

To: Director, Special Devices Center

From: Jay W. Forrester and Robert R. Everett

Date: October 15, 1947

The following notes discuss in rather general terms some possibilities in the arrangement and use of high-speed digital computers for the analysis, evaluation and intercommunication of information in an anti-submarine naval group. Most decisions relating to the method of interconnecting systems and the way in which they are to perform are of an arbitrary nature, and the best method could only result from rather extensive studies. The general characteristics of the system can be itemized as follows:

1. Primary information gathering equipment exists as for example, radar, sonar, listening devices, visual sighting, radio direction findings, etc. Information gathered by these methods is fed to the computing system either automatically or after manual observation and the setting of indicators.

2. The computer on each test group unit accepts data on observed targets and friendly ships and compares positions with all units previously known to exist. Appearance of a new target or unidentified object is presented on a special display. Information from each sighting is correlated with all previous existing information to obtain the best new position for the object sighted and to obtain some measure of the accuracy of this information.

3. The correlated information from each ship is transmitted to the command unit where further correlation is executed and the best overall picture obtainable is generated.

4. The command ship transmits back to each unit of the group information sufficient to present the best picture available based on the information gathering facilities of the entire task group.

5. Intercommunication between task group units is initiated and carried out automatically under the control of the computing equipment.

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THE SYSTEM: Figure 1 illustrates the type of Naval Task Group being discussed in this memorandum. Five surface ships and one aircraft are illustrated with two targets, one surface, and one submerged. All units collect such information as they are able by the various methods noted. The computation and information system must make use of this total body of information to the best possible advantage.

For simplicity, the control of communications is illustrated on an echelon basis where the command ship has control of the communication channel and outlying units transmit only on request. Computing and radio equipment in all units can be identical, and the command function can be taken over by any other unit in the group as the situation may require. Transfer of the command function in emergencies could be automatic if desired. If automatic, the transfer would depend on some criteria such as failure of communication at the command ship.

Figure 2 illustrates a possible block diagram arrangement of a computer and radio equipment to accomplish the functions illustrated in Figure 1. The stepping register illustrated is normally a part of the input and output mechanism of the computer, but in this application might also serve as a source of signals for the radio transmitter and as a receiver of signals from the radio receiver.

The stepping register is provided with two additional digit positions to be used in the identification of call signals, computed orders, and the distinction of these two from numerical values. Assuming that the computer uses a sixteen binary digit number, the groups transmitted by radio link would consist of eighteen digits. All receiving units would monitor all transmissions and a receiving unit would take action only in response to its own call letters. The first two digits used for identifying and distinguishing call letters from other numerical values would occur at the beginning of each number group. The communication system outlined implies the ability to transmit the digits 0 and 1 and to indicate the beginning of a new number group. Transmission might be by three distinct types of transmitted signal or perhaps by the transmission of the digit 1 as a pulse with spaces for the digit 0 and with a longer space or a long pulse separating number groups. An example of the two-digit code preceding a number might be as follows:

A 00

B 01

C 10

These combinations might indicate the following information regarding the digits that would appear in the stepping register. 00 might indicate that the number in the register is an ordinary numerical value to be used by the receiving computer. The digits 01 might indicate that the stepping register contains control instructions for the receiving computer. The digits 10 in the first two places of the register might indicate that the register holds call letters to initiate a communication with one of the remote computers.

In the system illustrated, only one message is being transmitted at any given time over the frequency channel used by the combined system. Other channels are of course obviously possible. On this single transmission system, all radio receivers monitor and receive all messages on the communication band. The computer as such takes no part in this operation except when the digits 10 appear in the first two positions of the stepping register following the transmission of a number. The digits 10 indicate that the stepping register contains a call number and the computer must at that time examine the call number to see if it is the unit being called. If the call letters do not correspond to the identification of the local unit, the local unit is free to continue with whatever computation might be in progress. Certain call letters might indicate various groupings of units wherein several or all units might receive a transmission.

In Figure 2 the normal internal high-speed storage of the computer is used as a buffer between computer operations and the radio link. For a relatively simple system of the type illustrated where messages will consist of not more than a few hundred number groups, this type of storage may be preferable because of the greater flexibility which is available. In such a system, only one type of storage is required and this storage may be used for the most urgent of the existing requirements, that is, it may be used at one time for computing programs, at other times for the internal storage of data for computer use, and at other times may be used predominately as a buffer storage for information relay purposes. Such a decision is of course arbitrary and might be altered in light of detailed system studies.

<u>OPERATION OF SYSTEM</u>: Each computer might store part or all of the following information relating to each other unit or target in the vicinity.

1. X-coordinate of target position.
2. Error probability in X-position.
3. Y-coordinate of target position.
4. Error probability in Y-position.
5. Z-coordinate of target position.
6. Error probability of Z-coordinate.
7. Component of target speed in X-direction.
8. Component of target speed in Y-direction.
9. Target turn rate.

10. Turn acceleration of the target.

11. Time of the last target observation.

12. Existence probability used to distinguish noise from repeating signals.

13. Identification, which may include in one storage register indication of friend or foe and target kind - that is, submarine, surface ship, or aircraft.

14. The group unit and detector making the first target contact.

Information in the above fourteen entries would be used and corrected for each new target observation made by a detector unit. The information in any computer unit represents the best information available based on the detectors directly available to that unit. In addition, the unit will receive from the command ship the best information based on all information available in the task group.

The computer system on any individual unit of the task group will accept from its own detector systems information whenever data is available. This data will be correlated with other available information and will be transmitted to the command ship upon request. In the command ship, the computer control program will be so arranged that the computer will periodically, at sufficiently frequent intervals, interrogate each other unit in the system at which point the remote unit will transmit all of the information which it normally supplies.

Written or teletype information might be readily handled on the same system using the computer merely as a switching mechanism to transfer the incoming message from the radio receiver to one of the input and output devices of Figure 2 where it may be visually observed. Also, since the transmitting or command ship may, if desired, have control of all internal storage of the remote unit computers, it is entirely possible that the controlling programs in these computers can be altered from time to time as necessary for the tactical situation. For example, if a particular unit is to execute an attack and is no longer needed for correlation of incoming data, the computing program might, if the computer were heavily overloaded, be replaced by the program necessary for steering of the ship and for firing of weapons.

In order to make available the best form of information for presentation purposes, the computer might be expected to supply data in the proper form for the presentation device. For example, the command ship in this illustration might transmit to the local units the proper X, Y, and Z coordinates of all known targets and units in the area indicating whether they be friendly or not and transmitting also information about their speed, bearing, and the probable area in which targets are located. Such a presentation as is shown in Figure 3 would be calculated by the local computer based on the above information supplied. The local computer would need to convert to coordinates with respect to the local ship and transmit data in the proper form for use by the presentation mechanism. In Figure 3 all friendly units are shown as dots on the surface of a cathode ray tube. All unfriendly units are shown as circles or ellipses indicating the uncertain area within which the target may lie. On all units, the indicated line shows the bearing of the unit and the length of the line indicates the speed of the unit. The indication types here required are all available in a cathode ray tube which is supplied by deflection voltages upon which are superimposed varying magnitudes of sinusoidal voltages. Straight lines can be represented by sine voltages which are in phase and of the proper magnitude on each pair of deflection plates while open figures, either circles or ellipses, are presented by the proper magnitudes of voltages which are 90 degrees out of phase.

Also, the computer units can intercommunicate data tables and other information from one to the other, as for example, the sonar vertical angle correction table shown in Figure 4. This correction table might be automatically computed at the command ship after water temperature data had been obtained and the new sonar correction table transmitted to all units using sonar detectors. These units would then use the proper correction factors in their data evaluation. The table shown in Figure 4 is a function of two variables and gives the correction in observed vertical angle as a function of the observed angle and the observed range. The computer would transmit the information shown in Figure 4 by transmitting the numerical values of the indicated points on the curves. Receiver units would interpolate between these information points as required.

DAMAGE CONTROL. To insure reliable operation of the computers, it will be necessary that all signal transmissions be checked. One way of doing this would be to transmit information one register length at a time to the receiver unit which would then retransmit to the sender for checking purposes. If the retransmitted signal checks, the transmitter would continue with the next number group in the message. Failure to receive a check after several attempts or failure over a certain time interval would automatically turn in an alarm signal. If interrogation by the command ship fails to receive a response from a remote unit, the command ship might automatically relay messages by way of some other unit in the task group which might be more favorably located. Such facility might, for example, be desirable if the task group is spread beyond reliable communication range.

EVALUATION OF DETECTOR INFORMATION. The principle problem falling to the computers illustrated in the various task group units of Figure 1 will be the evaluation of data from sonar, radar, visual sightings, etc.

In order that information be as reliable as possible, all known characteristics and circumstances regarding the detector unit should be incorporated in the data evaluation. For example, the computer should have available computing programs and stored information regarding known required corrections to data coming from each detector unit. For example, misalignment of a radar antenna might cause an error in the bearing angle observed. Primary data should first be corrected for these known schematic errors. After all known systematic errors have been corrected, there remain the unknown accidental errors that may be present in the individual reading of the equipment. These accidental errors will depend upon the sensitivity of the detector equipment, upon the operator, and the kind of relay equipment between a detector unit and the computer. In order that observation from different types of detector systems, for example, search radar and fire control radar, may be properly correlated and the best available information extracted from the data, some indication of probable accuracy must be used in data evaluation.

The form of error distribution curve assumed for this memorandum is called the normal error curve several of which are shown along with their equation in Figure 5. The choice is arbitrary. Other curves could be used if more suited to the data being correlated. The normal error curve is described by a single constant, the precision "h". Also shown in Figure 5 is the Probable Error which is a quantity such that one half the errors of the measurements are greater than it and the other half less than it. Both the precision and the Probable Error are used in this correlation study. The higher the precision, the higher will be the curve, and the steeper will be its sides.

Figure 6 shows how two or more measurements of the same quantity may be combined, the most probable value discovered and the precision of that value computed. Shown are two measurements of the same quantity. These measurements have different precisions. The measurements are weighted according to the squares of these precisions and the most probable value is closer to the measurement with the higher precision. The precision of this derived result is somewhat greater than the precisions of either of the measurements going into it.

The normal error curve may be extended to more than one dimension. Figure 7 shows a ship viewing two radar targets which must be described by two coordinates. In general, the precision of the measurement is different along the coordinates. The left-hand target in Figure 7 is measured with different precision in range and bearing. The contour lines showing target position probability are shown as ellipses although more strictly the major axis of each ellipse should be the arc of a circle. This representation for two-dimensional target position probability leads to very complicated solution. For the purposes of this study, therefore, the precision of a measurement is assumed to be symmetrical as shown in the right-hand target in Figure 7. The probability surface is simply a surface of revolution formed by the normal error curve. For the rest of this memorandum a target measurement will be shown by the point described by the measurement and a single circle about that point with radius equal to the probable error. This circle describes the precision of the measurement. Actually, in any complete correlation problem, both the shape and the size of the probability pattern will be determined by the instrument doing the measuring. In this study, only the size or precision of the probability pattern will be assumed to be dependent upon the radar set doing the measuring.

Figure 8 is a three-dimensional view of two measurements of a target position and of the probable position derived from those measurements. The probability surface is a sort of hill about each measurement of height determined by the precision of that measurement. The same equations are used for determining the probable position as were used in the one-dimensional case. The probable position lies on a straight line between the two measured positions and has a precision slightly higher than either of them.

The probability pattern may be extended to three dimensions in the same manner as to two dimensions and with the possibility of a different precision in the third coordinate. This memorandum considers a two-dimensional problem only.

The normal error curve assumes a finite probability over the entire infinite area. For the purposes of this memorandum, probabilities less on a certain pre-assigned amount result in target rejection.

<u>TIME EFFECTS</u>. Targets are in general moving and measurements of their position are not simultaneous. Account must be taken of the time elapsing between the last fix and the present measurement, and the probable motion of the target must be predicted. As time passes, therefore, the precision of the fix on the target's position decreases since knowledge of the target's rates are less accurate than knowledge of its position and are also subject to control of the target operator. If enough time elapses between fixes, information as to the target position will have decreased below the useful point. The target has in effect disappeared. This reduction of precision with passing time can be used in discriminating against one-time or noise signals.

<u>THE PROBLEM PROPOSED FOR SOLUTION</u>. Restrictions on the problems studied are as follows:

1. Objects are considered in two dimensions only.

2. Objects are represented by symmetrical error curves.

3. Precision of target position from several measurements is computed by the simple methods mentioned above.

4. Targets are not assumed to exist if their probability lies below a certain assumed minimum. There is thus a maximum

circle about each target position where the target is assumed to lie. Consideration of the matching of a target and a signal can be done on the basis of the intersection of these circles. Also, noise signal, destroyed targets, and targets going out of range of the system are removed when their probability is reduced below this minimum point.

5. Targets closer together than the resolution of the radar are considered as lumped at the CG.

6. The number of targets and the number of radars is arbitrary.

The problem can be extended to include the following:

1. Three dimensions.

2. Other instruments than radar.

3. Non-symmetrical probability.

4. More exact probability computation.

5. Detection and correction for unexpected set bias including throwing out data from improperly operating sets.

6. Automatic triangulation.

The attack on the problem is described in Figure 9 which shows the path of a moving target and the fixes obtained on that path. The target is picked out at t_o in the upper center part of the drawing. The first measured position is plotted and the solid circle about this position represents the precision of that fix obtained from knowledge of the radar which obtained it. At t_1 another fix is obtained on the same target. By this time the precision of the early fix has been reduced since the target may have moved and there is no way to know in what direction it may have gone.

At t_1 a new measured position is obtained, this time with a higher precision radar giving a smaller precision circle. As a start on the prediction problem, the target is assumed to have been moving on the line between the two fixes at the average speed expected for an airplane. This gives EP the new expected position at t_1 of the target picked up at t_o. The precision of the expected position is assumed to be about the same as that of the measured position before the prediction was carried out. The probable position is now computed. It lies on the line between EP and MP for t_1 and is closer to the measured position because of the higher precision of the radar which measured this position. Also the precision of this new fix, or probable position, is assumed to be somewhat better than either of the two measurements from which it was obtained.

A new fix has been obtained and with it an estimate of the bearing and speed of the target. At some time later, t_2, a new measured position is obtained once again with a high precision radar. The target position is extrapolated to a new EP. Using the old target path and target velocity, the precision of the fix is decreased quite radically because the target bearing and rate are still poorly known. The new probable position and precision are computed and the target bearing and rate corrected.

At t_3 a new measured position is obtained with a somewhat lower precision radar than the last two fixes. The target position is extrapolated to the new EP. Its precision is reduced but not so radically as before because information as to target bearing and rate have been somewhat improved. The new probable position and precision are computed and the process is continued. t_4 represents another fix by a radar of about the same quality as the t_3 fix.

At t_5 still another measure is obtained, this time by another high precision radar. The result of the fix is of quite high precision. The bearing and rate of the target are also fairly well known by this time. This process is continued as long as the radars can obtain signals from the target. Centered about the last probable position is a dashed circle marked - "minimum probability circle". This is the circle described above within which the target is absolutely assumed to be. Any signals whose minimum probability circles lie outside of this one are assumed to have no effect upon the position of this target.

Also shown on Figure 9 are two other signals assumed to have been obtained at t_o. The one on the left is a noise signal which was picked up at t_o. As time proceeds to t_1, t_2 etc., the precision of the fix obtained is decreased until finally beyond t_4 the precision is assumed to have reached below that minimum assumed for existing targets. As time proceeds the precision of the fix decreases.

Also shown is a fix obtained on a stationary target. The first fix is rather poor but as fixes are obtained at times t_1, t_2, t_3 and so on, the precision of the fix increases. The sizes of the probability circle shown for this target and the noise signal are not at all to scale.

<u>TARGET SELECTION:</u> One of the main problems in the correlation is to determine those targets which are near enough to an incoming signal so that the signal may be considered as a new fix upon their position. If there are many targets and they are all checked, this problem becomes one of considerable magnitude, the amount of computing varying about as the square of the number of targets. It is desirable, therefore, not to examine all targets but only those targets which are reasonably close to the incoming signals. Since the targets are continuously moving, this problem is not an easy one. There are many possibilities, one of which will be described here.

The X-coordinate of the entire area being considered is cut into sections, thus dividing the area into a number of north-south strips of constant width. The targets are distributed as they occur in these slices. Figure 10 shows a small part of the divided total area. The number of targets in each slice will be relatively few. The X-coordinate of the signal being considered can be used as in interpolation to select the area slice in which the targets to be considered are located. The drawing shows eight slices only. There would actually be more, possibly thirty-two or so, depending upon the number of targets to be considered.

If a sufficient section of storage is to be allocated to store all possible targets using this slice method, then an amount of storage equal to the product of the number of slices times the maximum expected number of targets per slice will be required. It would further be necessary to keep track of the number of targets in each slice. The total amount of storage might be excessive. A more economical method is to put all targets in a single table in order of their X-coordinates without regard to what slice they may be in. Then, allow only one storage register per slice and in that register store the register number in the target table of the left-most target in the area. Hereafter, the table of the left-most target in the area slices will be called Stack 1, while the table of all targets in X-coordinate order will be called Stack 2.

The procedure for selecting those targets to be examined, is as follows:

1. Determine what slice the incoming signal is in, using an interpolation procedure.

2. Extract from ~~Slice~~ STACK 1, the register number in Stack 2 which holds the code for that target. Then go to Stack 2, extract the code number, and check on that target. After checking that target, check the next one to the right which will also be the next one in Stack 2; continue until that target is reached whose X-coordinate is greater than the coordinate of the signal. It will actually be necessary to decrease the signal's X-coordinate slightly in selecting the area slice in case the probability circle of the signal crosses a demarcation line between two slices. In this case the left-hand slice is taken and the selection procedure in Stack 2 will check all targets until one is reached whose X-coordinate is beyond that of the signal.

The price to be paid for a system such as this is the extra necessity of keeping the Stacks 1 and 2 in order. Every time a target moves, Stacks 1 and 2 must be examined to make sure that they have not either crossed the path of another target or moved into another slice. This price seems well worthwhile in view of the great saving in scanning time. Note that it is not necessary to scan all targets in the slice but only those lying between the left edge of the slice and the signal.

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PROBLEM SOLUTION. Figure 11 shows the general flow diagram for the radar correlation problem. It consists of two parts: the Signal Program is used whenever a signal comes in from any of the radars. Its purpose is to find if the signal represents a new target or an old one. If it represents an old target, the target position and range are modified to take account of the new information. The Target Loss Program is carried on whenever signals are not being computed. Its purpose is to check on the time elapsing since a fix was obtained on each target. If the probability for any target drops below a pre-assigned minimum, the target is dropped.

The first box in the Signal Program takes R and θ data from the radar, corrects for any known set errors and transforms the position to X, Y position coordinates. The probability is attached according to the known characteristics of the radar obtaining the signal.

The second box selects the area slice for target comparison as described above. The third box extracts targets from Stack 2 and examines them to find out if they lie within the probability circle of the new signal. An index is kept which tells whether a match has been obtained and, if so, how many. The third box examines the index and transfers the control to a different set of operations, depending on how many matches have been obtained.

If there were no matches between signal and existing target, the signal is presumed to represent a new target. Then its position and probability are sent to the new target plot and to the main plot.

If there is a match, a check is made to see whether there is exactly one or more. If there is one match only, the new signal is presumed to add information to the previous fix on that target. The new probable position of the target and the probability of that position are computed. Corrections are made to the stored rates for that target. The new target information is then set for the main plot.

If the new signal matched with more than one existing target, the targets are too close for the resolution of the radar. Correction is made by computing the expected position of the CG of the target in question, comparing that with the measured position obtained from the radar, correcting the CT position according to the probability and then apportioning this correction to the several targets according to the precision of their fix. The corrected information is then sent to plot for all the targets. All necessary work has now been done on this signal and the computer can return to other duties.

In the Target Loss Program, the targets are taken one by one. The time of the last fix is stored with each target. Present time is obtained by reading some master clock. The elapsed time since the last fix is used to decrease the stored probability of the target position. The next box checks on the probability remaining for that target fix. If the target has been lost, the information is sent to the plotting board and the target is removed from Stacks 1 and 2. All targets are checked in turn. If a signal arrives during

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the course of the Target Loss Program, the target loss check is deferred until the signal has been cared for. The computer then returns to the target loss examination at the point where it stopped.

The flow diagram for this problem has been carried out in considerably greater detail than shown in Figure 11, but the complete coding of the orders has not been done. Estimation from the detailed flow diagrams shows that about 450 orders are required for both the Signal Program and the Target Loss Problem. Of these, almost 400 are required for the Signal Program alone.

It is not necessary to go through the entire 400 orders of the Signal Program for each signal coming in. On the average, assuming not more than three targets in an average slice, and this estimate seems high, a total of 300 orders is required for each signal. Estimated information on the problem is given below:

Total orders required	450
Average operations per signal in	300
Average computing time per signal in (WWI)	6 milliseconds
Data storage required irrespective of targets and radar	100 registers
Storage required per target	12
Storage required per radar	3

The total time and capacity required for a problem consisting of a maximum of fifty targets and ten radar sets is as follows:
The sets are assumed to have an average sweep period of ten seconds.

Storage capacity required for targets	600 registers
Storage capacity required for radars	30 registers
Storage capacity required for data	100 registers
Storage capacity required for orders	450 registers
	1180 registers
Time required	300 milliseconds per second

This problem requires roughly one-half the storage capacity and one-third the operating time of WWI.

Figures used in this memorandum:

1	B-31091
2	B-31092
3	A-31093
4	B-31094
5	A-31095
6	A-31096
7	A-31097
8	A-31098
9	B-31099
10	A-31100
11	A-31101

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JWF:RRE/has:vh

B-31091

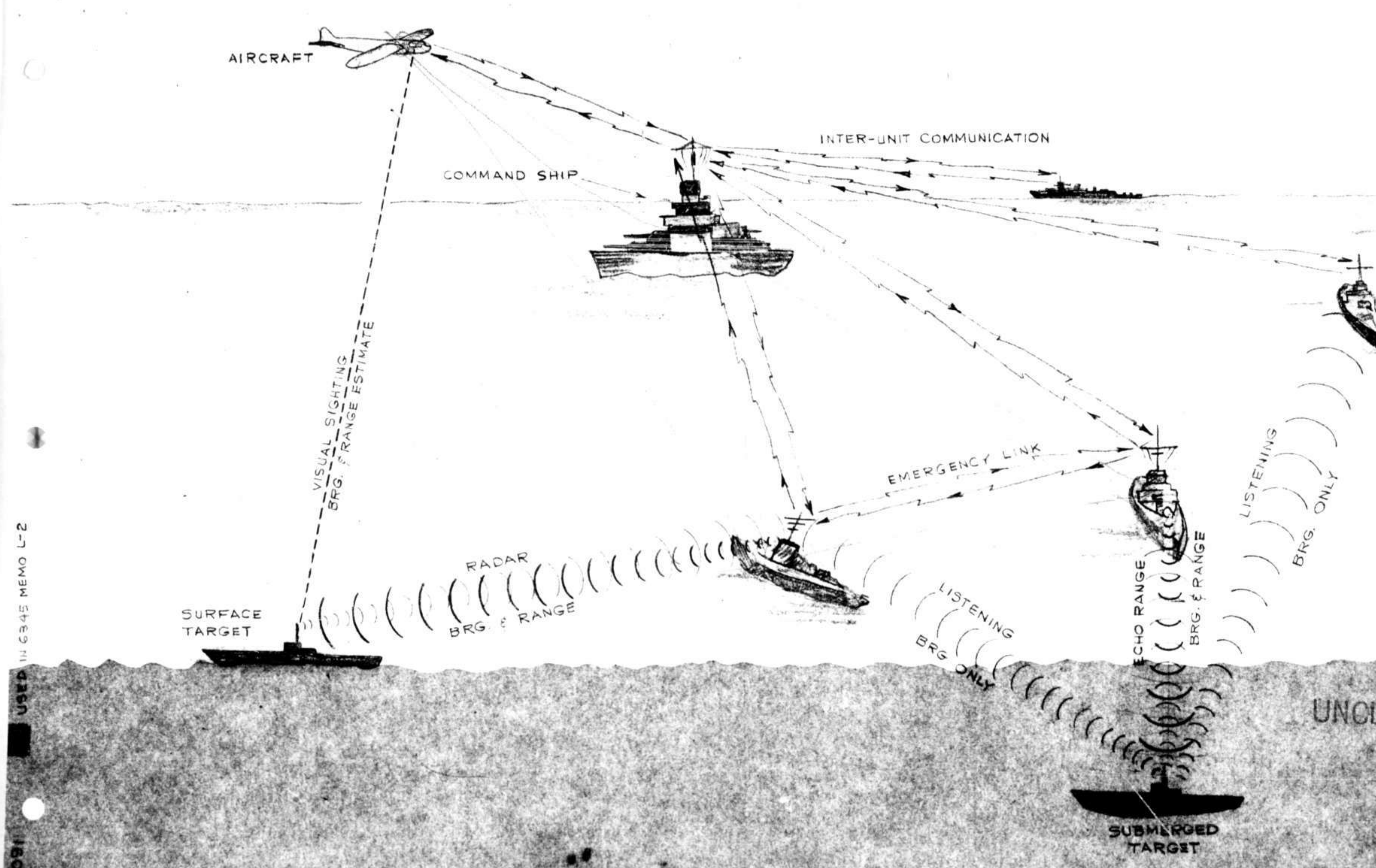
AIRCRAFT
INTER-UNIT COMMUNICATION
COMMAND SHIP
VISUAL SIGHTING
BRG. & RANGE ESTIMATE
EMERGENCY LINK
RADAR
BRG. & RANGE
SURFACE TARGET
LISTENING
BRG. ONLY
ECHO RANGE
BRG. & RANGE
LISTENING
BRG. ONLY
SUBMERGED TARGET

FIG. 1

B-31092

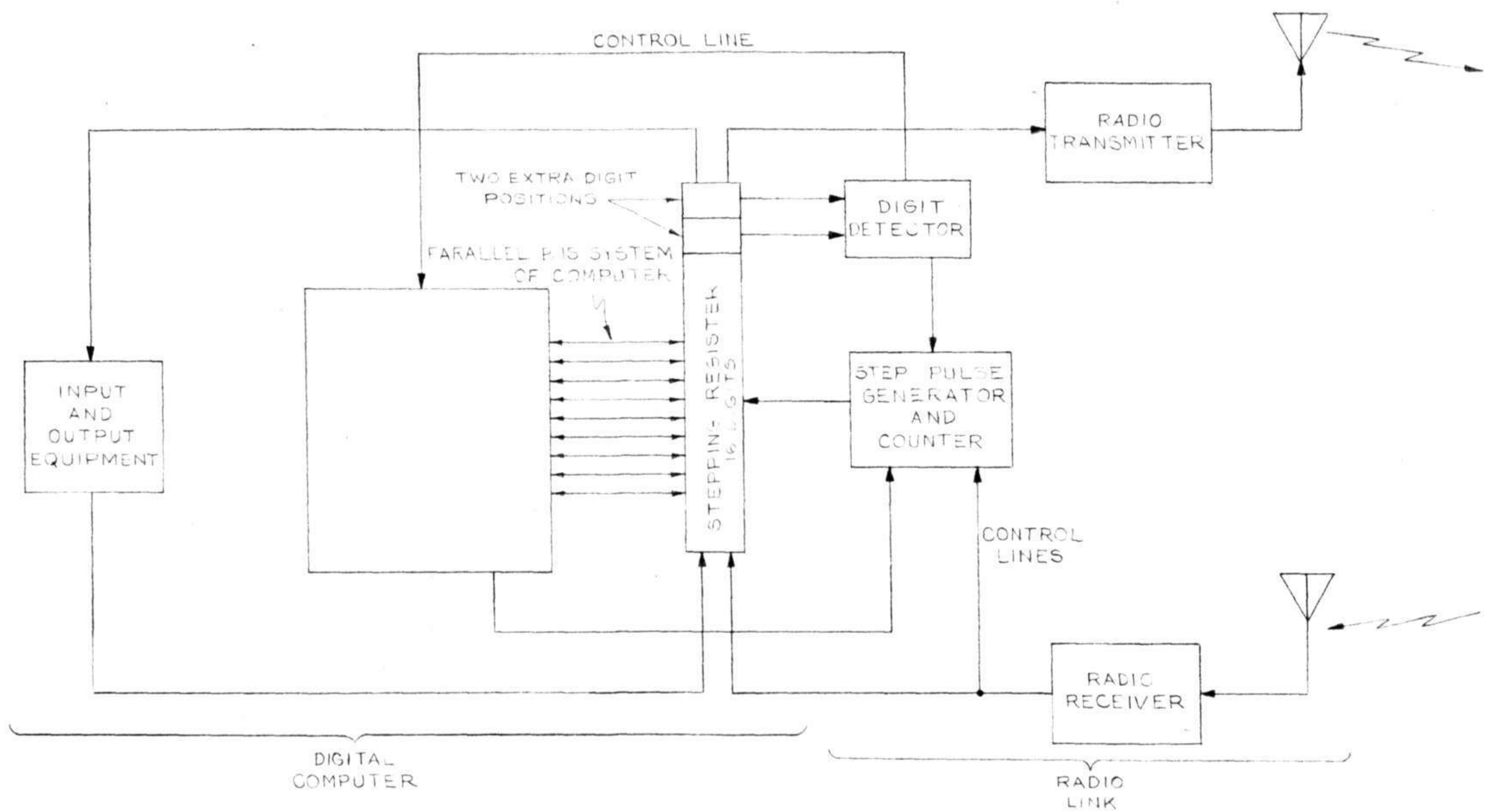

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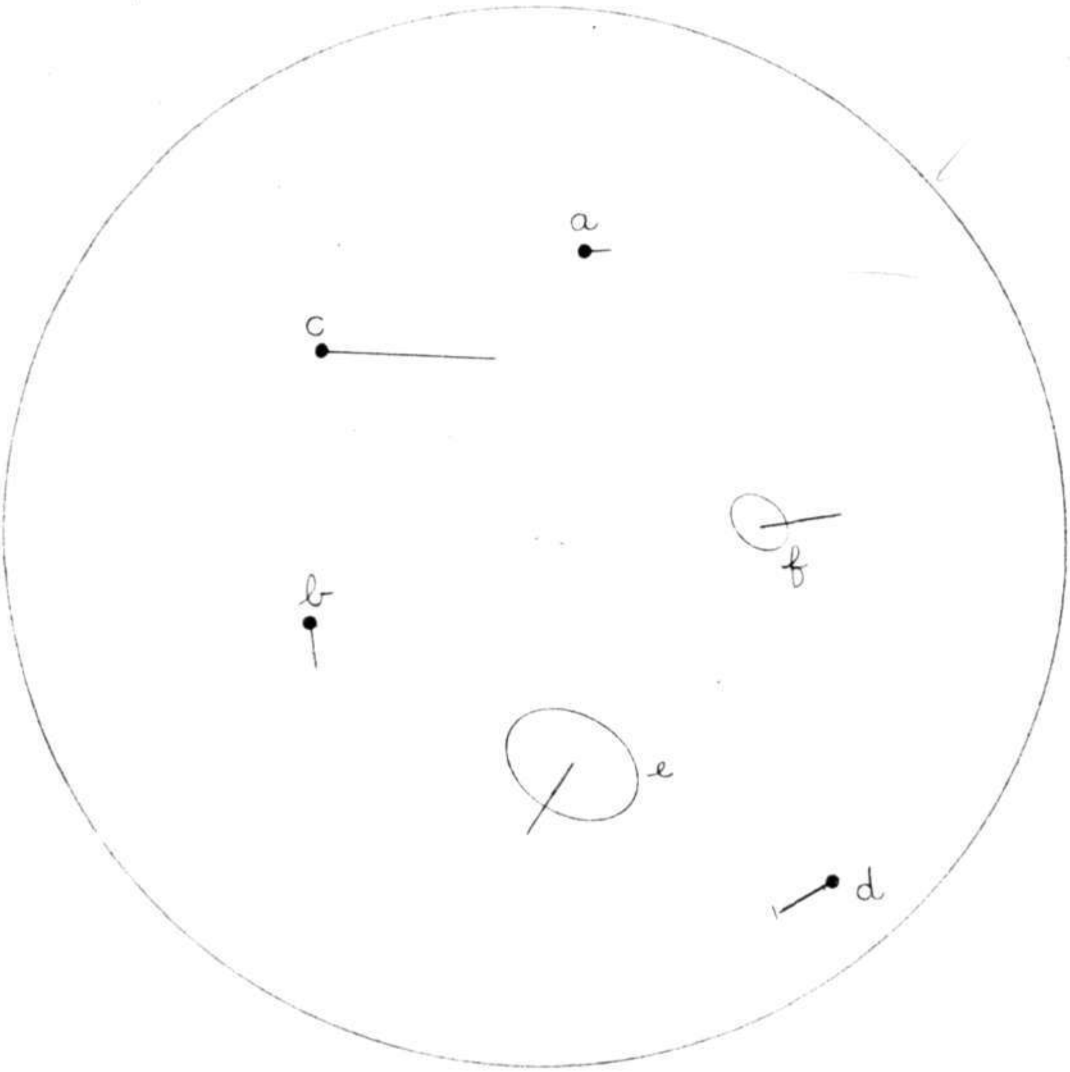
FIG.2

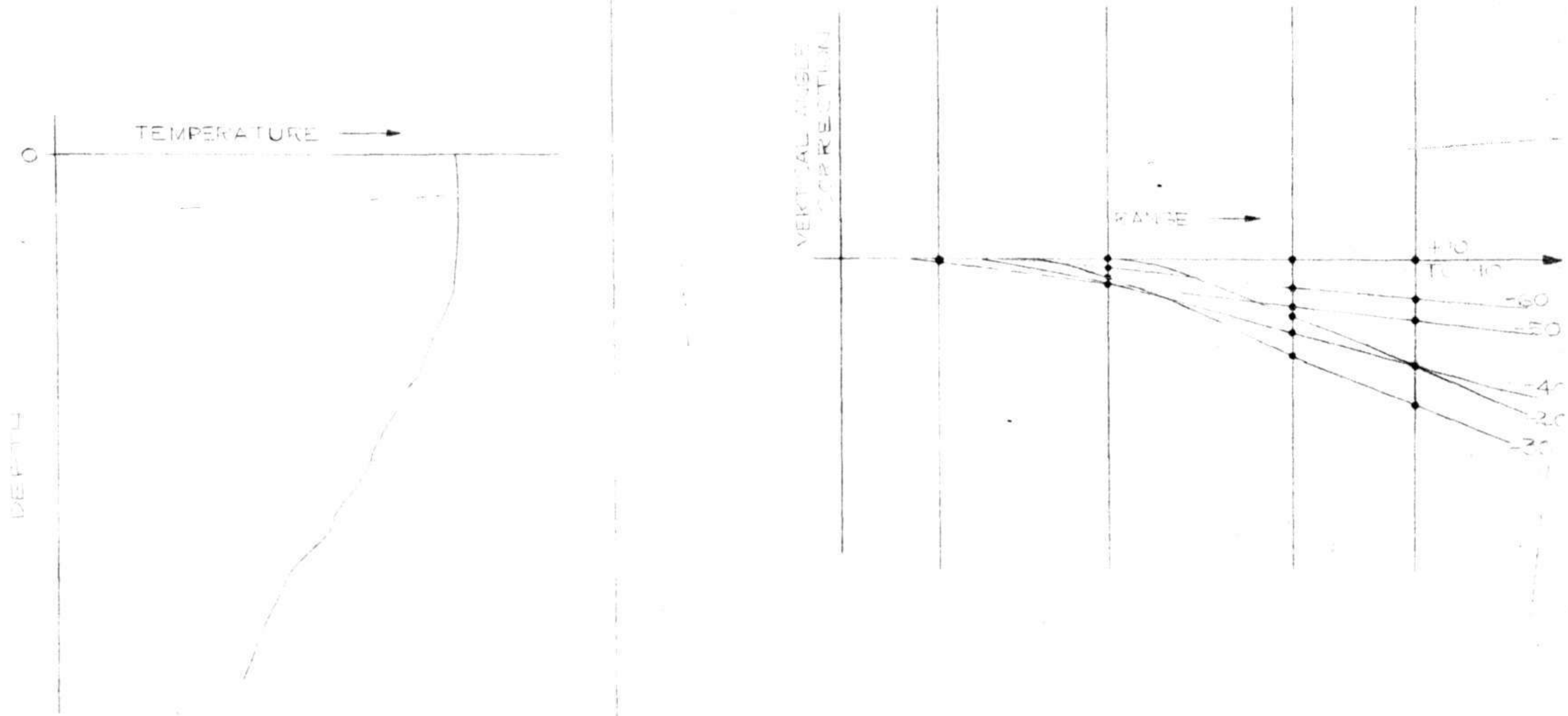
B-31092



DATA PRESENTATION

FIG. 3

B-31094



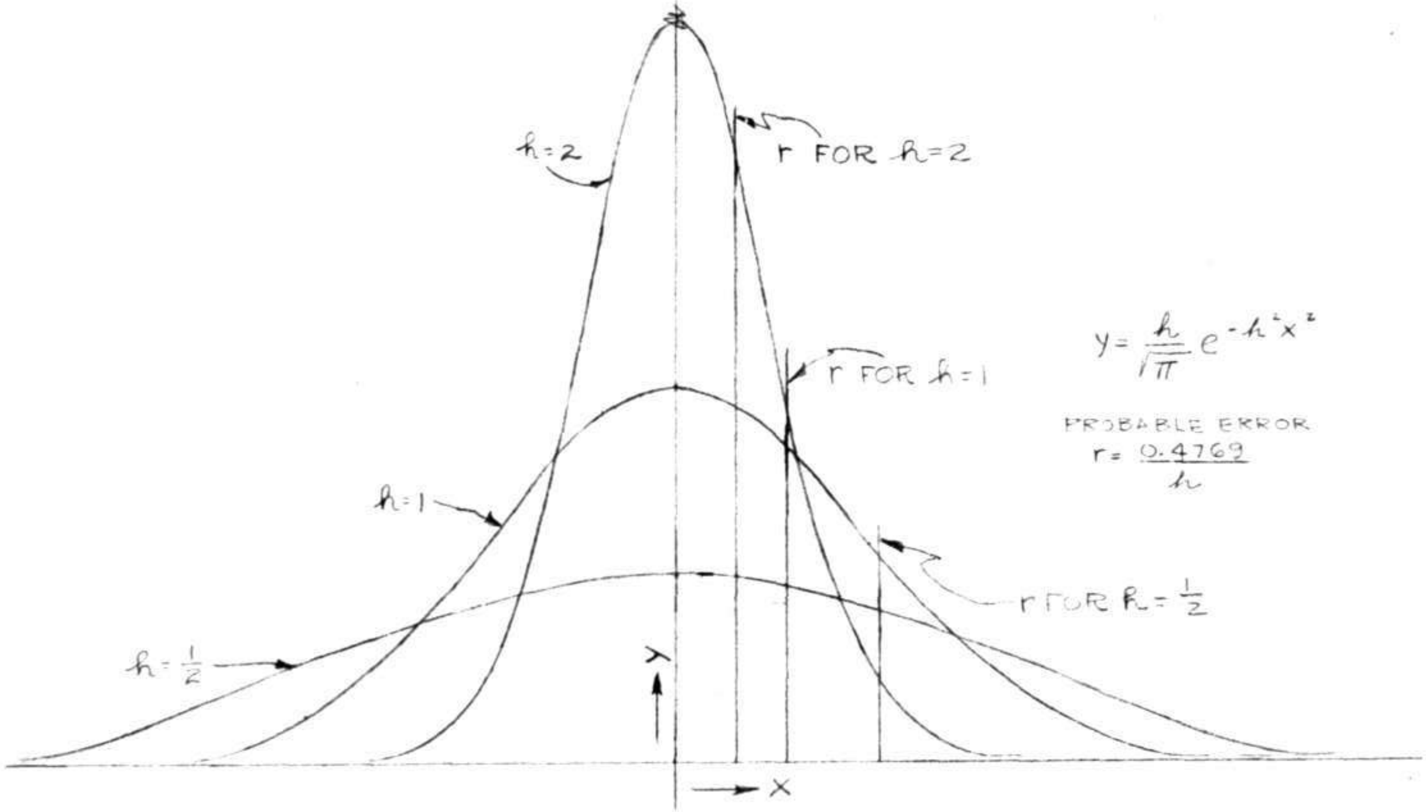
TEMPERATURE PATTERN MIKE AND VERTICAL ANGLE CORRECTION TABLE.

FIGURE 4.

USED IN 6345 MEMO L-2

B-31094

A-31095 USED IN 6345 MEMO L-2



NORMAL ERROR CURVES

FIG. 5

[redacted]

A-31096 USED IN 6345 MEMO L-2

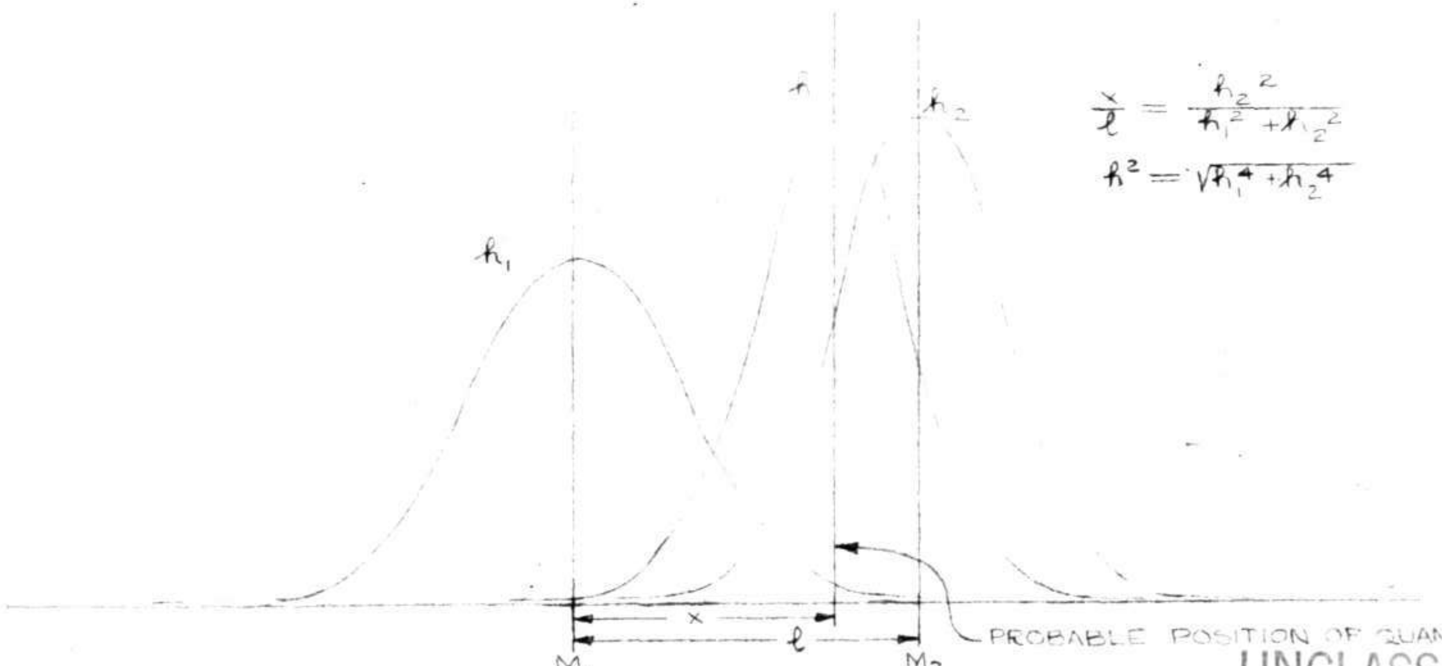


FIGURE 6
TWO MEASUREMENTS OF KNOWN PRECISION.

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[redacted]

A-31097

USED IN 6345 MEMO L-2

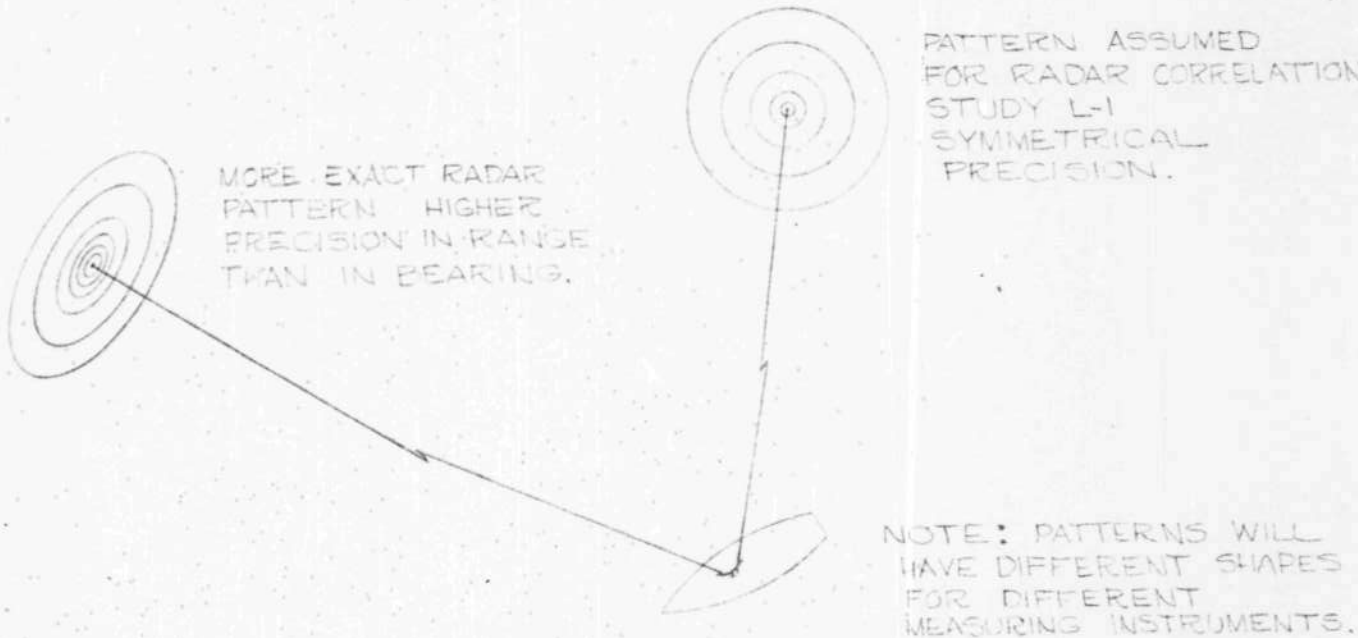

FIGURE 7
PROBABILITY PATTERNS FOR RADAR CORRELATIONS

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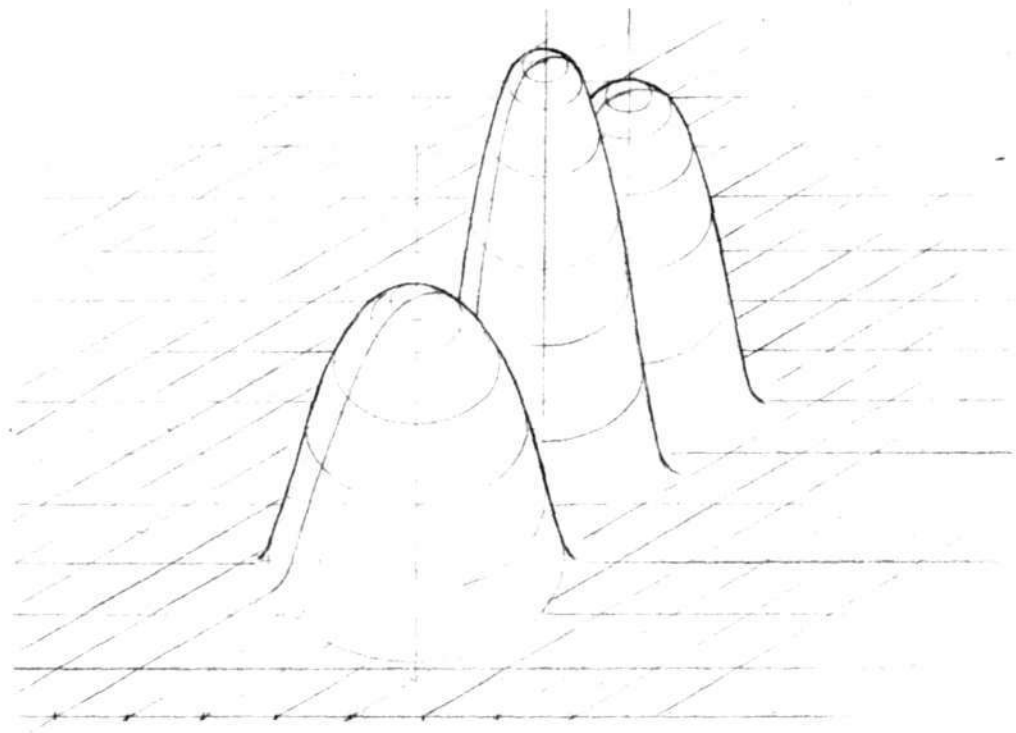

TWO-DIMENSIONAL ERROR CURVES

FIG. 8

B-31099

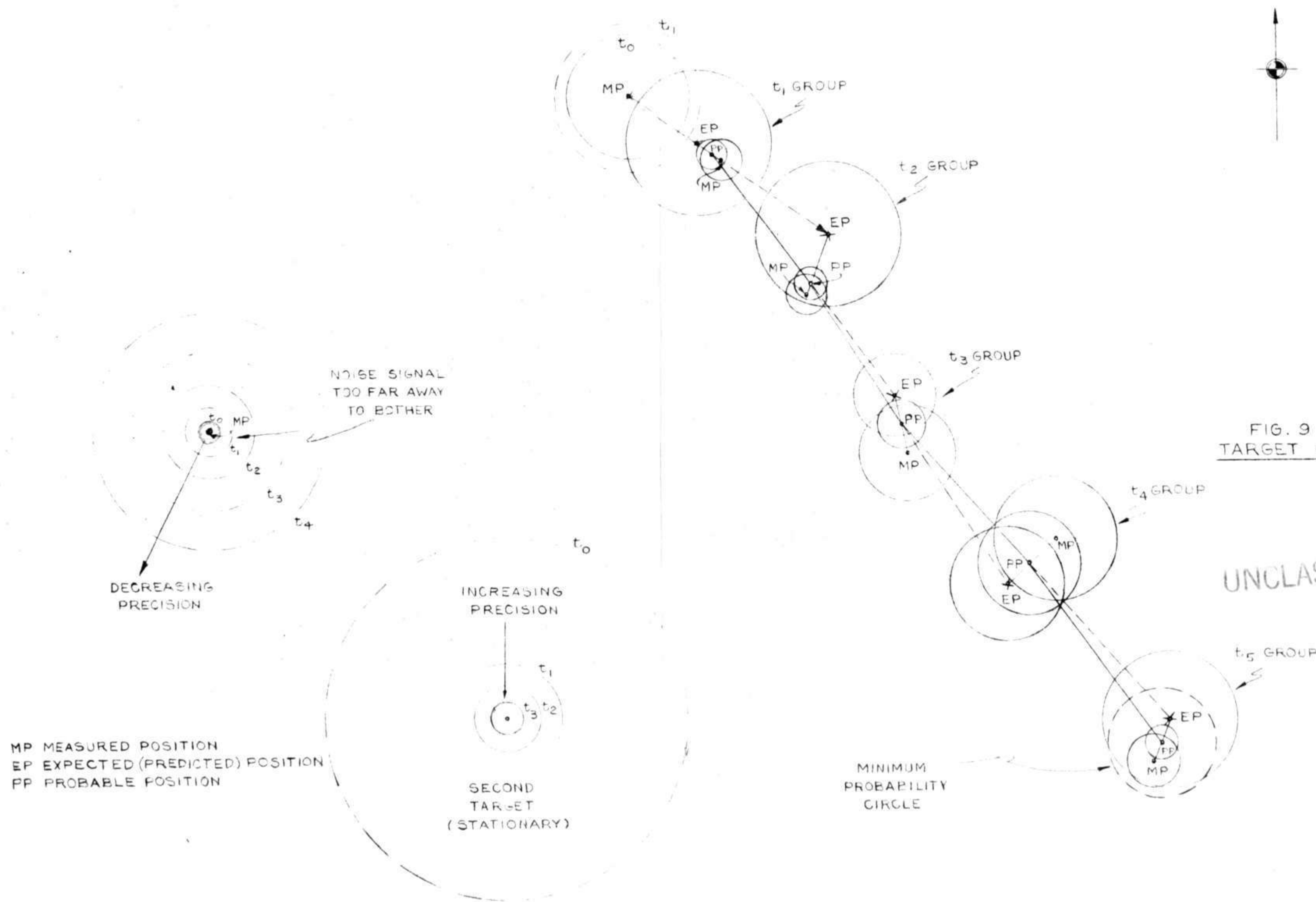

FIG. 9
TARGET PATH

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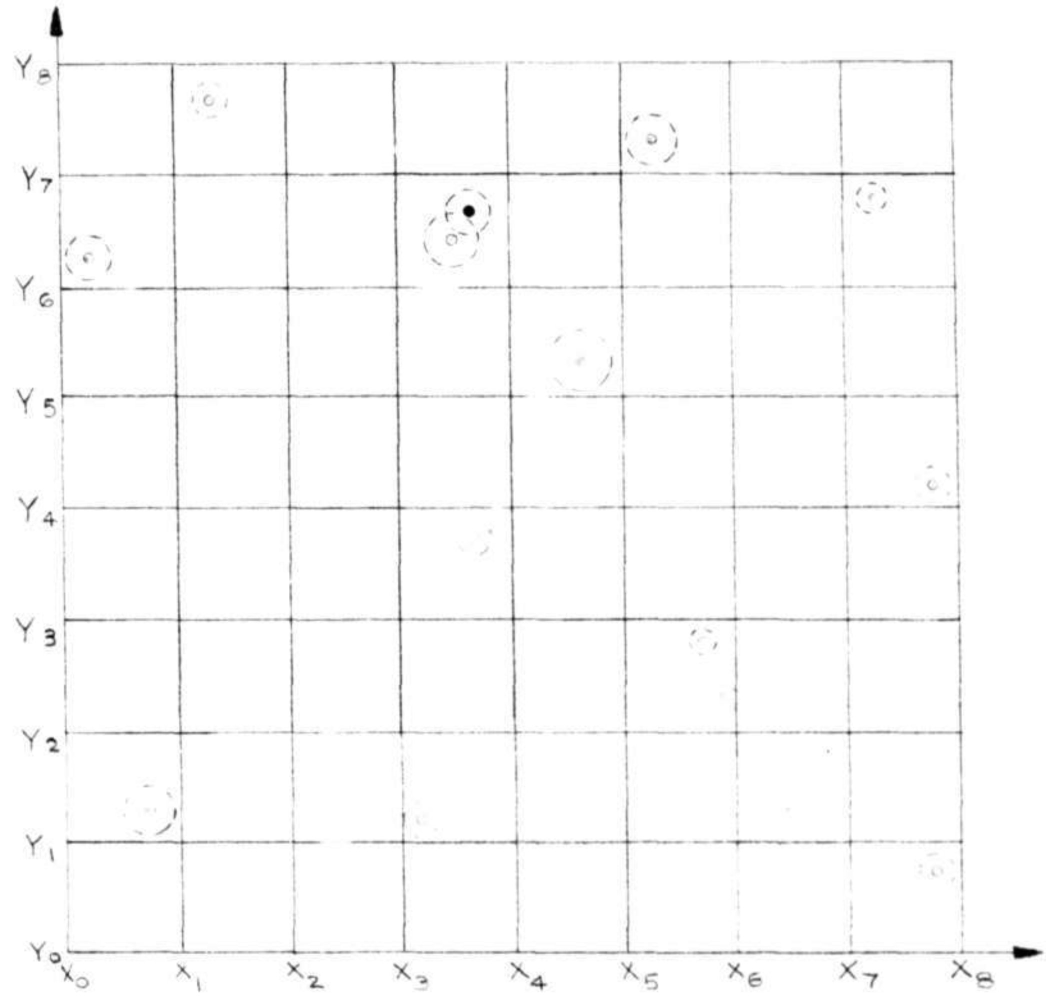
B-31099 USED IN 6345 MEMO L-2



EXISTING TARGETS ◦
SIGNAL •
PROBABLE ERROR CIRCLE

FIGURE 10.
TARGET DISCRIMINATION BY AREA.

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[redacted]

A-31100 USED IN 6345 MEMO L-2

A-31101

FIG. 11
GENERAL FLOW DIAGRAM -- RADAR CORRELATION

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[redacted]