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SHIPBORNE RADAR FIRE CONTROL FROM THE SYSTEM VIEWPOINT

by

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ABSTRACT

Radar fire control involves more than the tracking radar, which is the primary source of target position information during the tracking phase of the fire-control process. The task before the system engineer, concerned with the design or critical evaluation of a fire-control system, is to follow the flow of target information from the search radar which originally detects the target, through the various steps by which the original low-precision target information is finally transformed into high-precision gun orders. Both the time spent in deriving the gun orders and the accuracy of the orders themselves, as well as certain other matters, must be considered in judging the performance of the entire system. The factors effecting data accuracy at each step of the process, as well as the data "matching" problem presented by the steadily increasing data accuracy required by each successive step, are analyzed.

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SHIPBORNE RADAR FIRE CONTROL FROM THE SYSTEM VIEWPOINT

Robert M. Page and John B. Trevor, Jr.*

INTRODUCTION

The papers that have appeared to date in the technical press on radar as applied to fire control have dealt with circuit and operating details of specific fire-control radars. This class of radar generates present position information of targets for injection into a gun-order computer.

It is not our purpose to add to the available information on fire-control radars (or, as we prefer to call them, "tracking radars") but rather to examine the whole process of radar fire control, and to see where the individual radars and other components fit into the fire-control system. We shall confine ourselves to the most complex form of radar fire control, calling for the greatest refinement of equipment and the most careful integration of components, namely, shipborne radar fire control. Emphasis will be on the antiaircraft aspects of this type of fire control.

A complete fire-control system is composed of a chain of at least two radars, and a number of other electronic and electromechanical units. The design of any one unit must take into account the overall system specifications, and particularly the output characteristics of the preceding unit and the input characteristics of the following unit in the chain of components. This state of affairs is commonplace in the engineering disciplines: the unique feature of the fire-control situation is that target-position information, and a derived quantity, gun orders, are the elements which are passed on from stage to stage.

We shall see that the basic problem in the design of a fire-control system is the need to transform the target-position information collected by the search portion of the system at low precision, into the high-precision information needed to develop gun orders. The order of magnitude of the errors in the original data, the additional errors which are added as the data flows through the system, the means which are taken to increase the accuracy of the original data, and the required precision of the final output, will be considered.

Turning to Figure 1, we see a typical block diagram of a complete shipborne antiaircraft fire-control installation. No particular existing or proposed system is intended; all elements have been kept as general as possible. The system is supposed to be in action against an approaching aircraft flying a radial course toward the installation at a speed of 200 knots. The upper portion of the figure is a plot of target range versus time. At zero time the airplane comes within the maximum theoretical range (30 miles) of the system for a target of its type and altitude. The initial contact, however, is not made until three minutes later. This contact is made by the first unit of the system, the "Search Radar". This radar is designed to keep a large surface area, and a large aerial volume, about the ship

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under nearly continuous observation. The introduction of radar at this point in the fire-control system replaces the optical search of older systems. The most outstanding advantage of radar is its freedom from visibility and lighting restrictions. The output of this stage is the approximate position of the target, together with some information on course, size, and type of target. A truly surprising amount of information can be read from the search-radar indicator by a skilled operator. We shall see later, nevertheless, that, at this stage, there are very severe limitations on the accuracy at which the target position information can be collected.

The second stage, named "IFF," establishes if the target is a friend or a non-friend. Electronic methods of establishing this point have much the same advantages over optical methods that radar search has over optical search. In the example under consideration, the IFF establishes that the target is a non-friend.

The information collected in the first two steps is passed on to the "Evaluator". This individual, combining the information of the first two steps with other data, reaches the decision, in our example, that the target is to be tracked by one of the director tracking radars.

He notifies the "Designator" to this effect. (The evaluator and the designator may, in an actual system, be the same individual. They are shown separately here because the two functions are essentially distinct.) The "Designator" selects a particular gun director from those available and orders it to track this particular target. This decision takes into account the fire-power and present assignments of the various directors.

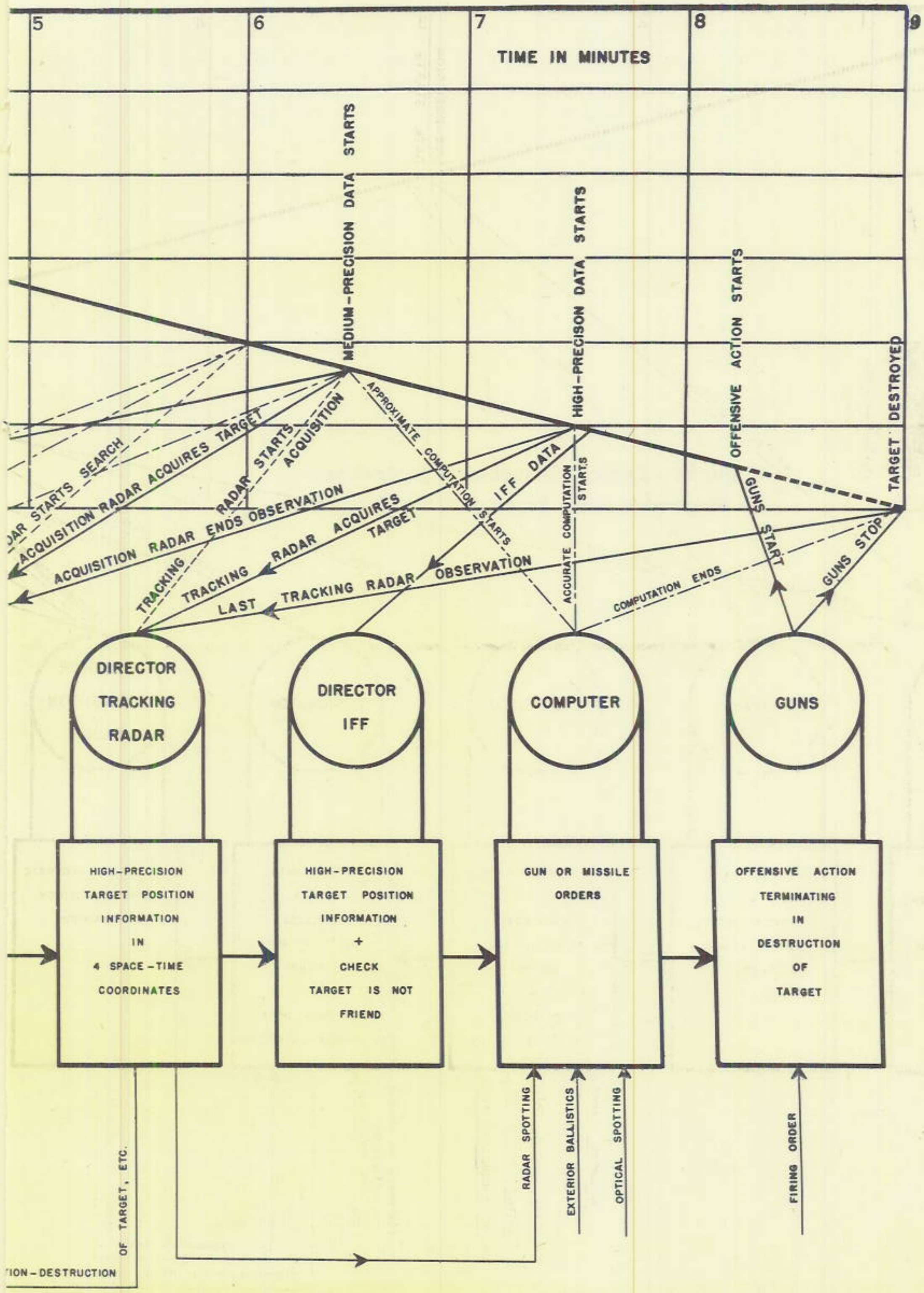
The director which has had the target designated to it receives the "Search Radar" data, modified by the delays and inaccuracies that exist in the designation system, and then attempts to "acquire" this target. In our example, acquisition consists in first putting the "Director Acquisition Radar" on target, and then the "Director Tracking Radar". The first of these radars has an antenna beam width intermediate between the broad-beam "Search Radar" and the pencil-beam "Tracking Radar". It is able to get on target rapidly with the relatively inaccurate search data, and once on target, it gives medium-precision target position information needed to put the "Director Tracking Radar" on target. It might be remarked that the "Director Acquisition Radar" does not have to be a separate radar from the "Tracking Radar;" the latter may have a "wide-beam" adjustment for acquisition. It may even be possible to put the "Director Tracking Radar" on target without an intermediate step.

When the "Director Tracking Radar" is on target, the generation of high-precision target position information starts. This radar continues on target until contact is broken off with the target. There may be a check by the "Director IFF" to be sure that a friendly target, somehow or other, is not being tracked instead of the designated target.

The "Computer" transforms the target position information into gun orders. The high-precision target-position information is required for generating accurate orders but there may be some saving in time by feeding the medium-precision target-position information to the computer before the "Director Tracking Radar" is on target.

The "Guns," in response to a specific firing order, transform the gun orders into offensive action.

There are certain pieces of information which must be conveyed from one part of the system to another. Radar spotting may give information to correct inaccuracies in gun orders. The director must notify the designator on the result of the offensive action.



hipborne Anti-Aircraft Fire Control

Figure 1 - Typical Sequence of Operations in Shipborne Anti-Aircraft Fire Control

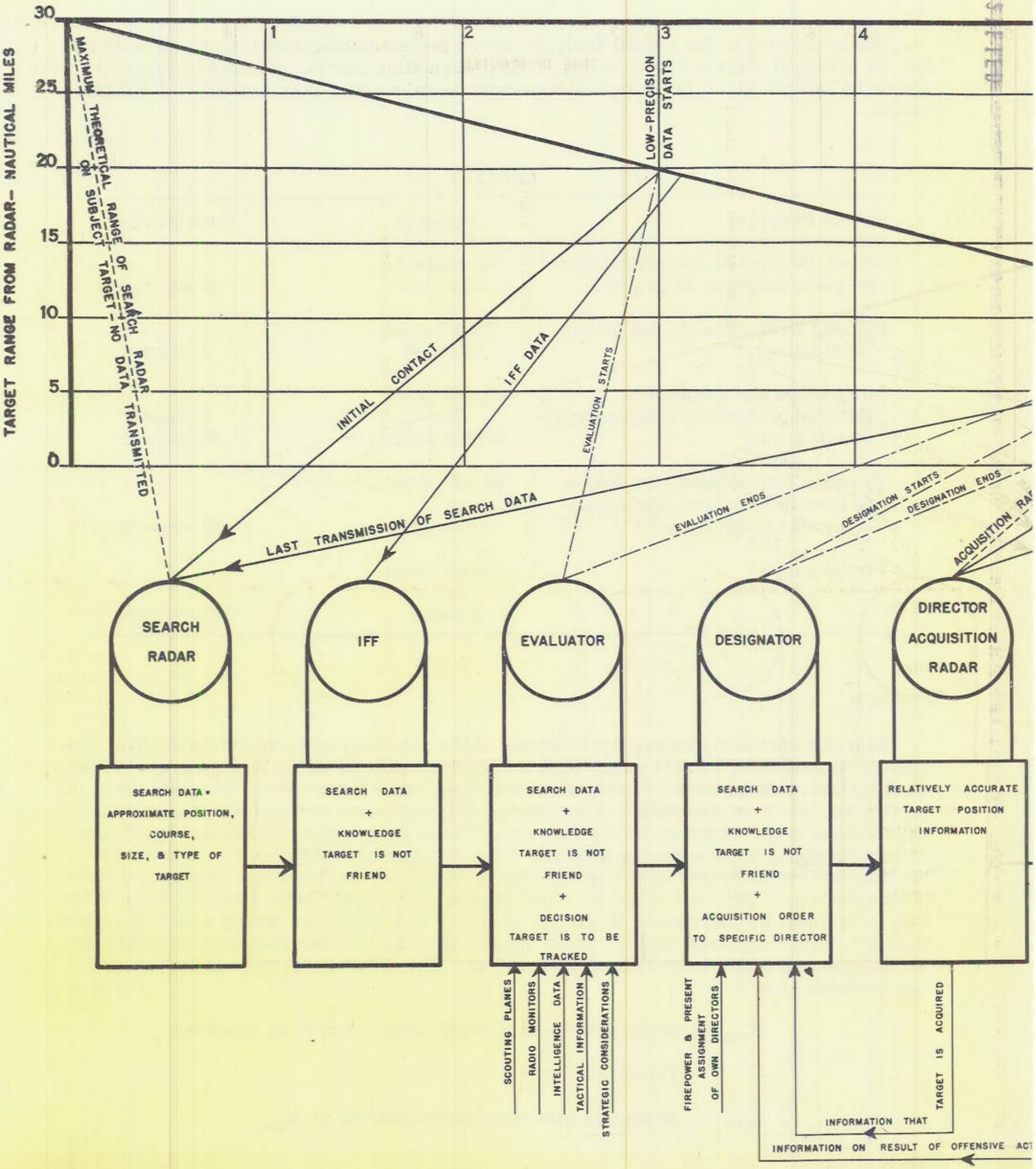


Figure 1 - Typical Sequence of Operations in S

Before turning to the formal analysis, let us see something about the times available for the principal stages of the process. This information, for the example of Figure 1, is shown in Table 1 which gives typical approximate values at a target speed of 200 knots radial.

TABLE 1

Step of Process	Distance	Time Available
Search (Maximum theoretical range on given target is 30 miles)	30 miles to 20 miles	3 minutes
IFF and Evaluation (Initial pickup at 20 miles)	20 miles to 10 miles	3 minutes
Designation and Acquisition (Maximum tracking radar range 20,000 yards)	20,000 yards to 10,000 yards	1 minute 30 seconds
Tracking and Computation of Gun Orders to first shot (Maximum gun range 5,000 yards)	10,000 yards to 5,000 yards	45 seconds
Firing Range	5,000 yards to 0 yards	45 seconds

SEARCH

Search radar provides the first warning of the existence of enemy targets. The high speed of present-day targets requires that search be carried out to a long range. There is, therefore, a large surface area of sea and land, and a large volume of space above the earth's surface to be kept under observation. All portions of the region to be examined must be kept under as nearly continuous surveillance as possible, so that excessive target motion between glimpses can be avoided. The search radar performs its examination of the searched region by the rotation or oscillation of a directional antenna which successively illuminates all portions of the searched region. The requirement that continuity in the time coordinate be approached limits the accuracy with which the spatial coordinates can be found. The roll, pitch, and turning of shipborne mounting decreases the accuracy of the search-radar data to an even greater extent. The effect of the various factors will now be found. Let

$R_{\max}$ = Maximum range at which targets are to be observed

C = Velocity of light

$t_{\max}$ = Maximum echo time corresponding to $R_{\max}$

Then

$$t_{\max} = \frac{2R_{\max}}{C} \tag{1}$$

The quantity $t_{\max}$ is the time of two-way travel for echoes from targets at maximum range. For the purposes of this paper, we must increase $t_{\max}$ as derived from (1) by a minimum of perhaps 50 percent to allow for circuit recovery time and to reduce long-range echoes of the previous transmitter pulse. This step gives the minimum allowable interval between successive pulses. We shall see that it is advantageous to use the minimum value.

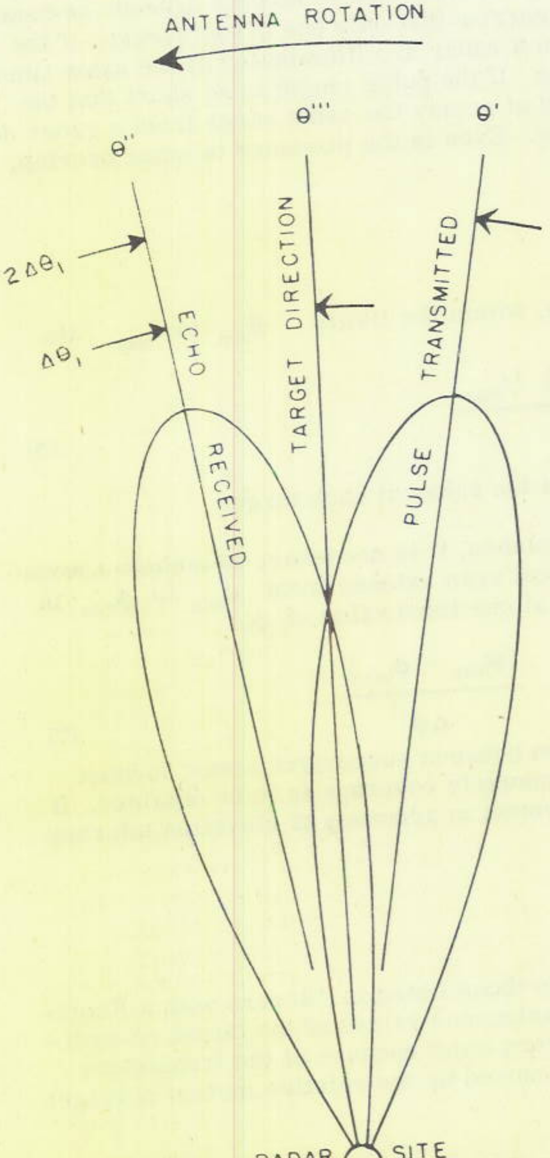


Figure 2 - Error in Target Bearing Due to Antenna Rotation

Errors with a Fixed-Base Search Radar and a Fixed Target

The first angular error to be considered is $\Delta\theta_1$, the error due to angular motion of the antenna during $t_{\max}$. The value of $\Delta\theta_1$ in terms of the rotation $d\theta/dt$, is given by:

$$\frac{d\theta}{dt} = \frac{2\Delta\theta_1}{t_{\max}} \tag{2}$$

This relation can be verified from Figure 2. During the time $t_{\max}$ the antenna moves from θ' to θ''. The target is actually at the intermediate position θ'''.

A second source of bearing error, originating in the finite width of the antenna beam, will be called $\Delta\theta_2$. Suppose, during the time the antenna beam scans a target, a single pulse is emitted. If the antenna beam width is θ_B, then $\Delta\theta_2$ will be of the order of $\pm\frac{1}{2}\theta_B$. If there are N pulses emitted while the antenna moves an angular distance θ_B (where N is an integer sufficiently great so that the degree of resolution of the cathode-ray screen is reached) we can reduce $\Delta\theta_2$ to its minimum by writing for N

$$N = \frac{\theta_B}{2\Delta\theta_2} \tag{3}$$

The corresponding relation between the angular velocity of the antenna and $\Delta\theta_2$ is:

$$\frac{d\theta}{dt} = \frac{\theta_B}{N t_{\max}} = \frac{2\Delta\theta_2}{t_{\max}} \tag{4}$$

Establishing the criterion that

$$\Delta\theta_1 = \Delta\theta_2 = \tfrac{1}{2}\Delta\theta$$

where $\Delta\theta$ is the total angular error from both causes we can write:

$$\frac{d\theta}{dt} = \frac{\Delta\theta}{t_{\max}} \tag{5}$$

Conventional designs of search radar hold $d\theta/dt$ to a low value, reducing $\Delta\theta$ to a very low magnitude compared to the errors still to be considered. The low value of $d\theta/dt$ allows a relatively large number of pulses to fall on each target during every scan; the cumulative addition of successive echoes causes an increase in the effective signal-to-noise ratio.

Data accuracy in the presence of two or more closely spaced targets depends on beam width and pulse length. If the beam width is so narrow that only one of two targets at the same range and at nearly the same bearing from a radar are illuminated at the same time, bearing resolution of the two targets is complete. If the pulse length is so short that the echoes from two targets at the same bearing and at nearly the same range from a radar do not overlap in time, range resolution is complete. Even in the presence of some overlap, two closely spaced targets can be resolved.

The Scanning Time

Given scanning in one co-ordinate plane only, within the limits $\theta_{\min}$ to $\theta_{\max}$, the minimum value for T, the scanning time, is

$$T = \frac{(\theta_{\max} - \theta_{\min})\ (t_{\max})}{\Delta\theta} \qquad (6)$$

The quantity T is the interval between "looks" of the radar at each target.

With scanning in both vertical and horizontal planes, it is necessary to include a term to take care of vertical scan. If the angle of vertical scan extends from $\phi_{\min}$ to $\phi_{\max}$ in steps, and a complete horizontal scan takes place at one fixed value of ϕ,

$$T = \frac{(\theta_{\max} - \theta_{\min})\ (t_{\max})}{\Delta\theta} \cdot \frac{(\phi_{\max} - \phi_{\min})}{\Delta\phi} \qquad (7)$$

The quantity $\Delta\phi$ is the angular distance in elevation between successive scans; it must not be greater than the beam width in elevation if complete coverage is to be obtained. It may be somewhat less than this value with improvement in accuracy of elevation information.

Additional Search Errors with Moving Targets

A fixed-base radar is subject to errors, besides those listed in "Errors with a Fixed-Base Search Radar and a Fixed Target," in the instantaneous values of the target co-ordinates if there is motion of the target. The same errors exist because of the translatory motion of a ship-mounted radar. These errors are caused by the relative motion of target and radar during the interval T.

While these errors may exist in any of the three spatial co-ordinates in which target position information is collected (bearing, elevation, and range) the most serious error, from an operational standpoint, is the bearing error. If $\Delta\theta_v$ is the bearing error from this cause, $V_{\max}$ is the maximum target velocity, and R is instantaneous range,

$$\Delta\theta_v = \frac{T V_{\max}}{R} \qquad (8)$$

Assuming a target with a V_{max} of 200 knots, and assigning $T = 10$ seconds, $\Delta\theta_V$ may have an instantaneous value up to 6 degrees at a range of 10,000 yards. The same value of T will give, by substitution into (6) for a total scanning range of 360 degrees and a t_{max} of 1,000 microseconds, $\Delta\theta = 0.036$ degrees.

This example brings out a difference in the requirements of search for early warning and for fire control. Early-warning search requires extreme long range, with little regard to the value of T. Fire-control search, on the other hand, with its lesser emphasis on maximum range, can afford to do without the increased signal-to-noise ratio and the low $\Delta\theta$ associated with a large value of T, in order to get substantial reductions in $\Delta\theta_V$.

Errors Due to Deck Motion

The deck of a ship is subject to roll, pitch, and turn. The deck motion is imparted to a search radar fixed on the ship. The effect of this motion is to cause extremely large errors in the search data, and more particularly, in the data after it has passed through the designation system. These errors can be divided into three parts:

(A) Errors with respect to the instantaneous deck plane itself,

(B) Errors with respect to the horizontal plane,

(C) Additional errors with respect to the deck plane and the horizontal due to the time delay in the designation system.

Search data collected on a rolling, pitching, and turning deck is, at the instant of collection, and with respect to the deck plane itself, only slightly less accurate than the same data collected by a fixed-base radar. The additional sources of error come about from great angular rates of the antenna scan at the instants when deck motion and antenna motion are additive, thus increasing $\Delta\theta$; from errors due to targets being missed on some scans, thus increasing $\Delta\theta_V$ and the errors in range and elevation associated with T; and principally, from the deterioration of resolution and precision due to the "smearing" of the indicator presentation. In spite of these difficulties, if the search information could be used instantaneously to set a deck-mounted tracking radar on target, the additional errors due to deck motion might not be too serious. It is, of course, unavoidable that a delay should take place between the collection of the data and its use; during this interval the deck moves and substantial errors appear.

The existence of the aforementioned delay makes it essential to refer the data to a fixed frame of reference. The horizontal plane is defined as the plane tangent to the earth's surface at the point instantaneously occupied by the surface ship. The correction to the horizontal may be made by mounting the search radar antenna on a device which removes some or all the components of deck motion, by correcting the data to the horizontal after collection by the radar, or by both methods used together. Stabilization of the antenna removes the errors with respect to the deck plane, and hence is to be preferred. Complete stabilization, by use of a stable platform, may be too bulky; if so, partial stabilization in level (that is, in the vertical plane containing the line of sight) or in cross-level (that is, in the vertical plane normal to the vertical plane containing the line of sight) may be used. All types of stabilization equipment have residual stabilization errors which may have to be considered in an actual installation.

The effect of the time delay in the designation system on the magnitude of the errors depends both on the delay itself and on the periods of the roll and pitch. For a given value of roll and pitch, the total error may vary from zero to twice the maximum error of the search data with respect to the horizontal. This upper limit is reached if the search radar collects the data at one extreme of deck tilt, and the tracking radar is set at the other extreme.

Figure 3 shows the relation between true and indicated bearing and elevation for a certain angle of deck tilt and for a target at a relative bearing B_R from the bow and an elevation E from the horizontal. The angles B_R' and E' are the indicated bearing and elevation in the absence of cross-level stabilization. When cross-level stabilization is applied, B_R'' and E'' are the corresponding angles. The substantial correction in the bearing co-ordinate due to cross-level stabilization is apparent.

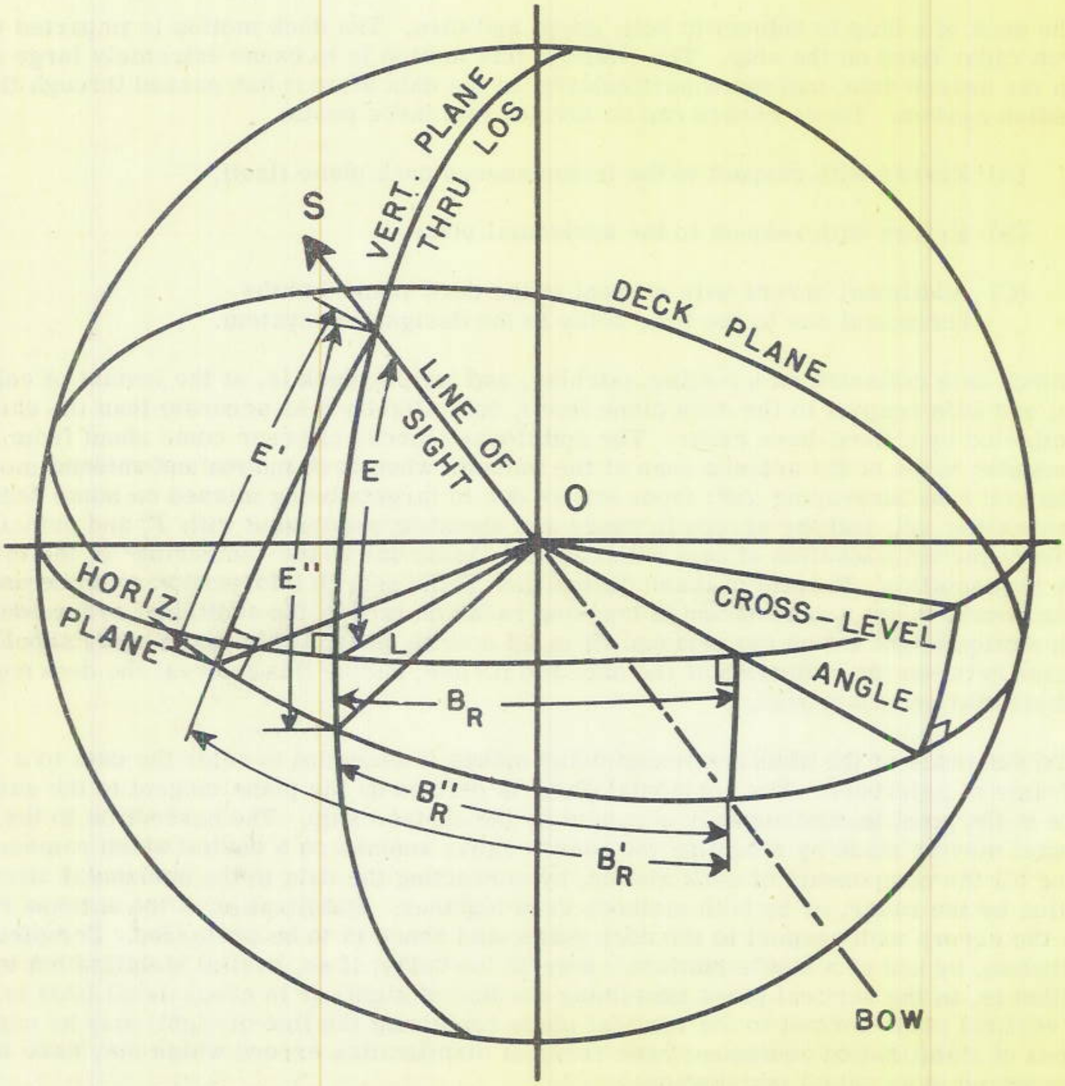


Figure 3 - Target Angles and Deck Tilt

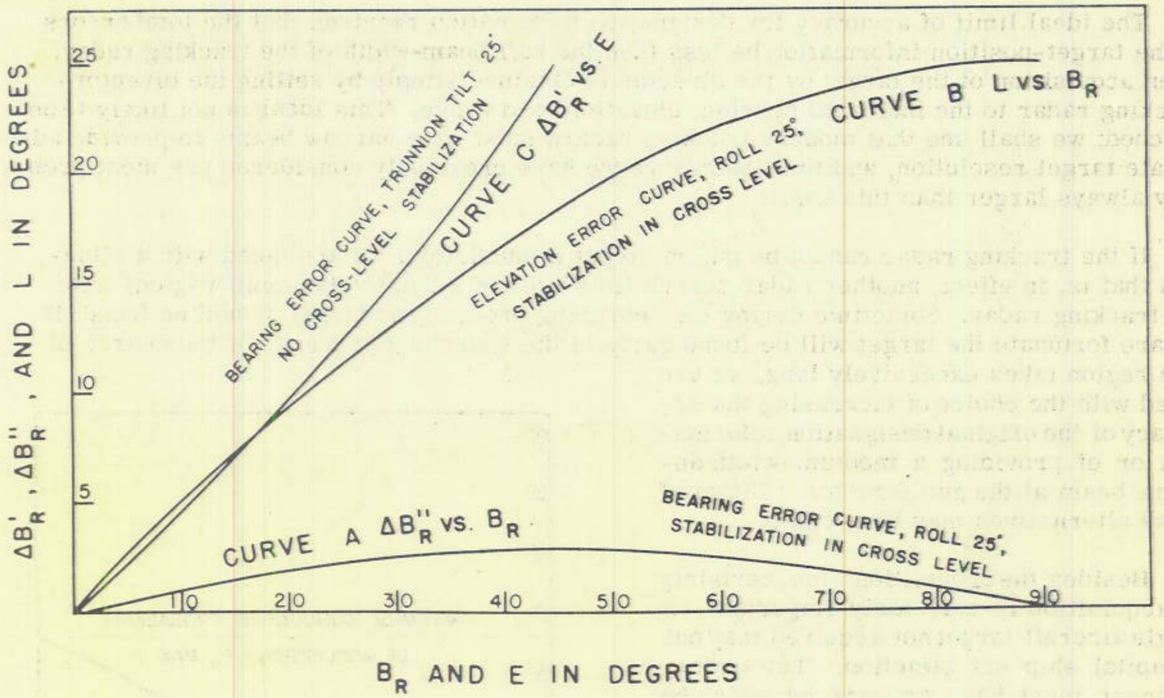


Figure 4 - Angular Errors Due to Roll

Some idea of the amplitude of the errors with unstabilized search and cross-level stabilization for roll only with a maximum amplitude of 25 degrees is given by Figure 4. Curve A shows the maximum value of $\Delta B''_R$, the difference between the correct value of the relative bearing B_R in the horizontal plane and the value as measured in the deck plane. The quantity $\Delta B''_R$ is plotted against the correct value of B. Curve B is a similar curve for the elevation error L in the presence of cross-level stabilization. Curve C shows the bearing error $\Delta B'_R$, without cross-level stabilization as a function of E, the elevation angle. This curve is taken for an antenna trunnion tilt of 25 degrees.

DESIGNATION AND ACQUISITION

Once the target position information reaches a director, it is used to put the director on target. There is a definite relationship between the accuracy of the designation information and the time it takes to put the director tracking radar on target. And time is a vital factor in target acquisition. The director should be on target and generating accurate gun orders at least by the time the target reaches maximum firing range. There is also another reason why acquisition should be rapid--the designation process ties up personnel and equipment which may be needed for other designations.

The target position information of the search radar comes to the gun director with the errors previously considered and also with any inherent errors which may exist in the designation system. There may be bias errors, backlash, or dispersion errors of minor or major importance.

The ideal limit of accuracy for designation information requires that the total errors in the target-position information be less than the half beam-width of the tracking radar. Then acquisition of the target by the director is obtained simply by setting the director-tracking radar to the indicated bearing, elevation, and range. This ideal is not likely to be reached; we shall see that modern tracking radars must have narrow beams to provide adequate target resolution, and that the errors we have previously considered are most probably always larger than this limit.

If the tracking radar cannot be put on target immediately, we are faced with a situation that is, in effect, another radar search (this time of a relatively small region) with the tracking radar. Sometime during the searching process the target should be found; if we are fortunate the target will be found early in the searching process. If the search of this region takes excessively long, we are faced with the choice of increasing the accuracy of the original designation information or of providing a medium-width antenna beam at the gun director. Either of these alternatives may be adopted.

Besides the acquisition time, certainty of acquisition is extremely important. A single aircraft target not acquired may put a capital ship out of action. The system engineer must have criteria by which he can measure these two acquisition factors. A convenient measuring system is provided by the curve of Figure 5. Suppose that a certain time T_A can be assigned for acquisition. Normally, this time will be the time it takes for a target to travel from maximum tracking radar range to maximum gun range. It can be shown, for any given system, that the cumulative probability of acquisition increases from zero (at the instant acquisition starts) to some maximum value less than 100 percent at T_A. The maximum value, and probably the form of the curve, vary with different systems and different operating conditions. The curve of Figure 5 is theoretical; the given conditions are only approximately those of any existing system. From this curve we define the maximum cumulative probability of acquisition as the cumulative probability of acquisition at T_A. The acquisition time is defined as the time at which the cumulative probability of acquisition reaches some substantial value, say 90 percent of its final value.

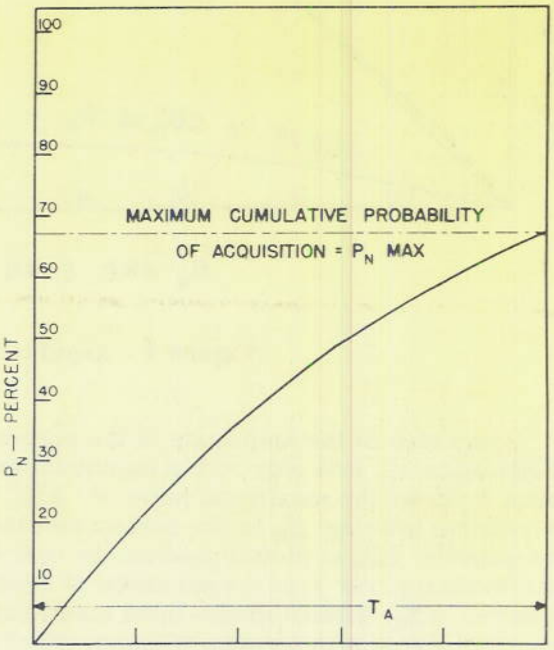


Figure 5 - Cumulative Probability of Acquisition

The present practice, in many acquisition tests, is to fit the standard cumulative probability curve to the acquisition data and take the asymptote and the 90 percent point as the maximum cumulative probability and the acquisition time. This practice eliminates the derivation of special acquisition curves.

The determination of acquisition criteria for any system cannot safely be found in any way except by measurement. The system itself, as well as the test conditions, such as target courses, amount of roll and pitch, and personnel ability, must all be specified. It is desirable to make definitive acquisition tests under conditions approximating the operational situation. The need for fixing the test conditions, however, makes it undesirable to hold the tests on shipboard. A roll-and-pitch platform allows control of the test conditions to a satisfactory extent. An important feature of acquisition tests is the statistical analysis of data so that the reliability of the results are known.

TRACKING

We have already indicated that a wide beam on a tracking radar antenna facilitates acquisition and that a narrow beam favors accurate tracking. We will now indicate what is the required accuracy of tracking and find the maximum beam width that will allow this accuracy.

Briefly, the data accuracy of the tracking radar should be such that the survival probability of a target being shot at is limited only by the characteristics of the computer, the guns, and the shells. These last-named units are certain to have errors such that even if the target position is given at all times with complete accuracy there will be bias errors and dispersion errors which prevent every shot from exploding within lethal distance from the target.

An ideal overall system always places the shell explosions within the maximum distance to the target at which there is severe damage. The required accuracies of bearing, elevation, range, and time can be computed if the effective target volume, range, speed, and course of the target are known.

Assuming a low-flying aircraft on a pass course, with a speed of 200 knots, and an effective target length (actual length plus distance at which shell explosion is lethal) of 300 feet, an effective target height of 220 feet, the maximum allowable deviations of ballistic quantities from those for a direct hit are given in Table 2 for a range of 1000 yards, 5000 yards, and 10,000 yards at the point of closest approach. These accuracies are derived from simple geometrical considerations.

TABLE 2

Range-yds	Range Accuracy-%	Bearing Accuracy	Elevation Accuracy	Time Accuracy-sec
1000	± 5	± 2°52′	± 2°8′	± 0.30
5000	± 0.5	± 0°34′	± 0°25′	± 0.30
10,000	± 0.25	± 0°17′	± 0°13′	± 0.30

Now let us see how we can relate the tracking accuracy with the beam width. Angle position indication is provided in a lobe-switched tracking radar by balancing the signal from one lobe against that from the opposite lobe. Considering the effects of signal fluctuation and random noise, the limit to which the amplitude of the two lobes can be balanced is, perhaps, 5 percent of the amplitude of the on-target signal. Assuming that beam crossover is at the half-energy point, and that the antenna pattern for one lobe can be represented by the conventional sin x/x form, the ratio of overall beam width (between the two half-energy points away from the center of the beam) to the overall tracking accuracy is approximately 100:1. If we wish the tracking radar to have a high accuracy compared to the allowable errors shown in Table 2, we may say that the ultimate accuracy is to be ± 2 minutes. This gives a total beam width for acquisition of over 3 degrees, and a lobe beam width of over 1.5 degrees. These figures are presented to illustrate the method of computation, not as examples of present-day practice.

The ultimate accuracy we have derived from antenna patterns is the accuracy we can expect to approach on isolated fixed targets. On moving targets, the instantaneous angular rates which the gun director is obliged to develop will effect the accuracy. These rates may be extremely high. A low-flying aircraft passing a radar at a minimum distance of 500 yards at a speed of 300 knots calls for angular velocities up to 19 degrees per second and angular accelerations up to 4.2 degrees per second per second to stay on target. The angular errors of the director servo-mechanisms, including the effects of any human links in the chain, must be evaluated for the required maximum rates. Such evaluations can be made analytically, although the experimental procedure is advisable where definite information on a particular system under actual operating conditions is needed. The solid curve of Figure 6 shows the result of a typical tracking run.

Instantaneous vertical and lateral deviations are plotted against time and range. True target bearing and elevation are found by optical means and the radar errors found by

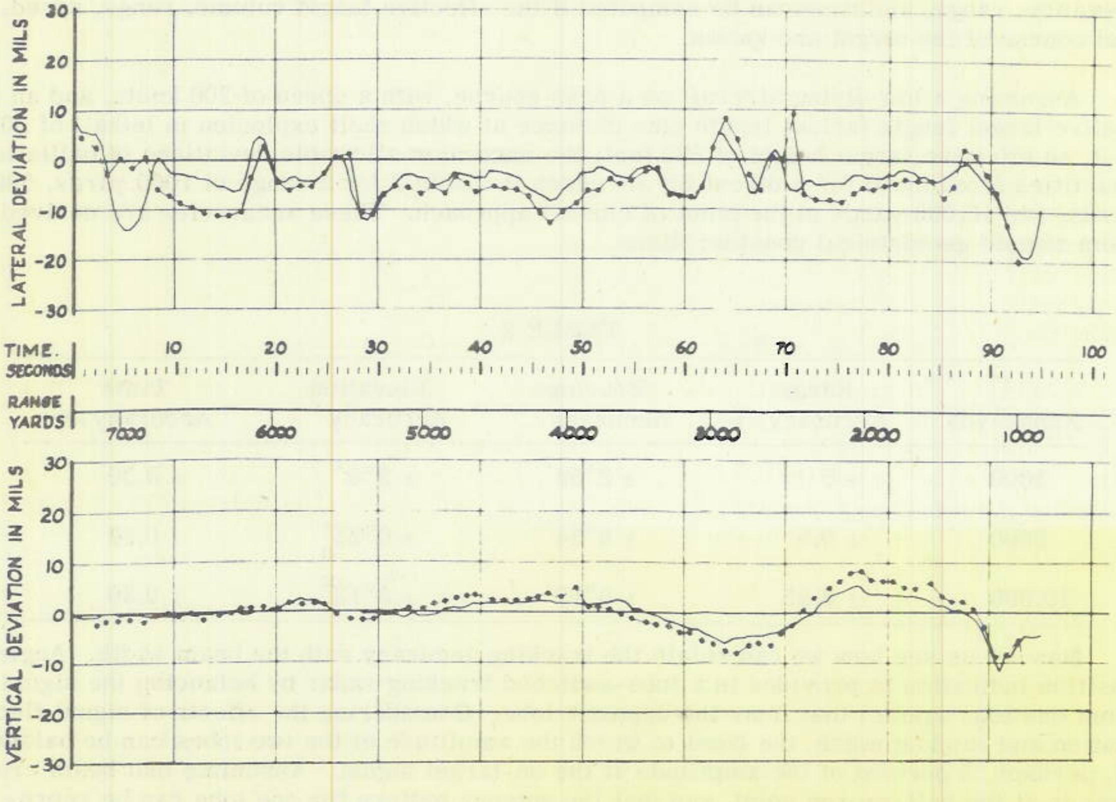


Figure 6 - A Typical Tracking Run

taking the difference between radar and true values. A number of such runs, under different conditions, form a complete tracking study of a tracking radar. These runs can be analyzed for mean error, error as a function of angular rates, and cyclic components in the errors. The existence of certain frequency components in the errors may excite resonant oscillations in certain portions of the equipment.

It might be remarked that a single tracking test, involving a few dozen runs, can yield tens of thousands of individual computations. The scientists of Radio Division III responsible for tracking tests have developed electromechanical methods of data processing that materially cut down the time and personnel requirements of these tests.

ACCURACY OF GUN ORDERS AND FIRING

The tracking radar information is applied to the computer for the solution of gun orders. Solution errors can be found if corrected target position information, as given by a tracking test, is used to compute "gun orders to hit" with the aid of ballistic information on the shells to be employed. Actual gun orders, as generated by the computer when supplied with the radar tracking data, are compared with gun orders to hit. Error curves similar to the beaded curve of Figure 6 can be prepared for solution errors. The time scale of the tracking data is displaced by the time of flight of the projectile so that corresponding tracking and solution errors are in the same vertical line.

Solution errors can be analyzed for mean error, and error as a function of angular rates. It is also of interest to know the "solution time," or period from the initial injection of tracking information into the computer until an accurate solution is generated. The solution time has an important bearing on performance with changing or evasive target courses.

The final test, including errors in all parts of the tracking system, is the firing test. This test is a dramatic demonstration of how the entire system performs, but yields relatively little engineering information which cannot be found more easily and accurately by the detailed tests.

SUMMARY

This brief and superficial analysis of shipborne radar fire control is intended to indicate the methods by which individual radars and other fire-control components are judged from a system standpoint. Besides the matter of data accuracy, a complete evaluation calls for an exhaustive analysis of many other factors, such as the effect of land clutter on data accuracy, weight and reliability factors, and general adaptability to naval service.

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