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SOME TACTICAL LIMITATIONS OF BEAM-RIDER, COMMAND, AND SEMI-ACTIVE HOMING GUIDANCE SYSTEMS

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ABSTRACT

A discussion is given of the tactical problem of Naval air defense. Assumptions are made as to the most probable types of aircraft targets to be engaged by the Fleet in the next five to ten years. Factors pertaining to target detection and acquisition are discussed and assumptions are made as to the probable time requirements for each, thereby obtaining the status of each of the targets at the time of acquisition by the shipboard tracking radar. A discussion of the low-angle tracking problem is given and a target summary is made for the condition when equivalent free-space tracking is first reached.

In the light of the targets, detection, acquisition, and radar tracking criteria assumed, the probable tactical effectiveness of beam-rider guidance with wide-angle beam capture is discussed. The same considerations are given the case of beam-rider guidance with guidance during the boost phase. Possible guidance errors of the beam-rider system are discussed, giving consideration to errors caused by system noise, by target maneuvers, and by failure of the tracking radar to discriminate between multiple targets. A hypothetical probability of kill is reviewed to illustrate the meaning of the errors and to indicate the reason for terminal guidance for medium- or long-range missiles. One- and two-beam command guidance systems are reviewed in the light of the previous assumptions and compared with the beam-rider system.

Semi-active homing systems are discussed which employ, in order to combat reflection problems, (a) high frequencies, (b) programmed initial flight, and (c) minimum-altitude control. It is concluded that the system with minimum-altitude control is superior. The problem of multiple-target discrimination is discussed.

A comparison is made of the target status when the beam-rider, one-beam command, two-beam command, and semi-active homing guidance systems each may first be launched against them. Conclusions are reached as to the comparative tactical effectiveness of the different systems and recommendations are made based upon the assumptions of this study.

PROBLEM STATUS

This is an interim report; work is continuing on the problem.

AUTHORIZATION

NRL Problem R05-48R
NR 505-480

SOME TACTICAL LIMITATIONS OF BEAM-RIDER, COMMAND, AND SEMI-ACTIVE HOMING GUIDANCE SYSTEMS

1.0 INTRODUCTION

1.1 That portion of the scientific program of the Naval Research Laboratory which is concerned with control states in part: "Devise and develop new and improved systems for automatically controlling or assisting in the guidance and control of missiles" (1). Problem R05-48R, entitled "New Missile Guidance Techniques," was initiated by the Naval Research Laboratory to provide for the exploitation of new ideas or techniques for missile guidance and control.

1.2 The work of Radio Division III of the Naval Research Laboratory, in the field of fire and missile control systems, has been preponderantly in the field of anti-aircraft defense. Active work in missile guidance and control has been largely confined to ship-to-air missiles. The guidance systems studied and developed by this group have included beam-riding guidance, command guidance, and semi-active homing guidance.

1.3 In the course of the work on beam-rider and command guidance systems at the Naval Research Laboratory it has been reported continually that there exist limitations in the use of these systems against tactical targets (2,3). The most stringent limitations are in the cases of the low-flying target and multiple targets. In addition there exist major problems, as yet unsolved, in the tactical employment of launching and capture systems for either beam-rider guidance or command guidance. The problem of launching dispersions, inherent in the airframe, has also been pointed out.

1.4 The use of command and beam-rider guidance systems has, in general, been relegated to that of midcourse guidance, i.e., serving the functions of bringing the missile to a point where a terminal guidance will take over control of the missile. The use of semi-active guidance systems has been confined to terminal guidance use, acting as an adjunct to midcourse guidance to obtain greater accuracy in the final flight phase with correspondingly higher kill probability. The development of higher powered magnetrons for shipboard fire-control and search radars, which may be used for target illumination, have increased the potentials of the semi-active guidance system to the point where it may be considered feasible to employ such a system from launching to target interception. Superficially it would seem that, if this accomplishment is feasible, a guidance system using only semi-active terminal guidance would be far simpler both in concept and in equipment than a system which involves launching, midcourse, and terminal guidance.

1.5 The purpose of this report is: (a) To examine the probable targets which can be expected in airborne attacks within the next ten years, and (b) to review, examine, and compare the tactical limitations of beam-rider, command, and homing guidance in the light of the most probable airborne attacks.

2.0 THE TACTICAL PROBLEM

2.1 The problem of Naval air defense, in its simplest elements, consists of detecting an enemy airborne target and destroying it before it reaches the critical range at which it can complete its mission of attack, against either the defending ship or another ship of the task force. The problem of air defense is broken down in accordance with the capability of the weapons used to defend the individual ship or task force. In general, the defending weapons fall into three classifications: Defense by combat aircraft; defense by guided missiles; and defense by gunfire.

2.2 Defense by combat aircraft involves the peripheral defense of a task force. While the tactics utilized by this specific means of defense are not under discussion in this report it should be noted that all three defense methods must be integrated in their use in order to make the defense absolute. The relative merit of defense by combat aircraft is indicated by the statistical summary of suicide attacks in the Pacific, which indicate approximately 78 percent of the attacking planes were shot down by the combat air patrol (4). With the advent of higher speeds of combat aircraft it would seem probable that the duration of flight time of the protecting combat plane will be considerably reduced, and the tactical use of the combat air patrol may vary radically from the past. It may well be that the future air defense by combat plane will be of a guided-missile character, that is to say, one in which the combat planes will be maintained in readiness on catapults and dispatched under guidance when a target is detected.

2.3 The tactical employment of air defense by guided missiles will encompass both the defense of other ships and the defense of own ship. The function of the surface-to-air missile will be to engage aircraft targets within the annulus of defending combat aircraft. No statistical data exists as to the effectiveness of the weapon, but the development of tactical missiles and guidance systems must be dedicated to making the defense absolute within the natural limitations of the weapon.

2.4 The final defensive ring is that of gunfire. It is felt that, with the advent of higher target speeds and more difficult targets, the primary usefulness of gunfire will be in defense of own ship. This does not imply that the gun will not represent a weapon against a plane attacking another ship in the fleet, but it is believed that both the character of future targets and greater dispersion of ships within a task force will tend to make the gun become an individual defense mechanism. The relative merit of defense by gunfire is shown by the suicide attack statistics which indicate destruction by gunfire of 75 percent of planes taken under fire (subsequent to destruction of 78 percent by Combat Air Patrol) (4).

3.0 THE ANTI-AIRCRAFT TARGET

3.1 It is recognized that any attempt to visualize probable future targets and target tactics presents an argumentative topic. There are, however, generalizations which may be employed as a basis for the establishment of numbers which will eventually lead to the development of performance characteristics required by the defensive guided missile. One such generalization is that we may expect any future enemy to approach or equal our own development in the field of airborne attack. We may also expect an enemy to be guided by somewhat similar economic and logistic problems. On this basis, for the next five to ten years, it is suggested that the general problem of aircraft defense may be resolved by preparing for five types of targets:

Target One - Piloted aircraft at altitudes up to 50,000 feet, whose attack is directed at an element of the task force or at a land target beyond the defending ship, which may employ air-to-surface guided missiles or which may be fighter protection for low-flying attack aircraft.

Target Two - Piloted torpedo bombers attacking the defending ship.

Target Three - Piloted dive bombers attacking the defending ship.

Target Four - A homing torpedo carrying a missile of the Kingfisher type attacking the defending ship.

Target Five - A homing powered glide bomb at supersonic speed.

3.2 It is assumed that all of the piloted aircraft are subsonic. This assumption is made because, while supersonic piloted aircraft are easily within the realm of possibility, the mechanization of accurate bombsights at supersonic speeds presents a more difficult problem. Further, the employment of supersonic aircraft presents a problem of economics and logistics that renders such use doubtful. It is assumed that piloted targets may have maximum speeds up to 550 knots but probably will attack at speeds of 400 to 450 knots and will be capable of maneuvers up to 6 g's. The guided missiles visualized as possible targets are assumed to be launched from a parent aircraft and, depending upon the character of its mission, may be either subsonic or supersonic.

3.3 These assumptions of most likely types of targets are made to establish the tactical usefulness of a defensive missile guidance system, since it is felt that all, or combinations of all, of these types will be met in any war in the near future. It is impossible within the scope of this report to weigh the proportional probability of occurrence of any specific type of attack, but it is believed that a defensive guided missile, in order to be a truly tactical weapon, must be able to defend an individual ship against any of them. One point is axiomatic. Tactics are evolved from experience at war. If a weakness in defense exists against any type of attack, that tactic becomes the most probable type of attack.

3.4 From the point of view of the defender, the targets must be taken under attack and destroyed before they have reached the critical range at which their mission is accomplished. From the point of view of the attacker, the aircraft must amploy tactics which will increase the probability of accomplishing the mission. This may be done by: (1) Making the aircraft more difficult to detect, (2) making the aircraft more difficult to track, (3) employing maneuvers, and (4) reducing its vulnerability. It can be expected then, that in order to avoid detection, the target will employ tactics such as low-altitude flying to reduce the range at the time of detection, or have an outer coating of material designed to reduce radar relfectivity. The aircraft can be made difficult to track by flying at low altitudes, by jamming, or by otherwise inhibiting the proper use of the tracking device. By proper maneuvers the aircraft may confuse computers, create saturated demands on missile-guidance systems, and increase errors in both tracking and guidance systems. The aircraft may be reduced in vulnerability by decreasing the size of vulnerable areas and by carrying heavier armor.

3.5 In addition to the above and other items, which may be predicted as positive actions taken by an enemy to reduce the probability of kill of his aircraft, as speeds increase the problem of detection and tracking is naturally increased, both as a function of high range rates and by the fact that the aerodynamic shapes of high-speed aircraft present poorer radar reflectors than do those of aircrafts of lower speed.

3.6 Offsetting these difficulties are the positive improvements which may be expected of shipborne search radars, such as the AN/SPS-2, and precision tracking radars, such as the AN/SPG-49. The AN/SPS-2 radar is expected to have an effective coverage out to more than 250 nautical miles to an altitude of more than 75,000 feet for detection of combat aircraft (5). Against a low-flying target the range of any shipborne detection radar is necessarily limited by the radar horizon. Figure 1 shows the radar horizon in altitude of the target (for a radar 100 feet above sea level) vs. range. It can thus be seen that if the target chooses to fly at less than 100 feet altitude it cannot be detected by shipborne radar until the range has closed to less than 17.6 nautical miles.

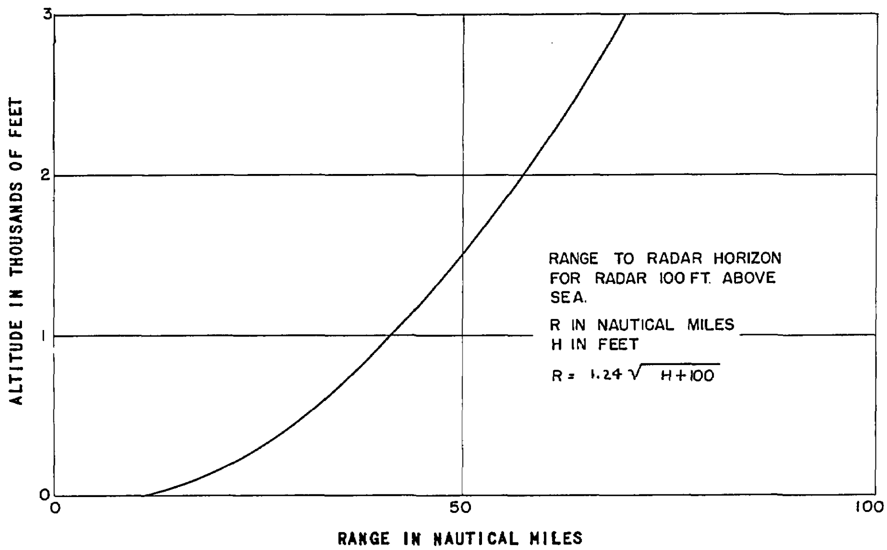


Figure 1

3.7 While it is true that the detection range may and will be extended by the use of airborne search radars, it must be assumed that airborne search is not always available, so that the primary source of detection information must be considered to be that of a shipborne search radar. Further, despite the fact that airborne search may indicate the existence of a target beyond the radar horizon, all of the presently planned ship-to-air missile-guidance systems require that the ship which launches the missile contribute to the guidance of the missile. This necessitates that the defending ship detect, identify, and acquire the target within the limits of the radar horizon.

3.8 In an effort to put numbers to the tactical problem, specific assumptions about the five types of targets are made. In order to investigate the complete tactical system, an estimate of the time existing between detection and completion of the target mission must be made; an estimate of the maximum range of detection and tracking and minimum range by which the target must be destroyed is also desired. The elevation angle subtended between the horizon and the target is a factor in locating and tracking the target and presents a problem in the tactical employment of guided missiles. It is recognized that the assumptions which are made in connection with service speeds and flight paths of the targets have an infinite number of variations, but an effort has been made to put down the most probable conditions which have been indicated in conversation with pilots, purchasers, and manufacturers of Navy military aircraft.

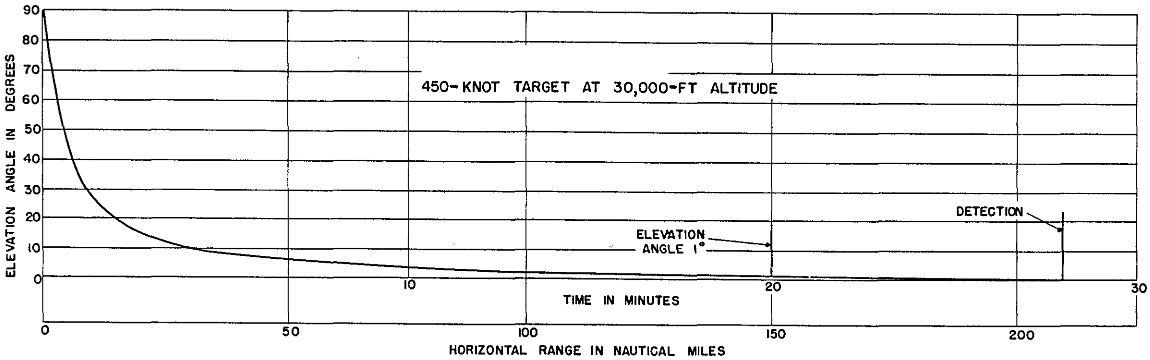


Figure 2

3.9 Target 1. Target 1 is an aircraft whose primary mission is to attack beyond the defending ship. It is probable that such a target would fly both high and fast. It is expected, as an example, that a target flying at an altitude of 30,000 feet could be detected at a slant range of approximately 210 nautical miles by a search radar. At a speed of 450 knots, with the target flying directly toward the defending ship, it will be overhead 28 minutes after its initial detection. Its height will not be determined until the range has closed to approximately 140 miles. It is obvious that time is not a restriction insofar as this target is concerned and that the target can be engaged by the missile as soon as tracking and guidance ranges permit. Figure 2 shows the plot of elevation angle vs. time andrange for Target 1.

3.10 Target 2. Figure 3A illustrates a possible trajectory for an airborne torpedo attack in which the attacking plane flies at an altitude of 100 feet or less to delay detection, then climbs to an altitude of 2500 feet, at which time a glide approach is made to the point of torpedo release, approximately 2000 yards from the defending ship. A plot of elevation angle is shown in Figure 3B, expressed against time in seconds and range in yards. It will be observed from Figure 3A that this 450-knot target will be detected by the search radar at approximately 17.5 nautical miles or 135 seconds before the completion of its mission.

3.11 Target 3. Figure 4A illustrates a typical dive attack on a defending aircraft in which the attacking plane flies at a low altitude to avoid detection, then climbs to approximately 10,000 feet and dives into the attack. A plot of the evaluation angle in degrees is given in Figure 4B against time and range. It will again be seen that the detection of this 450-knot target is limited by the radar horizon and that its probable maximum range at time of detection is about 17.5 nautical miles with 148 seconds remaining before completion of its mission.

3.12 Target 4. Target 4 is assumed to be a torpedo-carrying homing missile which has been released by a parent aircraft at a range of approximately 20 nautical miles. The guided missile flying at 350 knots contains an active homing device, so that the continued presence of the parent aircraft is not required after the missile is released. It is obvious that the most satisfactory solution to this problem would be to destroy the parent aircraft before it has the opportunity of releasing its missile. One critical factor as to whether or not the destruction can be accomplished by a ship-to-air missile released by the defending ship is the altitude of the parent aircraft at the time of release. If the altitude is such that the attacking aircraft is close to the radar horizon, it is apparent that the missile could be released and the parent plane start its return before the tracking

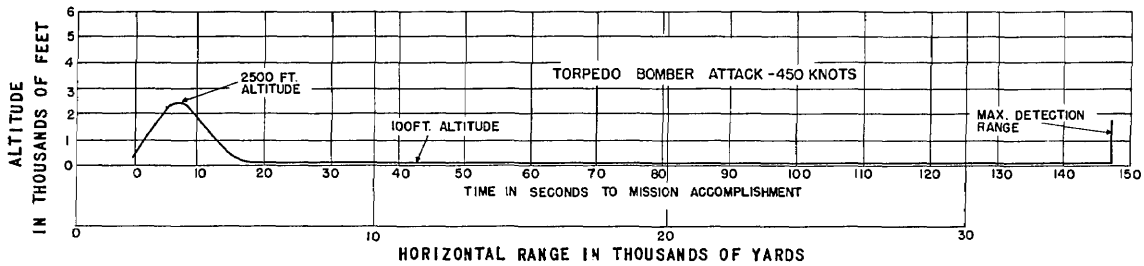


Figure 3A

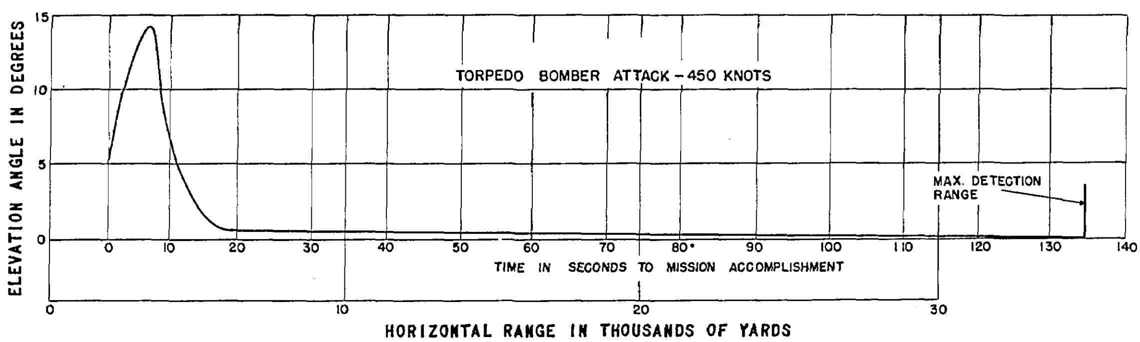


Figure 3B

radar on the defending ship has acquired it as a target. The critical minimum tracking angle for the ship radar is a function of the beamwidth of the radar employed. On the other hand, if the parent aircraft elects to attack at a high altitude, the range of detection will be limited only by the ability of the search radar, and this target becomes the same as Target 1.

3.13 Figure 5A shows one possible trajectory for a torpedo-carrying homing missile released at 500 feet and maintaining a constant altitude until completion of its airborne mission approximately 2500 yards from the defending ship. It should be noted that the radar horizon for the parent plane at 500 feet altitude is approximately 28 miles (Figure 1), so that release of a homing missile from this low altitude at a target 20 miles away is possible. At the same time, while the parent plane can be detected by search radar, its height cannot be determined, nor can it be engaged by any missile defensive system of present design. Figure 5B shows the elevation angle of the target plotted against time in seconds to mission completion and range in yards to defending ship.

3.14 The dashed lines on Figures 5A and 5B show the possible trajectory of a torpedo-carrying homing missile which is dropped or released at 30,000 feet altitude. For a short period of time, during the early portion of this alternative trajectory, the target is at a sufficiently high elevation angle so as to permit tracking in all coordinates if it can be acquired and if its reflecting area is of sufficient magnitude. It will be observed that the target will be detected at range of release 20 nautical miles or 193 seconds before completion of its mission.

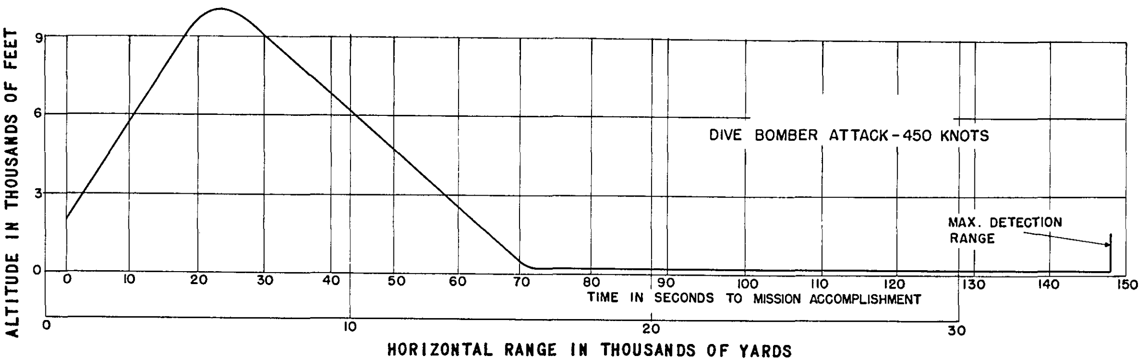


Figure 4A

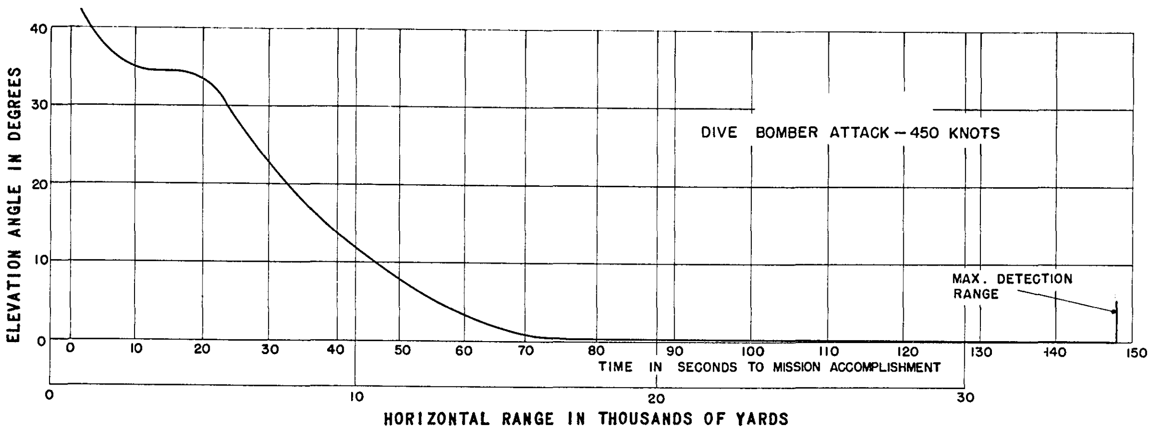


Figure 4B

3.15 Target 5. Target 5 is assumed to be a supersonic homing powered glide bomb, released from a parent aircraft at a range of approximately 20 nautical miles. The homing device is assumed to be of an active type which will not require the presence of the parent aircraft after the release of the missile. The qualifications of difficulty of engaging the parent aircraft are the same as discussed under Target 4.

3.16 Figure 6 shows the trajectory of a powered bomb homing on a ship 4000 yards beyond the defending ship, with a minimum horizontal range of 500 yards. The velocity of the bomb is assumed to be supersonic, at 1260 knots, approximately an average Mach number of 2. A plot of elevation angle against time in seconds until completion of mission is also shown in Figure 6. It will be observed that the target is assumed to be detected at range of release, 20 nautical miles, and that only 58 seconds are available before mission completion.

4.0 DETECTION OF TARGET

4.1 One major assumption that has been made in the preceding discussion is that the defending ship is equipped with a search radar, or combination of radars, having characteristics comparable to those estimated for the AN/SPS-2, that is to say, capable of detecting

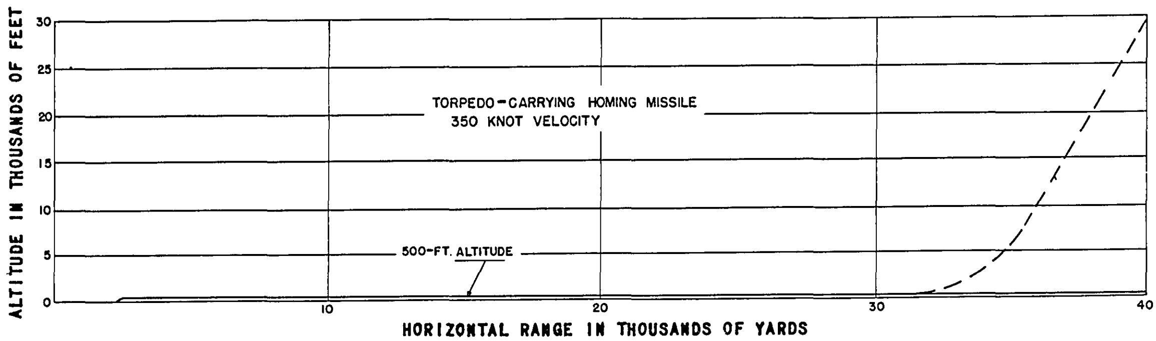


Figure 5A

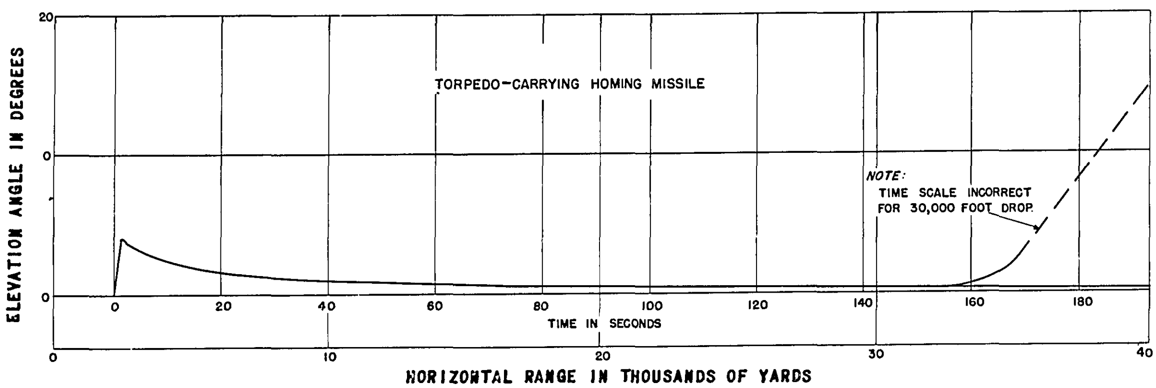


Figure 5B

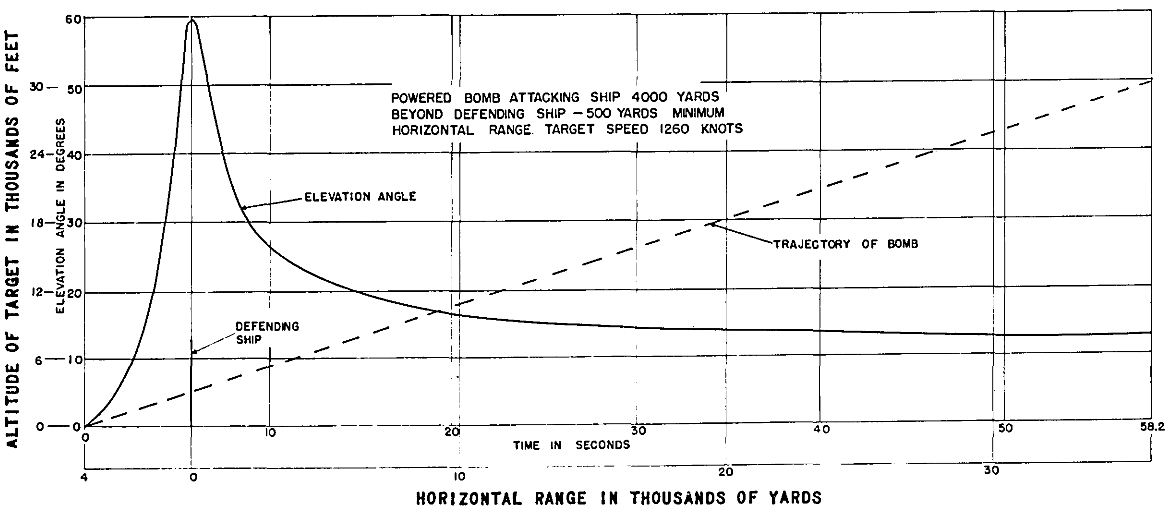


Figure 6

all of the assumed targets when they appear above the radar horizon. Search radars presently employed on shipboard have major limitations when related to the targets and trajectories of the targets herein assumed.

4.2 The tactical usefulness of any means of defense of the ship will depend greatly upon the ability of the ship to detect, evaluate, and designate the targets to the tracking radars and gun directors. This need is recognized, as evidenced by reports and by work presently being done (6,7).

4.3 In addition to the ability of a search radar to detect a target, there are other factors in connection with the search radar that affect the tactical usefulness of the over-all defense system. Tests with the Radar Equipment Mark 40 against an F6F at 180 knots, using a better-then-average operating crew, indicated that "a difference of 10,000 yards or more may exist between the range at which the target echo may be seen and at which it is likely to be discovered." (8). The figure reported is explicit only for the specific equipment tested.

4.4 In an analysis which concerns specific combinations of equipment for shipboard use, it is desirable to consider the assumed targets in the light of the ranges at which the accumulated probability of discovery of the target approaches unity as established by tests. The accumulated probability of detection for any specific condition may be computed (9) from the formula:

$$P = 1 - e\left[\frac{-PoR^2 \max}{3TW(R_{max}-R_1)}\right]\left[\left(1 - \frac{r}{R_{max}}\right)^3 - \left(1 - \frac{R_2}{R_{max}}\right)^3\right]$$

in which

P = accumulated probability of detection
P_O = operator's attention factor
R_{max} = extrapolated range when blip-scan ratio = 0
R_1 = extrapolated range when blip-scan ratio departs from unity
R_2 = max sweep range
T = interval in seconds between scans
W = target velocity
r = target range.

4.5 Assuming the AN/SPS-2 radar is used by the defending ship, this formula indicates that the probability of detection is nearly unity when targets 1, 2, and 3 become visible above the radar horizon, and at the range at which targets 4 and 5 are assumed to be released from their parent aircraft. Since targets 1 to 3 are indicated to be of saturation level to the radar when they appear above the horizon and are undetected only because of the horizon obstruction, it would seem valid to compute the probability of discovery of the target on the basis of the radar operator's attention factor only. This factor is, of course, highly variable and for these targets is assumed to be 0.4; in other words, there is a forty-percent probability that the operator will detect the target on the first scan of the radar. It would be expected that in the cases of targets 4 and 5 the radar operator may already be aware of the parent aircraft and will be alerted to possible use of guided missiles. The operator's attention factor for targets 4 and 5 is assumed to be 0.7.

4.6 The accumulated probability of detection, based on operator's attention factor only, is

$$P = 1 - (1 - P_O)^N$$

where P_O = operator's attention factor, and N = number of scans. In order to obtain an accumulated probability of detection of more than 90 percent, five scans will be required in the case of targets 1, 2, and 3, and two scans will be required for targets 4 and 5. Since the AN/SPS-2 interval between scans in 6 seconds, it is assumed that, for targets 1 to 3, 30 seconds may elapse between the time the target first appears and its discovery; 12 seconds may elapse in the cases of targets 4 and 5.

5.0 TARGET ACQUISITION

5.1 After the target has been detected it is required to identify and evaluate the target, to designate the target to the tracking radar, and to acquire it by the tracking radar. All of these operations now involve human operators and, while it seems probable that the functions performed can be simplified, since the element of judgment is present the time required will continue to depend partially on human factors that are difficult to assess.

5.2 One of the conclusions reached on the tests of the Radar Mark 40 Mod 0 was that "The designation system used is a notable advance in the field of target designation" (8). These tests were performed to determine the time required between detection of a target and the acquisition of the target by the Gun Director Mark 37-Radar Mark 12. The Designation Officer was not required to evaluate or identify the target; he was merely required to designate it by means of positioning electronic markers on a PPI scope. The average time required to designate range and bearing only was 4 to 7 seconds; it was estimated that inclusion of the third coordinate of elevation would require an additional 4 seconds, making the total average time for three coordinate designations 8 to 11 seconds. The average total time from start of designation until the target was gated by the Radar Mark 12 was between 17 and 31 seconds. Allowing 5 seconds for identification and evaluation, the average total time from detection to acquisition would be from 22 to 31 seconds. Despite the fact that this designation equipment represents an advance over equipment now in use, it is obvious that considerable improvement is still required.

5.3 The Bureau of Ordnance has estimated the time for identification of target as equal to the time required by the radar to scan the hemisphere, time for evaluation as 1 to 2 seconds, time of designation as the time required to slew the director through 90 degrees, and time to acquire the target as from 2 to 5 seconds (6). On the basis of these assumptions, the estimated total average time might vary from 10 to 24 seconds depending upon the search radar, tracking radar, and accuracy of designation employed.

5.4 For the purpose of this report, it is assumed that within ten years target designation between search and precision tracking radars will be improved, at least to the degree that no more than 20 seconds elapse between detection of a target in free space and acquisition of that target by the tracking radar.

6.0 TARGET SUMMARY AT ACQUISITION

6.1 On the basis of Figures 2 to 6 inclusive, and the additional assumptions on detection and acquisition in the preceding paragraphs, the status of the targets is summarized in Table 1. The maximum range and time remaining for mission accomplishment of the target is indicated for the first possible detection of the targets. The time remaining is reduced by the time between possible detection and 90-percent probability of detection in accordance with the assumptions of paragraph 4.6. The time remaining is again reduced by the time required to acquire the target by the tracking radar after discovery, in accordance with the assumptions of paragraph 5.4. The range and elevation angle at the time of acquisition are included.

TABLE 1

Target No.	Max Range at Possible Detection	Max Time from Detection to Accomplishment of Mission	Time from 90% Probable Discovery to Accomplishment of Mission	Time from Acquisition to Accomplishment of Mission	Range at Acquisition	Elevation Angle at Acquisition
1. High-alt. Bomber	210 nautical miles	28 min	27 min 30 sec	27 min 10 sec	202 miles	0.1°
2. Torpedo Bomber	35000 yds	135 sec	105 sec	85 sec	22600 yds	0.2°
3. Dive Bomber	35000 yds	148 sec	118 sec	98 sec	22600 yds	0.2°
4. Torpedo Missile	40000 yds	193 sec	181 sec	161 sec	33600 yds	0.2°
5. Powered Bomb	36000 yds	58 sec	46 sec	26 sec	14000 yds	15°

6.2 The figures given in this table cannot be considered as precise because they are based wholly upon a series of assumptions. In general, the assumptions are of such character as to be slightly favorable to the defending ship, in that target velocities could easily be higher and the range of mission accomplishment increased. The assumptions as to time required for the discovery of the target and the time required for acquisition are again favorable to the defending ship, inasmuch as the figures represent an improvement over the best practice in the Fleet today. In review of the general picture disclosed by Table 1, it is felt that the summary presents a reasonable picture of what might be expected in the way of detection, discovery, and acquisition of targets, of the type chosen, within the next ten years. In actual trials, some of the targets might never be discovered or acquired; others might be engaged more rapidly than indicated.

6.3 From Table 1 it will be seen that the range to Target 1 is too great for acquisition by any existing or presently planned fire- or missile-control radar, all of which are limited to about 100 miles or less maximum range. Time is not an element in the engagement of this target. Targets 2 to 5 are well within the maximum range of acquisition of most precision tracking radars, but the elevation angle is too low for precise tracking. This suggests the desirability of a review of the factors affecting low-angle tracking. Target 5 is at close range, presenting no problem insofar as elevation angle is concerned, but the time and range remaining are so short as to indicate the desirability of further analysis in the light of these factors.

7.0 LOW-ANGLE TRACKING

As indicated in paragraph 1.3 and elsewhere in the preceding test, a stringent tactical limitation on presently planned guidance systems is imposed by the difficulty of tracking by radar the low-flying target. This problem is not new; its existence imposed grave limitations in fire control, acquisition, and detection during the last war. This problem led to early developments in radar—the use of the Radar Mark 22 as an auxiliary with the Radars Mark 4 and 12 and eventually to the present day developments of narrow-beam precision-tracking radars. Since it is a fundamental problem, it is generally accepted as a natural limitation, with the result that little exploratory work is being done in the field.

7.1 Figure 7A shows a typical one-way power pattern of a radar beam. This particular pattern is that of the AN/MPQ-5 (10). It will be observed that the beam width is three degrees at the half-power points and that the total scanning angle is two degrees. If a target is assumed to be on the radar beam, and if each radar pulse is assumed to be constant

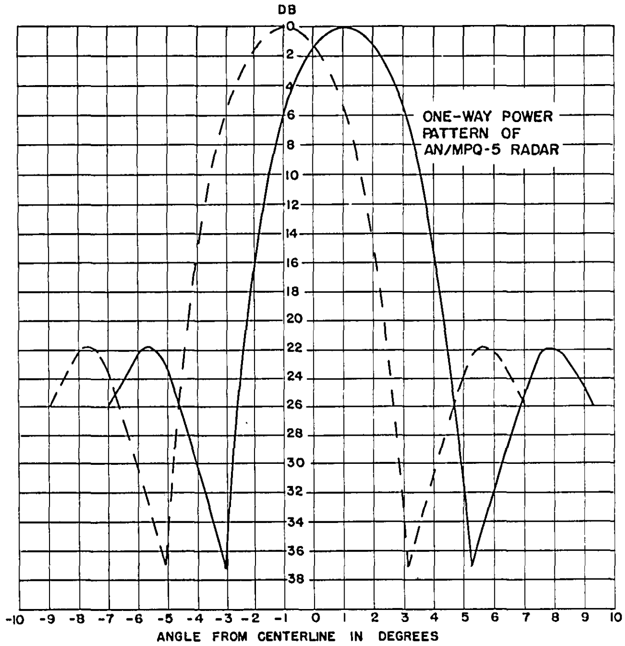


Figure 7A

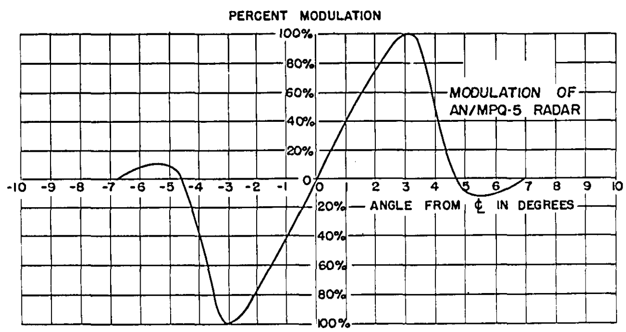


Figure 7B

in amplitude, the envelope of the detected pulses will be uniform throughout the entire scanning cycle. If the target is moved away from the beam center in any direction, the envelope of the pulses detected by the receiver will be modulated sinusoidally. The amplitude of the modulation envelope will be the difference in power between opposing sides of the power pattern as the beam is scanned or nutated. The average level of the modulation is maintained by the AGC circuits of the radar, so that the percentage of modulation is the difference between the power of opposing pulses divided by the sum of the power of the pulses. From this is developed the modulation curve plotted in Figure 7B. Similar modulation curves may be drawn for simultaneous lobing or monopulse radars.

7.2 Figure 8 illustrates, in solid lines, the modulation curve perceived by the radar at a low elevation angle over a perfect reflecting surface of water. In dashed lines is shown the reflected beam, which is graphically displayed as a phantom beam at the same angle as the direct beam but with reversed polarity beneath the water line. It is observed that the two modulation curves overlap. An envelope of the sum and difference of the modulation of the direct and reflected beams is plotted, superimposed on the modulation curves. Within this envelope is drawn a series of curves which represent the modulation perceived by the radar and caused by interference between the direct and reflected energy. At any given point above or below the beam center the modulation signals perceived by the radar are those indicated by the interference curves, rather than the actual modulation of the radar in free space. It will be observed from this diagram that if a target exists at the center of the radar beam, the radar perceives a modulation to exist. This modulation when translated into a signal, will cause the radar beam to move, in error, upward, away from the target. As soon as the radar changes its position the modulation signals also change so that the condition illustrated is transient and for specific conditions only.

7.3 When the elevation angle of the radar is increased until the crossover of the first side lobe of the phantom beam is in coincidence with the center of the direct radar beam, there no longer exists fictitious modulation signals which develop correspondingly fictitious error signals, except of minor character (depending on the magnitude of the side lobe).

The subtended angle between target and water surface is then equal to or less than one-half the angular measurement between the center of the radar beam and the point at which zero modulation is reached by virtue of the crossover with the first side lobe. Referring to Figure 7B, it will be seen that for the AN/MPQ-5 radar the minimum reliable elevation angle for low-angle tracking will be one-half of 4.6 degrees or approximately 2.3 degrees. In actual practice the minimum elevation angle for tracking will be less than this because the effect of interference diminishes in magnitude until masked by other noise, and the full 180-degree phase shift between the main beam and the first side lobe requires a finite angle for accomplishment. A more detailed discussion of the reflection problem will be found in a report now being prepared for issuance by the Naval Research Laboratory (11).

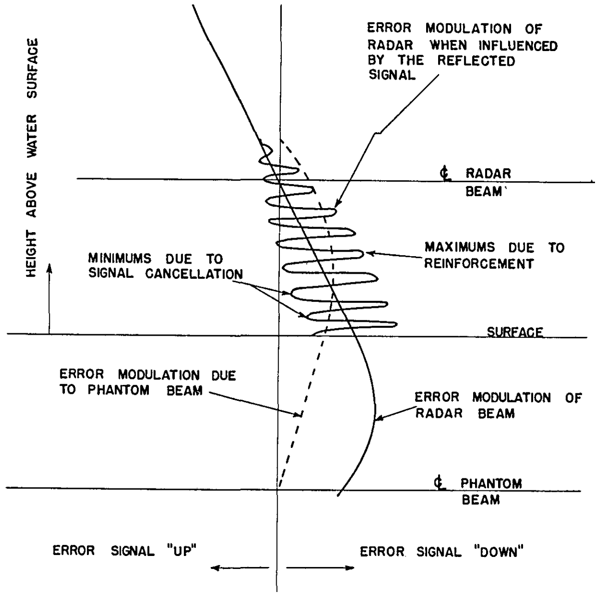
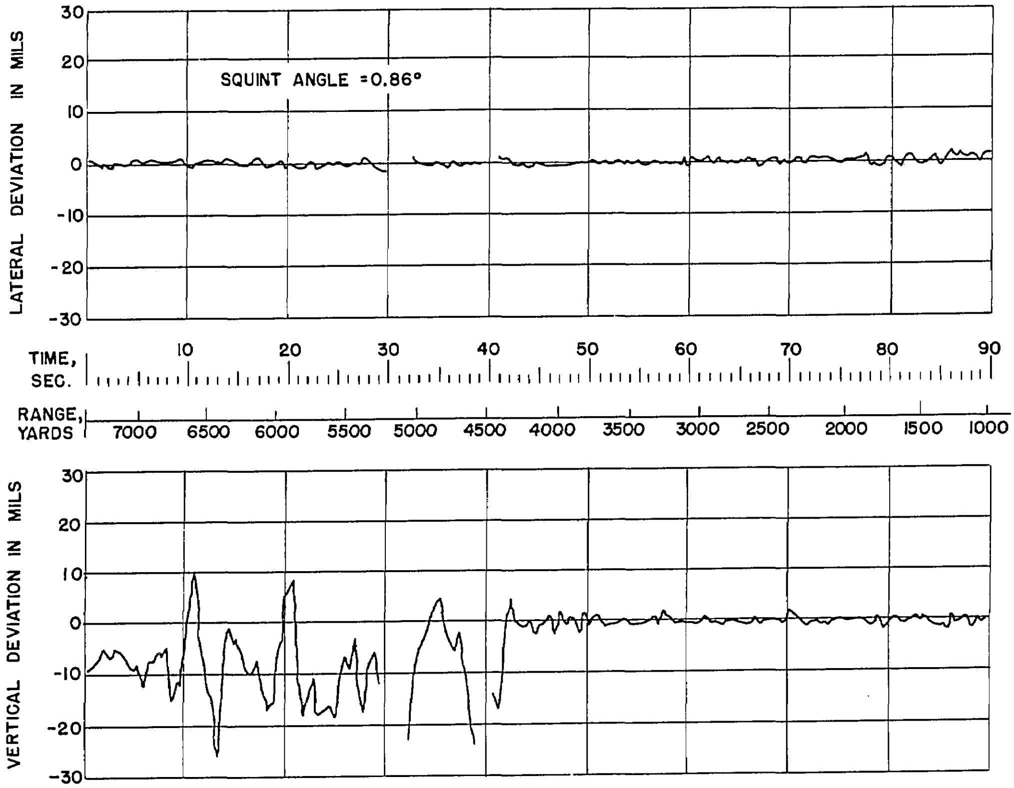


Figure 8

7.4 It should be carefully noted that there are many variables which affect the minimum tracking angle of a radar. The amplitude of the excursions in the vertical plane will vary with range. At long range, when the elevation angle is extremely low, radars will usually track the target quite well, with the standard tracking deviation from the target approaching the minimum values obtained in free space, since the angle subtended between the target and the water is extremely small. As range decreases, the tracking errors increase until the elevation angle has increased to the degree that substantially free-space tracking is obtained. The scan and pulse frequencies and the polarization of the radar will vary the degree of the effect of the reflected energy. The condition of the water surface affects the coefficient of reflection, as does the grazing angle which varies with range to a constant-altitude target. The character of the circuitry and the manner in which the signals are utilized will affect the degree to which a specific radar is affected by the interference of the reflected energy. If the distance traveled by the energy in the reflected path differs in length from the direct path by a wavelength or a multiple of a wavelength, a null or minimum signal return exists. The number and location of the nulls (often described as "fading"), by the geometry of the particular situation, is dependent upon the height above water of the radar. Because of the many variables, although it can reasonably be predicted, the performance of a specific radar against low-flying targets can best be determined by tests under the specific conditions in which it is to be tactically utilized.

7.5 Radar Equipment Mark 7 was subjected to a series of tests at the Chesapeake Bay Annex of the Naval Research Laboratory. This radar is a conically scanning type and has been indicated to be superior in its tracking performance to any radar now in Fleet use. When tracking targets in free space, the statistically measured tracking performance of the Mark 7 radar indicated its standard radial deviation "s" to be under 0.5 mil. Radial "s" is defined as the square root of one-half the sum of squares of the vertical and lateral deviations. This X-band radar has a beam width of 1.6 degrees at the half-power point of its antenna pattern; in these tests it used a total scanning angle of 0.86 degree. Figure 9 shows a typical test run with an approaching SNJ-3 as the target flying at 200 feet altitude.



RADAR MK 7, MOD 1, TRACKING SNJ-3
AT 200 FT. ALTITUDE

Figure 9

It will be observed that from the start of the run, at 7500 yards, until the range had closed to approximately 4000 yards, the excursions of the radar were of such amplitude that the centerline of the radar beam was often pointed below the horizon line.

During these tests, the Radar Mark 7 was located approximately 105 feet above the water surface. Figure 10 shows the geometry of the test. The critical angle at which substantially free-space tracking occurs, as discussed in paragraph 7.3, here becomes the angle designated as α and not E, the elevation angle. The data of Figure 9 indicates that for values of α greater than 0.9 degree equivalent free-space tracking exists. In the more common case aboard ship, the radar is located nearer to the water surface and at long ranges the angles α and E approach the same value. Throughout this discussion, in connection with the problem presented by low-altitude targets to the shipboard tracking radar, the term elevation angle has been used, for purposes of simplicity, as being synonymous with the angle α. Similar information at longer ranges is not available because of the difficulties of long-range photography over water. It is believed that the tracking illustrated by this run is typical for low-angle tracking of any precision radar now planned for Fleet use.

7.6 Of the radars now in the Fleet, or under development for Fleet use, the performance objectives of the Radar AN/SPG-49 would indicate that it will be the most suitable radar for use with guidance systems. The proposed beam width for this system is given

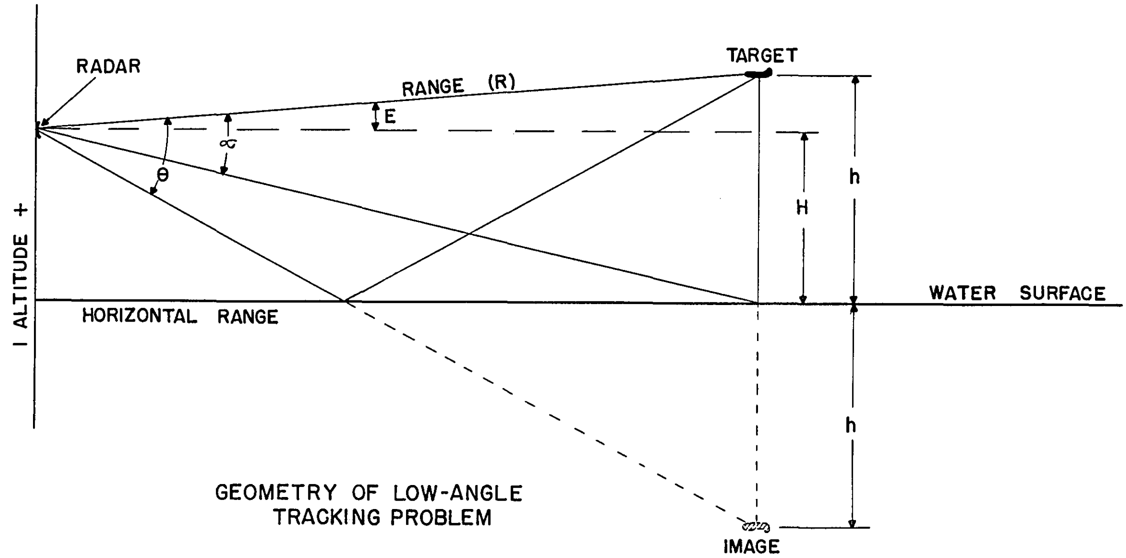


Figure 10

as 1.5 to 2.0 degrees. In the absence of test data or specific information on the SPG-49, it can be assumed that it will approach, but not better, the low-angle tracking characteristics of the Radar Mark 7. On this basis it will be assumed that the tracking radars employed in the guidance systems to be discussed will approximate free-space tracking accuracies above one degree. Below one degree the elevation outputs of the radar can be considered unusable, although tracking in train is acceptable.

8.0 TARGET SUMMARY FOR FREE-SPACE TRACKING

8.1 On the basis of the assumption in paragraph 7.6 that free-space precision tracking does not exist in elevation below one degree elevation angle, Table 2 summarizes the situation for the five probable targets when it is first possible, on this basis, to launch a guided missile which is dependent on the radar for guidance information to intercept them.

8.2 Target 1 is still at too great a range to permit tracking by the precision radar. Targets 2 to 5 are critical by virtue of the short ranges and times remaining before intercept must be accomplished. It is proposed to examine next the three types of guidance under consideration to determine if individually further limitations exist.

9.0 BEAM-RIDING GUIDANCE

9.1 In a beam-riding guidance system a radar is employed simultaneously to track the target and to transmit guidance intelligence. The guidance intelligence is of such character that a missile within the beam can determine its position with respect to the center of the beam. The radar does not track the missile; the missile tracks the radar beam. This is accomplished by impressing on the scanning beam a modulation, usually pulse time modulation, that permits a missile-borne receiver to determine the coordinates with respect to the beam centerline and furnishes a reference which is used to indicate direction of error. This modulation may be of any of many types—pulse time modulation, pulse frequency modulation, coded pulses for different quadrants, etc. The amplitude modulation of the scanning beam is employed to determine the magnitude of error.

TABLE 2

Target No.	Range	Time Remaining to Mission Accomplishment	Elevation Angle
1- High-alt. Bomber	150 nautical miles	20 minutes	1^0
2- Torpedo Bomber	5400 yards	16 seconds	1^0
3- Dive Bomber	15500 yards	70 seconds	1^0
4- Torpedo Missile	9300 yards	34 seconds	1^0
5- Powered Bomb	14000 yards	26 seconds	15^0

9.2 There are many methods of establishing guidance reference. Varied guidance circuitry of complex and less complex character has been tested by many groups with some degree of success. Evaluation within types of guidance systems is not within the scope of this report. Viewed from the most elemental aspects, in beam-rider guidance the missile must be brought within the radar beam before guidance can be established; the radar must rack the target in such a manner that the missile is not lost from the beam; the guidance intelligence must direct the missile correctly within the beam; and the beam-rider guidance system must bring the missile to a point where it is possible for the homing system to take over control, if terminal guidance is used.

9.3 The simplest method of getting the missile into the radar beam is to use a missile and booster of sufficiently stable flight characteristics that it may be launched into the beam. Unfortunately, the manufacture of missiles and boosters is not of precise character, with the result that considerable dispersion occurs during the launching and boost phases of flight. Statistical data are not available on specific missiles in sufficient quantities to provide quotable figures. Missile manufactures have indicated a belief that 95 percent of the missiles may be contained within ±5 degrees at the end of the boost period, considering ballistic and booster errors only. An evaluation of the Seaslug gathering problem (19) indicated that ballistic angular errors only might be assessed at ±4 degrees, with 95 percent of the missiles to be contained with this estimated dispersion.

9.4 In addition to the ballistic dispersion in angle, other dispersions exist which affect capture. In a preset launching system it is necessary to compute the future position of the tracking radar beam so that the missile may intercept the beam at some predetermined time of flight after launching. Ballistic errors in range may affect this computation; the tracking radar, the computation of future position and parallax, and the unforseen accelerations of the target all add to the total possible dispersion of the missile as related to the radar beam center. It would be expected, then, under the present state of the art, that the total dispersion of a preset launching system to include 95 percent of the missiles launched might be 5 to 7 degrees. Inasmuch as the tracking accuracy and the maximum range of a precision radar are dependent, in part, on the beam width of the radar, every effort is made to keep the beam narrow—2 degrees or less. The tracking radar cannot be compromised to the degree that is necessary to permit the capture of missiles directly in the radar beam. It is felt that precision production methods of manufacture may do much toward reducing the ballistic dispersion of missiles, but such techniques may be prohibitively expensive when missiles and boosters are made in limited quantities.

9.5 There have been various alternatives proposed to the direct or preset capture of the missile by the tracking radar. The most commonly suggested alternative is the use of a wide-angle beam for capture as an auxiliary to the tracking radar. There have been many variations of the wide-angle beam idea proposed, but all prove tactically unusable when investigated in connection with low-flying targets. As an example of the difficulty involved, assuming that the wide-angle capture radar has a beam width of 8 degrees and a scan angle of 3 degrees, free-space conditions would not exist below approximately 5 degrees elevation angle. In a beam-riding system, guidance information is obtained from the modulation of the radar beam; this intelligence is modified as described in paragraphs 7.1 to 7.3 inclusive, the only difference being that the transmission is on a one-way basis rather than a two-way basis. Depression of the beam, chosen as an example, below 5 degrees elevation angle results in the missile tracking on erroneous information. Depending on the dynamics and stability of the particular equipment and the situation, the missile may do many things—from crashing into the water to being lost from the beam—but the probability is that it will ride above the beam center. The amount of vertical error will be a function of many varying parameters, but it would seem highly improbable that capture can be affected by the tracking radar beam if it is at one degree elevation angle (12). The picture is further complicated in that the effect of the reflected energy from side lobes becomes more serious as beam widths are increased.

9.6 Let us assume that launching must be delayed until the elevation angle is 5 degrees. Table 3 summarizes the status of the targets at that time.

TABLE 3

Target No.	Range	Time Remaining to Mission Accomplishment	Elevation Angle
1- High-alt. Bomber	60 nautical miles	7.6 minutes	5^0
2- Torpedo Bomber	4300 yards	11 seconds	5^0
3- Dive Bomber	12700 yards	56 seconds	5^0
4- Torpedo Missile*			
5- Powered Bomb	14000 yards	26 seconds	15^0

*Cannot be intercepted on basis of these assumptions

9.7 Target 4 never reaches an elevation angle of 5 degrees and, on the basis of the conditions stated, it cannot be intercepted by a beam-riding missile using the assumed wide-beam capture system. It will be noted that Target 5 is unaffected by the parameter of elevation angle and is retained on this tabulation in the condition of acquisition. It may be argued that, since at least parallax computation is required to position the capture beam so as to intercept the tracking beam, a finite solution time may be required before launching. It is believed that the computation involved can be reduced to a servo problem and the time required may be made negligible.

9.8 In addition to creating capture difficulties, missile dispersion creates a second problem in that the error caused by the dispersion must be removed by the guidance and control system before the missile can intercept the target. Figure 11 illustrates an example of the trajectory of a missile with respect to the control line. In this example, the missile at the end of the boost period is flying at an angle θ to desired line of fire. In actual practice, the missile will not only be displaced from the guidance line, but will probably reach that displacement by virtue of flying a curved trajectory, so that the heading of the missile at the end of the boost period is at an angle greater than θ away from the control line. In addition to the curvature of trajectory during the boost period, the missile is subject to dispersion in angle of attack to its trajectory so that the case illustrated in Figure 11 is oversimplified. In any event, the control system or sequence of systems must serve the function of returning the missile close enough to the control line to effect target interception. The possible characteristics of the control system are many. Here illustrated is a less than critically damped system wherein the missile travels the path of a damped sine wave. This is the most likely character of a control system to be employed for missile control. The x ordinate of the envelope of the less than critically damped sine wave can be shown to be $e^{-\omega t/2}$, in which ω is the bandwidth of the control system and t is time as plotted along the Y axis, with no consideration being given to system nonlinearities.

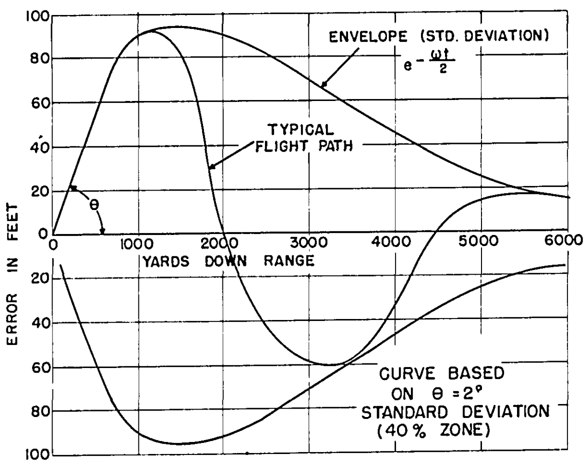


Figure 11

9.9 The selection of the bandwidth is determined by many parameters of the system and by the operational characteristics of the job the missile must accomplish. In order to minimize the effects of noise, the bandwidth selected is usually chosen to be the minimum consistent with the performance required by target motion, possible transient demands, and trajectory requirements. From past experience in the field, it would be expected that ω would be in the range of from 0.2 to 1.0 radian per second. An ω = 1.0 radian per second, the most rapid control, will be assumed. The error must be reduced to a value that will place the missile within the probable error attributable to system noise. For the moment it will be arbitrarily assumed that the standard deviation due to noise is 1.5 mils. An attempt to justify this assumption will be made later. The assumption that θ = 5 degrees (95 percent) is favorable to the missile, inasmuch as it has been previously pointed out that additional dispersions may exist by virtue of the curvature of trajectory during boost and angle of attack of the missile. If it is assumed that no saturation exists by demands for angular acceleration from the missile beyond that which it can supply, that the system is linear in character, and that the distribution of dispersion errors of the missiles is normal, then 40 percent of the missiles will be within 1.5 mils of the control line at approximately 6 seconds after separation. This time is substantially less than those obtained in experimental Lark flights with systems of somewhat similar parameters. If the missile is assumed

TABLE 4

Target No.	Range	Time Remaining to Mission Accomplishment
1 - High-alt. Bomber	59 nautical miles	17.4 minutes
2- Torpedo Bomber	2600 yards	3 seconds
3- Dive Bomber	11000 yards	48 seconds
4- Torpedo Missile	----	----
5- Powered Bomb	9000 yards	18 seconds

to be flying at a Mach number of 2 (a favored velocity among missile designers, and herein chosen as the minimum velocity, considering Target 5) and that a two-second boost period exists, the down-range distance from launching until the missile is within the noise of the controlling system is approximately 5100 yards.

9.10 Table 4 summarizes the status of the targets when the launching dispersion has been reduced to the equivalent of the assumed guidance error due to noise.

9.11 Target 1 can be assumed to be still too far away for missile interception. The probability of intercepting Target 2 is extremely low since it is well within the range at which the launching errors are high. Target 3 is capable of interception. Target 4 cannot be intercepted on the basis of assumptions in paragraph 9.6. The interception of Target 5 is possible on the basis of the assumptions. It will be noted that no consideration has been given to the possible time requirements to shift from control of the wide-angle capture beam to the control of the tracking beam. It is possible that transfer of guidance could be accomplished without any appreciable time being consumed for transfer of control. It is also probable that a step function will be inserted into the system at the time of transfer because of lack of coincidence of the two beams or for other reasons, so that additional time may be required to damp it out. In general, then, it is felt that the assumptions made greatly favor the guidance system.

9.12 As an alternate to the wide-angle auxiliary capture radar, the use of inertial or other guidance during boost may be considered. There are several methods which might be used to accomplish such guidance; but regardless of the method employed a separate launching guidance will undoubtedly be used because of the radical difference in the parameters of the airframe with and without the booster attached. By reference to Figure 7B it is seen that capture must occur within the bounds of maximum modulation of the radar and that it is desirable to obtain capture well within that tolerance if possible. With a tracking radar of the characteristics of the AN/SPG-49, a permissible dispersion for 95 percent of the missiles of ± 1.5 degrees may be assumed to be the maximum tolerable to permit capture. This may be possible but, considering the various sources of errors, as discussed previously, it will be difficult to obtain. If, however, it is assumed that a launching guidance system including inertial components, controllable boosters, and prediction and parallax computers (all as yet undesigned) can meet this tolerance, then approximately 5 seconds after launching

TABLE 5

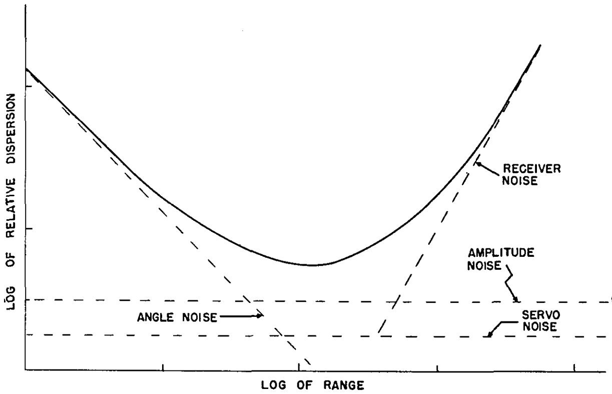
Target No.	Range	Time Remaining to Mission Accomplishment
1	149 nautical miles	19.9 minutes
2	4200 yards	11 seconds
3	14500 yards	65 seconds
4	7900 yards	29 seconds
5	10200 yards	21 seconds

and 2900 yards down range may be considered the point at which the dispersion of launching has been reduced equal to the assumed standard deviation of missile guidance accuracy of 1.5 mils. These figures are obtained as outlined in paragraphs 9.8 and 9.9.

9.13 On the basis of these assumptions it is possible to establish in Table 5 a summary of target status for direct capture, using guidance during boost as compared to Table 4 for capture by a wide-angle beam, at the time when the launching dispersion is reduced to 1.5 mils. Target 1 is still too far away for interception. Targets 2 to 5 would seem to be possible of interception. Comparison between Tables 4 and 5 would indicate that guidance during the boost period is desirable.

9.14 It would seem from the foregoing discussion that one method of reducing the time required to damp out the dispersion errors would be to increase the bandwidth of the control system. While it is desirable to have a bandwidth adequate to perform in any tactical condition, other factors limit the extension of this principal. The limitations are primarily two, the airframe characteristics and the noise conditions. Natural resonances in an airframe, or an airframe and autopilot combination, prohibit wide bandwidths. The accuracy of intelligence is dependent, in part, upon noise (extraneous signals) and an increase in bandwidth will, in general, reduce guidance accuracy. In the design of a specific system, where all parameters are known, control bandwidth is obtained as a result of many compromises between what is demanded operationally and what is available as invariants in the airframe and other components. The bandwidth utilized in the study above was the result of such compromises.

9.15 One of the questions which comes out of the target summary is that of the necessity for homing guidance. Targets 2 to 5 inclusive are at close range before a guidance system may be employed to intercept them, and it may therefore be argued that a beam-riding system without homing should be employed. Consider the general sources of noise which determine how accurately the missile tracks the radar line of sight to the target (noise being herein defined as extraneous or unwanted signals to the beam rider regardless of source, which contributes erroneous information). The total noise may be considered to be the root-mean-square of the noise contributed by the separate elements, for discussion separated into: servo noise, amplitude noise, receiver noise, and radar noise. Servo noise is considered to be that contributed by extraneous airframe motion and unwanted signals contributed by control elements. Amplitude noise is assumed to be irregularities of radar intelligence transmission. Radar noise is assumed to be caused by tracking errors of the guiding radar. Receiver noise is, of course, inherent with the missile receiver, and since it is one-way transmission it would be expected to increase as the second power of range. It is impossible to assess the individual contributions of the separate elements without statistical information on the specific equipment under consideration. Superficial inspection of the potential noise sources may indicate, however, the approximate order of magnitude of the errors resulting. The servo noise input is a function of the external forces exerted upon the missile, such as wind gusts. If a separate autopilot



RADAR RELATIVE DISPERSION vs RANGE

Figure 12

loop is employed to correct these and other aerodynamic deficiencies, the control bandwidth may be made narrower than when the servo loop is employed to compensate for these difficulties. If all components are of the optimum design and balance without incompatible airframe resonances, the errors caused by servo loop noise would be expected to be only a few yards and may be constant in linear dimension despite increase in range. The contribution to error caused by amplitude noise, since one-way transmission exists, should, with good design, be only a fraction of a mil. The inclusion of receiver noise is academic, since it is expected, with superheterodyne receivers, that the minimum range at which receiver noise would become an appreciable part of the total error would be beyond the usable range of antiaircraft missiles.

9.16 Radar tracking noise is expected to be the greatest contributor to beam-riding error. Figure 12 indicates the relationship between the log of relative dispersion and the log of range for a tracking radar. The total dispersion is indicated to be the square root of the sum of the squares of the contributing dispersions, which are herein broken down as dispersions due to servo noise, amplitude noise, angle noise, and receiver noise. Servo noise is contributed by the control elements from the output of the error signal from the radar to the positioning of the radar antenna in tracking the target. This noise is attributed to both the electronic and mechanical elements of the servo system. Amplitude noise is a function of the beamwidth and results in part from variations in the scanning mechanism and fluctuation pulse-to-pulse of the amplitude of the signal echoed from the target. Amplitude noise is theoretically absent in a monopulse system. Both servo noise and amplitude noise would be expected to be constant in angular measurement with range. Angle noise is frequently called “glint” and is the result of the target being of finite size so that the center of reflection varies over the complex reflecting area of the target. Since it is basically a function of the size of the target and the geometric relationship between target and radar it would be expected to decrease on a -1 slope as range increases. Receiver noise voltage, since a two-way transmission path is involved, will increase as the square of the range and is therefore indicated as having a slope of +2 on Figure 12. The validity of the form of the curve of total dispersion has been indicated by the results of radar-tracking tests at the Bell Telephone Laboratories (7) and the Naval Research Laboratory. A more detailed examination of dispersion due to noise, directed toward the isolation of noise contributed by each of the separate elements of the problem, is now under way at the Naval Research Laboratory (12).

9.17 The effect of the radar-tracking dispersion on the accuracy of missile guidance will depend upon the judicious selection of bandwidths for the radar-tracking loop and the missile-control loop. If the noise is of constant amplitude and uniformly distributed over the frequency spectrum, it is usually assumed that the amplitude of the spectrum envelope is shaped by the closed-loop transmission characteristic of the tracking radar. If the bandwidth of the missile-control loop is considerably (about a decade) narrower than the bandwidth of the tracking radar, the missile would be expected to wander over the amplitude of the low-frequency components of noise of the tracking radar and to attenuate the higher-frequency noise. If the bandwidth of the missile loop is equal to or higher than that of the radar-tracking loop, all of the tracking dispersion will appear as missile dispersion.

The magnitudes and frequencies of radar-tracking dispersions can only be determined, at present, by test data taken on specific combinations of equipment and targets.

9.18 The results of tests made by NRL using an AN/APW-4 receiver automatically controlling an SNB in flight may furnish an index as to the order of magnitude of the beam-rider errors which may be expected to result from noise. Using an AN/MPQ-5 radar with the beam fixed, the data obtained indicated a standard deviation of 0.35 mils at 8000 yards with a fixed radar beam. This deviation represents the summation of beam-riding errors previously defined in paragraph 9.14 as servo noise, amplitude noise, and receiver noise, but does not include radar tracking noise discussed in paragraph 9.16, since the beam was fixed. The AN/MPQ-5 radar, in other tests, has been indicated to have a standard deviation of 0.5 to 1.0 mil with conventional aircraft targets and low rates of angular motion. If it can be assumed that the magnitude of the combined standard deviation of the missile from the line of sight to the target will approximate the root mean square of these two standard deviations, then that value becomes, in this instance, 0.6 to 1.1 mils.

9.19 One of the difficulties in predicting possible accuracies of tracking radar or guidance systems in tactical use is the inevitable deterioration in performance of equipment between the laboratory and the Fleet. There are many factors involved in this, varying from differences between laboratory and production equipment to differences in personnel using and maintaining it. But, however difficult it may be to rationalize and gauge the difference in performance, that difference exists. A correction factor is frequently employed, commonly called a bugger factor, which is chosen at a value of from 2 to 4 to estimate the deterioration between controlled laboratory tests and Fleet performance of tracking radars. In other words, if a radar has a standard deviation of 0.5 mil in laboratory evaluation tests, it is expected to have a dispersion of from 1 to 2 mils in operational use. The NRL tests described above were made under conditions of close control. It is felt, even including the intangibles of improved radar tracking and missile guidance, that the standard deviation to be expected in service use from noise alone will be no less than 1.5 mils.

9.20 If it is desired to inspect the total error existing at any moment along the flight path, it is also necessary to consider the systematic errors caused by target motion. If high angular rates are demanded from the radar by reason of target motion, the center of the beam will lag the target; coincidentally, the missile will lag the radar beam center. With complete information as to the characteristics of all components involved, the magnitude of these dynamic errors are readily calculable; conversely, if the amount of systematic error that can be tolerated is known, the control system may be designed to keep such errors within the specified tolerance for given target courses. Tests made by NRL with AN/APW-4 beam-rider receiver controlling an SNB in flight along a sinusoidally programmed beam moving at 0.17 radians per second with an amplitude of 1.5 degrees peak-to-peak indicated a standard deviation of 2.9 mils. This represents, to a target at 10,000 yards, a sinusoidal evasive course with less than 1/2 g acceleration. The standard deviation of 2.9 mils represents both errors attributable to noise and systematic errors caused by the missile lagging the beam. This does not include any error of the radar in following target motion since the beam was programmed and was not tracking a target.

9.21 In the foregoing discussion only single targets were considered. When defense against multiple targets is paramount, the inability of the tracking radar to discriminate between them radically affects beam-rider missile accuracy. The simplest case is that of two targets flying side by side. Consider a typical modulation curve such as Figure 7B. If two targets were presented to the radar with uniform and equal reflecting areas, it might be suspected that they would have to be separated by the full angular measurement from 100-percent modulation in one direction to 100-percent modulation in the other before the radar would lock on one target only, thereby discriminating between them. Practically,

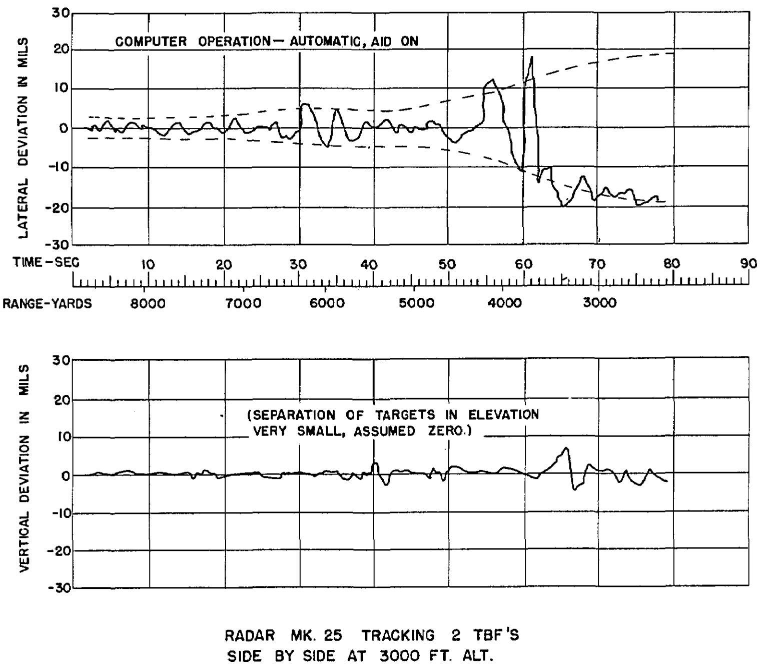


Figure 13

however, despite the fact that the two planes may be similar, the energy reflected from each will vary radically in a random manner so that the radar will oscillate between the planes until such time that one only will be tracked. The separation between the two planes at the point of discrimination would be expected to approach the angular measurement between the radar centerline and the angle of maximum modulation. By use of properly selected bandwidths of the tracking radar the angular discrimination might possibly be reduced to about half of that value. As a typical example of present radars, Figure 13 shows a test using a Mark 25 Radar on two TBF's flying side by side. It will be noted that the radar settled down to track one target only when the separation between them was somewhat over 20 mils. If the radar guiding a beam-rider missile has discrimination characteristics no better than the example shown, the missile will attempt to integrate the oscillations and go between the two targets, with a maximum error of about 10 mils to either target.

9.22 Figure 14 was constructed to give a visualization of the meaning of the errors discussed in the preceding paragraphs. A completely hypothetical case of missile warhead and target was chosen wherein a standard deviation miss distance of 45 feet would give a kill probability of 50 percent (13). If an inspection is made of the targets it will be seen that they fall into two groups—the long-range target, Target No. 1, and the short-range targets, Targets 2 to 5 inclusive. Taking, as an example, Target 3, the first probable interception will occur at somewhat more than 10,000 yards. In paragraph 9.17 it was estimated that a missile in service use might have a standard deviation of 1.5 mils, which at 10,000 yards is 45 feet. On the basis of this hypothetical case, the probability of kill will be 50 percent. The inclusion of systematic errors by reason of evasive target motion may increase the standard deviation to 3 mils, depending on system constants. At this standard of error, equivalent to 90 feet at 10,000 yards, the probability of kill is reduced to about 19 percent. In the case of multiple targets, if the discrimination of the radar were equivalent

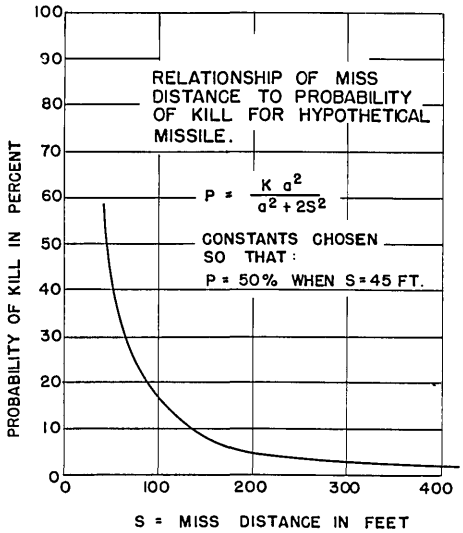


Figure 14

to the example given, the miss distance, at maximum, is increased to 10 mils or 300 feet, so that the probability of kill may drop to little more than 2 percent. The rapid deterioration of probability of kill with increase in miss distance, plus the fact that with beam-rider guidance only the miss distance will increase as range to target at interception increases, indicates that for targets of medium or long range it will be essential to use some form of terminal guidance. It is noted that this conclusion has also been reached by several studies of the Operational Evaluation Group (13,14).

9.23 In the case of extremely short-range targets such as Target 2, the torpedo bomber, it is extremely doubtful if the inclusion of homing guidance in combination with beam-rider guidance will offer any reduction in miss distance (and consequent improvement of probability of kill) over beam-riding guidance only. If a missile were fired at this target when the tracking radar first reached 1 degree, interception would occur at about 4800 yards range, less than 7 seconds after launching. The possibility of serious transients resulting from transfer of control from beam rider to terminal guidance will exist, particularly in view of probable extreme target accelerations. It is believed, then, that a combination of beam-riding and terminal guidance systems must be versatile enough to permit selection of guidance in accordance with demands of target parameters.

10.0 COMMAND GUIDANCE

10.1 In a command-guidance system a shipboard radar is employed to track simultaneously a target and a beacon-equipped missile. The guidance intelligence is originated by measuring the angular location of the missile and comparing the actual position with the desired position at the radar. The error so measured is transmitted to the missile as continuous or intermittent commands employing modulation of the radar transmission or a separate communication link.

10.2 Command systems are frequently spoken of as being of the one-beam or two-beam type. In systems where one beam only is employed to track both the target and missile the problem becomes identical with that of a beam rider, since the missile is guided to fly the center of the tracking radar beam. In such a system all of the considerations of capture and launching are identical to those of the beam riding, and the difficulties previously outlined will equally apply. Insofar as errors due to noise only are concerned, since the problem of tracking is invariant between the two systems (except that the possibility of eliminating radar servo noise exists), and the problem of missile location in either system involves only one-way transmission (since a beacon is employed), there should be little or no difference between the accuracy of error information gathered. However, since in the command system an additional link is required which may add noise inherent to it, it may be said that a command system of optimum design will approach a beam-rider system of optimum design insofar as errors due to noise only are concerned. Since the same trajectories are required of both systems, dynamic errors should be equal. Lack of discrimination between two or more targets by the tracking radar is equally serious to either system. The one-beam command system, then, would be in equal need of terminal guidance for medium- or long-range targets.

10.3 The differences between beam riders and one-beam command systems are principally those of equipment complexity and traffic handling. The beam rider, once fired, is on its own; the command system requires continual observation of missile location. This means not only the use of an additional intelligence link, but the use of a beacon in the missile (which discloses pertinent information to the enemy) and substantially an additional receiver at the radar. If we consider, academically perhaps, the problem of traffic control—two or more missiles in the same beam at the same time—the equipment complexities are somewhat increased.

10.4 The two-beam command system is one which employs one radar to track the target and a second radar to track the missile. Intelligence gleaned by comparison of the two radar positions is used to command the missile to the desired trajectory. Considerable flexibility as to the trajectory of a missile employing such a guidance system is possible. If a missile is launched near vertical and leveled off to a horizontal trajectory at the desired attitude, it will consume less fuel to reach a desired range and attitude than if it follows a beam-rider trajectory. The maximum range for a given missile is obtained with this type of trajectory, as discussed in Nike reports. Again, a true intercept trajectory may be flown, computed from future target position, so that accelerations at the terminal portion of the flight may be reduced.

10.5 Considering the potential flexibility of trajectories in the light of the propounded targets, a maximum range trajectory is most desirable for Target 1, the high-altitude bomber, whereas a computed intercept trajectory will be most desirable for the remaining targets. In the case of Target 1, this would permit interception at the maximum range inherent with a given missile; in the case of the other targets, the possibility of serious transients during transfer from command to terminal guidance is reduced.

10.6 The low-angle tracking problem in a two-beam command system is unchanged from the beam-rider system since it is basic with the tracking radar. The effect of launching dispersion is alleviated since the radar tracking the missile is in itself potentially a launching-guidance system. If it is assumed that the missile radar tracks the missile off the launcher (using a suitable delay in the beacon response to achieve short-range tracking) and that the low-angle tracking characteristics of the missile-tracking radar are equal to those of the target-tracking radar, then the position of the missile is known at all times and command signals may be generated to guide the missile to and along its desired trajectory immediately after launching. If no inertial system is employed to reduce launching dispersion during the boost period, it will be necessary to elevate the launcher to such angle that the missiles are not launched into the water. On this basis, computed as in paragraph 9.8, it is estimated that the missiles fired will have a standard deviation of approximately 1.5 mils at 5100 yards range and 8 seconds after launching.

10.7 Table 6 summarizes the status of the targets when the missile has been fired when the elevation angle reaches 1 degree as shown by Table 2 and the launching dispersion has been reduced to the equivalent of the assumed guidance dispersion of 1.5 mils.

10.8 Target 1 is, as usual, too far away for immediate consideration. Target 2 and the missile intercept before the missile launching dispersion has been reduced to its ultimate guidance dispersion. Targets 3 to 5 inclusive would seem possible of interception. The conclusion reached by this summary is that the narrow-beam launching-guidance

TABLE 6

Target No.	Range	Time Remaining to Mission Accomplishment
1-High-alt. Bomber	149 nautical miles	19.9 minutes
2-Torpedo Bomber	3600 yards	8 seconds
3-Dive Bomber	12000 yards	62 seconds
4-Torpedo Missile	8300 yards	28 seconds
5-Powered Bomb	8200 yards	18 seconds

system inherent in two-beam command guidance is superior to a wide-angle beam-capture system, but inferior to guidance during boost.

10.9 In considering the potential accuracy of a two-beam command-guidance system as compared to beam-rider guidance, the same tenets may be applied as in the case of the one-beam system. There should be no appreciable difference in the accuracy of intelligence gathered. The additional command link may add to the total noise dispersion. The use of computers between the two beams will add another potential source of error. The advantage of the two-beam system is the potential flexibility of the missile trajectory which may be employed to improve the performance potential of the missile proper and result in reduced bandwidth requirements, with possible increase in accuracy.

10.10 The two-beam command-guidance system, if it is used for launching guidance, has the additional disadvantage of extremely limited missile traffic since it requires a radar for each missile in the air. The missile-tracking radar could be employed as a shepherding device between the launcher and the target-tracking radar, but a glance at time remaining (Table 6) will indicate that, although this is possible, the feasibility is extremely limited. This system suffers, with the others, in the problem of discrimination between two targets in the range gate of the tracking radar. From the previous examination of this problem and system dispersions it is again believed that for medium- or long-range targets a terminal-guidance system may prove necessary.

11.0 SEMI-ACTIVE HOMING

11.1 There are three general types of missile homing systems used for engaging a radiating target. These are conventionally designated as passive, semi-active, and active systems. In a passive system the target itself must emit radiation which is usable to a missile-borne receiver for guidance intelligence. In a semi-active system a transmitting source, such as a shipboard radar, illuminates the target; a receiver in the missile homes on the radiation reflected from the target. In an active system the transmitting source and the receiver are both carried by the missile. For antiaircraft missile use the passive system is rejected since the elements of target radiation are not controllable. An active homing system requires that the missile carry, in addition to the receiver, both a transmitter and a power source for the transmitter, so that with aircraft targets and at conventional radar frequencies, only limited range is possible, compatible with size and weight considerations of antiaircraft missile design. In a semi-active system the range is limited only by practical considerations of missile antenna design and power transmission limitations. The semi-active system may employ either a monopulse or sequentially lobed type of receiver, so long as a different scan frequency from the radar scan is employed in the receiver to prevent the homing intelligence from being modulated by the shipboard radar tracking errors. No attempt will be made herein to explore or differentiate between different types of semi-active homing receivers.

It is proposed to examine several variations of semi-active homing guidance from launching to interception in the light of the tactical targets earlier assumed. Where assumptions have been made previously in the discussion of beam-riding and command systems as to missile velocity and other parameters, the same assumptions will automatically apply commonly to the semi-active homing system. Since we are considering the use of equipment available in the next five to ten years, the discussion is directed toward the use of presently planned major components, such as the AN/SPG-49.

11.2 The first consideration of semi-active homing from launching is the maximum range potential of any specific system. In many reports dealing with maximum radar range, computations are made of this value from the fundamental radar equation, or one of its many variations:

$$R_{max} = \sqrt[4]{\frac{G_t G_r A_e^2 P}{16 \pi^2 P_{min}}}$$

in which

R_{max} = maximum range
G_t = gain of transmitting antenna
G_r = gain of receiving antenna
A_e = effective radar area of target
P = transmitted power
P_{min} = minimum power just equal to noise power of receiver.

11.3 Warning must be given as to the unrestricted use of this equation or modifications which take into account other radar parameters. Experimental maximum ranges invariably turn out to be less than theoretical maximums computed from the above equation. Further, the principal tactical interest exists in determining the maximum "reliable" range at which a target may be acquired rather than the maximum range to which a target may be tracked after having been acquired. The definition of "maximum reliable ranges" is not standardized; in past reports from the Fleet it was usually considered to be two-thirds of the maximum range to which a specific target could be tracked by a specific radar. In some theoretical and experimental investigations at the present date it is chosen as the range at which the probability of detection or acquisition is 90 percent. Superficially, it is possible that the two definitions may approximate each other.

11.4 If a specific system of semi-active homing from launching is considered in which the operational performance of the shipboard radar is known, the reliable range of the homing receiver against a specific target may be approximated readily. If it is assumed that the noise factor of the missile-borne receiver is approximately the same as that of the shipboard radar, the reliable range of the receiver may be determined by the equation:

$$R_m = \frac{G_t + G_r}{2G_t} R_s$$

in which R_m = reliable range of missile receiver with specific target
R_s = reliable range of shipboard radar with same target
G_r = gain of missile receiver antenna in db
G_t = gain of shipboard radar antenna in db.

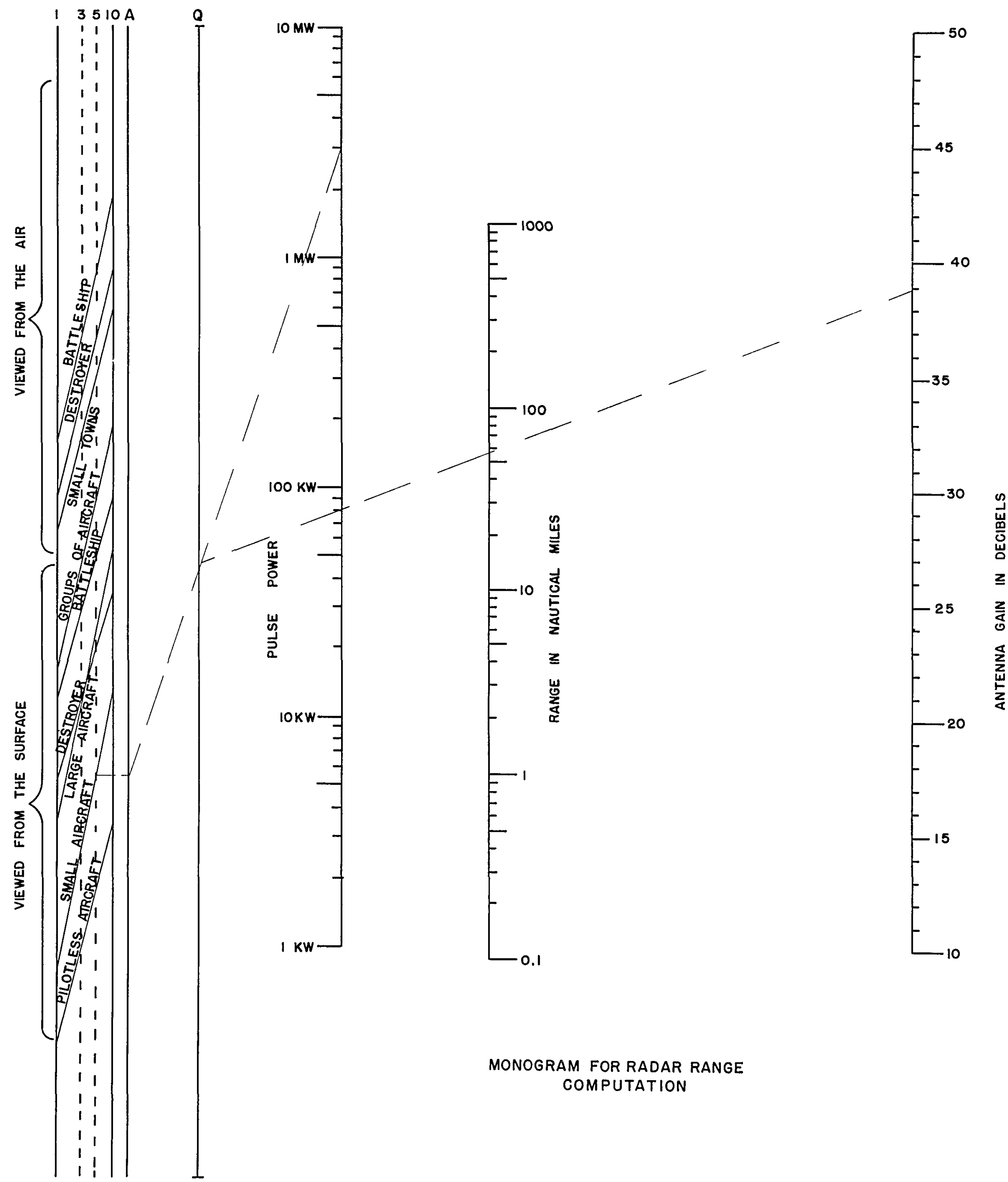
Table 7 gives the gain in decibels for antennas of various sizes and for conventional radar frequencies.

11.5 If it is desired to investigate the approximate reliable range in which the parameters of a proposed system are being explored, but where no statistical experimental data exists, it is suggested that the most recent version Radar Range Calculator written by Bell Telephone Laboratories for the Bureau of Ordnance be employed. The data given are extrapolated from Fleet reports of radar performance to cover wide variations of several radar parameters. A nomogram, derived principally from the data in the calculator, is included herein as Figure 15 for convenient use in this discussion. This nomogram is oversimplified to the extent that the pulse repetition is considered constant at 1000 pulses per second and the pulse duration as one microsecond, and receiver noise is estimated at 18 db. The ranges obtained by use of this nomogram can be considered approximations only; accurate range information must be obtained by tests with actual system equipment.

11.6 Let us assume that the AN/SPG-49 is used as the shipboard radar for a homing-from-launcher system. It is proposed that the AN/SPG-49 radar will ultimately have 3 megawatts peak power at 5.3 centimeters and a beamwidth of approximately 1.5 degrees (15). Enteringg-Figure 15 with this information (antenna gain of 39 db obtained from Table 7), it is indicated that the reliable range to a small aircraft will be about 56 miles. This example is shown in Figure 15. It is proposed that this radar will employ 3-microsecond pulses at a pulse repetition rate of 500 pps for long-range targets and 0.3-microsecond pulses at 800 pps for intermediate-range targets. Using the Radar Range Calculator mentioned in paragraph 11.5

TABLE 7

Diam. in (inches)	Wavelength in Centimeters							
	1 cm		3 cm		5 cm		10 cm	
	Gain (db)	Beamwidth (degrees)	Gain (db)	Beamwidth (degrees)	Gain (db)	Beamwidth (degrees)	Gain (db)	Beamwidth (degrees)
5	30.0	4.8	20.0	14.3	15.5	24.0	10.0	48.0
10	35.5	2.4	25.5	7.0	21.0	12.0	15.5	24.0
20	42.0	1.2	32.0	3.6	27.5	6.0	22.0	12.0
30	45.0	0.8	35.0	2.4	30.5	4.0	25.0	8.0
40	47.5	0.6	37.5	1.8	33.5	3.0	27.5	6.0
50	49.5	0.5	39.5	1.4	35.5	2.3	29.5	4.6
60	51.0	0.4	41.0	1.2	36.5	2.0	31.0	4.0
70	52.5	0.35	42.0	1.0	38.0	1.7	32.0	3.4
80	53.5	0.3	43.5	0.9	39.0	1.5	32.5	3.0
90	55.0	0.26	45.0	0.8	40.5	1.3	35.0	2.6
100	55.5	0.23	45.5	0.7	41.5	1.1	36.0	2.3



MONOGRAM FOR RADAR RANGE COMPUTATION

Figure 15

and the additional parameters of the radar, the reliable range is approximately 67 miles and 41 miles for the long and intermediate modes of operation, respectively, of the AN/SPG-49 radar against a small aircraft target. This example also serves to indicate the inaccuracies of the oversimplified range calculation of Figure 15.

11.7 Having established an approximate figure for the reliable range of the shipboard radar, the range of the semi-active receiver may be estimated. If the receiver employs a 15-inch paraboloid antenna, which would be about the size for a 20-inch diameter missile, the antenna gain, from Table 7, is approximately 24 db at 5.3-centimeter wavelength. From the equation given in paragraph 11.4 the reliable range of a semi-active homing receiver with a 15-inch antenna will be approximately 45 miles if the reliable range of the AN/SPG-49 radar is taken from Figure 15.

11.8 Inspecting the targets it may be assumed that Target 1, a high-altitude bomber, is a large aircraft; Target 2, the dive bomber, and Target 3, the torpedo bomber, may be assessed as small aircraft; Target 4, the torpedo-carrying missile, and Target 5, the powered glide bomb, may be classified as pilotless aircraft. Using Figure 15, Table 8 has been developed to show the estimated reliable ranges for each target using the AN/SPG-49 as the shipboard radar and a missile-borne semi-active radar receiver with a 15-inch paraboloid antenna.

TABLE 8

Target	Estimated Maximum Reliable Range
Target 1 - High-Altitude Bomber	93 nautical miles
Target 2 - Torpedo Bomber	45 nautical miles
Target 3 - Dive Bomber	45 nautical miles
Target 4 - Torpedo Missile	17.5 nautical miles
Target 5 - Powered Bomb	17.5 nautical miles

11.9 If it is assumed that the antenna of the radar receiver in the missile is bore-sighted with and slaved to the shipboard tracking radar before launching, then acquisition by both radars should be simultaneous if the reliable range of the missile-borne receiver is sufficient. Comparing the ranges given in Table 8 with range at acquisition given in Table 1, it is seen that the estimated maximum reliable range is great enough to engage all targets. If it is assumed that the estimated ranges may be in error by as much as 25 percent, the acquisition of Target 4, the torpedo missile, is the only one in doubt.

11.10 Homing from Launcher

The usual method considered for homing from the launcher is to gate the target with both the missile receiver and the tracking radar and, by computation, launch the missile on a straight-line trajectory to intercept a predicted future target position. At the terminus of the boost phase the trajectory would then approach the navigational trajectory computed by the homing system. The missile-borne receiver is required to track, but not guide, the target throughout the boost period. If the target engaged is at low altitude, the trajectory will be correspondingly almost parallel to the water surface so that the problem of low angle tracking exists not only at launching but throughout the missile flight. Referring to Table 7 it is seen that a 15-inch-diameter paraboloid antenna at 5.3-centimeter wavelength has a beamwidth of about 9 degrees. It would be expected, then, that free-space tracking conditions for this radar receiver would not exist until the angle subtended by the altitude of the target above the water is about 5 to 6 degrees. Under these conditions the situation is analogous to that of the wide-angle beam capture, which was illustrated by Tables 3 and 4 to be unsatisfactory. Target 2, the torpedo bomber, and Target 4, the torpedo missile, cannot be engaged with any significant probability of kill.

11.11 In order to engage all of the targets it is necessary to consider a change in some parameter that will decrease the beamwidth of the missile-borne radar receiver antenna to an acceptable value. The parameters which can be varied are limited, since the beamwidth, in a paraboloid antenna, varies only with antenna diameter and the wavelength. The diameter of the antenna is limited by the diameter of the missile, which in turn is limited by payload, range requirements, and aerodynamic characteristics. It is noted that in a recent proposal for a very long range missile (100 miles range, ground-based), an antenna diameter of 18 inches was proposed, for use with a 24-inch-diameter fuselage. It is believed that for shipboard use the 15-inch-diameter antenna example used herein approaches the upper limit on size. The wavelength is the only parameter that may be substantially varied if we ignore the possible benefit from research on other types of antennas. With X-band (3-centimeter wavelength) the beamwidth will be approximately 5.5 degrees and it would be estimated that free-space tracking will be obtained above 3.0 to 3.5 degrees elevation angle. With K-band (1-centimeter wavelength) the beamwidth will approximate 1.8 degrees, and it can be estimated that free-space tracking may be obtained above 1 to 1.25 degrees elevation angle. Assuming that the missile can be launched when the target has reached 3.5 degrees elevation angle with an X-band system and 1.25 degrees with a K-band system, Table 9 indicates the target status at the time of launching for both systems.

TABLE 9

	X-Band (3.5 Degree Elev. Angle)		K-Band (1.25 Degree Elev. Angle)	
Target Number	Range at Launching	Time Remaining to Mission Accomplishment	Range at Launching	Time Remaining to Mission Accomplishment
1- High-alt. Bomber	75 naut. miles	10 minutes	140 naut. miles	18.7 minutes
2- Torpedo Bomber	4600 yards	13 seconds	5200 yards	16 seconds
3- Dive Bomber	13500 yards	60 seconds	15200 yards	68 seconds
4- Torpedo Missile	2800 yards	4 seconds	8000 yards	30 seconds
5- Powered Bomb	14000 yards	26 seconds	14000 yards	26 seconds

11.12 Target 1 is beyond immediate concern in either case. Target 2 is a low-probability interception for X-band, marginal for K-band. Targets 3 and 5 are possible of interception in either case. (It will be noted that Target 5 has been maintained in the condition of acquisition since its elevation angle is high throughout its trajectory.) Target 4 cannot be intercepted, using these assumptions, with an X-band system since its mission will terminate before interception occurs; interception would seem possible with K-band. On this basis, only the K-band semi-active homing system will be considered further. When dispersion at launching is considered, the situation becomes comparable to the launching conditions of the two-beam command system in which the missile must be launched at about 5 degrees elevation angle to prevent loss at launching. Since no launching guidance is assumed, Table 6 will apply approximately, within the bounds of accuracy of the assumptions, to the target status when the launching dispersion of the K-band semi-active homing missile has been reduced to a sufficiently small guidance dispersion.

11.13 The next step is to determine if a satisfactory K-band shipboard radar is feasible. If it is assumed that a one-degree beamwidth for the shipboard radar is as narrow a beam as can be tolerated for reasons of acquisition, then from Table 7 it can be estimated that the antenna will be 25 inches in diameter with a gain of 43.5 db. To estimate the required power we can assume that the range must be sufficient to engage Target 4 (shown by Table 8 to be the most critical) at an acquisition range of 17 miles with the semi-active homing receiver. By the use of the tables and nomogram given herein it is indicated that the required peak power is about 800 kw. As far as is known there is no available K-band pulsed magnetron which even begins to approach this power requirement; the present-day maximum values are less than 100 kw for pulsed magnetrons. This is also true of K-band magnetrons for CW use (since the average power requirement remains unchanged). The major reason for the loss of available range by increasing the frequency is that considerable gain must be sacrificed in the shipboard tracking antenna so that the beam may be wide enough for acquisition. In addition, there is greater atmospheric attenuation at K-band than at lower frequencies. The use of homing from the launcher, on the basis of the assumptions and for low-altitude targets, reaches an incompatible design situation between the missile-borne antenna beamwidth on the one hand and power requirements for the transmitting radar on the other.

11.14 Consideration may be given to the use of a radar employing two frequencies. If the AN/SPG-49, for example, were employed to track the target, it might be possible simultaneously to inject K-band energy into the same plumbing. In this case, the problem of target acquisition is solved by acquiring and tracking the target with the 5.3-centimeter wavelength. With the AN/SPG-49 aperture the K-band beamwidth would be about 0.2 degree. Tracking inaccuracies against the low-flying target would exceed this value at intermediate ranges, so that the average power reaching the K-band homing receiver would be reduced, with possible reduction in reliable range. With this type of system, in order to engage Target 4 at 17 miles range, it is estimated that the required peak power will be approximately 500 kw. K-band magnetrons of this power are, presumably, not impossible to achieve, but their achievement and the manufacture of a dual-frequency radar would require a major research and development program, both time-consuming and expensive.

11.15 Homing with Programmed Initial Trajectory

If homing from launching is to have tactical value against all of the assumed targets, then one of the conditions previously assumed must be varied radically. The most obvious variation results from a change in the trajectory in the initial portion of the flight. It must be remembered that in a semi-active homing system relatively large inaccuracies from both the tracking radar and the launching system may be accepted. As long as the tracking radar illuminates the target within the half-power points of its transmitting beam, the average power reflected by the target is equal to that used in the computation for range; no intelligence is generated by the shipboard radar for guiding the missile. Further, once the missile-borne receiver has gated the target, the outputs from the auto pilot are used to stabilize the line of sight of the antennas to the target, so that the limit of error which can be tolerated during the launching phase is dependent upon the angle through which the gimballed antenna can turn without loss of the target. It is proposed, then, that as soon as the target is acquired by both the tracking radar and the missile-borne receiver, the situation be considered wherein the missile is launched at such an angle as to gain altitude above low-flying targets and is programmed in its initial phase of flight. In this case it is not necessary that either the shipboard radar or the missile receiver track the target accurately at the time of launching; it is only necessary that the target not be lost during

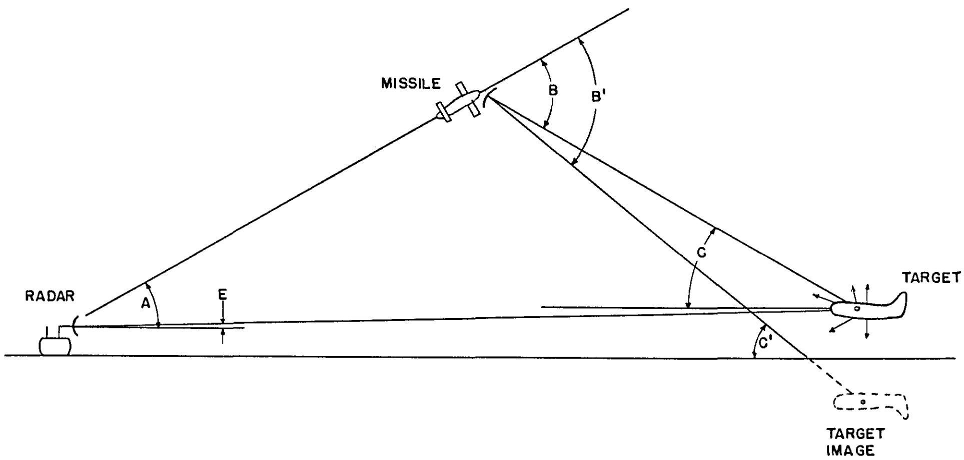


Figure 16

launching. During the boost phase, and as long after as may be necessary, the missile is controlled only by its own inherent stability and roll control. After a determined period of time, or when a known altitude is reached, control of the missile is taken over by the semi-active homing system. Figure 16 illustrates this condition of flight.

11.16 Examination of Figure 16 will bring out several pertinent facts. Under this mode of operation, free-space tracking never exists; the problem of reflection of the target image becomes somewhat similar to the problem of discrimination between two targets. If, in imagination, the target and ship are held still and the missile is moved up and down along its projected line of launching, when the missile homes on the image it will strike the water well in advance of the target at low angles and will pass closer to the target as the angle between missile and target image approaches the vertical. Simple calculation indicates, however, that the angle C′ must be 60 degrees before the miss distance to the target equals the altitude of the target above the water. Because of time required to gain this angle and the large transients imposed when the homing system takes control, there is little to be gained by further discussion of this steep-diving type of trajectory.

11.17 Another possibility which offers itself for discussion is range discrimination by engaging always the closer of the two apparent targets, since the image is always, except when viewed from the waterline, at greater range to the missile than the real target. If some quick assumptions are made, the potential value of range discrimination can be more readily discussed. With a 0.3-microsecond pulse, the gate length will be about 170 feet. With proper circuit and filter design it is estimated that discrimination is possible to one half the gate length—in this case about 85 feet. With the target at 100 feet altitude, this condition is reached when the angle C′ of Figure 16 is greater than about 26 degrees. This angle is an inverse function of target altitude and, in order to make this type of discrimination usable at more likely angles of reflection (say, for example, 6 degrees), then the target altitude must be about 850 feet. In order to employ this type of discrimination in tracking from the launcher the target altitude would have to be so high that free-space tracking would exist at usable ranges.

11.18 The problem of sea clutter in this instance should not be serious as long as the energy re-radiated by the missile is not excessive. In Figure 16 it will be observed that the major portion of energy is directed toward the target at very small angles of incidence

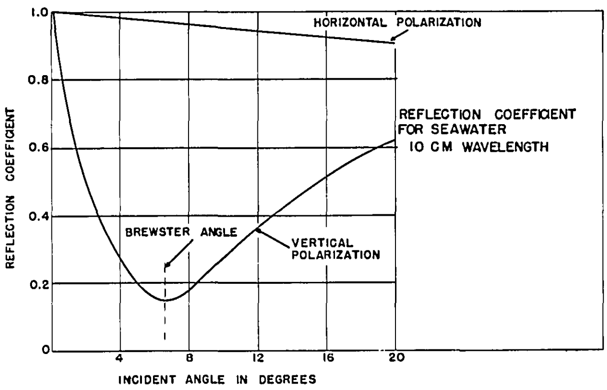


Figure 17

with the reflecting surface. There will be some reflection upward from the sea to the missile, but the situation differs radically from that of air-to-air surface semi-active or active systems wherein the transmitting or illuminating source is looking downward at the sea and target and considerable energy at high signal levels is reflected back to the missile throughout the range scale. There should be but little difficulty because of sea return from the shipboard radar; in this case the target becomes the transmitting source and the reflection problem becomes primarily that of discriminating between the target and its image.

11.19 If vertical polarization is employed, advantage may conceivably be taken of a well-known reflection phenomenon. Figure 17 shows the relation between the incident angle and the reflection coefficient for 10-centimeter wavelength and sea water for both horizontal and vertical polarization(16). As can be seen, in the vicinity of 6 degrees, the coefficient of reflection is at a minimum for vertical polarization; this angle is known as the Brewster angle and varies slightly with the wavelength at conventional radar frequencies and largely with the dielectric constant of the reflecting surface. If, then, the incident angle C′ of Figure 16 can be maintained at or near the Brewster angle, the power from the image will be, on the average, about 10 db down from that reflected by the real target. On the basis that the missile is launched at a specific preset upward angle and the semi-active homing guidance is not employed until a programmed time has elapsed, the following equation closely approximates the computation involved:

$$t = \frac{R_2 \tan C' - h_2}{M_V \sin L + M_V\, 2 \tan C' \cos L + T_V\, 2 \tan C'}$$

in which t is the time after launching when control is taken over by the homing system, and

R = range to target at launching
C' = incident angle (Figure 16)
h_2 = height of target above water
M_V = missile velocity
L = launching angle (Figure 16)
T_V = target velocity.

This equation is simplified by ignoring the reduced missile velocity during boost and the height of the launcher above the water. On the other hand the computation need not be overly critical, and the target unknowns do not seriously affect the solution if in error by a reasonable percentage.

11.20 Assuming that C′ is 6 degrees and using the assumed parameters of Target 2, the torpedo bomber, with a 15-degree elevation angle of the missile at launching, the guidance system will assume control at 11.8 seconds after launching. Approximately 13 seconds remain to interception if the missile is launched at the time of acquisition. The same computation may be applied to Target 3, the dive bomber. Against Target 4, the torpedo missile, control would be assumed at 18 seconds, with approximately 18.7 seconds remaining to interception. In each case, ample time remains to damp out the initial large transient of change of flight-path angle when the guidance system takes control. Target 1, the high-altitude bomber, and Target 5, the powered bomb, can be intercepted without programming during the early portion of flight. It would seem, from this superficial inspection, that there exists the possibility of taking advantage of the low coefficient of reflection at the Brewster angle by using a programmed phase during the initial portion of the flight. By increasing the elevation angle at launching, the time of unguided flight may be substantially reduced, but this makes necessary extremely wide limits through which the gimballed antenna must turn and correspondingly large transients when the guidance system assumes control. The possibility of target maneuvers during the long unguided part of the flight also must be explored in establishing the antenna gimbal requirements.

11.21 The problem of discrimination between the target and its image should be relieved by use of vertical polarization and by keeping the image at or near the Brewster angle. The receiver at long range will see only one target, the combination of the signal from the target and its image. The AGC gain of the receiver is thus adjusted to the combined power of the two. As the range decreases and discrimination becomes possible, the image, which is about 10 db below the target in power returned, may not even be perceived as a separate target, since the AGC has served to further reduce its apparent signal to the receiver. In any event, it would seem that there is a very high probability that the missile-borne receiver would lock on the real target to the exclusion of the image. As far as is known, there is no available test data to confirm or to refute this supposition.

11.22 It is not enough, however, that the missile choose only the real target; the missile must make the choice early enough in flight that it can turn through the angle of its uncertainty and intercept the real target. If we consider the possible case wherein the homing receiver oscillates between the target and its image but finally locks on the real target, it is possible to put down some numbers indicative of the demands on the missile. On the basis of the discussion in paragraph 9.21 and elsewhere, it can be estimated that, with 5.3-cm wavelength and a 15-inch missile-receiver antenna, the angle of uncertainty in reflection may be about 5 to 6 degrees. If it is assumed that the missile is intercepting a target flying at an altitude of 100 feet and is on a downward trajectory such that the angle C′ in Figure 16 is about the Brewster angle, the target and the water do not subtend a 6-degree angle until the range to the target has closed to about 300 yards. Despite the fact that the tracking information may be oscillating between the target and its image, the control circuits of the missile will tend to integrate such oscillations and the trajectory flown would be expected to approximate a sine wave of low amplitude around the bisector of the 6-degree angle. This condition can be made valid or improved by adjusting control bandwidths with range. The homing missile is required, then, to turn toward the real target during the final portion of its trajectory with an acceleration demand of about 6 times that of gravity. While it is true that the maximum error in bisecting the distance between the target and its image is only 100 feet (the altitude of the target) the missile will splash too far ahead of the target if it does not turn in time. As the target altitude is increased, the acceleration demands are reduced. In any case, it must be pointed out that this projected system, of homing after a programmed initial trajectory, is completely untested as far as is known. Considerable experimental work will be required to determine the feasibility of its use.

11.23 Homing with Minimum-Altitude Control

In a system which employs a minimum-altitude control, the target is detected and then acquired by the tracking radar and the semi-active receiver in the missile. The launcher is positioned by computation, if high target-tracking rates exist, to launch the missile on an intercept course. The launching elevation angle need be only high enough, in case of low-altitude targets, to be sure that the missiles do not splash during the boost period.

The missile may be launched immediately after acquisition of the target has been accomplished. The semi-active homing system assumes control immediately after separation occurs. The missile receiver can track accurately in train at all times, but the outputs in elevation will be in error when engaging low-altitude targets. However, since an altimeter or some form of minimum-altitude control is employed, this is of no particular importance at long range, since the missile cannot splash into the water. The oscillations of the radar tracking head in the missile may be variably filtered as a function of range so that the resultant missile motion is not serious enough to reduce the velocity seriously. In the case of high-altitude targets the interception is normal; the altitude control is inactive.

11.24 The use of a minimum-altitude control when only beam-riding or command systems are employed is of no benefit to system accuracy when the interception occurs at an angle below free-space tracking conditions. It has been demonstrated in the previous discussions that the beam-rider and command systems become unusable when the shipboard tracking radar, which is the essential intelligence-gathering device, is in error. For example, on the basis that 1 degree represents the minimum elevation angle for free-space tracking, then, for a target interception at 10,000 yards, the altitude of the target cannot be measured by the radar below 550 feet. At 20,000 yards, the altitude uncertainty could be as great as 1100 feet. Under such conditions, the probability of kill becomes arithmetically interesting, but little else.

11.25 It must be assumed that any surface-to-air guided missile will be equipped with a proximity fuze. The effective pattern for detonation of a proximity fuze would be expected to be evolved from warhead size and character of fragmentation, the missile velocity and the character of the mission for which the missile is employed. If the missile is flying a long range line-of-sight course against a low-flying target, it is obvious, because of the curvature of the earth, that the fuze can be triggered by the proximity of the water long before it reaches the target. This implies, then, that for any missile to be employed tactically at long range against low-flying targets, it may be desirable to employ some form of minimum-altitude control to prevent premature detonation of the missile. An alternative to this may be to employ an electrical safety which is released immediately before interception. This can be accomplished inherently with a homing system if range to the target is measured, and by a command system, since the missile and target are both tracked; but this would introduce new problems into a beam-rider system wherein no range from the missile to the target is available. However, arming by range to target is unsatisfactory since the detonation may still be premature if the target is at sufficiently low altitude and the range measurement is inaccurate.

11.26 The use of a minimum-altitude control with a homing system presents no difficult problem. The homing receiver, in flight, will continue to track the target accurately in azimuth, but will oscillate in elevation until the target subtends a sufficiently large angle with the water so that free-space tracking exists. It is believed the problem of sea return will not be serious by reason of the location of the transmitter, unless the re-radiation from the missile is excessive. This may be minimized in the case of the missile by proper precautions, but it may cause difficulty in simulated test flights with conventional aircraft. The setting of the altimeter will probably depend largely upon the maximum radius to trigger the proximity fuze, plus an allowance for tolerances in the altimeter control. The radial miss distance to a target at altitude below the preset minimum altitude would be computed from the miss distance in the horizontal plane and the difference between the preset missile altitude and the target altitude. Obviously, if the target were at the water's surface a miss would result.

11.27 In order to put some numbers to the problem, let us assume that a target moving with a velocity of 450 knots is to be intercepted at 20,000 yards range from the defending ship. It has already been pointed out that the uncertainty of the shipboard tracking radar as to the location of the target in altitude was about 1100 feet. Assume that the missile has a velocity of Mach Number 2, is equipped with a semi-active homing system operating at 5.3 centimeters, and is using an antenna of 15 inches diameter. Substantially free-space tracking will result when the angle subtended between the target and the water (angle α, Figure 10) is about 5 to 6 degrees. It is assumed that the parameters of the proximity fuze and the tolerances of an altimeter control are such that the missile may safely be flown at an altitude of 250 feet. Figure 18 shows the missile approaching a target illustrated to be at three discrete altitudes: T_1 at 250 feet, T_2 at 500 feet, and T_3 at 1000 feet. The interception of T_1 presents no problem since it is being tracked in bearing and is flying at the altitude maintained by the missile. Altitude T_2 subtends an angle α of 6 degrees to the water at a range of approximately 1600 yards, with about 1.6 seconds of flight time remaining. The average acceleration required to turn through the 250-foot separation in altitude is roughly 6 gravities. In the case of T_3 an angle of 6 degrees is subtended between the target and the water at a range of approximately 3200 yards, with approximately 3.25 seconds of flight remaining. The average acceleration required to hit is only 0.6 gravity.

11.28 From the foregoing discussions of possible semi-active homing systems, it would seem that a system employing some form of minimum-altitude control will be inherently the least complicated and offers the most promise. It nullifies the detrimental effect of surface reflection of the low-flying target, until such time as the system perceives the target under conditions equivalent to free space. The kinematic demands upon the missile and control system at the terminus of the flight are not unreasonable. For those targets which lie below the minimum altitude, the probability of kill may be enhanced by release of altitude control at some minimum range, if further investigation should indicate the necessity for it. The altitude at which the missile will fly is determined by the proximity fuze plus an allowance for lack of accuracy in the altitude-controlling device. The probability of kill then may be poor in the case of targets extremely close to the water surface, and will be in part dependent upon the accuracy of the altimeter, but the limits are derived from factors extraneous to the type of guidance system.

11.29 Discrimination in the Homing Problem

Figure 19 illustrates the situation wherein a missile is attempting to intercept two approaching targets, both within the range gate of the missile receiver. The targets, separated by a distance D, subtend an increasing angle θ at the missile as the range decreases.

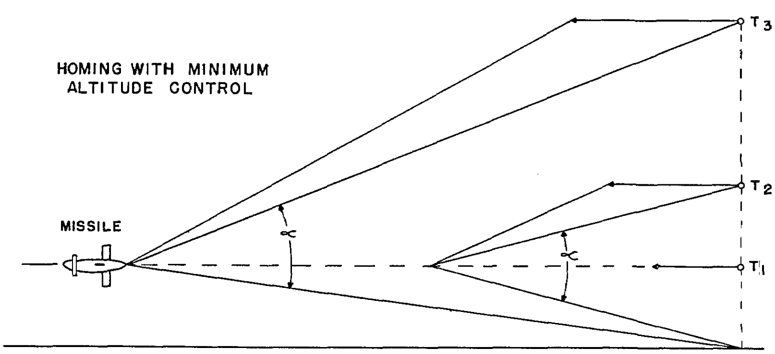


Figure 18

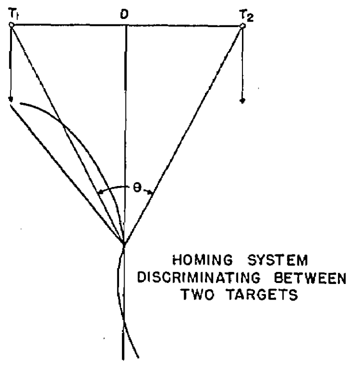


Figure 19

The receiver antenna tends to oscillate between them until only one target is chosen; the missile path tends to oscillate around the bisector of the angle θ until then. If we assume a 15-inch-diameter antenna and a wavelength of 5.3 centimeters, on the basis of extrapolation of existing data it is estimated that one target will be selected when θ is around 5 to 6 degrees. Homing systems utilize computed collision courses for interception; with the apparent shift of target position, as the missile engages one only of the two targets, a new intercept course must be computed. If the same assumptions are again made, as used on the beam-rider discussion with two approaching targets 600 feet apart, by the geometry of the situation one target will receive the isolated attention of the homing receiver approximately 2 seconds before interception. This requires that the missile turn at an average acceleration equal to about 5 gravities. This value is reasonable for missile design.

11.30 An additional discrimination requirement is imposed on homing systems inasmuch as some protection must be provided for the surrounding ships. If a missile were homing on a target which passed over another ship of the task force, the energy reflected from the ship will present a large signal compared to the plane so that the missile will home on the ship. Range-rate discrimination must be provided, therefore, to prevent homing on large fixed targets.

11.31 There exists also the possibility that the shipboard radar and the homing system may choose two different targets. This situation is somewhat alleviated when both the shipboard and missile systems acquire the designated target prior to launching. There does remain the possibility that the apparent single target initially engaged turns out to be a group of targets which can scatter so that the shipboard radar tracks one, while the homing system chooses another. However, as the range closes between the missile and target, the required signal return from the target may be reduced considerably without adversely affecting the performance of the homing system, and, provided the signal level is above noise, it does not matter if the target is illuminated by the main beam or by a side lobe.

11.32 Accuracy of Homing Systems

The accuracy and corresponding probability of kill of a homing system is difficult to define in finite numbers. Among other parameters in the design of a homing system, the interrelated problems of receiver tracking noise, target and missile kinematics, and method of computation of the intercept course may exhibit incompatibilities which must be resolved by judicious compromises on the part of the control system designer. Because of the complexity of analysis of homing systems in relation to specific targets, in either the frequency or time domains, the accepted method of investigation of such systems is by use of simulators. Unfortunately certain parameters, notable among them being radar noise at close range to the target, are not yet resolved in finite value, so that the results of simulation are in question. The accuracy of the intelligence utilized in guidance generally varies as an inverse function with range to the target. Since with beam-riding and command-guidance systems the termination of the flight is at increasing ranges while with homing the range continues to decrease, it is to be expected that homing guidance will be inherently more accurate than command or beam riding only. Further, the demands on the missile at the termination of the flight are inherently less in a computed collision trajectory than with a line-of-sight trajectory.

11.33 In view of the high price paid in probability of kill for each unit of miss distance, considerable experimentation, analysis, and simulation is under way. The Naval Research Laboratory is attempting, by experiment, to isolate angle noise for specific aircraft targets. Consultants to the Fairchild Guided Missiles Division have attempted to determine the optimum transfer characteristics of the control loop of a homing missile system based on tracking noise consideration. The Massachusetts Institute of Technology, working on the Meteor project, is engaged in simulator studies on this subject. Transfer characteristic studies and tests in relation to this problem are underway at the Naval Research Laboratory and elsewhere. In view of the attention being paid to this subject, it might be well to examine, even superficially, the homing problem to see wherein the incompatible elements lie.

11.34 A computing homing system will have to accomplish the following (17):

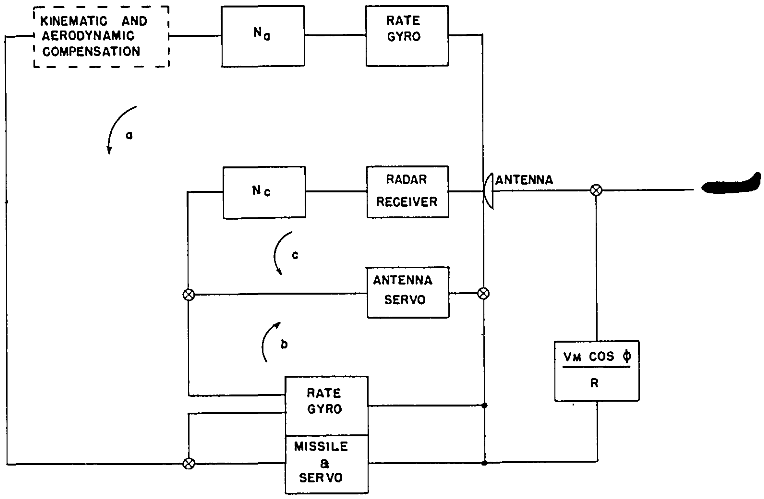
(a) The missile-control system must cause the missile to follow the desired trajectory with accuracy consistent with the tactical requirements.

(b) The tracking radar antenna should be stabilized in space against missile motion due to trajectory-following and missile motion caused by air gusts and similar outside disturbances.

(c) The radar must be capable of tracking the target, and its tracking loop should add no phase shifts or otherwise impair the performance of the missile-motion stabilization or the missile-control system.

11.35 The missile-control system, in causing the missile to follow the desired trajectory, has, implicitly, as one of its functions, that of computation or navigation since it is desired that the missile heading be such as to intercept a target at some future position. In general the trajectories which have been examined for homing use are (18): (a) The pursuit trajectory—in which the missile is always pointed at the present position of the target without computation (sometimes employed in flight tests for simplicity, but not considered for tactical use because of infinite turning rates imposed at the end of the trajectory); (b) the deviated pursuit trajectory—in which the missile is pointed at a fixed lead angle toward the target (which is all right only if it is possible to measure the lead angle correctly at launching and the target does not maneuver); (c) the proportional navigation trajectory; and (d) the constant true-bearing trajectory. The latter two are those generally considered for homing use. In the proportional navigational trajectory the rate of change of the missile heading is made to equal a constant multiple of the rate of change of bearing to the target. In the constant true-bearing trajectory the missile control functions to keep the rate of change of bearing to the target at zero. In only this latter type of trajectory, when the speed of the missile is equal to or greater than that of the target, the acceleration demanded from the missile is never greater than target acceleration.

11.36 In Figure 20 is disclosed one of many possible versions of a homing system in which the three requirements of the homing system (paragraph 11.32) are illustrated as separated into three control loops. Loop (c) is the missile-borne receiver tracking loop; the outputs of the radar receiver are fed to the antenna servo which it positions so as to track the target within the limits of antenna motion. Loop (b) is the antenna stabilizing loop; if a gust of wind or some outside force were to disturb the heading of the missile, the rate gyro in that loop measures the motion and corrects the position of the antenna with respect to space. Loop (a) is the missile-control loop; the rate gyro measures the motion in space of the antenna dish, its outputs being fed to the missile servo which changes the missile heading until the rate of change of heading becomes zero. As the missile



BLOCK DIAGRAM OF SEMI-ACTIVE
HOMING SYSTEM

Figure 20

changes heading on its trajectory, loop (c) keeps the antenna heading unchanged. The term $V_M \cos\phi / R$ (in which V_M is missile velocity, ϕ is the angle between missile and target, and R is the range between missile and target) results from the geometry of the problem and represents the effect of changes in missile heading on the true bearing from the missile to the target (17). It will be noted that this term represents a change of gain with range—as the range decreases the gain increases. This can readily be seen by the following example: A change in position of the target of five yards at a thousand yards range subtends an angle of five mils at the missile receiver; the same change at 500 yards is 10 mils; at 250 yards it becomes 20 mils, etc. For each halving of range the gain of the system increases 6 db. No system can be constructed to accept an infinite change in gain without becoming unstable; in missile-control systems the change in gain is frequently extremely limited by resonances in the airframe or components which are invariants to the control designer.

11.37 One option of the control designer is to cut off further guidance intelligence at a specific minimum range and to permit the missile to fly the remaining distance on its own inherent stability; the magnitude of the miss is then dependent upon the dynamics of the target and missile geometry at the time of cut-off. A second option is to permit instability to develop, if the time remaining to interception is so short that the missile oscillations will not have time to be of serious consequence. If range is measured within the missile, the effect of the gain change because of range may be compensated for by introducing this quantity into the loop where noted in Figure 20 as kinematic compensation. Other effects which may require compensation are created by the fact that the transfer characteristics of the missile vary as functions of its mass, its velocity, and the density of the air in which it flies. Unfortunately, many proposed homing systems do not measure range to the target, while in others the minimum range measured is large, so the problem of gain change and instability becomes important in the consideration of miss distance.

11.38 In order to consider the effect of tracking in the missile-borne receiver noise, let us review Figure 12. At short range, which is the primary interest in this problem, the tracking dispersion is the root-mean-square of the summation of amplitude noise (a function of beamwidth), servo noise, and angle noise (a function of target characteristics), with angle noise predominating more and more as the range decreases and the target subtends a greater and greater angle to the missile radar receiver. Although the total amplitude of dispersion may seem large when viewed as an angular measurement, it will, when angle noise predominates, be well within the angle subtended by the target. The usual value of angle noise assumed is one-sixth of the angle subtended by the target, with other guesses running less than this. At the present time the magnitude of this dispersion is under intense investigation (12).

11.39 Unfortunately, the effect of the noise cannot be confined within the missile-borne receiver tracking loop by narrowing the bandwidth of the network N_c, since the tracking-loop bandwidth must be considerably greater than that of the missile-control loop. To restrict it will introduce phase shifts into the missile-control loop which can cause it to become unstable. The missile-control loop, since it is a lead-computing device, inherently acts as a multiplier of the receiver tracking errors. The effect, on operational accuracy, of the noise introduced into this loop is not only a function of the bandwidth of the network N_a, but also of the transfer characteristic of the loop. The effect of noise cannot be eliminated by closing down the bandwidth of N_a, since the requirements of some tactical situations (discrimination between multiple targets, for example) require adequate bandwidths at closing range and the speed of response to input transients is a function of the bandwidth. These apparent incompatibilities, in combination with the potential instability resulting from gain change with range, explain the effort now being put into this phase of missile guidance. While it is difficult to generalize about complex systems of this character, it is believed that a great deal is to be gained both by separating the interrelated control loops, so that the individual problems of each may be separately treated, and by the measurement of range to the target so that gain change from this source is removed from the problem.

12.0 COMPARATIVE SUMMARY OF GUIDANCE SYSTEMS

12.1 From the tables given in the individual discussions of the guidance systems, it is possible to compare the status of the assumed targets at that instant when a missile may first be launched at the target by each of the guidance systems. Table 10 is a compilation of this information. The individual systems will be re-examined and compared with some thought given to the realism of the basic assumptions.

12.2 Beam-Rider or Single-Beam Command System with Wide-Angle Beam Capture

The basic assumption governing the tactical use of this system is that the launching is delayed until the guidance information obtained from the wide-angle beam is of sufficient accuracy to permit capture by the narrow beam, since the reflection disturbs not only the tracking mechanism of the shipboard radar but also the intelligence impressed on the beam for guidance. The assumption that the angle subtended by the altitude of the target be 5 degrees when the missile is launched may be modified by actual statistical data on launching dispersion with corresponding modification of the capture beam parameters. It may be argued that the missile can be launched prior to the 5-degree angle being reached, since in any attack the angle subtended is increasing with decreasing range between target and ship. Such an argument has merit; but it does not touch upon the basic facts that the target assumptions favor the missile-guidance problem, and that for the short-range tactical problem the dispersion of the missiles must be a minimum if any reasonable probability of kill is to be achieved. The conclusion, then, that Target 2, the torpedo bomber, and Target 4,

TABLE 10

Target	Beam Rider or Single Beam Command—Wide Angle Beam Capture		Beam Rider or Single Beam Command—with Guidance During Boost		Two-Beam Command		Semi-Active Homing—with Minimum-Altitude Control	
	Range	Time to Mission Accomplishment	Range	Time to Mission Accomplishment	Range	Time to Mission Accomplishment	Range	Time to Mission Accomplishment
1	60 miles	7.6 minutes	150 miles	20 minutes	150 miles	20 minutes	202 miles	27.2 minutes
2	4300 yards*	11 seconds*	5400 yards	16 seconds	5400 yards*	16 seconds*	22600 yards	85 seconds
3	12700 yards	56 seconds	15500 yards	70 seconds	15500 yards	70 seconds	22600 yards	98 seconds
4	X	X	9300 yards	34 seconds	9300 yards	34 seconds	33600 yards	161 seconds
5	14000 yards	26 seconds	14000 yards	26 seconds	14000 yards	26 seconds	14000 yards	26 seconds

* Interception occurs before launching dispersion is damped out.

the torpedo missile, will be of low-order probability of kill seems justified. In addition, multiple plane attacks, at intermediate or long ranges without homing guidance, present a natural means of rendering this type of guidance ineffective.

12.3 Beam-Rider or Single-Beam Command System with Guidance During Boost

This system presents the best picture of those which depend on the shipboard radar for primary intelligence, since the limiting assumption is the low-angle tracking ability of the shipboard radar, which is assessed as satisfactory intelligence when an angle greater than 1 degree is subtended by the target altitude. Test evaluations of current shipboard radars indicate that this figure is not being achieved, although the margin is close. However, it is believed that improvements are possible, so the assumption may become reality with detailed investigation. On the debit side is the fact that the range of the attacking plane for mission accomplishment may be much greater than herein assumed, in the case of Target 2, the torpedo bomber, in particular. This makes the interception of the torpedo bomber one of doubtful probability. Multiple plane attacks again present a means of making this system relatively ineffective.

12.4 Two-Beam Command System

The limiting assumption of this system lies in the launching dispersion; for, although the missile may be launched when the shipboard radar is capable of disseminating correct intelligence at 1-degree elevation angle, the missile, being launched at an angle from the guiding line and dispersed from the angle of launching, must be shepherded back to it with corresponding loss of time and short-range effectiveness. The torpedo bomber, Target 2, is the only target indicated to be of doubtful probability since the interception occurs before launching dispersion is damped out. As in the previous case, this system will be at a greater disadvantage if assumptions of increased mission completion range are employed. Lack of discrimination against multiple attacks again reduces kill probabilities.

12.5 Semi-Active Homing with Minimum-Altitude Control

This system enjoys a large advantage in range of attack since the limiting assumption is only that the missile-borne receiver be able to lock-on and automatically track the target in order that it may be launched. The inaccuracies of intelligence against low-altitude targets are nullified by use of the minimum-altitude control, which prevents loss of the missile until free-space tracking of the target is possible. The limiting element in tactical use of this system has frequently been considered to be maximum range. It is believed that tests have demonstrated that range requirements can be met. It may be argued that the computation to position the launcher will require that Table 10 be modified to include the time of computation. Further system analysis may indicate that, because of the long ranges, the initial rates will be so low that the missile can be launched on a line-of-sight trajectory. Minimizing the dispersion will benefit the use of this system against short-range targets; it should be remembered that dispersion in this case produces only a change in lead angle, whereas in a line-of-sight system a lateral displacement from the guide line is also introduced. The problem of discrimination between multiple targets is of simple solution in this case; however, it introduces transients at the terminus of the flight which may require considerable analysis for optimum bandwidth determination. The problem of discrimination against other ships of the Fleet exists in this system only.

12.6 Detection and Acquisition

Several major assumptions were made in this general category. One assumption was that the ship carried a radar or combination of radars capable of detecting any of the targets when they appeared above the radar horizon, and another was that only the attention factor of the operator need be considered in the probability of detection. This is not realistic in the Fleet today; the eventual realism of the assumption depends largely upon the search radar program—on research, development, manufacture, and the economics of so equipping the required number of ships. Another basic assumption is that the time from detection to acquisition (and by acquisition is meant that the controlling radar is automatically tracking the target) is only 20 seconds. This implies improvement in identification and automatic data-disseminating systems presently unrealistic to Fleet performance. Major effort is being expended to accomplish these objectives; on the success of this effort will depend largely the tactical usefulness of any anti-aircraft defense.

12.7 Altitude Control

It was assumed that because of the use of proximity fuzes it will be desirable to employ some form of minimum-altitude control as an adjunct to any missile-control system tactically employed against low-flying targets. It is believed that this assumption is realistic. This presents an operational handicap since, if the tolerance of the altimeter device is high, the low-flying plane may pass through the interception untouched if its altitude is less than the tolerance allowed to prevent self-destruction of the missile. The need for a highly accurate altitude control for missiles becomes important. Only in the case of homing from launching does the use of an altimeter control improve the system parameters; in the other guidance systems it merely becomes a safety device to prevent premature detonation of the missile. In the case of the homing system, if range to the target is measured, investigation may indicate the feasibility of removing the minimum-altitude control at a minimum range to improve probability of kill on low-flying targets.

12.8 System Complexity

It is believed that the following list of guidance systems is in the approximate order of increasing system complexity, considering equipment both in the missile and on the ship:

(a) Beam Rider with Wide-Angle Launching Guidance
(b) Beam Rider with Guidance During Boost
(c) Semi-Active Homing from Launching

(d) One-Beam Command with Wide-Angle Launching Guidance
(e) One-Beam Command with Guidance During Boost
(f) Two-Beam Command

The listing is made from superficial considerations of research, development, and operational complexities without detailed examination of possible tube and component complements. Security considerations also will undoubtedly increase the complexity of some systems more than others. It must be stressed that, in eventual service use, system simplicity will be an important factor.

12.9 Traffic Handling

On the basis of experience in missile-flight tests, the consideration of traffic handling (i.e.,simultaneous control of multiple missiles against the same target) of these guidance systems may seem somewhat academic. However, as missiles approach operational usefulness this consideration will be important. It is believed the following list presents the approximate order of ability to handle traffic, with the better systems leading the list:

(a) Semi-Active Homing from Launching
(b) Beam Rider
(c) One-Beam Command
(d) Two-Beam Command

12.10 Trajectory Demands

The turning rates and probable input transients demanded by the trajectory contingent upon the guidance system is a parameter of prime importance to the control designer. Many mathematical treatises have been written on this subject (18). Under certain conditions accuracy may be an inverse function of control-system bandwidth, and control-system bandwidth is in turn a result of trajectory and transient demands. The trajectory demands, which may be implicit with a type of guidance, form an index of merit of the system. The following list is in increasing order of trajectory acceleration demands, without consideration of possible target maneuvers:

Trajectory	Guidance System
(a) Constant true bearing	Homing and two-beam command
(b) Proportional navigation	Homing
(c) Line-of-sight	Beam rider and one-beam command

13.0 CONCLUSIONS

13.1 The probable tactical effectiveness of beam-rider and one-beam command systems without homing guidance against low-altitude attacks is poor for the following reasons:

(a) Defense cannot be undertaken except at short range with critically limited time remaining until the target completes its mission.

(b) The use of wide-angle beam capture, which is required by reason of launching dispersion, will result in complete ineffectiveness against some types of low-altitude attacks.

(c) Launching dispersion must be reduced, either by improving inherent missile stability or by some form of guidance during boost, to permit effectiveness at short range.

(d) The problem of target reflection, inherent with low-angle shipboard radar tracking, mitigates tactically against any system which depends upon accurate intelligence gathering on shipboard.

13.2 The lack of discrimination between multiple targets by the shipborne radar may make beam-rider and command systems, without homing, ineffective.

13.3 The probable tactical effectiveness of the two-beam command system without homing guidance is no better than the beam-rider or one-beam command system when used against low-altitude attacks or multiple targets.

13.4 On the basis of the assumptions made in this report, semi-active homing is tactically superior to active or passive homing systems against airborne targets.

13.5 The use of a semi-active homing system in conjunction with beam-rider or one- or two-beam command systems offers no tactical advantage over the use of the semi-active homing system alone, where the range limitation is such that the homing system may assume control from the time of launching.

13.6 It is concluded, from the assumptions, that semi-active homing from the launcher, in combination with minimum-altitude control, offers the greatest promise for tactical defense against aircraft targets of the guidance systems herein considered.

14.0 RECOMMENDATIONS

14.1 It is recommended that increased effort be put into the research investigation of, and the means for, reducing the launching dispersions of tactical missiles. The short-range effectiveness of a missile will largely depend upon its behavior during the boost phase, regardless of the type of guidance employed. If the dispersion cannot be reduced inherently within the airframe of the missile and booster, then it is recommended that the development of a guidance system for control during the boost phase only be undertaken.

14.2 It is recommended that a research study be undertaken in an effort to determine the complete parameters of the low-angle-tracking problem. Such work should be directed toward the improvement of this quality in existing radars, since it is highly important in fire as well as missile control. (NRL Problem 36R05-53R, BuOrd Problem 0220, has been initiated as a result of this study.)

14.3 It is recommended that increased efforts be applied on the investigation of discrimination between multiple targets and the possibility of developing a means of improving the discrimination characteristics of shipboard tracking radars. This again should be made applicable to existing radars, for this problem is important in fire as well as missile control.

14.4 It is recommended that further investigation be made of semi-active homing from launching systems, in the light of additional probable targets, to determine the optimum character of the system and missile which should be employed in tactical defense.

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