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FIRE CONTROL REQUIREMENT FOR EX 83

Final Report on  
EES/GIT Project A-1854  
PO No. SD310K

Submitted to  
GENERAL ELECTRIC COMPANY  
AIRCRAFT EQUIPMENT DIVISION  
Lakeside Avenue  
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By

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PART I

## A. INTRODUCTION AND SUMMARY

This final report documents the effort by Georgia Tech to assess radar fire control system requirements for the EX 83 Naval Mount and GAU-8 Gun Systems as a point defense anti-missile system. Emphasis is on radar parameter synthesis. Included within the scope of this effort was an assessment of the G.E. fire control systems concept, based on the ULTRA Phased Array Antenna Design.

The primary emphasis was on synthesizing parameters and techniques which would meet the concept mission requirements. This process permitted an objective evaluation of the concept and identified areas for further investigation.

Although the system concept includes classical AAW, surface warfare, and missile defense roles, the emphasis is on the latter. Therefore, this report deals with the secondary roles in a cursory manner and concentrates on the missile defense role.

Part II of the report discusses the ships and missions envisioned for the EX 83 system. Applicability was judged to be for all combatants from Patrol Craft size to Aircraft Carrier size and for some non-combatants. Four types of targets were identified: missile, manned aircraft, major combatant, and small combatant. The impact of the missile target dynamics on the fire control system was addressed.

Part III discusses the phased array concept and such considerations as "On-Mount vs. Off-Mount" and "Dedicated vs. Semi-Dedicated" in terms of the mission requirements identified in Part II. Since the general concept

has been identified by this point, the remainder of Part III discusses the reaction time and error budget for the concept.

Part IV specifies the basic detection range performance and error allocation which results from the reaction time and error budget of Part III. The range performance and error allocation are used in turn to determine the radar parameters. The determination of radar parameters permits the general nature of the hardware to be specified.

The final part of the report provides a general discussion of three special topics: the cross section enhancement of projectiles for round tracking purposes; a brief discussion on low elevation angle tracking; and disclosure of an unique approach to determining aim point criteria.

## B. CONCLUSIONS AND RECOMMENDATIONS

The most important conclusion that can be drawn from this investigation is that the G.E. Phased Array Radar Fire Control System (EX 83 RGFCS) concept is valid. It is concluded in Part II that two configurations of the basic concept would permit the EX 83 RGFCS to perform its role for the platforms (ships) mentioned and their missions. The two configurations are the "On-Mount/Dedicated" and "Off-Mount/Semi-Dedicated" configurations.

The basic ULTRA antenna does not have the characteristics to make the EX 83 RGFCS concept feasible. In hypothesizing antenna changes, it became necessary to select Ku (i.e.  $f \approx 16$  GHz) as the operating frequency band. The primary constraint which forced the selection of Ku were cost, antenna size and power dissipation capability of antenna phase shifters.

Changes in any of the above areas could make lower frequency bands feasible. A relaxation of cost and antenna size constraints would permit more elements, which would permit a higher average power, and the lower antenna gain which would result at X-band. For a particular number of elements, an increase in the average power handling capabilities of the elements would have a similar effect in permitting operation at lower frequencies.

Projectile cross section enhancement for purposes of round tracking is seen as feasible on the basis of projections of the achievable cross section and directional characteristics for a single round. The ULTRA concept has the inherent potential of tracking projectiles at any point

in their trajectory which is unique and may prove to be advantageous over tracking only in the vicinity of the target.

The low elevation angle tracking problem is addressed only as a brief survey of current approaches to the problem. A full analysis of performance in this area is needed.

Part V, Section C, contains a discussion of Aim Point Criteria. These criteria are not unique to the EX 83 insofar as potential application but may be very unique to the anti-missile point defense GFCS scenario.

Georgia Tech's recommendations are based on the premise that key issues related to the EX 83 GFCS concept should be resolved to the extent that technical risk is sufficiently lowered to permit an engineering development decision. The recommendations are as follows:

- Decide which configurations are to be pursued.
- For On-Mount configurations, perform an investigation to determine the detrimental effects of mount and gun barrel proximity to main lobe and side lobe.
- Decide whether cost constraints dictate staying with the original single array concept or whether multiple arrays are acceptable.
- In conjunction with the above multiple array decision, determine if advances in array element power handling capabilities permit operation at frequency bands below Ku and if so whether X band is more or less desirable than Ku.

- Carry the basic concept design to a more detailed level after the above prerequisite decisions and determinations are made.
- Perform a detailed performance analysis of the final design configuration, making extensive use of computer programs which have been modeled for such analyses.
- Perform projectile modification and cross section measurements to confirm round tracking projections.
- Delineate round tracking techniques and usage of the round tracking information.
- Investigate in detail the low elevation tracking performance of the synthesized design.
- Perform a detailed Aim Point Criteria analysis.
- Perform an extensive analysis of foul weather and clutter environment performance.

PART II

## A. APPLICATIONS (SHIPS AND MISSIONS)

The EX 83 system is potentially applicable on surface vessels ranging in size from less than 100 ft., such as patrol craft, to much larger vessels such as aircraft carriers. In between these two extremes are major combatants such as Destroyer Escorts, Frigates, and Cruisers. In the case of patrol craft, the system would more than likely serve as the entire defensive armament, including anti-aircraft and anti-surface craft roles, and, when used alone, would serve as the total offensive armament. More often than not in the offensive role, the EX 83 would be secondary to a surface-to-surface missile system.

On larger combatants, the system would be used almost exclusively in a point defensive role. On larger surface vessels which are not major combatants, such as Tankers and Tenders, the Ex 83 system's role would be more inclusive. Unlike the small combatant case however, it may be used in conjunction with and possibly even interfaced with other weapons and sensors and would probably not be the primary weapon system in certain roles.

On small interdiction craft which are not equipped with missile systems, the EX 83 system would be required to detect, track, and deliver fire against other surface craft. These craft of the Coastal Patrol and Interdiction Craft (CPIC) type are primarily intended to patrol and interdict other small surface craft, including missile boats, and larger non-combatants. On a CPIC type craft, the EX 83 system could be assumed to comprise the entire armament (i.e., weapons, weapon control, fire control, and sensor systems). Therefore, in addition to the surface mission, the EX 83 system would have to provide the anti-air warfare (AAW) defense capability for the craft. It

would also be desirable for the system to provide a CPIC type craft with an anti-missile capability, but this is not seen as a hard requirement. A craft of the CPIC variety, while being less expensive and having a lower complement than larger combatants, is also less vulnerable to surface missile attacks; not invulnerable but less vulnerable. The basic air threat to a CPIC type vessel would be a subsonic manned aircraft.

For the missile equipped small craft, the EX 83 system could expect to fulfill similar roles as for the CPIC type craft. In addition, the system could be expected to be required to provide over-the-horizon detection performance on large surface craft and missile boats for targeting of the missile system.

On auxiliary type vessels such as cargo ships, etc., the EX 83 system would probably not serve as the primary surface weapon system and might not interface with a surface missile system, even if the ship were so equipped. Its primary usefulness would be as an AAW system against both manned aircraft and missiles.

On major combatants, the EX 83 could be expected to serve almost exclusively as a last ditch, point defense system and would be integrated into the ship's combat system.

## B. TARGET MODELS AND SCENARIO

From the discussion of the previous section, it appears that four types of targets may be engaged by the EX 83 system. These are the small, high speed, low elevation angle missile, the sub-sonic manned aircraft, small patrol type craft and larger surface vessels. In addition, the system may be expected to perform sensor and fire control computational chores in conjunction with other systems for over-the-horizon engagements of both large and small surface craft.

The platform on which the EX 83 is used will determine its performance requirements. It is important to be aware of the probability that the performance requirements against a particular target may vary according to the host vessel for the EX 83 system, due to its different mission requirements and to the variety of other weapons equipment with which the EX 83 may be interfaced. It is also likely that the engagement scenario will vary as to both the quantity and frequency of required target engagements. The degree of autonomy and scope of the EX 83 system is also likely to vary according to platform. The different possible degrees are:

- Weapon System
- Weapon and Fire Control System (Includes Sensors)
- Weapon and Weapon Control System (Includes Fire Control)
- Combat System (Includes all of the above plus additional ancillary equipment)

With the knowledge tucked away in our minds that EX 83 performance for a particular target may vary, we will specify the target models.

### Target #1 (Missile Target)

The missile target may be alone or may be only one in a multiple missile scenario. Its angle of arrival may be from  $0^\circ$  to  $60^\circ$  in elevation angle. The possible launching platforms include shore sites, submarines, missile boats, and manned aircraft. Terminal phase guidance for the missile may be active or passive. Other missile target characteristics include the following [1]:

- Velocity (V) -- Mach 3.5
- Radar cross section ( $\sigma$ ) --  $0.1 \text{ m}^2$
- Maneuverability -- Acceleration (a) of 15 G's

The worst case scenario will be two pairs of missiles arriving at 5 seconds separation in time. The separation of missiles within a pair is taken to be 1/2 second. The angular separation between two missiles of a pair as well as between the pairs is assumed to be  $45^\circ$ .

### Target #2 (Attack Aircraft)

The manned attack aircraft is assumed to have the following characteristics:

- V = 700 knots
- a = 5 G's
- Radial straffing run attack pattern
- $\sigma = 1 \text{ m}^2$

A single aircraft attack scenario is assumed.

### Target #3 (Small Boat)

The small boat target is assumed to have the following characteristics:

- $\sigma = 10 \text{ m}^2$
- V = 50 knots
- a = 1 G

#### Target #4 (Large Surface Vessel)

The large surface vessel which will be sensed and tracked only is assumed to be much larger than  $100 \text{ m}^2$  but a  $10 \text{ m}^2$  cross section should be used in assessing over-the-horizon performance. It is assumed to be capable of 30 knots and to be relatively non-maneuverable.

### C. DYNAMIC SYSTEM IMPACT

The target's dynamics will obviously have an impact on the system. This impact may be realized as scintillation, glint, dynamic lags, etc. These potential impacts will place constraints on the selection of system parameters such as I/O rates, tracking bandwidths, reaction time, etc. In order to develop the basis for such analysis, this section models and analyzes target dynamics from the perspective of the reference frame that the EX 83 will operate in. Particular attention is given to the missile target since it is the one of greatest concern.

If the missile target were to fly in a tight circle, pulling a maximum 15 G radial acceleration, the diameter of the circle would be

$$D = 2 \frac{|v|^2}{|a|}$$

where

D = circle diameter

|v| = absolute value of maximum target linear velocity

|a| = maximum acceleration

Henceforth the absolute value signs will be dropped for convenience. Substituting the numerical values for velocity and acceleration, we compute the diameter of the circle as

$$D = 2 \frac{[1.16 \times 10^3 \text{ m/s}]^2}{1.47 \times 10^2 \frac{\text{m}}{\text{s}^2}} = 1.83 \times 10^4 \text{ m, or } 18.3 \text{ Km}$$

The circle is shown in Figure II-1.

The circle describes the limit of engagement capability for the missile. Only if our vessel lies on or outside the perimeter of the circle can we be intercepted by the missile. If the missile therefore approaches our vessel with a terminal phase, maximum acceleration maneuver, we may describe its motion during this phase as an arc length of this circle.

For any particular range and velocity vector orientation of the target, we may define a center of curvature, which is the point of intersection of all of the missile's radial acceleration vectors as it flies on an arc. For reference purposes, we will define a line between our vessel and this center of curvature as the angular reference of  $0^\circ$ . We will define  $\theta$  as the angle between the line of radial acceleration and the reference line. This is shown diagrammatically in Figure II-1. We will define  $\theta$  as the angle between the reference line and line-of-sight (LOS) to the target. This is also shown in Figure II-1. With these definitions we may express  $\theta$  as a function of  $\theta_1$ .

$$\theta = \text{Arctan} \left[ \frac{\text{Sin } \theta_1}{1 + \text{Cos } \theta_1} \right]$$

By taking the derivative of  $\theta$  with respect to time and using the notation  $\dot{\theta} = \frac{d\theta}{dt}$ , we may express  $\theta$  in terms of  $\theta_1$  and  $\dot{\theta}_1$ .

$$\dot{\theta} = \frac{\dot{\theta}_1}{\left[ 1 + \left( \frac{\text{Sin } \theta_1}{1 + \text{Cos } \theta_1} \right)^2 \right]} \left[ \frac{\text{Cos } \theta_1 (1 + \text{Cos } \theta_1) + \text{Sin}^2 \theta_1}{(1 + \text{Cos } \theta_1)^2} \right]$$

The above expression simplifies to become

$$\dot{\theta} = \frac{1}{2} \dot{\theta}_1$$

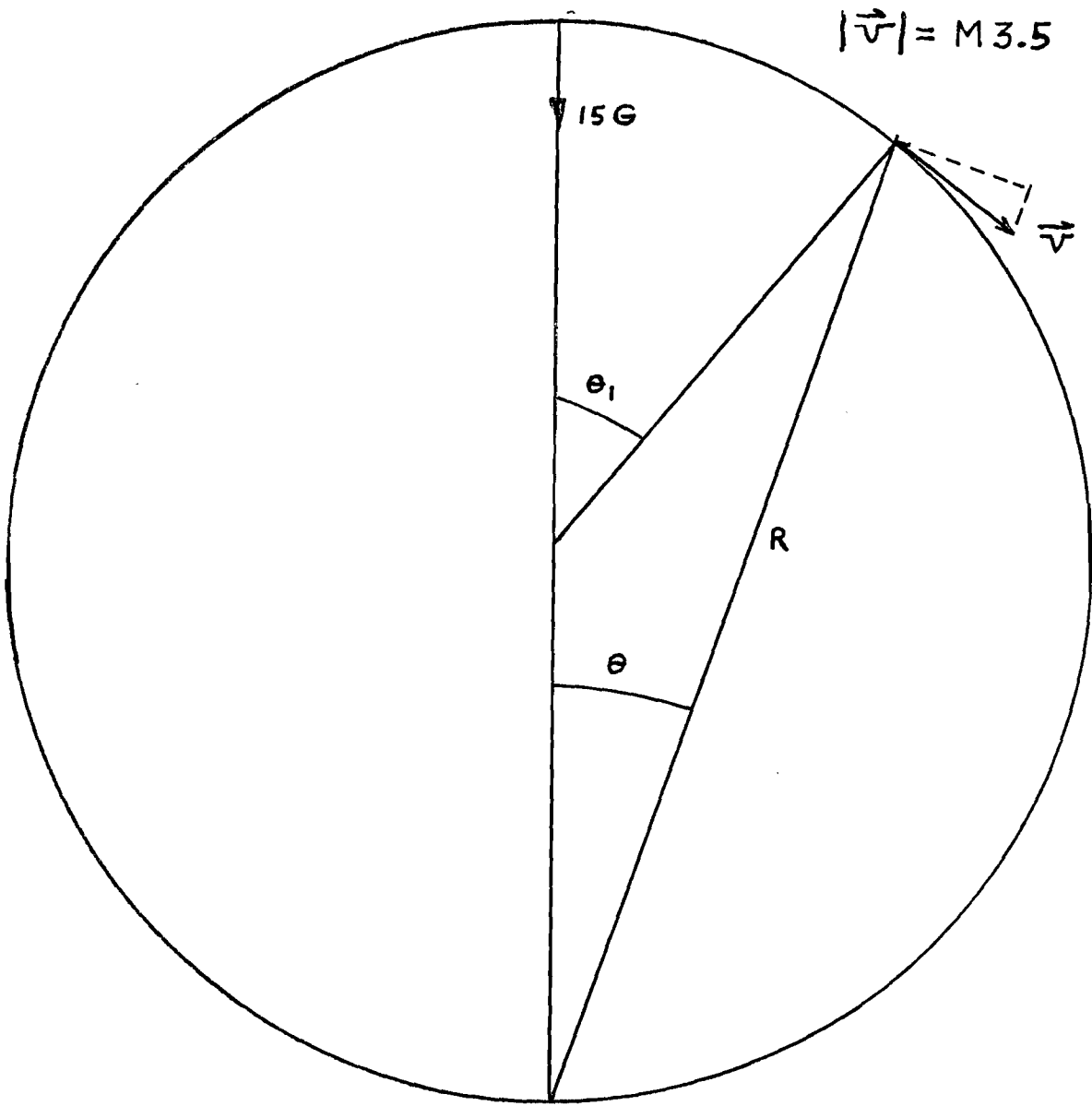


Figure II-1. Radial acceleration circle of motion.

The range to the target may also be expressed as a function of  $\theta_1$  and the diameter of the circle and is

$$R = \frac{D}{2} \left[ (1 + \cos \theta_1)^2 + \sin^2 \theta_1 \right]^{\frac{1}{2}} .$$

It is interesting to note that for the scenario described, where the target is pulling a maximum acceleration maneuver, the target's angular rate is a constant. Under these conditions, there would be no angular acceleration. It is also interesting to note that the radius of curvature (i.e.  $\frac{D}{2}$ ) is approximately 9.15 Km. Even with a 15 G acceleration, the large radius of curvature for the missile flight path, caused by the high linear velocity, results in relatively low angular rates if the missile is to intercept our vessel. It is this high velocity result that makes the lower speed, lower acceleration, manned aircraft a more troublesome target in terms of angular rates and accelerations. We may compute the maximum  $\dot{\theta}_1$  as

$$\dot{\theta}_1 = \frac{v}{\text{Radius}} = \frac{1.16 \times 10^3 \text{ m/s}}{9.15 \times 10^3 \text{ m}} = 0.13 \frac{\text{rad}}{\text{s}}$$

or  $7.26 \frac{\text{deg}}{\text{sec}}$

This corresponds to a maximum angular rate of the target's LOS of

$$\dot{\theta} = \frac{1}{2} \dot{\theta}_1 = 3.63 \frac{\text{deg}}{\text{sec}} .$$

As revealing as the foregoing example is about the physical limitations on target dynamics as viewed from the EX 83 system, it is unlikely that our target would pull such a predictable and easily modeled maneuver. We will assume instead a maneuver of the type illustrated in Figure II-2. The scenario represented by this figure is one in which the target is continuously maneuvering by accelerating first in one direction across the original

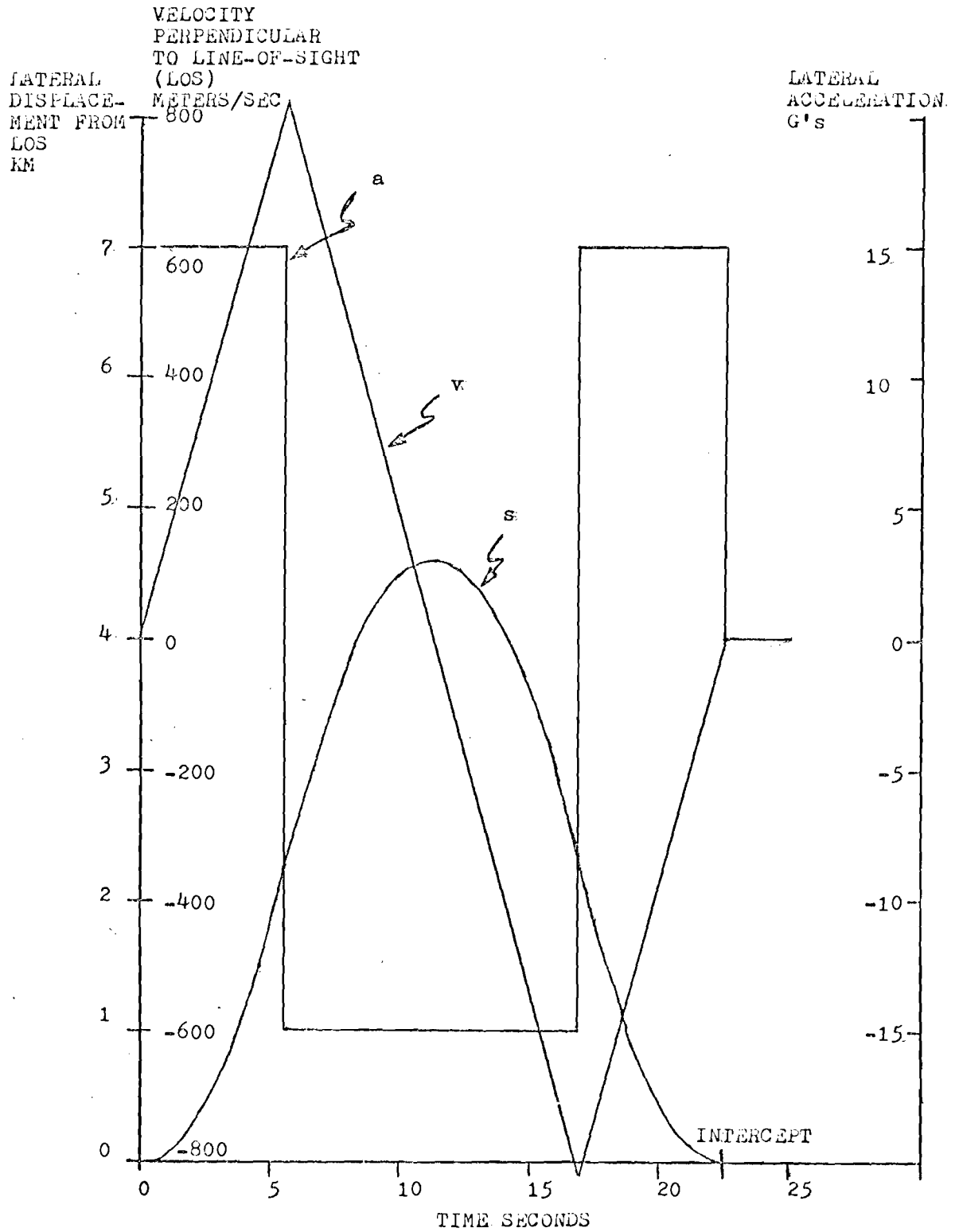


Figure II-2. Target maneuver scenario

LOS to our vessel and then in the opposite direction. Each time the direction of acceleration is reversed, the new acceleration is maintained until the angle between the missile's velocity vector and the LOS from the missile to our vessel reaches an assumed maximum seeker head angle. The maximum seeker head angle is assumed to be approximately  $45^\circ$ .

As indicated by the dashed line which represents lateral displacement from the original and terminal LOS's, it is only possible for the target to exercise one such maneuver over a time period of about 22.5 seconds. Under such conditions, the target's average range rate would be 1.06 Km/s. The target therefore would have to commence such a maneuver at a range of 23.85 Km/s. The target also has a problem; it must allow some margin for tracking errors, servo response, anomalous aerodynamic occurrences, and maneuvers on our part. These errors and conditions will result in the missile missing our vessel unless compensated for. Hence, it is appropriate to allow some time for such compensation. The amount of potential miss distance for which the target may correct, at various levels of acceleration, is shown as a function of allocated time for corrections in Figure II-3. Figure II-4 shows the same relationship at 15 G's with different scale factors. We will assume that 2.5 seconds are permitted for such compensation. If the target's maneuvers were ideal, no servo response lags or anomalous aerodynamics were encountered, and our vessel did not maneuver; then the last 2.5 seconds of the missile's flight would be radial. The target's intended scenario time would be 25 seconds in either case. A 25 second flight time at an average rate of about 1.06 Km/s would correspond to a range of about 26.5 Km at the beginning of the target's maneuver.

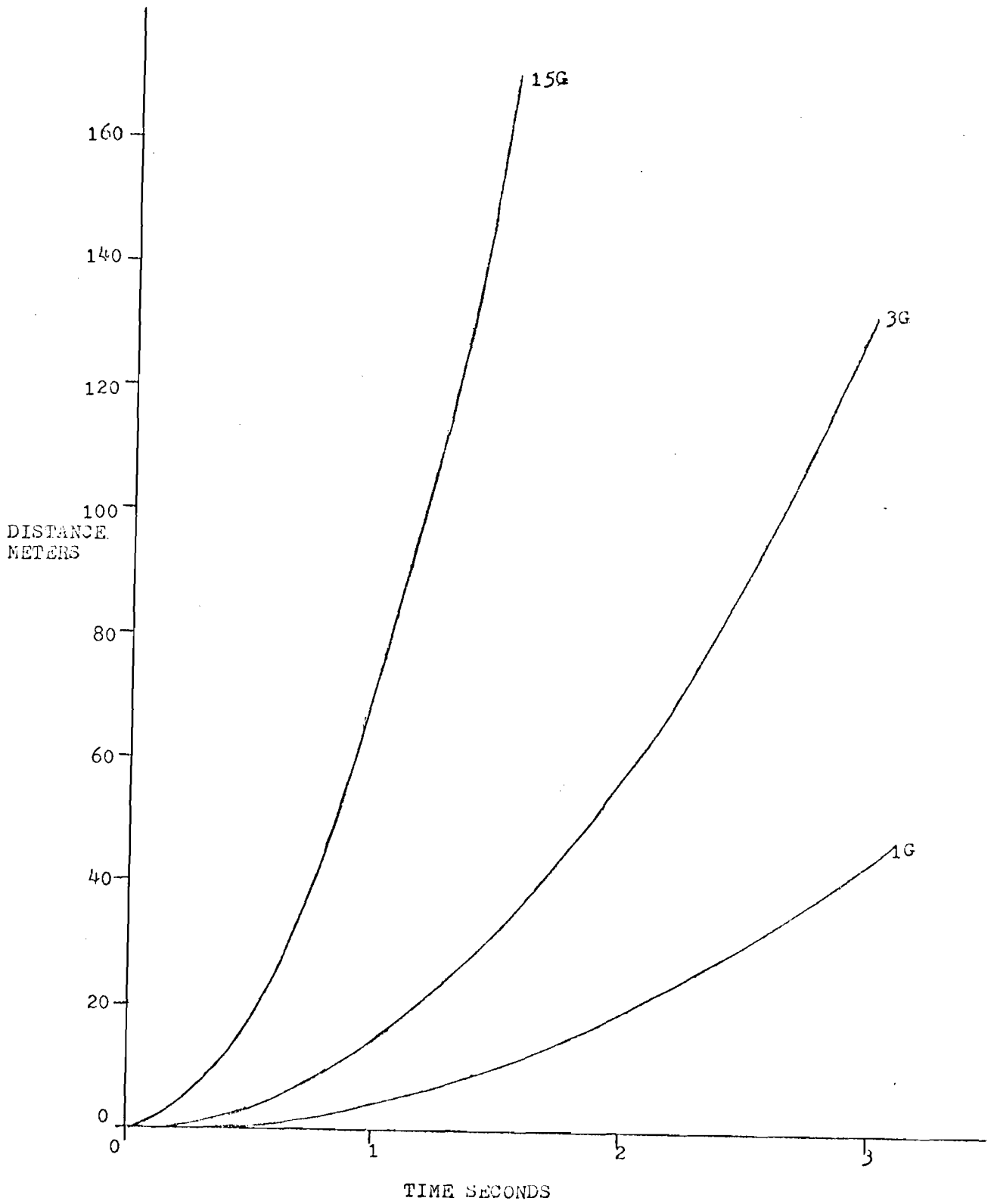


Figure II-3. Potential Miss Distance - Scale 1.

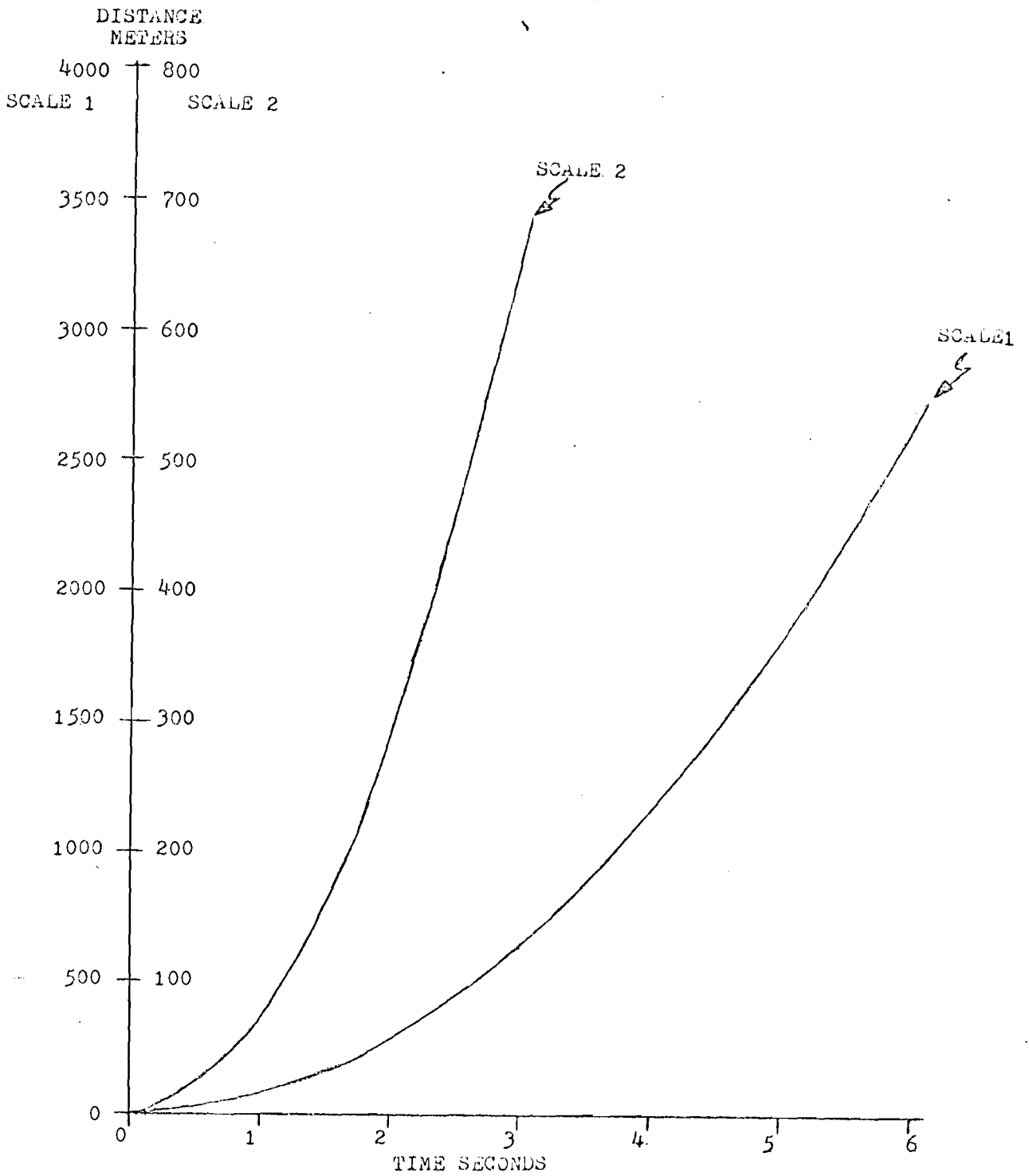


Figure II-4. Potential Miss Distance - Scale 2.

In the model, it is assumed that the velocity component perpendicular to the LOS is related to the range rate such that the total velocity is a constant [i.e.  $v = [(R\dot{\theta})^2 + (\Delta R)^2]^{1/2}$ ]. Of course, the velocity perpendicular to the original LOS, shown in Figure II-2, is not really the same as the velocity perpendicular to the constantly changing LOS. The simplifying assumption in this model that the two are equivalent is justified in that the model is only an approximation. Table II-1 lists the range and range rate for the scenario as a function of time from the beginning maneuver.

Since,

$$\theta = \text{Arc Sin } \frac{s}{R}$$

where  $s$  = displacement from initial LOS

and  $R$  = present range,

then,

$$\dot{\theta} \approx \frac{\Delta(\text{Arc Sin } \frac{s}{R})}{\Delta t}$$

The results of this expression are also shown in Table II-1.

It is not surprising that the worst case angular rate (i.e.  $|\dot{\theta}| = 3.49 \frac{\text{deg}}{\text{sec}}$ ) approaches the angular rate of  $3.63 \frac{\text{deg}}{\text{sec}}$ , which was derived earlier as a rate that the target could not exceed and still intercept us. This occurs at a range of 7.98 Km. Had we not assumed an additional 2.5 seconds maneuvering time allocation for the missile, the range where this maximum rate occurred would have been about 2.7 Km and the corresponding angular rate would have been approximately  $4.9 \frac{\text{deg}}{\text{sec}}$ . At this rate, the missile could not hit us. Although these calculations are coarse, they serve to illustrate the extent of the missile's problem and one reason for allowing additional error compensating time.

TABLE II-1  
TARGET SCENARIO

Scenario Time t (seconds)	Time Before Intercept	$\dot{R}$ (Meters/ Seconds)	R (Kilo- meters)	$\dot{\theta}$ $\frac{\text{deg}}{\text{sec}}$
1	24	$1.15 \times 10^3$	25.47	0.16
2	23	$1.135 \times 10^3$	24.33	0.53
3	22	$1.095 \times 10^3$	23.25	0.94
4	21	$1.03 \times 10^3$	22.24	1.40
5	20	948	21.34	1.88
6	19	885	20.54	2.42
7	18	926	19.75	2.33
8	17	$1.02 \times 10^3$	18.83	2.16
9	16	$1.09 \times 10^3$	17.85	1.95
10	15	$1.13 \times 10^3$	16.82	1.75
11	14	$1.155 \times 10^3$	15.74	1.49
12	13	$1.155 \times 10^3$	14.63	1.16
13	12	$1.14 \times 10^3$	13.49	0.74
14	11	$1.105 \times 10^3$	12.33	0.18
15	10	$1.05 \times 10^3$	11.18	-0.59
16	9	970	10.06	-1.66
17	8	883	9.01	-3.10
18	7	904	7.98	-3.49
19	6	$1.01 \times 10^3$	6.89	-3.19
20	5	$1.08 \times 10^3$	5.78	-2.88
21	4	$1.125 \times 10^3$	4.63	-2.42
22	3	$1.15 \times 10^3$	3.48	-1.60
23	2	$1.16 \times 10^3$	2.32	-0.16
24	1	$1.16 \times 10^3$	1.16	0
INTERCEPT 25	0	$1.16 \times 10^3$	0	0

In the analysis of missile target dynamics, it has been assumed thus far that the missile would fly such a trajectory as to hit the EX 83 system sensor or miss the platform vessel altogether (in which case it would not be a threat). In fact the missile could potentially miss the EX 83 system by tens of meters and still hit the host vessel. The angular rates and accelerations associated with the high target velocity in conjunction with the close proximity miss distance will be much more severe than those analyzed thus far. The miss distance which should be used in analyzing target dynamics depends on the size of the host vessel and the location of the EX 83 system. Since no one specific host vessel has been identified, a reasonable miss distance of 50 m will be selected for the analysis.

Figure II-5 shows the angular velocity which results from the 50 m miss distance and  $1.16 \times 10^3$  m/s linear velocity as a function of range. As can be seen at short ranges (e.g.  $R \leq 700$  m), the effects which were just described are much more significant than those due to target maneuverability. For the previously defined scenario, the angular rate due to miss distance and linear velocity will become greater than those caused by target maneuvering at a range of about 2.7 Km. We will therefore define the scenario as a combination of the two considerations previously discussed. Figure II-6 shows the absolute value of the angular rate as a function of range for the composite scenario.

Figure II-6 is a dramatic illustration of how non-severe the modeled missile target is to track as far as angular rates and accelerations. The maximum angular rate which must be handled is about  $3.6^\circ/\text{s}$  while the maximum angular acceleration is about  $7^\circ/\text{s}^2$ . A reasonable minimum open fire range of 1 Km was selected on the basis of an assumed minimum desirable round

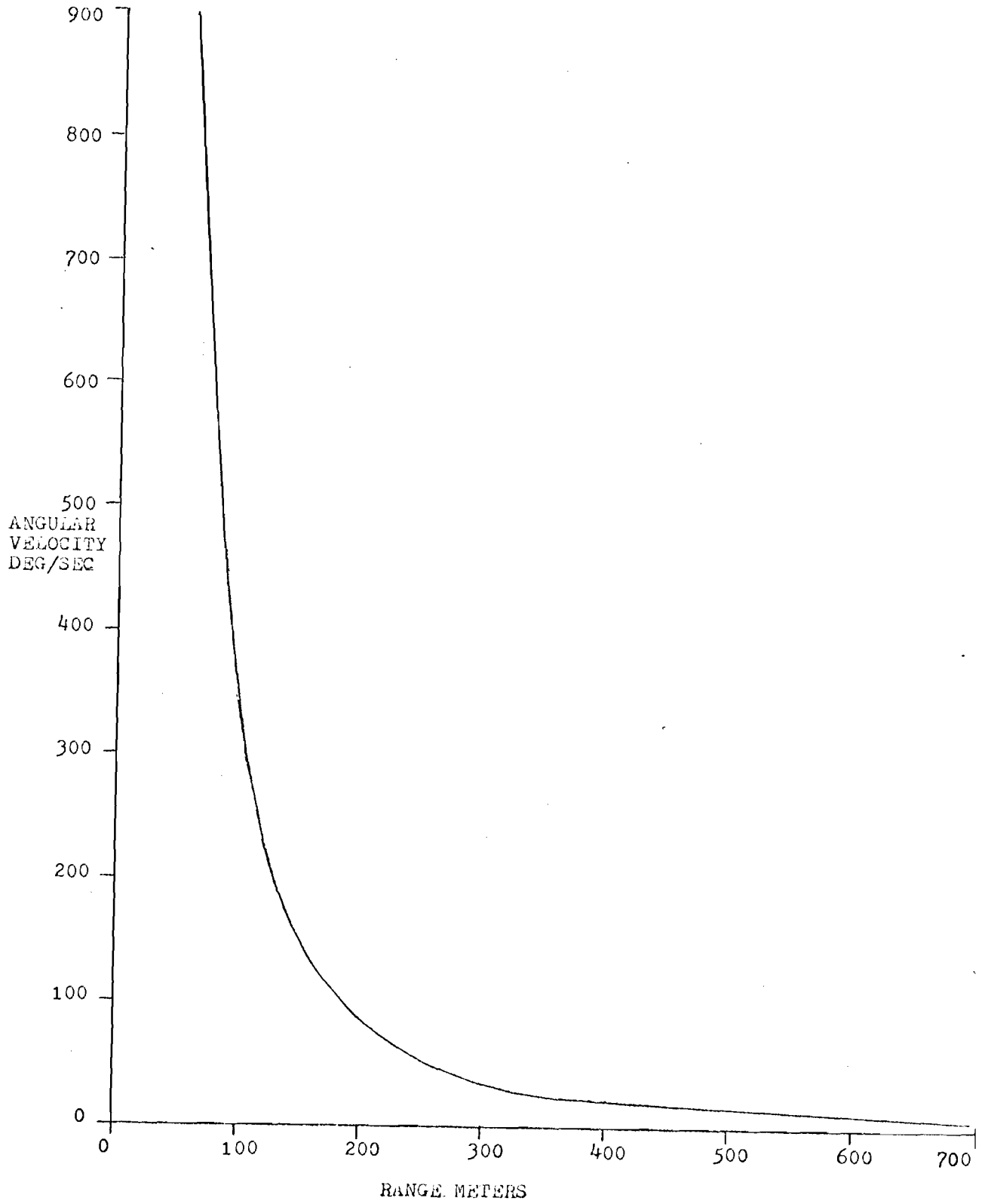


Figure II-5. Angular velocity vs. miss distance.

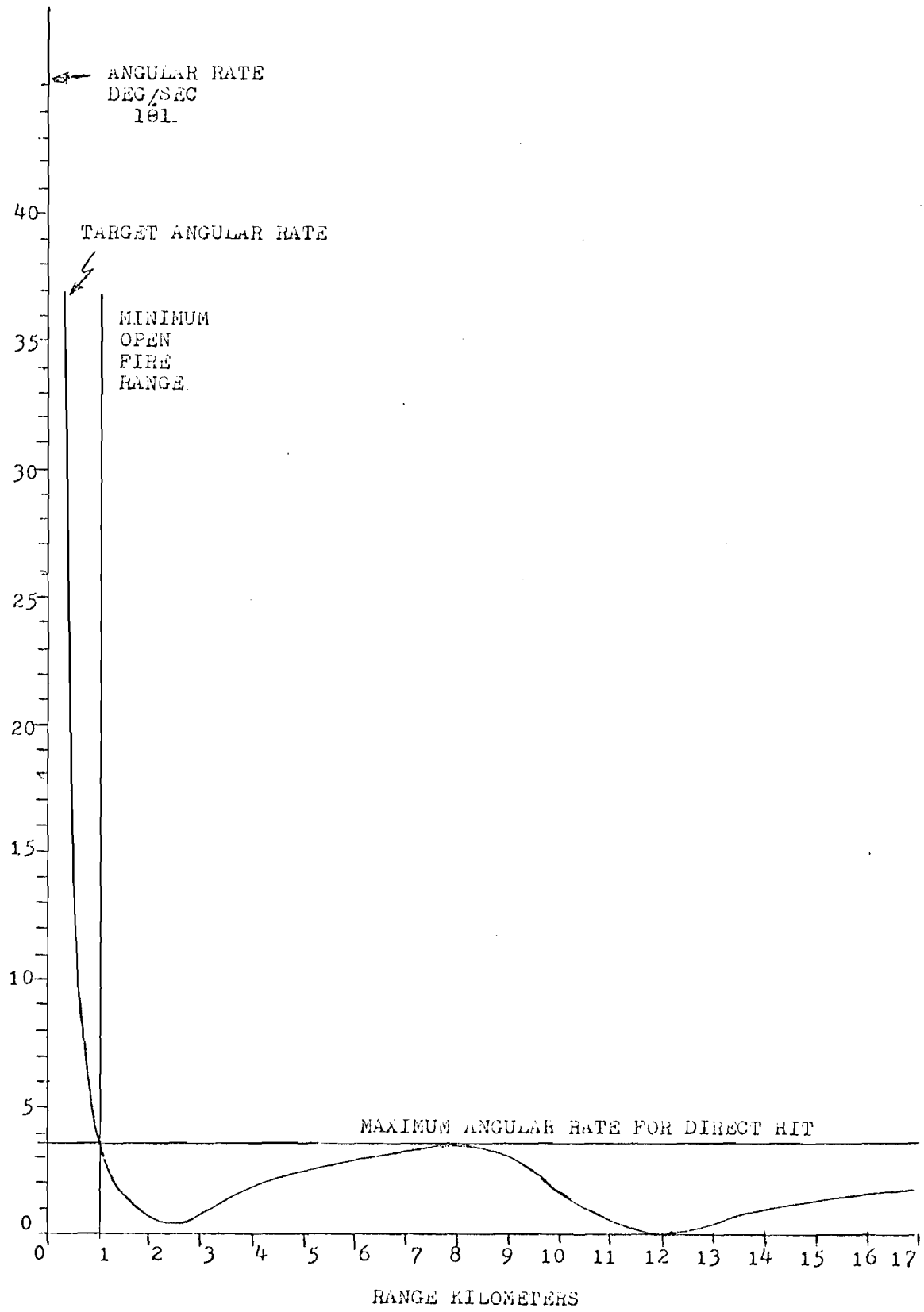


Figure II-6. Angular velocity - composite scenario.

impact range of about 500 m and an assumed time-of-flight of roughly 1/2 second.

In many ways the manned aircraft will present more of a challenge than the missile target discussed above. One reason is because the manned aircraft can make repeated attacks. This requires that the system either maintains continuous track or be capable of reacquiring rapidly. A second reason is that the aircraft need not have a radial trajectory during any particular part of its flight path. Other reasons could be cited.

We will not specify an attack scenario for the manned aircraft but instead will calculate the range of angular velocities and accelerations which could be encountered by the EX 83 system in countering the air threat. We will assume that the target will never be within 50 m in range and that it will otherwise have the characteristics listed under Target #2 in Section B. Under these conditions, the maximum angular velocity will be

$$\dot{\theta} = \frac{V}{R} = \frac{360.1 \text{ m/s}}{50 \text{ m}} = 7.2 \frac{\text{rad}}{\text{s}}$$

or

$$412.7^\circ/\text{s}$$

Similarly the maximum average angular acceleration computed over a one second interval will be

$$\ddot{\theta} \Big|_{\text{max}} \approx 7.07 \frac{\text{rad}}{\text{s}^2} \quad \text{or} \quad 405.8^\circ/\text{s}^2$$

where

$$\ddot{\theta} \Big|_{\text{max}} \approx \frac{\dot{\theta}_{\text{max}} - \dot{\theta}_{\text{max} - 1}}{1 \text{ s}}$$

This approximation is valid for time interval averages of 1 second. This angular acceleration is due to the targets linear velocity in conjunction with its trajectory miss distance or closest-point-of-approach (CPA). The largest angular acceleration that could be realized strictly due to target maneuverability would be

$$\ddot{\theta} \Big|_{\text{maneuver}} = 0.98 \frac{\text{rad}}{\text{s}} \quad \text{or} \quad 56.2^\circ/\text{s}^2$$

where

$$\ddot{\theta} \Big|_{\text{maneuver}} = \frac{a_{\text{max}}}{R_{\text{min}}} \quad \text{and} \quad a_{\text{max}} = \text{maximum acceleration of 5 G's.}$$

Surface target dynamics may seem relatively unimportant in comparison to those of the manned aircraft. While it is true that the surface target is much less maneuverable, it is also probable that the surface target will be tracked by different techniques and at a different data rate than the air target. Therefore the dynamics must still be examined and put in perspective.

The characteristics listed for Target #3 in the Target Model section are assumed. A minimum tracking range of 50 m is assumed. By treating the surface craft in a manner similar to that for the manned aircraft, we calculate a maximum angular velocity of

$$\dot{\theta} \Big|_{\text{max}} = \frac{25.7 \text{ m/s}}{50 \text{ m}} = 0.51 \frac{\text{rad}}{\text{s}} \quad \text{or} \quad 29.48^\circ/\text{s}$$

and a maximum angular acceleration of

$$\ddot{\theta} \Big|_{\text{max}} = 0.11 \frac{\text{rad}}{\text{s}^2} \quad \text{or} \quad 6.15 \frac{0}{\text{s}^2}$$

From a dynamic viewpoint, if the system is designed to handle the small boat, Target #3, it can easily handle Target #4.

PART III

## A. PHASED ARRAY CONCEPT

This section describes the GE phased array concept by discussing it in the context of a total system. This section is not intended to be an extensive description of the concept since such definition has been generated by GE. Rather the objective of this section is to define the concept to the extent that succeeding sections of this part of the report may be understood without the necessity of referring to other documents.

Since many terms that are used in describing systems related to the weapon control function are often confused, a general definition of the terms as used herein is provided. (See Figure III-1.)

The following indented list corresponds with the figure.

Weapon System

Weapon

Weapon Control System

Sensors

Radar  
E-O  
Other

Fire Control

Gun Order Module  
Target Tracking Module  
Other

Ancillary Equipment

Stabilization Sensor  
Control and Display Consoles  
Interface Equipment  
Other

This report deals mainly with various subcategories of the Fire Control System and the Phased Array Radar sensor.

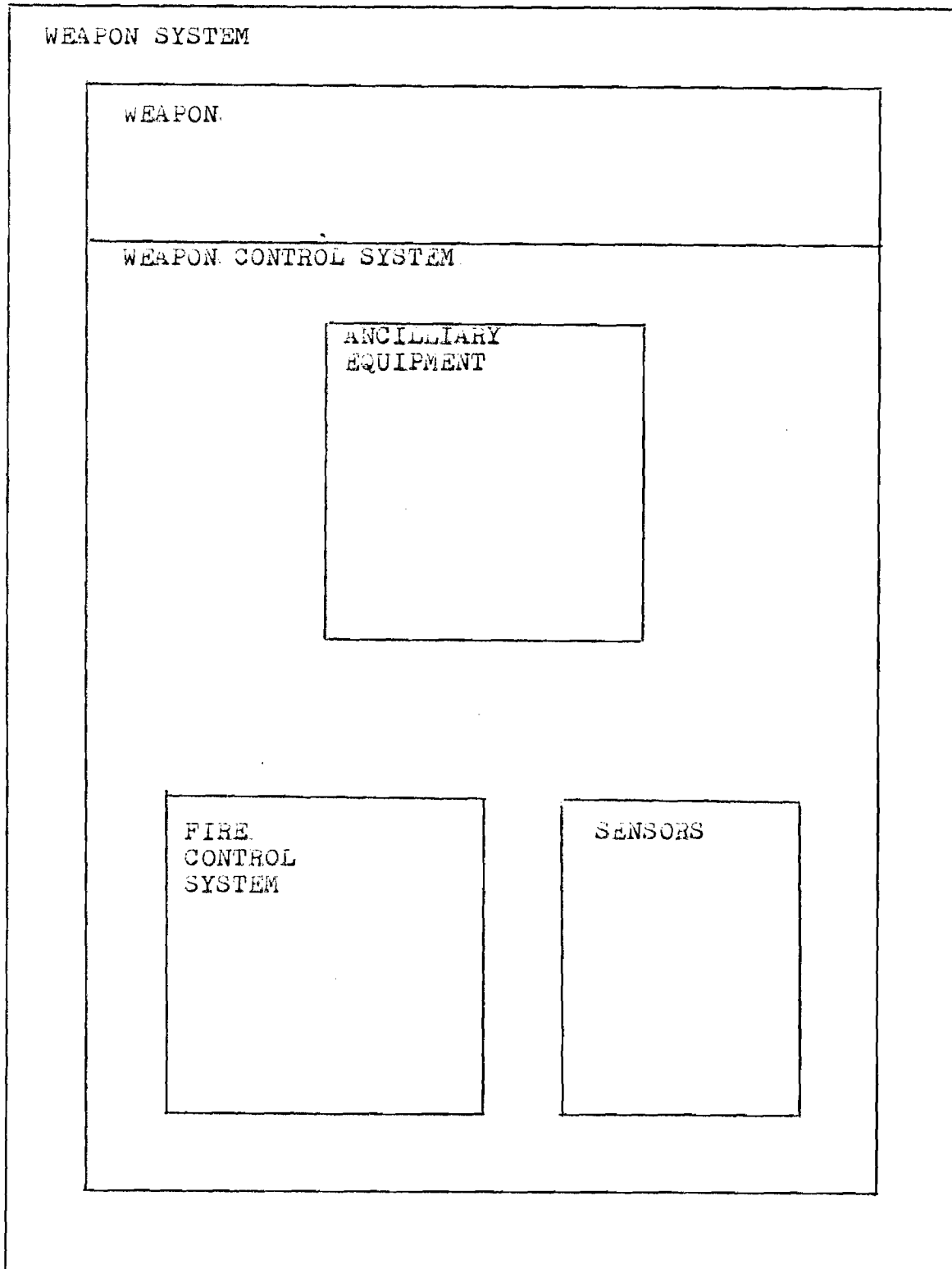


Figure III-1. Fire control system definition.

The purpose of the Weapon Control System (WCS) is obviously to control the weapon, which is the GAU-8/A gun system and naval mount.

"The gun is an externally-powered, Gatling-type mechanism. Each of the gun's seven barrels fires only once during each revolution of the barrel cluster. The GAU 8/A operates on the same principles as the 20 mm Vulcan and 7.62 mm Minigun. Parts wear, schedule maintenance, and number of gun failures are all reduced through the use of seven separate barrels, with individual bolts cammed into sequential operation by simple, continuous rotary motion. Proven performance, high reliability, and variable firing rates are advantages inherent with the Gatling concept." [2]

The gun mount which is designated as the EX 83 Mod 0 Naval Gun Mount is currently being developed by GE under an IR & D program. It is an enclosed, compact, lightweight device which is capable of achieving relatively high angular rates and accelerations (i.e. 1.6 rad/sec and 4.6 rad/sec<sup>2</sup>). Herein, in referring to the weapon, we will generally be referring to the mount in conjunction with the gun.

The WCS must provide the capability of pointing and firing the weapon effectively. In so doing, it must detect the intended target, predict the target's future position, provide pointing orders commensurate with the prediction, and provide for actually firing the projectiles. One or more sensors provide the detection capability. We are mostly concerned with the phased array radar. The major function of the fire control system is to predict the target's future position, based on a tracking solution, and to account for ballistic effects.

The EX 83 system concept for controlling the EX 83 weapon is best introduced with an exercise in deductive reasoning. The kill probability for a particular target results from the probability of hit and the probability of kill per hit. The probability of hit is directly related to fire control system accuracy and target vulnerability. Hence for a particular target of known vulnerability, the combination of round lethality and system accuracy must be sufficient to produce a high kill probability. Sufficient system accuracy and round lethality through necessary are not sufficient conditions to insure a high kill probability. The cumulative number of rounds which can be fired is also important. The number of rounds which can be fired is constrained by system reliability, firing rate, and system reaction time. This logic is shown diagrammatically in Figure III-2. A deficiency in any one of the blocks of Figure III-2 or in others not shown can cause the system to be ineffective. It is assumed that target vulnerability has been determined. An assessment of Round Lethality can best be determined by testing against target models. It is assumed that this has been accomplished. GE has conducted extensive analyses which address both the probability of hit and means of improving the probability of hit. [3] In performing these analyses, assumptions have been made with respect to gun pointing accuracy and system reaction time.

#### The Role of the WCS

It must provide sufficient accuracy (from both a systematic and random error viewpoint) and reaction time (this consideration includes detection range performance) to support the validity of the total EX 83

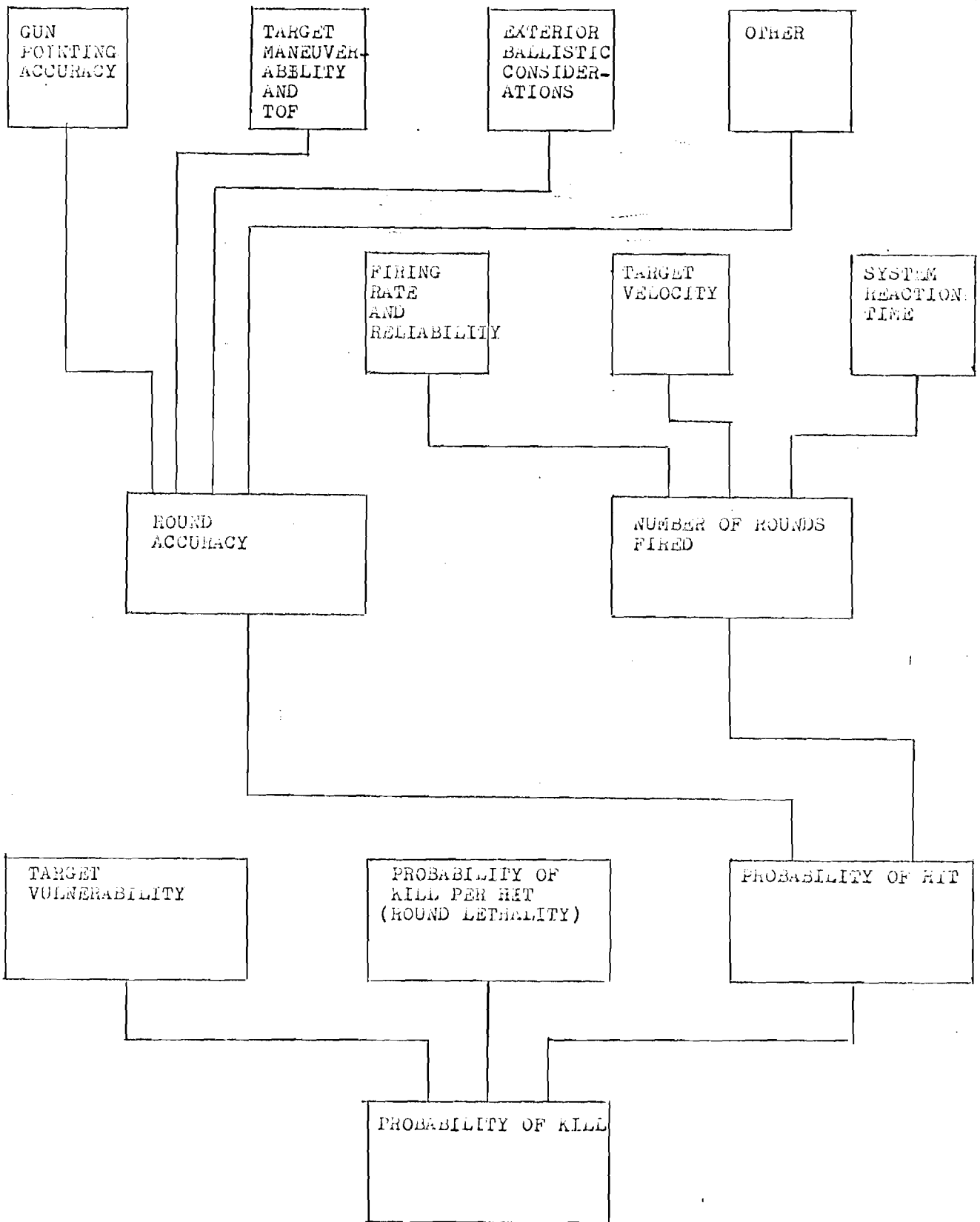


Figure III-2. Probability of kill logic.

Weapon System concept. These requirements will constrain the selection of parameters later and will be important criteria in selecting configuration variants. The variants will be discussed in the sections immediately following this section.

The GE EX 83 WCS concept includes as its major sensor a phased array radar. [4] Other sensors are also called out. Together these sensors provide information for display, threat assessment, and tracking. Tracking data in turn are used for prediction and gun order generation.

How does the EX 83 WCS concept differ from classical concepts? At first glance, the answer seems to be "very little". The sensors, including the phased array radar, provide data for detection, display, and tracking; the fire control system performs the tracking function, predicts target future position, performs ballistic computations and points the weapon; the weapon fires the projectiles on a trajectory which hopefully intercepts the target at its future position. Some of the ways in which the concept varies from the classical approach can only be appreciated by looking at a greater depth.

One variation from the classical approach is the use of a phased array radar. Classically, separate radars are specified for the functions of surveillance and tracking. Radar parameters which were optimized for the surveillance function were not compatible with those of the track radar. Shipboard air surveillance radars required wide vertical beamwidths so that a hemispherical-like volume could be searched in a short time interval (e.g. several seconds). During the 1960's, air surveillance radars which had narrow vertical beamwidths and were electronically scanned in elevation

received wide usage. A typical radar of this type was the AN/SPS-52 radar which was used as the surveillance radar in conjunction with Tartar missile systems. One of the primary reasons for the introduction of these types of radars was to maintain a stabilized search pattern in an environment where the platform (i.e. the ship) was rolling and pitching. Another reason was that some elevation information was provided. This reduced the time and increased the probability of acquisition by the track radar. The key to this increased capability was the rapidity with which the beam could be scanned. This was greater than what was practically achievable with mechanical systems. This permitted the reduced beamwidth in the elevation pattern and hence increased elevation information was achieved. The search pattern was compensated for roll and pitch by using a beam steering computer to change the orientation of the beam, relative to the ship's deck, electronically. These radars were at that time still primarily surveillance radars however.

Track radars on the other hand were characterized by narrow beamwidths which permitted good angular accuracy. Tracking errors were discerned through the use of special scan or sampling techniques such as conical-scan, sequential lobing, or monopulse. The detected tracking errors were used to update the servo drive signals to an inertial pedestal. The tracking techniques required that the antenna be continuously boresighted (i.e., pointed) at the target being tracked.

The GE phased array concept is one wherein the surveillance and track functions are performed by a single radar. Rapid beam movement is achieved electronically in both azimuth and elevation and the antenna need not be

boresighted on a tracked target. This permits multiple target tracking with a single radar. The radar is freed from needing to be boresighted on the target by the fact that target angular position is not entirely determined by the direction in which the antenna is pointed. The beam may be steered from the boresight position electronically. Hence, detected target position is the vector sum of boresight position, beam position with respect to boresight, and the location of the target with respect to the beam. The detected position is stored in a computer and extrapolated while the beam is steered through a search pattern or to another target position. In this manner, many targets may conceivably be tracked.

Another way in which the EX 83 WCS concept differs from the classical system is in that the phased array participates in another detection and tracking function. The detection of surface targets in the classical system was performed with yet another radar. The tracking of surface targets was usually performed with track radars which were designed primarily for anti-air-warfare (AAW) roles. It is not surprising that tracking performance was poor on surface targets. The GE phased array radar concept is entirely compatible with the modern approach to surface tracking (i.e. a priori elevation and track-while-scan, TWS, in azimuth and range).

Hence the GE phased array approach permits one radar to perform the functions of at least three radars in the classical system.

There are other ways, of course, in which the EX 83 WCS concept differs from the classical approach but we will now look at the phased array radar in greater detail. The GE phased array concept is based on the characteristics of the ULTRA antenna. The ULTRA antenna is described in reference [5].

Briefly the ULTRA is a monopulse space fed planar array. Each element in the array functions as a programmable phase shifter. The relative phases among each of the elements determines the angle of the radiated beam pattern with respect to the normal to the array. The difference in phase of the signals in adjacent elements to achieve orientation at a particular angle is

$$x = \frac{2\pi d}{\lambda} \sin \theta \quad , \quad [6]$$

where

$x$  = phase difference

$d$  = distance

$\lambda$  = wavelength

$\theta$  = angle off normal.

Another property of phased arrays which is important in our analysis is that the beamwidth varies as a function of the angle from normal. This variation may be approximated by the equation

$$\theta_B(\theta_0) = \frac{\theta_B(0)}{\cos \theta_0} \quad , \quad [6]$$

where

$\theta_B(\theta_0)$  = beamwidth in the  $\theta$  direction at a scan angle of  $\theta_0$

$\theta_B(0)$  = beamwidth at normal

$\theta_0$  = scan angle

Another approximation equation which is important in our considerations is that for the gain as a function of scan angle,

$$G(\theta) = \pi N \cos \theta_0$$

where

$$G(\theta_0) = \text{gain at scan angle } \theta_0$$

$$N = \text{number of elements (assuming separation of } D = \frac{\lambda}{2}$$

The ULTRA antenna is a digital loaded line type. The element-to-element phase may be changed in minimum steps of  $45^\circ$  (3 bits). This quantization will result in several undesirable effects. Each of these must be taken into account.

One such effect is the reduced net antenna gain. The antenna gain will change by an amount,

$$\Delta G \approx \frac{\pi^2}{3 \cdot 2^{1P}} \quad , \quad [7]$$

where

$\Delta G$  = the change in antenna gain from that with no quantization effects

$P$  = number of phase shifter bits

A second undesirable effect is the higher side lobes associated with fewer bits of quantization. An approximation to the rms side lobe level is

$$S \approx \frac{5}{2^{2P} N} \quad [7]$$

A third effect of concern is the granularity with which the monopulse null steering may be moved. The appropriate equation is

$$\delta\theta = \frac{9\theta_B(\theta_0)}{N \cdot 2^P} \quad [7]$$

In addition to the above information, which is generally applicable for phased arrays, the following information, specifically applicable to the ULTRA antenna, was obtained. [8]

TABLE III-1  
ULTRA CHARACTERISTICS

---

Beamwidth	4° x 5° at boresight
Scan Volume	Boresight ± 60°
Peak Sidelobe Level	< - 16 dB
No. Phase Shifter Bits	3
Phase Shifter and Element Losses	3.1 dB
Power Capacity	
Peak	1.2 - 1.5 kw
Average	100 w
No. of Elements	502
Aperture Diameter	18"
Weight	52 lbs.
Cooling	Forced Air

---

These characteristics will be taken into account in the synthesis of Section IV.

## B. ON-MOUNT VS. OFF-MOUNT CONSIDERATIONS

There are several advantages and disadvantages to both on-mount and off-mount configurations. The relative importance of the advantages and disadvantages will be affected by the platform and the associated roles of the GAU-8 Weapon System. First we will discuss some of the advantages and disadvantages and then the relative importance of these in different roles.

One obvious advantage of the on-mount configuration over the off-mount configuration is that the entire system could be installed in modular fashion at a single location on the host ship. This should simplify the actual physical installation as well as the pre-installation planning and preparation. The associated wiring and electrical interface should be simpler for the on-mount configuration. Fire control computations should be simpler for the on-mount configuration since parallax between the antenna and mount will have been eliminated. Finally, one of the most important advantages of the on-mount configurations is that greater accuracy is achievable. The greater accuracy would be possible since the possibility of flexure of the intervening ship's hull will have been eliminated.

Advantages of the off-mount configuration are mostly related to the independency in locating and positioning the antenna. The height for the gun mount is restricted due to its weight. Since the antenna in an off-mount configuration need not be restricted to the mount's location, it can be positioned higher on the ship thereby providing the potential for increased detection range for low flying and surface targets. The independency in positioning, inherent in the off-mount configuration, also means that the antenna may be positioned to minimize the view blockage due to

the ship's superstructure. The off-mount configuration would have the advantage of being less exposed to shock and vibration due to the gun firing. The off-mount configuration will not impact the servo response and mechanical design of the gun mount as will the on-mount version.

Section A of Part II discussed the various types of ships and associated missions to which the GAU-8 system may be applied. In the case of major combatants, where the GAU-8 system would serve primarily as a point defense type system against missiles, the advantages of an on-mount configuration appear to outweigh those of the off-mount configuration. For auxiliary ships and small combatants of the patrol craft variety, the off-mount configuration seems more advantageous. Where the EX 83 system were being used in a more general role, it would not be considered desirable to have the mount slew to operate the radar. The more general purpose usage of the GAU-8 system on these vessels would also definitely favor the higher antenna placement available with an off-mount version. An on-mount configuration would not be suitable for some applications, especially those of the patrol craft type. If this is accepted, then one is forced to the conclusion that an EX 83 based system must be designed as an off-mount system if it is to find application on the patrol craft type combatant. If it is felt that the advantages of the on-mount version are sufficiently desirous to require an on-mount version for major combatants, then two versions should be made available. The alternative is to forego small combatant applications of the patrol craft type.

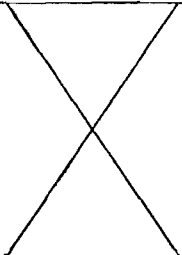
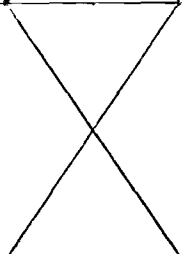
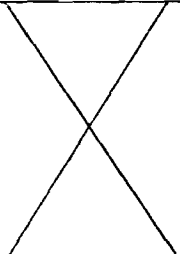
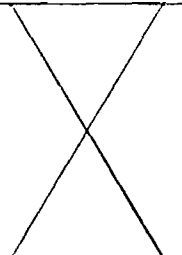
### C. DEDICATED VS. SEMI-DEDICATED

The terms "dedicated" and "semi-dedicated" herein refer to the control of the EX 83 weapon by the EX 83 Weapon Control System. If the WCS controls only the EX 83 weapon to the exclusion of all others, it is said to be dedicated. If the WCS is to control other weapons in addition to the EX 83, it is said to be semi-dedicated. For the applications considered in Part II of this report, the EX 83 WCS would be dedicated for major combatants and semi-dedicated for auxiliary vessels. Both dedicated and semi-dedicated versions would be called for in the case of small combatants. A matrix, Table III-2, shows the potential configurations for three major types of applications. From the matrix, it is apparent that two types of system configurations would meet most applications: On-Mount Dedicated and Off-Mount Semi-Dedicated. The Off-Mount Dedicated configuration for the small combatant could easily be accommodated as a simplified version of an Off-Mount Semi-Dedicated system.

There are of course other measures of dedication than have been considered here. For example, the system may not be dedicated exclusively to weapon control but may also be assigned to a general surveillance and navigation role. In fact, this is likely for the small patrol craft type of application.

At this point, we have evolved three types of system configurations. The On-Mount Dedicated major combatant; the Off-Mount, Semi-Dedicated auxiliary vessel; and the Off-Mount, Semi-Dedicated or Dedicated small combatant with ancillary functions. It is likely that the small combatant

TABLE III-2  
 POTENTIAL EX 83 WCS CONFIGURATIONS

	Small Combatant	Auxiliary	Major Combatant
Off-Mount Dedicated			
Off-Mount Semi-Dedicated			
On-Mount Dedicated			
On-Mount Semi-Dedicated			

version could be very similar to the auxiliary vessel version and that the dedicated version could be viewed as a simplified version of the semi-dedicated configuration. Figures III-3, III-4, and III-5 show the three baseline configurations.

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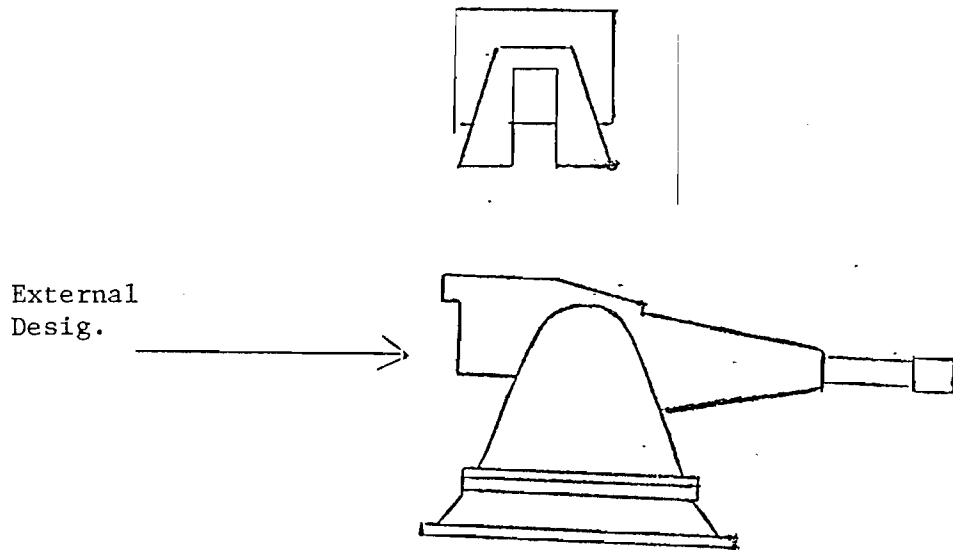


Figure III-3. On-mount, dedicated, major combatant configuration.

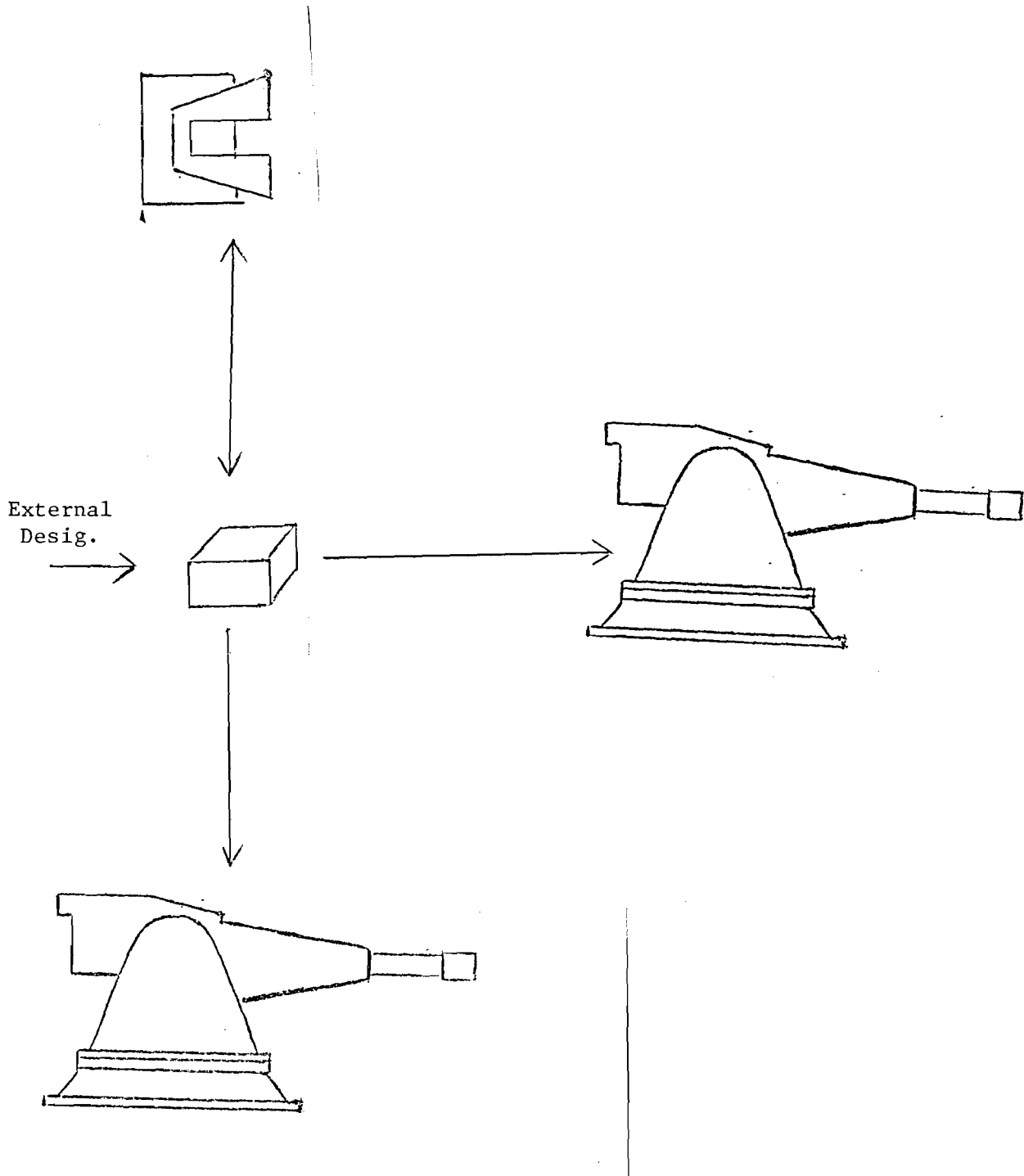


Figure III-4. Off-mount, semi-dedicated, auxiliary configuration.

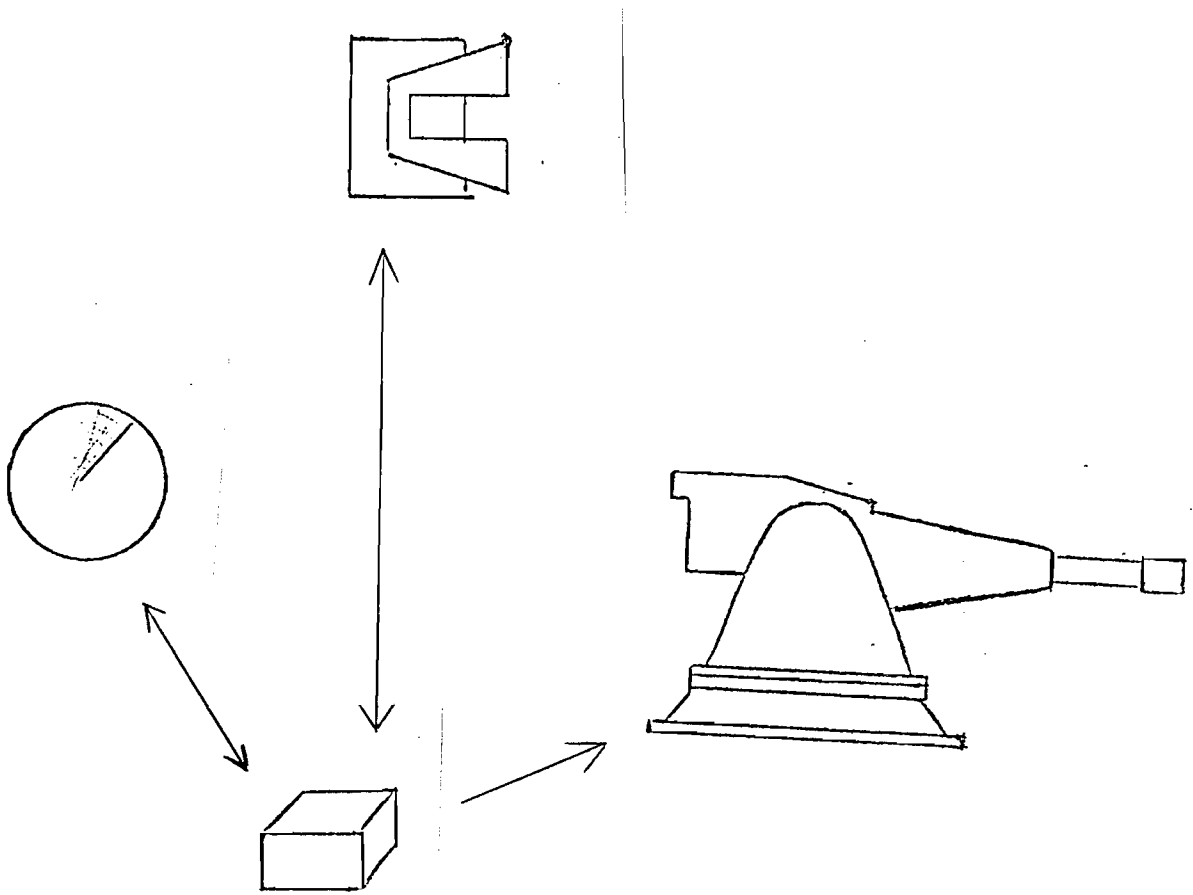


Figure III-5. Off-mount, semi-dedicated, small combatant configuration.

#### D. SYSTEM REACTION TIME

From a reaction time viewpoint, the most difficult target is the missile due to its high velocity. From Section II, the average range rate of the missile target is 1.06 Km/s. We will use this value to approximate the reaction time available.

The reaction time as discussed herein will reflect a control-by-negation firing doctrine. This doctrine is one wherein the target is processed sequentially through the various engagement phases without hesitation, including the firing phase, unless the process is halted by a purposeful act on the part of an operator. In the case of fully automatic equipment, this engagement philosophy is inherent. In the case of semi-automatic operation, this doctrine would require that any manual steps (e.g. closing a firing key) be performed in a minimal reflective reaction time and allows no time for manual evaluation or assessment of the threat. It is obvious that by using the control-by-negation philosophy, we will be judging the minimum system reaction time limited only by equipmental and human reflex reaction times. While we will be judging the minimum reaction time, we will assess it from a worst case basis; that is, we will assume maximum slew angles, etc.

For our purposes, we will define system reaction time as the elapsed time interval from initial detection until the firing key is closed, regardless of whether it is closed automatically or manually. We will also define engagement time as the elapsed time interval from initial detection until the last round is fired. Hence, engagement time is equal to system reaction plus burst length. The foregoing assumes that open fire will begin at such

time as to cause the initial round to arrive in the vicinity of the target at the maximum effective range of the round and that the final round is fired at such a time that the last round will arrive in the vicinity of the target at the minimum permissible kill range.

For calculating the burst length, we will assume a minimum permissible kill range of 500 meters and a maximum effective range of 4 Km. The burst length will equal the time the target requires to travel from a 4 Km plus one Time-of-Flight (TOF) range into a 500 m plus one TOF range. The TOF at 4 Km is approximately 8.6 seconds. The TOF at 500 meters is approximately 0.6 seconds. The target's range at open fire is  $4 \text{ Km} + \overline{v_T} \times 8.6 \text{ seconds}$ . The target's range at cease fire is

$$500 \text{ m} + \overline{v_T} \times 0.6 \text{ seconds},$$

where

$$\overline{v_T} = \text{target velocity.}$$

The range through which the target moves during the burst is

$$4 \text{ Km} + \overline{v_T} \times 8.6 \text{ seconds} - 500 \text{ m} + \overline{v_T} \times 0.6 \text{ seconds}$$

The time required for the target to traverse this distance and hence the burst length ( $t_B$ ) is the distance divided by the target's velocity or

$$\begin{aligned} t_B &= \frac{4 \text{ KM} - 500 \text{ m} + \overline{v_T} (8.6 - 0.6) \text{ seconds}}{\overline{v_T}} \\ &= 8 \text{ seconds} + \frac{3500}{1060} \text{ seconds} = 11.3 \text{ seconds.} \end{aligned}$$

It is appropriate at this point to mention that at least three realistic considerations could considerably reduce the burst length. One is to reduce the burst length time interval because of reliability considerations. For longer burst lengths where the excess rounds are fired at progressively

longer intercept ranges, the significant probability that the gun may fail after a given number of rounds causes a decrease in the probability of being able to fire at shorter ranges where the fire is more effective. It is beyond the scope of this report to assess these factors but the most effective burst length may be on the order of 5 seconds, from a reliability viewpoint. A second factor which would significantly affect burst length would be to reduce the open fire range under the knowledge that most of the burst length interval is due to the TOF of the round at 4 Km. A third factor which could cause a significant reduction in burst length would be to increase the velocity of the projectile. In light of the above considerations, it is not unreasonable to assume that the burst length may be considerably less than the derived 11.3 seconds. Nonetheless, because of other considerations, such as the possibility of a pre-firing calibration burst, we will retain the 11.3 second number as the time interval from when the first round is fired until the last round is fired and, for simplicity, will refer to the interval as burst length.

A second reaction time interval to be considered is firing key closure time. In the case of the fully automatic system, we will assume this interval to be on the order of milliseconds which is insignificant in comparison with other time intervals. For the semi-automatic system, we will assume a 1 second operator reaction time ( $t_{FK} = 0, 1.0$  seconds).

Another reaction time interval to be considered is mount slew time. At an angular acceleration of  $350^\circ/\text{sec}^2$  [9], we can calculate a time interval for reaching and descending from the maximum angular velocity of  $100^\circ/\text{sec}$  [9] of

$$t_{MSA} = 2 \times \frac{100^\circ/\text{s}}{350^\circ/\text{s}} = 0.57 \text{ seconds.}$$

During this time interval, the average angular velocity would be 50°/s, resulting in a net angular motion, during periods of acceleration and deceleration of

$$50^{\circ}/s \times 0.57 \times = 28.57^{\circ}.$$

If we assume a worst case angular slew angle from the ready air position of 165°<sup>[9]</sup>, we may calculate the added slew time at the full rate as

$$t_{MSW} = \frac{165^{\circ} - 28.57^{\circ}}{100^{\circ}/s} = 1.36 \text{ seconds.}$$

The total slew time is

$$t_{MS} = t_{MSA} + t_{MSW} = 1.93 \text{ seconds.}$$

We will round this figure off to 2 seconds.

Normally in a procedure like this, one would allocate time for achieving a stable ballistic solution prior to slewing the gun. We will allocate 1 second for this operation in the semi-automatic mode and will assume the ballistic solution to occur during gun slew time for the fully automatic mode, thereby requiring 0 seconds. ( $t_{BS} = 0,1.0$  seconds).

If no additional manual operations are required beyond those already discussed for the semi-automatic system, then the remaining reaction time intervals to be discussed would be identical for the automatic and semi-automatic systems. There will however be a difference between the reaction time intervals of the on-mount and off-mount configurations unless the mount is slewed during target processing and hand-over to track in the off-mount configuration.

The next question to be considered is the minimum period of time which the target must be tracked (in the monopulse mode) before an automatic threat assessment may be accomplished. The uniqueness of the EX 83 fire

control system concept permits an assumption of 0 seconds. This is so because of the dual nature of the ULTRA antenna concept. The surveillance and acquisition radars and the track radar are one and the same. The evaluation and threat assessment functions may be accomplished during the initial detection period in which the target is tracked sufficiently accurately in a TWS mode for threat assessment and for near instantaneous handover to the monopulse mode. Some interval from 3 to 5 seconds would be required to perform the indicated assessment in the TWS mode. An alternative would be to hand over the target to the monopulse mode immediately upon detection in the surveillance mode, which would permit the threat assessment in a fraction of the time (the higher monopulse data rate would provide the capability for quicker assessment time). However, at least part of the time gained in this manner would be lost due to increased acquisition time. The monopulse mode would take longer to acquire the target and reach a stable solution due to the poorer quality of the designation. There would also be another hidden disadvantage to utilizing this technique: either the time averaged energy density, data rate, or both would be decreased in the remainder of the surveillance coverage pattern when in the monopulse mode. If we permitted a transition to the monopulse mode upon each potential target alarm, the resulting detection range would be decreased. As will be seen later, we do not wish to sacrifice detection range. Also the added detection range due to operating exclusively in the TWS mode for the evaluation time interval will provide more reaction time, thereby further reducing the time advantage to be gained by switching immediately to monopulse. So that no time is wasted and to avoid the above pitfalls of switching to monopulse prematurely, the

TWS should have determined the target's state sufficiently accurately to insure a high probability of near instantaneous acquisition in the monopulse mode. (See Note.) The appropriate time period is 3 to 5 seconds. Hence we will assume a combined acquisition-threat assessment time interval of

$$t_{TA} = 5 \text{ seconds.}$$

To the above reaction times, we must add the surveillance data rate time interval which we will assume to be 1 second. The selected data rate is based on a compromise between detection range and required accuracy. The reasoning will be covered in Part IV.

Table III-3 summarizes system reaction time and engagement time.

TABLE III-3  
SYSTEM REACTION TIME SUMMARY

System Reaction Time (sec)	Engagement Time (sec)	
--	11.3	Burst Length
1.0 (0.0)	1.0	Firing Key Closure
1.93	1.93	Mount Slew
1.0 (0.0)	1.0 (0.0)	Ballistic Solution
5.0	5.0	Acquisition & Threat Assessment
1.0	1.0	Initial Detection (Disclosure)
9.93 (7.93)	21.23 (19.23)	TOTAL

NOTE: It is possible that a transition phase between TWS search and monopulse track modes could reduce this reaction time to less than 1 second. Such a mode would be an alarm detection mode which would quickly evaluate whether alarms were targets or noise.

## E. SYSTEM ERROR BUDGET

This section will identify the error allocated for the WCS, FCS, and radar for an EX 83 Weapon System. In previous conversation with GE personnel during the development of the EX 83 mount, a random error of approximately 2.5 mr has been mentioned as being tolerable for the controlling fire control system. This is not an unreasonably large value in view of the natural dispersion due to the weapon, round and ballistic effects. The natural dispersion is 5 mils. [10] A mil is approximately equal to a mr. We will assume a joint error allocation of 2.5 mr for the radar and fire control system, exclusive of ballistic computations.

Figure III-6 shows a functional breakdown of fire control and sensor errors. This report addresses those within the dashed enclosure. It is difficult to predict the error associated with the predictor portion of the tracker/predictor at maximum effective range due to the long TOF in conjunction with the possibility of target maneuvers.

We will briefly analyze for purposes of a realistic allocation, the predictor error in terms of the TOF at 4 KM and 500 m. These TOF's are 8.6 s and 0.6 s respectively. If we assume a 0<sup>th</sup> order (position only) tracker/predictor and our position measurements were exact, we would be subject to no error at all for a target with no relative motion. The predictions would not be accurate for a non-accelerating target with a relative velocity. The linear error in any coordinate direction would be the product of the velocity in that coordinate direction and the TOF of the projectile. If we had an exact first order tracker/predictor (i.e. one which measured and predicted position and velocity) we could perform

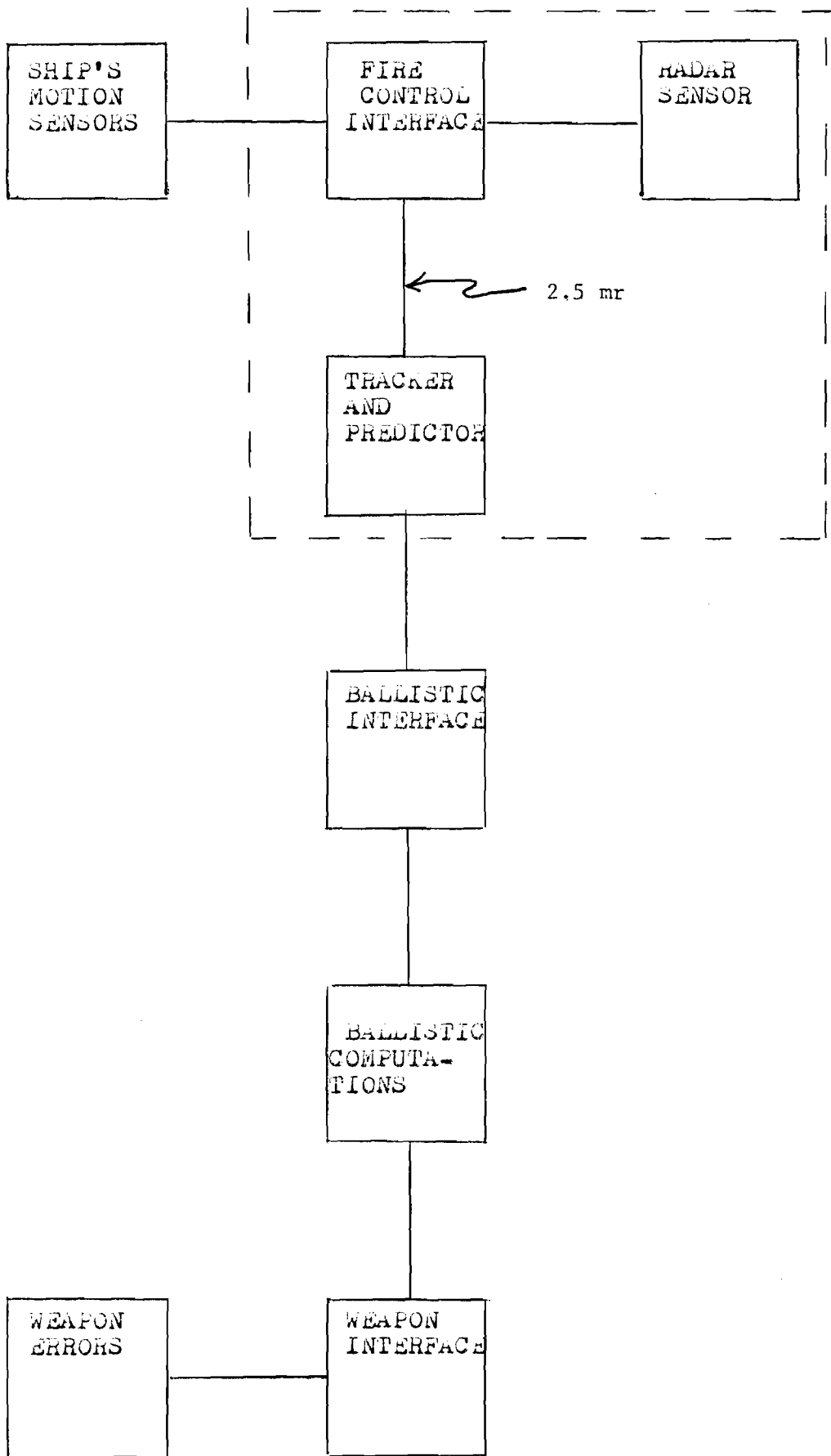


Figure III-6. System error budget.

perfect prediction for targets with constant velocities as well as stationary targets. We would still be subject to errors on accelerating targets, however. Suppose we had a second order tracker/predictor. We would find that we could perform perfect predictions on any target which was stationary, moved with uniform motion (i.e. constant velocity), or maneuvered with a constant linear acceleration. We would still be subject to errors, however, on the maneuvering target which has an acceleration change during the TOF. Figures III-7, III-8, III-9, and III-10 show the above conditions graphically. The four cases shown make it obvious that a position only tracker/predictor is absurd. It is also obvious that a second order tracker is no better than a first order tracker in predicting future position for the uniform motion case. In fact, it is doubtful that the second order tracker/predictor is in general better than the first order tracker/predictor in any maneuvering cases except that depicted by Figure III-9, the constant linear acceleration target case. This may be better appreciated if one considers a case wherein a target with an acceleration of + a at the time a projectile is fired were to reverse its acceleration to - a immediately thereafter. The first order predictor would be subject to an error of

$$E_1 = -\frac{a}{2} (\text{TOF})^2 \text{ meters}$$

$$E_1 (8.6\text{s}) = 36.98 \text{ meters}$$

The second order predictor would be subject to an error of

$$E_2 = 2\left(\frac{a}{2}\right) (\text{TOF})^2$$

(73.96 a) meters

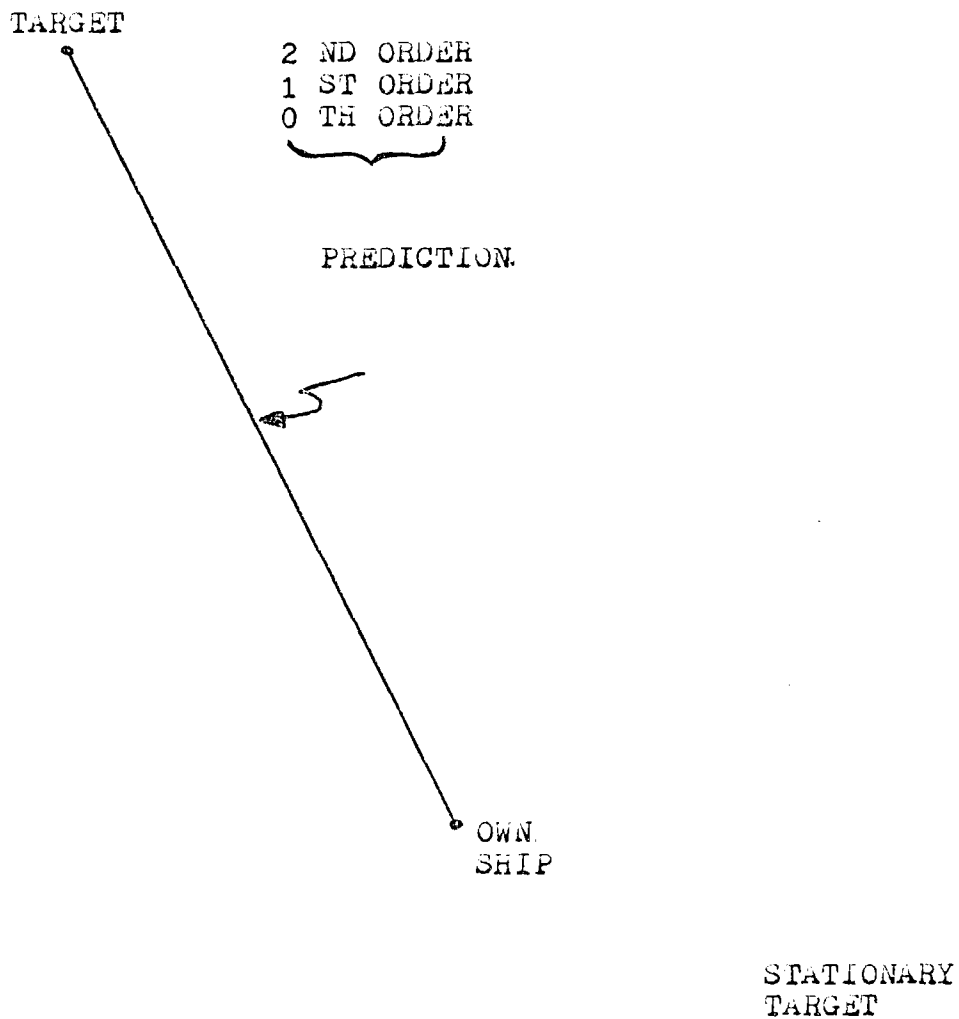


Figure III-7. Predictions for stationary target.

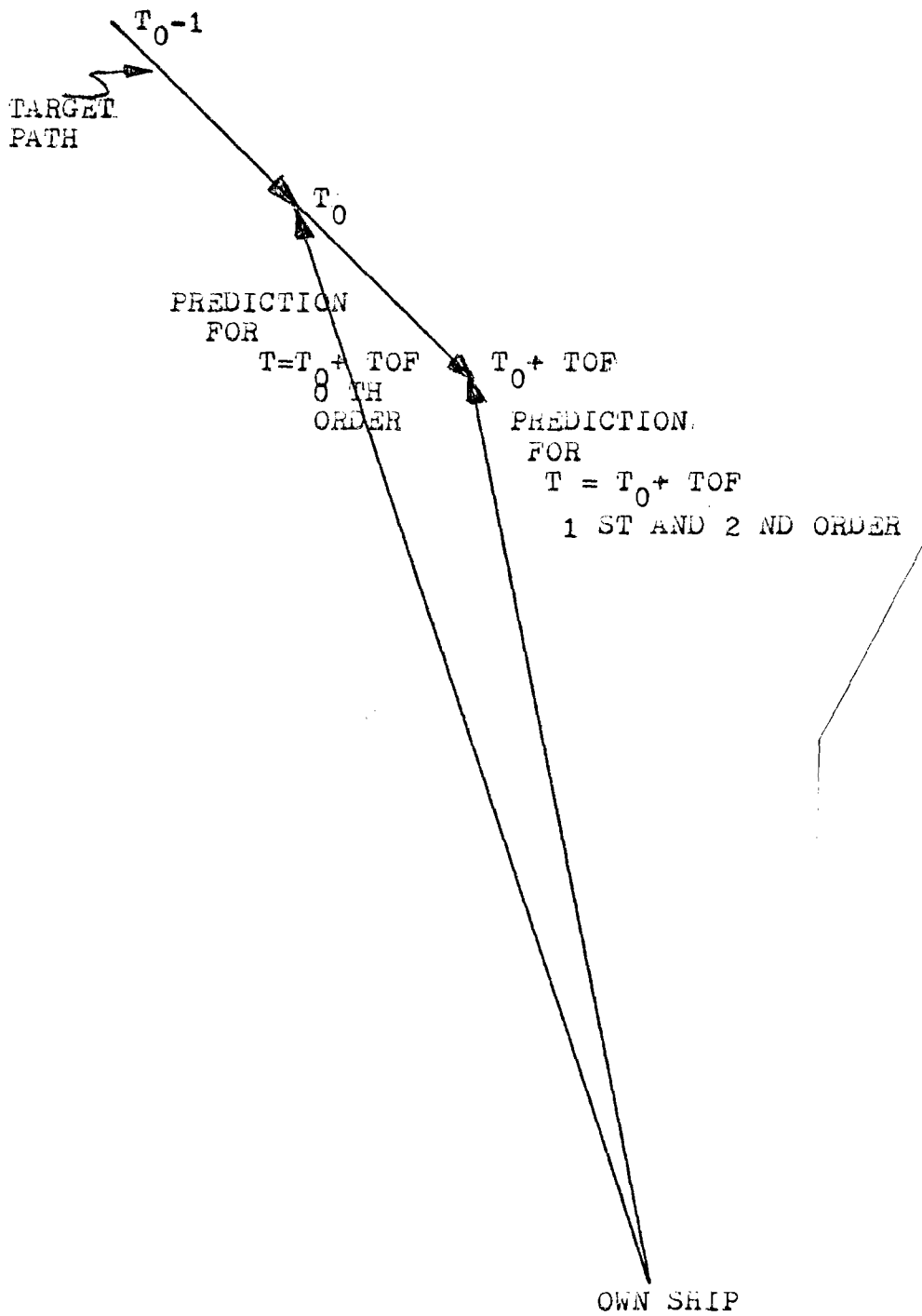


Figure III-8. Predictions for constant velocity target.

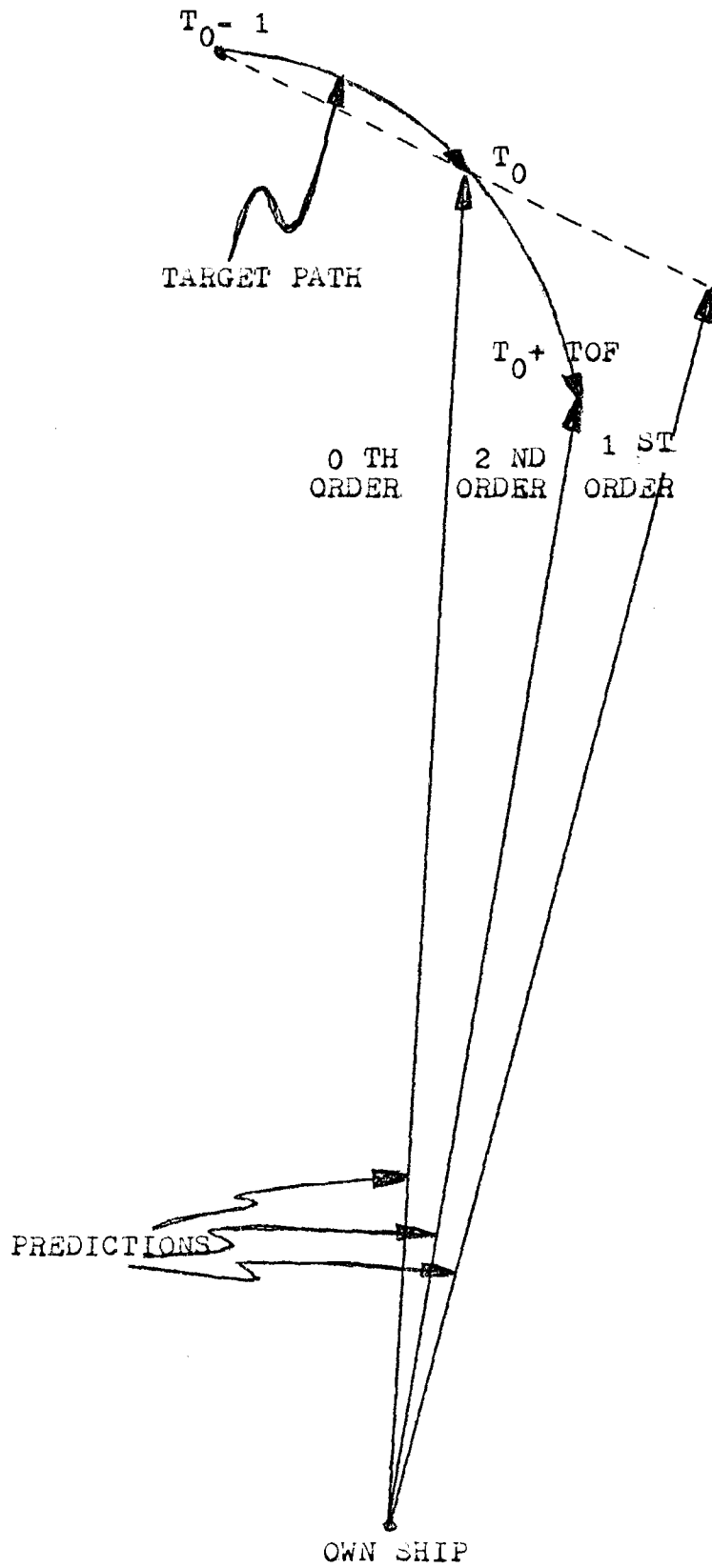


Figure III-9. Predictions for constant acceleration target.

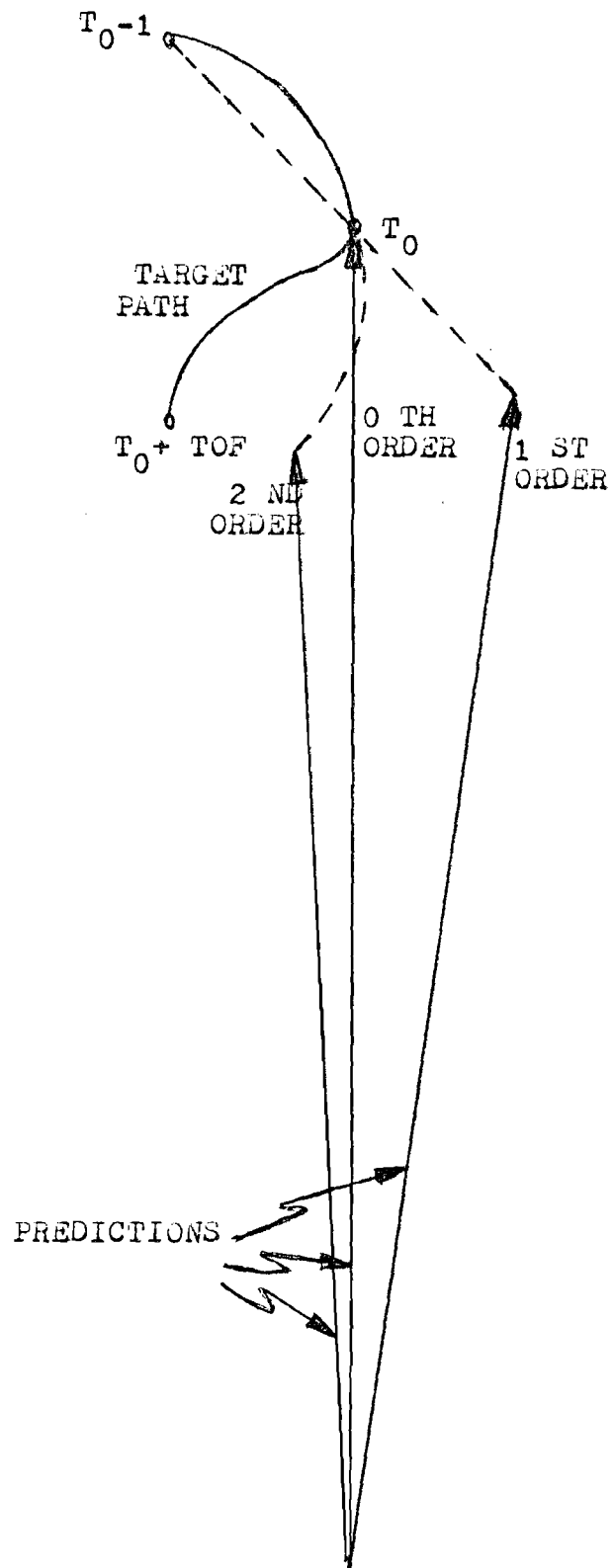


Figure III-10. Predictions for non-constant acceleration, maneuvering target.

Of course the predictions can be updated with more current information during the TOF but the projectile which was fired cannot be updated. Further projectiles may be fired at undated predictions but, once fired, they become subject to the TOF lag as in our example.

These considerations bring up an interesting point which is discussed in Part V, Section E, Aim Point Criteria. For the time being, we will restrict our attention to error allocation. It should be obvious by now that the TOF of the projectile has a magnifying effect in the predictor. At long TOF's, this effect is so great as to make conventional tracking errors insignificant in comparison. At shorter ranges where the TOF is less (e.g. 0.6s at 500 m future range) conventional tracking errors become relatively more significant. It seems astonishing but theoretically, at 4 Km future range on a target, the linear error could be as great as

$$\begin{aligned} E_2 &= 73.92 \times (15 G \times \frac{9.8 \text{ m/s}^2}{G}) \text{ meters} \\ &= 10.872 \text{ Km.} \end{aligned}$$

This corresponds to an angular error of

$$\sigma_{E2} = \frac{10.872}{4} \text{ r} \approx 2.72 \text{ radians} \quad !!$$

Of course, this is absurd for a number of reasons but it does illustrate the nature of the problem. For the case of a TOF of 0.6 s at 500 meters future range, the linear error would be

$$\begin{aligned} E_2(0.6 \text{ s}) &= 0.36 \text{ a meters} \\ &= 52.9 \text{ meters} \end{aligned}$$

which corresponds to an angular error of  $\frac{52.9}{500} = 0.105$  radians.

Now, the situation is not as hopeless as it appears for several reasons, not the least of which is that the target's accelerations must conform to the scenario which enables it to hit us in order for it to be a threat. We will make use of this fact in Section V. It is hoped that the foregoing discussion has served the purpose of illustrating the prediction problem sufficiently to warrant the following statement: Allocation of errors within the fire control system should be done on a basis other than setting the allocation according to the expected contribution of the predictor, since its contribution can be expected to be predominant. To the writer's knowledge, there are not currently in existence any good prediction algorithms for ballistic TOF predictions.

The remainder of the fire control and sensor related errors must be maintained as small as possible since their inaccuracies may be magnified by the predictor.

The tracker and predictor are closely related, especially mathematically. However, there are also some important differences. The tracker interpolates and smoothes using previous and current data, whereas the conventional predictor extrapolates on the basis of current data. In the paragraphs above, the time period of extrapolation (i.e. TOF) was seen to be an important factor. Similarly the filter response time of the tracker will be an important factor. Fortunately the ULTRA based concept permits more flexibility in adapting the filter response to the tactical situation than does a conventional inertial type tracker. Assuming that advantage will be taken of this flexibility, we can avoid the approach taken with the predictor. From experience, it is this writer's observation

that, if properly modeled, the track filter may be expected to provide a variance reduction to the order of 1/3 of that of the unfiltered data. In other words, the track filter will reduce rather than contribute to the system error, if modeled properly.

In view of the above reasoning, we will allocate an error of 2.5 mr to the radar and interfaces, will expect a reduction on the part of the tracker, and will look for a new solution on the part of the predictor. The 2.5 mr error is shown at the appropriate point in Figure III-6.

Thus far, we have discussed angular position error allocation. Other errors for the EX 83 WCS include a range error of no more than 10 m, a velocity error of no more than 3 m/s for velocities less than 30 m/s and no more than 30% for velocities greater than 30 m/s, and angular velocity errors no greater than  $\pm 5$  mr/s.

PART IV

## A. RADAR SYSTEM ERROR ALLOCATION

In Section E of Part III, we allocated a random error budget of 2.5 mrad to the radar system exclusive of the tracker. This section will define the various terms and errors to be encountered on the part of the radar system and will present the model for analyzing these errors, in the form of mathematical expressions. Parameter constraints will be derived in the following section in this part, Section B, by using the mathematical expressions explained in this section.

Barton's expression [11] for the angular error due to receiver noise for a monopulse radar is

$$\sigma_t = \frac{\theta}{km \sqrt{B\tau \left(\frac{S}{N}\right) \left(\frac{fr}{\beta n}\right)}}$$

where

$\sigma_t$  = thermal noise angular error

$\theta$  = 3 dB antenna beamwidth

km = error slope

B = IF bandwidth

$\tau$  = pulsewidth

s/n = signal-to-noise ratio

fr = pulse repetition frequency

$\beta_n$  = servo bandwidth

This error usually predominates near the maximum tracking range of the radar. Glint, the change in the apparent angular location of the target, is very complex and will not be discussed in detail here. Even if handled properly with appropriate design, glint is still usually a significant

fraction of the linear extent of the target across the line of sight. For glint calculations, we will use the expression

$$\sigma_g = \frac{0.4 \text{ Ly}}{R}$$

where

$\sigma_g$  = glint error

Ly = linear extent of target across line-of-sight

R = range

The glint error is usually predominant at short ranges and, for large targets or large antennas, can be quite severe. The glint error will be considerably less for the small missile target than for the larger manned aircraft target.

At the mid-ranges, where tracking radars usually experience their best accuracy, the limiting errors are those due to data granularity, mechanical noise and, in the case of Conical Scan Trackers (but not monopulse), scintillation. The task in connection with this error is to keep the causes as low as possible. It should not be too difficult to keep these errors below 2 mr.

When the three types of errors and the composite resulting errors are plotted on log--log type graph paper, they appear as shown in Figure IV-1. As can be seen from this figure, one task is to move the receiver noise limitation out in range. This can be done by increasing power, antenna gain, receiver sensitivity, reducing losses, and other methods. A second task is to minimize instrumental type errors and granularities to values which are acceptable in terms of the allocated error. Finally, the glint must be minimized by special techniques if it is significant at ranges of interest and for the target of interest.

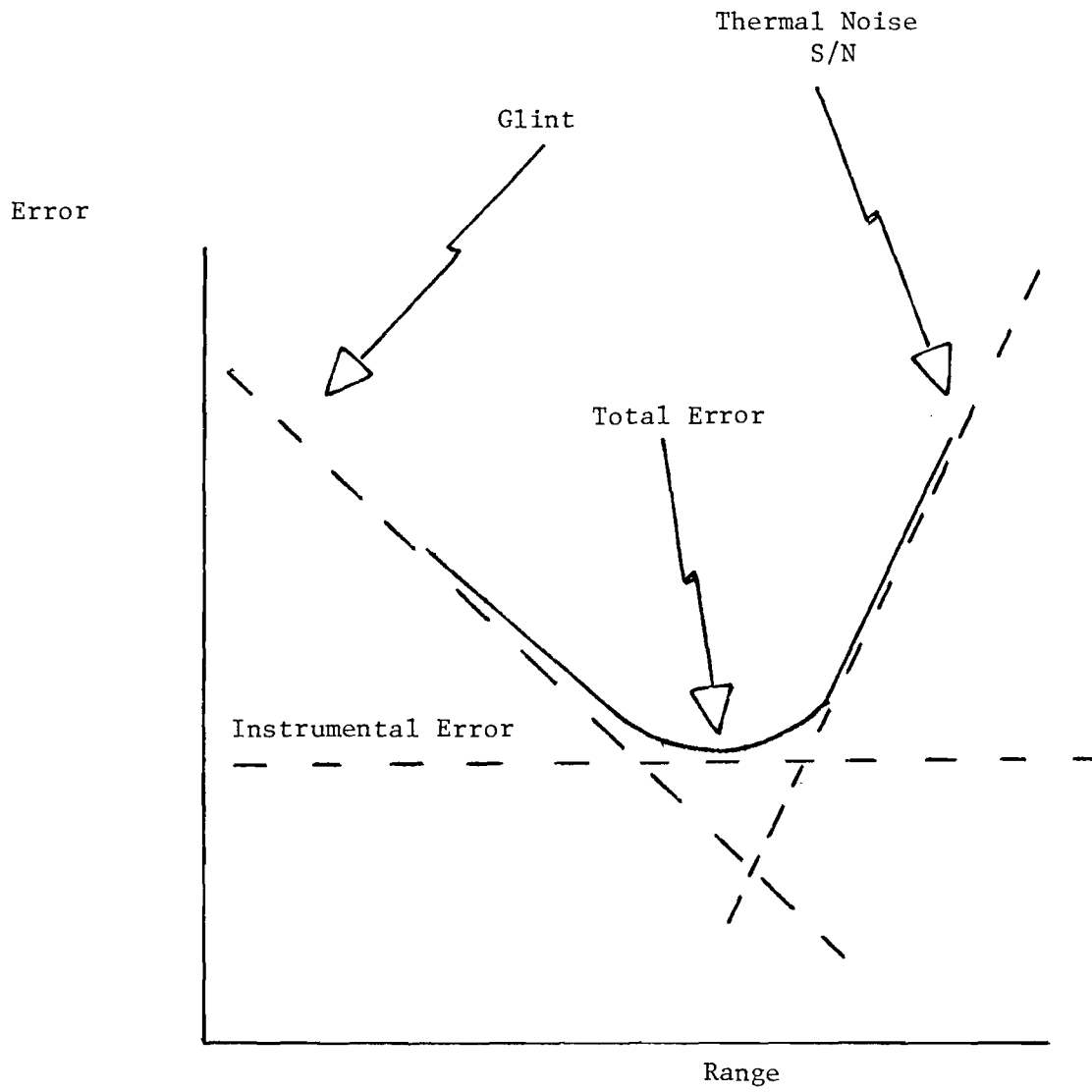


Figure IV-1. Tracking errors.

## B. SELECTION OF RADAR PARAMETERS (ERROR ALLOCATION)

In this section, constraints for radar parameter selection, as imposed by angular accuracy requirements, will be derived. Recall from the previous section that the equation for thermal noise error is

$$\sigma_t = \frac{\theta}{km \sqrt{B\tau} \left(\frac{S}{N}\right) \left(\frac{fr}{\beta n}\right)}$$

A typical value for  $km \approx 1.57$ . We will assume a reasonable  $B\tau$  of 1.5. The ratio  $fr/\beta n$  will probably lie somewhere in the region between 360 and 7200; both  $fr$  and  $\beta n$  are determined by other factors. These parameters result in an error of

$$.01 \frac{\theta}{\sqrt{\frac{S}{N}}} \leq \sigma_t \leq \frac{.03 \theta}{\sqrt{\frac{S}{N}}}$$

We will assume a worst case  $S/N$  ratio 10 dB. This is a worst case value in view of the fact that considerably higher  $S/N$  ratios will be required for initial detection in the surveillance mode. This will result in a thermal noise error of

$$0.003 \theta \leq \sigma_t \leq 0.01\theta$$

If we again choose worst case conditions setting  $\sigma_t = 0.10\theta$  and require  $\sigma_t$  to be less than 2.5 mr, we may solve for  $\theta$ .

$$\theta \leq 100 \text{ (2.5 mr)}$$

$$\theta \leq 250 \text{ mr or } 14^\circ$$

Had we used a  $S/N$  of unity, the beamwidth would have been  $\theta \leq 4^\circ$ .

Obviously the beamwidth requirements are not severely small from an angular accuracy viewpoint. Other factors will be seen to impose greater constraints.

From an instrumental error viewpoint, we must insure that the gear noise and angle indicating devices (e.g., synchros, etc.) are sufficiently accurate. Whether the antenna angular position is sensed and interfaced digitally or whether it is sensed in an analog fashion and converted to digital, the bit resolution for the digital portion should be sufficiently fine as to have little impact. If a binary coded angle format is used with the most significant bit equal to  $\pi$  radians, 14 bits should prove sufficient. Fourteen bits would result in a least significant bit value of  $0.022^\circ$  or 0.38 mr. The error contributed by a bit resolution of this amount would be 0.11 mr. We will allocate 1 mr for the combined effects of mechanical noise and data resolution.

If a multiple speed synchro type of interface is specified, caution must be exercised to see that the dynamic range of the synchro devices as well as the angle merging networks or routines are sufficient and that the conversion and duty cycle capabilities of the converters are sufficient.

Glint can be a large problem for some systems (e.g., manned aircraft) but will not be too serious for the EX 83 system against the missile target. This is due to the small missile size and relatively long range of the target at the time the rounds are fired. The best choice for reducing the susceptibility of a system of this nature, aside from varying power and antenna characteristics, is to optimize the estimate of target position by making the filtered estimate a deterministic function of the noise in the

angular position measurements. Figure IV-2 shows the expected angular error due to glint as a function of range, using the equation from Section A of Part IV. We will assume a physical cross section which includes all significant scattering points of  $1m$ . As can be seen from Figure IV-2, glint on this target is not the greatest of concerns for the ranges of interest and need not affect the selection of radar parameters.

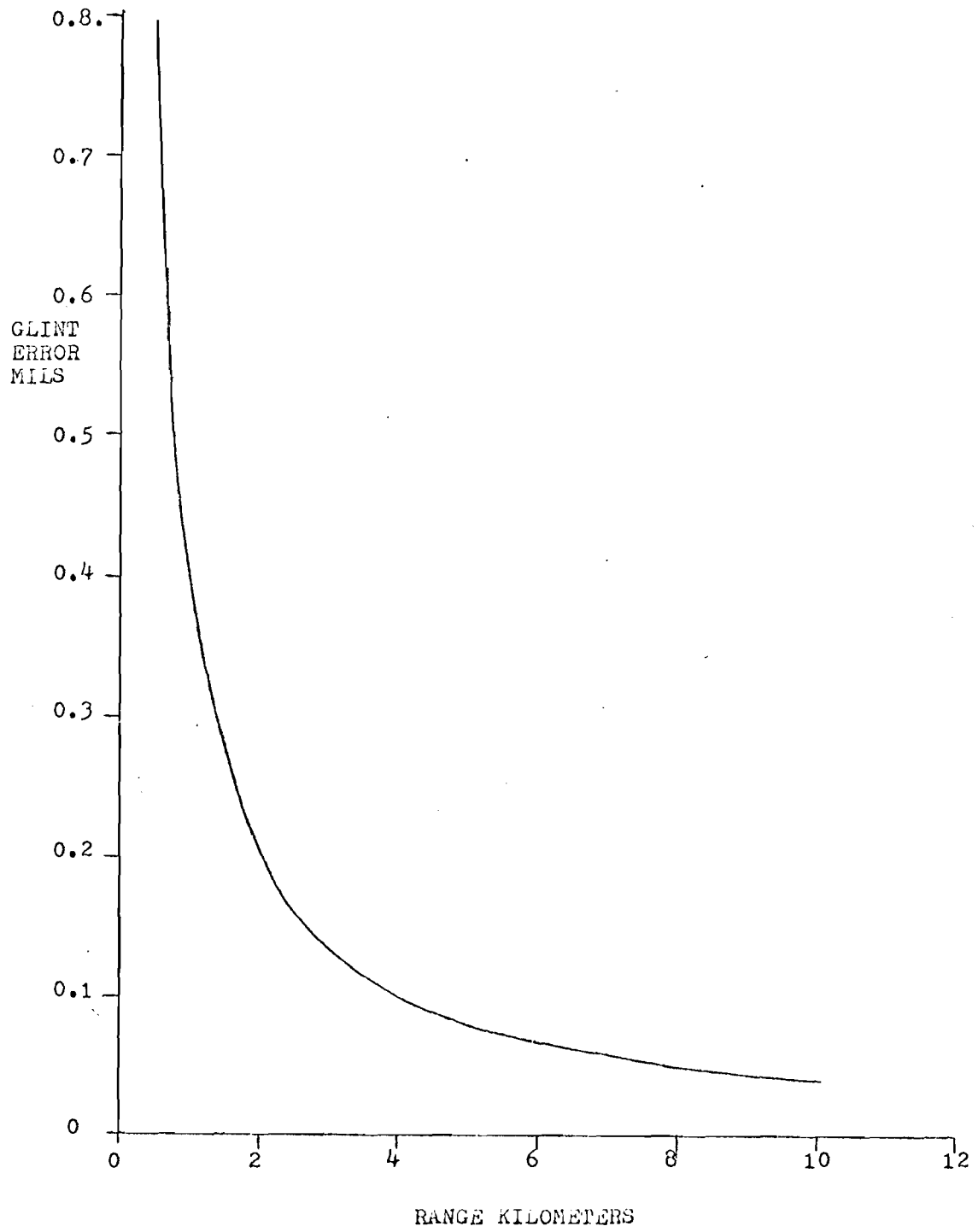


Figure IV-2. Glint error.

### C. SELECTION OF RADAR PARAMETERS (RANGE PERFORMANCE)

This section provides a discussion of the range performance which is required of the radar as a result of system reaction time considerations and an assessment of the resulting constraints imposed on the selection of radar system parameters.

From Part III, Section D, the system reaction time is 9.93 and 7.93 seconds for semi-automatic and automatic configurations respectively. We will use the 7.93 second figure for assessing range performance requirements in the automatic mode. The range of the target at open fire was

$$R \Big|_{\theta F} = 4 + 1.060 * 8.6) \text{ Km or } 13.12 \text{ Km}$$

the added reaction time of 7.93 seconds would place the initial detection range for the target at

$$R \Big|_{10} = 13.12 + 7.93 (1.06) \text{ Km} \\ \text{or } 21.52 \text{ Km}$$

Many parameters affect the range performance. The task of specifying constraints becomes more difficult when we consider the interdependence of the various parameters. Because of this complexity, and in view of the fact that many parameters are constrained or related to other requirements, we will draw on experience as a guide in the selection of a likely set of parameters in Section E of Part IV. The parameters thus selected must

- Provide the required range performance
- Meet constraints imposed by other system requirements
- Be realistically attainable with off-the-shelf components.

If it were not required that the weapon commence fire at the maximum effective range but rather the requirement was to commence fire at such time that an optimum burst interval (e.g. 5 seconds) were possible before the target's future range was projected to be at the minimum permissible kill range, the required detection range would be considerably reduced (e.g., from 21.52 Km to approximately 15 Km). We will, therefore, set the required detection range at 15 Km with a range performance of 20 Km or greater as desired.

#### D. SELECTION OF RADAR PARAMETERS (ENVIRONMENTAL FACTORS)

The missile target is the most difficult target under adverse environmental conditions. This is so because of its very small cross section. Therefore, by insuring that adequate performance is available for the missile target under stated environmental conditions, we will insure that performance is adequate for the other targets.

Two environmental conditions will be considered: rain and sea state. A 4 mm/hr rain will be used and the associated attenuation and backscatter accounted for. The cross section corresponding to sea state 4 will be used in calculating low angle relative target to clutter cross sections and performance.

From an attenuation viewpoint, the rain will affect the range performance as follows:

$$R = \left[ k e^{-2\alpha R} \right] \frac{1}{4}$$

where

R = range

k = all parameters other than absorption

$\alpha$  = attenuation factor

The  $e^{-2\alpha R}$  factor is often expressed as dB/Km. The transcendental nature of this equation makes it difficult to solve. One technique is to use graphical methods. [12] The graphical nature of the solution amounts to solving two simultaneous equations. Table IV-1 lists an HP calculator program which solves the two equations and, therefore, the range which fits the two conditions iteratively. The attenuation will be accounted

TABLE IV-1

HP-25 CALCULATOR PROGRAM FOR RANGE PERFORMANCE IN RAIN

<u>Program</u>	<u>Reg</u>	<u>Register Storage</u> <u>Contents</u>
RCL 2		
RCL 1	0	Max Range Without Attenuation (Km)
X		
10	1	Two-Way Attenuation (dB/Km)
÷		
10	2	Seed Range, much less than max (Km)
x $\Rightarrow$ y		
f $y^x$		
RCL0		
x		
RCL 2		
g x $\geq$ 0		
TO 30		
R/S		
.5		
STO + 2		
f PAUSE		
GTO 01		

NOTE: Once started the program iterates until an answer is achieved. The attenuated range will be available in Register #2 after the program stops.

for by insuring that the various selectable parameters (e.g., power, antenna gain, data rate) are selected such as to provide sufficient range performance under conditions of attenuation. The attenuation at X-band is  $\sim 8 \times 10^{-2} \text{ dB/km}$ . The attenuation at Ku band is  $\sim 2 \times 10^{-1} \text{ dB/km}$ .

The backscatter due to rain is a function of the pulse width, vertical and horizontal beamwidths, frequency, and range. The following equation approximates the backscatter:

$$C_r = \eta_R \times R \times \phi \times R \times \theta \times \frac{c\tau}{2} = \eta_R \frac{c\tau}{2} R^2 \phi\theta$$

where  $C_r$  = rain clutter,  $\eta_R$  = rain cross sectional area per unit volume,  $\frac{c\tau}{2} R^2 \phi\theta$  = resolution cell volume.

As we are restricted with the ULTRA antenna technology, we cannot use circular polarization or other techniques to reduce the per volume radar cross section. The range performance is a requirement rather than a selectable parameter. This leaves  $\tau$ ,  $\phi$ , and  $\theta$  as variables.

There are at least two basic approaches other than special polarizations to reducing the rain clutter to acceptable levels. One manner is to simply select the  $\frac{c\tau}{2}$ ,  $\phi$ , and  $\theta$  parameters appropriately. If, due to their impact on other requirements, acceptable values cannot be selected for these parameters, special processing techniques such as Moving Target Indication (MTI) may be specified. One measurement of the advantage to be gained using MTI techniques is Sub-Clutter-Visibility (SCV). SCV (usually stated in dB) is essentially a measure of how far below the clutter level the target may be and still be seen or a measure of relative target-to-clutter enhancement. Unfortunately, not only must the target level be observable

in clutter but must be larger by an amount determined by the acceptable false alarm rate due to clutter. If thought of analogously to signal-to-noise ratios, we may choose to express the target level required relative to clutter as signal-to-clutter (s/c) ratio. The required s/c ratio added to the SCV which is needed to see the target at a particular clutter level, where both are expressed in dB, yields the required improvement. The achievable improvement is

$$I = \frac{r_o}{r_i}$$

where

$I$  = improvement

$r_o$  = output ratio to target-to-clutter

$r_i$  = input ratio of target-to-clutter

This improvement must exceed the required improvement if the target is to be detected under the probability of detection and clutter false alarm criteria established.

We will use clutter backscatter ratios of  $3 \times 10^{-3} \frac{\text{cm}^2}{\text{m}^3}$  for X-band and  $3 \times 10^{-2} \frac{\text{cm}^2}{\text{m}^3}$  for Ku band in calculating the relative target to clutter ratio.

Sea clutter may be treated in much the same way as rain clutter. One of the differences, of course, is that sea clutter is an area phenomenon as opposed to the volume characteristic of rain. Consequently, the apparent average clutter will be a linear function of range and may be expressed as

$$\bar{\sigma} = R\theta \frac{c\tau}{2} \sigma^\circ$$

where

$\sigma^\circ$  = cross section per unit area.

The discussion of rain clutter reduction applies to surface clutter reduction.

Two points should be made before proceeding with the synthesis. First, the desirability of a high data rate may have to be traded off against the number of hits required to achieve a given improvement. The theoretical improvement is a linear function of the number of hits on the target when expressed in dB. Secondly, MTI techniques cannot be depended on for surface target detection enhancement since the surface target may not have a radial velocity. In this sense, at least, the surface target will be more difficult than the missile target. Therefore, special techniques are called for in handling the surface target, if the basic radar parameters do not provide the required capability.

## E. PHASED ARRAY RADAR SYNTHESIS

The objective of the synthesis was to identify a set of radar parameters that

- provided the required range performance,
- provided the required accuracy,
- were realistically achievable,
- provided the required clutter performance,
- provided the highest data rate commensurate with volume coverage requirements and the above provisions.

### Range Performance

The starting place for the synthesis was the present capabilities of the ULTRA antenna as defined in Part III, Section A. The parameters used and the resulting range performance are shown in Table IV-2. Obviously the performance is inadequate. An expression was derived to show the relationship of antenna area on range performance. For the ULTRA antenna, antenna area affects both gain and power. The expression is

$$R_{A1} = R_{A0} \left[ \frac{A_1}{A_0} \right]^{\frac{3}{4}}$$

It was also necessary to increase the frequency in order to increase the antenna gain for a particular area. The relationship between gain and the wavelength is

$$G = \frac{4\pi A}{\lambda^2} \rho \quad \sim$$

Table IV-3 shows the results of doubling the antenna size and changing the frequency from X-band to Ku-band. Table IV-4 shows the effects of reducing antenna losses by 1 dB and integrating 2 pulses vs. 1.

TABLE IV-2  
BASIC ULTRA RANGE PERFORMANCE

---

Radar and Target Parameters (Inputs)

Pulse Power, KW	125.0
Pulse Length, Microsec	.2200
Frequency, MHz	9375.0
Transmit Antenna Gain, dB	25.0
Transmit Transmission Line Loss, dB	0.0
Scanning Antenna Pattern Loss, dB	0.0
Antenna Ohmic Loss, dB	3.0
Pattern Propagation Factor	1.0
Solar and Galactic Noise	AVERAGE
Receive Antenna Gain, dB	25.5
Receive Transmission Line Loss, dB	0.0
Receiver Noise Factor (Figure), dB	6.0
Bandwidth Correction Factor, dB	0.0
Miscellaneous Losses, dB	4.0
Target Elevation Angle, Degrees	0.00
Target Cross Section, Square Meters	.1000
Number of Pulses Integrated	1
Probability of Detection	.950
False Alarm Probability, Negative Power of Ten	6.0
Swerling Fluctuation Case	1

\*\*\*\*\*

Calculated Quantities (Outputs)

Noise Temperatures, Degrees Kelvin

Swerling Fluctuation Case	Signal-to Noise Ratio, dB	Tropospheric Attenuation Decibels	Range Nautical Miles
1	24.29	.06	1.1

TABLE IV-3  
ULTRA CONFIGURATION A RANGE PERFORMANCE

---

Radar and Target Parameters (Inputs)

Pulse Power, KW	250.0
Pulse Length, Microsec	.2200
Frequency, MHz	16000.0
Transmit Antenna Gain, dB	33.5
Transmit Transmission Line Loss, dB	0.0
Scanning Antenna Pattern Loss, dB	0.0
Antenna Ohmic Loss, dB	3.0
Pattern Propagation Factor	1.0
Solar and Galactic Noise	AVERAGE
Receive Antenna Gain, dB	33.5
Receive TRANSMISSION Line Loss, dB	0.0
Receiver Noise Factor (Figure), dB	6.0
Bandwidth Correction Factor, dB	0.0
Miscellaneous Losses, dB	4.0
Target Elevation Angle, Degrees	0.00
Target Cross Section, Square Meters	.1000
Number of Pulses Integrated	1
Probability of Detection	.950
False Alarm Probability, Negative Power of Ten	6.0
Swerling Fluctuation Case	1

\*\*\*\*\*

Calculated Quantities (Outputs)

Noise Temperatures, Degrees Kelvin

Antenna (TA)	262.6
Receiving Transmission Line (TR)	0.0
Receiver (TE)	864.5
TE X Line Loss Factor = TEI	864.5
System (TA + TR + TEI)	1127.1
Two-Way Attenuation Through Entire Troposphere, dB	14.1

Swerling Fluctuation Case	Signal-To Noise Ratio, dB	Tropospheric Attenuation Decibels	Range, Nautical Miles
1	24.29	.32	2.5

TABLE IV-4  
ULTRA CONFIGURATION B RANGE PERFORMANCE

---

Radar and Target Parameters (Inputs)

Pulse Power, KW	250.0
Pulse Length, Microsec	.2200
Frequency, MHz	16000.0
Transmit Antenna Gain, dB	33.5
Transmit Transmission Line Loss, dB	0.0
Scanning Antenna Pattern Loss, dB	0.0
Antenna Ohmic Loss, dB	2.0
Pattern Propagation Factor	1.0
Solar and Galactic Noise	AVERAGE
Receive Antenna Gain, dB	33.5
Receive Transmission Line Loss, dB	0.0
Receiver Noise Factor (Figure), dB	6.0
Bandwidth Correction Factor, dB	4.0
Miscellaneous Losses, dB	0.00
Target Elevation Angle, Degrees	.1000
Target Cross Section, Square Meters	2
Number of Pulses Integrated	.950
Probability of Detection	6.0
False Alarm Probability, Negative Power of Ten	1
Swerling Fluctuation Case	

\*\*\*\*\*

Calculated Quantities (Outputs)

Noise Temperatures, Degrees Kelvin	
Antenna (TA)	255.5
Receiving Transmission Line (TR)	0.0
Receiver (TE)	864.5
TE X Line Loss Factor = TEI	864.5
System (TA + TR + TEI)	1120.0
Two-Way Attenuation Through Entire Tropospheric, dB	14.1

<u>Swerling Fluctuation Case</u>	<u>Signal-To Noise Ratio, dB</u>	<u>Tropospheric Attenuation Decibels</u>	<u>Range, Nautical Miles</u>
1	21.84	.37	2.8

At this point, a major change was made in the projected design. A magnetron had been assumed. It appeared desirable to increase the antenna size further in order to permit a higher average power and increased antenna gain. It was not desirable, however, to increase the peak power in order to achieve the greater average power. Therefore, a change was made to a TWT which, due to its higher duty cycle, could provide the greater average power at reduced peak powers. Table IV-5 shows the resulting performance. The greater average power per pulse was increased as well as the average power per scan as a result of an assumed greater PRF. The product of pulse width and PRF increase was assumed to be ten. The TWT duty cycle is 0.01 vs. 0.001 for magnetrons typically. As can be seen from Table IV-5, we are beginning to approach the value for required range performance which is 15 Km. In fact, were different fluctuation characteristics to be assumed, as in Tables IV-6 and IV-7, the performance would be marginally adequate.

Finally, Table IV-8 shows the range performance resulting from a further increase in antenna size, antenna gain, average power, and number of pulses integrated. As can be seen, the performance is close to being inadequate.

At this stage, we are approaching the point where most of our parameters have been maximized to provide better range performance, but more is desirable. We do not desire to increase the antenna size further to permit yet more power or to achieve greater antenna gain. Not only is the narrow beamwidth making the search problem more difficult but antenna size is also a limiting factor. It is undesirable to go to yet a higher frequency band because of component limitations and again the beamwidth would decrease, making the search problem more difficult. It would not be desirable to slow the surveillance data rate due to reaction time constraints. System losses have been reduced to a conservative minimum. To integrate more pulses at this point will provide

TABLE IV-5

## ULTRA CONFIGURATION C RANGE PERFORMANCE - SWERLING CASE I

## Radar and Target Parameters (Inputs)

Pulse Power, KW	100.0
Pulse Length, Microsec	1.0000
Frequency, MHZ	16000.0
Transmit Antenna Gain, db	36.5
Transmit Transmission Line Loss, dB	0.0
Scanning Antenna Pattern Loss, dB	0.0
Antenna Ohmic Loss, dB	2.0
Pattern Propagation Factor	1.0
Solar and Galactic Noise	AVERAGE
Receive Antenna Gain, dB	36.5
Receive Transmission Line Loss, dB	0.0
Receiver Noise Factor (Figure), dB	6.0
Bandwidth Correction Factor, dB	0.0
Miscellaneous Losses, dB	4.0
Target Elevation Angel, Degrees	0.00
Target Cross Section, Square Meters	.1000
Number of Pulses Integrated	4
Probability of Detection	.950
False Alarm Probability, Negative Power of Ten	6.0
Swerling Fluctuation Case	1

\*\*\*\*\*

## Calculated Quantities (Outputs)

Noise Temperatures, Degrees Kelvin	
Antenna (TA)	255.5
Receiving Transmission Line (TR)	0.0
Receiver (TE)	864.5
TE X Line Loss Factor = TEI	864.5
System (TA + TR + TEI)	1120.0
Two-Way Attenuation Through Troposphere, dB	14.1

Swerling Fluctuation Case	Signal-To Noise Ratio, dB	Tropospheric Attenuation, Decibels	Range Nautical Miles
1	19.51	.67	5.2

TABLE IV-6

## ULTRA CONFIGURATION C RANGE PERFORMANCE - SWERLING CASE II

---

 Radar and Target Parameters (Inputs)

Pulse Power, KW	100.0
Pulse Length, Microsec	1.0000
Frequency, MHz	16000.0
Transmit Antenna Gain, dB	36.5
Transmit Transmission Line Loss, dB	0.0
Scanning Antenna Pattern Loss, dB	0.0
Antenna Ohmic Loss, dB	2.0
Pattern Propagation Factor	1.0
Solar and Galactic Noise	AVERAGE
Receive Antenna Gain, dB	36.5
Receive Transmission Line Loss, dB	0.0
Receiver Noise Factor (Figure), dB	6.0
Bandwidth Co-recton Factor, dB	0.0
Miscellaneous Losses, dB	0.4
Target Elevation Angle, Degrees	0.00
Target Cross Section, Square Meters	.1000
Number of Pulses Integrated	4
Probability of Detection	.950
False Alarm Probability, Negative Power of Ten	6.0
Swerling Fluctuation Case	2

\*\*\*\*\*

## Calculated Quantities (Outputs)

Noise Temperatures, Degrees Kelvin	
Antenna (TA)	255.5
Receiving Transmission Line (TR)	0.0
Receiver (TE)	864.5
TE X Line Loss Factor = TEI	864.5
System (TA + TR + TEI)	1120.0
Two-Way Attenuation Through Entire Troposphere, dB	14.1

Swerling Fluctuation Case	Signal-To- Noise Ratio, dB	Tropospheric Attenuation, Decibels	Range, Nautical Miles
2	11.65	1.03	8.0

TABLE IV-7

## ULTRA CONFIGURATION C RANGE PERFORMANCE - SWERLING CASE 0

---

Radar and Target Parameters (Inputs)	
Pulse Power, KW	100.0
Pulse Length, Microsec	1.0000
Frequency, MHz	16000.0
Transmit Antenna Gain, dB	36.5
Transmit Transmission Line Loss, dB	0.0
Scanning Antenna Pattern Loss, dB	0.0
Antenna Ohmic Loss, dB	0.2
Pattern Propagation Factor	1.0
Solar and Galactic Noise	AVERAGE
Receive Antenna Gain, dB	36.5
Receive Transmission Line Loss, dB	0.0
Receiver Noise Factor (Figure), dB	6.0
Bandwidth Correction Factors, dB	0.0
Miscellaneous Losses, dB	4.0
Target Elevation Angle, Degrees	0.00
Target Cross Section, Square Meters	.1000
Number of Pulses Integrated	4
Probability of Detection	.950
False Alarm Probability, Negative Power of Ten	6.0
Swerling Fluctuation Case	0

\*\*\*\*\*

Calculated Quantities (Outputs)	
Noise Temperatures, Degrees Kelvin	
Antenna (TA)	255.5
Receiving Transmission Line (TR)	0.0
Receiver (TE)	864.5
TE X Line Loss Factor = TEI	864.5
System (TA + TR + TEI)	1120.0
Two-Way Attenuation Through Entire Troposphere, dB	14.1

Swerling Fluctuation Case	Signal-To- Noise Ratio, dB	Tropospheric Attenuation Decibels	Range, Nautical Miles
0	8.68	1.21	9.4

TABLE IV-8  
ULTRA CONFIGURATION D RANGE PERFORMANCE

---

Radar and Target Parameters (Inputs)	
Pulse Power, KW	100.0
Pulse Length, Microsec	1.5000
Frequency, MHz	16000.0
Transmit Antenna Gain, dB	38.0
Transmit Transmission Line Loss, dB	0.0
Scanning Antenna Pattern Loss, dB	0.0
Antenna Ohmic Loss, dB	2.0
Pattern Propagation Factor	1.0
Solar and Galactic Noise	AVERAGE
Receive Antenna Gain, dB	38.0
Receive Transmission Line Loss, dB	0.0
Receiver Noise Factor (Figure), dB	6.0
Bandwidth Correction Factor, dB	0.0
Miscellaneous Losses, dB	4.0
Target Elevation Angle, Degrees	0.00
Target Cross Section, Square Meters	.1000
Number of Pulses Integrated	5
Probability of Detection	.950
False Alarm Probability, Negative Power of Ten	6.0
Swerling Fluctuation Case	1

\*\*\*\*\*

Calculated Quantities (Outputs)

Noise Temperatures, Degrees Kelvin	
Antenna (TA)	
Receiving Transmission Line (TR)	
Receiver (TE)	
TE X Line Loss Factor = TEI	
System (TA + TR + TEI)	
Two-Way Attenuation Through Entire Troposphere, dB	

Swerling Fluctuation Case	Signal-To Noise Ratio, dB	Tropospheric Attenuation Decibels	Range, Nautical Miles
1	18.79	.91	7.1

diminishingly smaller increments of improvement with each additional pulse to be integrated and it would have to come at the expense of data rate.

One parameter which can be changed to provide increased performance at the cost of greater system complexity is the apparent fluctuation characteristics of the target. The use of frequency agility will cause the target's fluctuations to appear more like a Swerling Case II target, thereby decreasing the required single pulse s/n and, consequently, increasing the range performance. While the target's fluctuation rate is an advantageous factor, so is the relatively small amplitude of the fluctuation. Georgia Tech field demonstrations at GE-Utica, using an operational radar, have shown how advantage may be taken of these relative characteristics to suppress clutter. Therefore, by employing frequency agility, we may not only increase the range performance of our radar but at the same time substantially suppress clutter for both moving and stationary targets.

The increased range performance due to the different target fluctuation characteristics and the effects of lobeing should provide adequate range performance. Models for predicting the improvement for such complicated target model assumptions are complex and beyond the scope of this report. However, the expected improvement should be analyzed in greater detail before a commitment to design parameters is made. The performance improvement could be in the range from 0 dB to 9 dB. If we assume a 3 dB improvement, the range performance would be increased by approximately 20% and would become about 15.6 Km exclusive of pattern propagation factors.

#### Accuracy

In Part IV, Section B, a discussion of the relationship between radar parameters and angular error allocation was provided. Multipath phenomena

under conditions of low elevation angle tracking conditions was not discussed. Neither will this special consideration be considered here. Section B of Part V provides a discussion of low elevation angle tracking. This section addresses three error terms which, aside from multipath considerations, dominate in three tracking regions.

In the mid-range region, where instrumental errors predominate, close attention to engineering tolerances and allowances is the answer to meeting the error allocation. The goal of keeping the composite of these errors at less than 2 mr should be achievable.

The close region where glint becomes the predominant factor will intersect the mid-range regions at a range of 200 meters for the missile target. This range is less than the minimum acceptable present position for engagement purposes.

The long range region begins at the range where S/N ratio becomes the predominant error term. Using the S/N error equation from Section B, Part IV, we calculate this S/N to be 0.1 or -10 dB. If we assume that at least 100 pulses are integrated within the time period corresponding to the effective servo (i.e. filter) bandwidth, the range at which the S/N ratio became the limitation is  $\sim 70 \times 10^3$  meters. This is well beyond the maximum present position for open fire where the future position is within the maximum effective range.

A similar argument can be made for range accuracy as was made for angular accuracy, except that the results are different. One equation for computing range tracking noise is [7]

$$\sigma_{rt} = \frac{\tau}{\sqrt{\left(\frac{S}{N}\right) \frac{fr}{\beta}}}$$

If we assume the product of  $S/N \times fr/\beta$  to be greater than 100, then

$$\sigma_{rt} > \frac{\tau}{10}$$

where  $\tau$  is expressed as a distance.

In our case,  $\tau = 1.5 \times 10^{-6}$  s, therefore

$$\tau \left\{ \begin{array}{l} \\ \text{distance} \end{array} \right. = \frac{c\tau}{2} = 225 \text{ meters}$$

and  $\sigma_{rt} < 225$  meters.

This relatively high range noise can be reduced by artificially creating a synthetically narrow pulse width by employing a form of pulse compression. Even though a pulse compression approach is a more complex means of achieving good range resolution than a simple short pulse approach, our minimum pulse width is constrained by range performance requirements. There are practical limits on the amount of compression which can be achieved as well as the minimum compressed pulse width size. For example, if phase coding were impressed on the transmitted signal for purposes of compression, the minimum compressed pulse width attainable would be limited by the speed of operation of the receiver post-detection correlator device. If digital circuitry were employed, the present practical limit may be on the order of 150 MHz. Conceivably a compressed pulse width of

$$\tau_C = \frac{1}{150 \times 10^6} \approx 6.7 \text{ ns} \quad \text{is possible}$$

If this were achieved, the theoretical range accuracy will become

$$\tau_{RC} = \frac{\tau_C}{10} \frac{C}{2} = 0.1 \text{ meters} .$$

Actually, we are assuming digital techniques in the above example where the error due to the granularity or discreteness of the data is related to the uniform probability density function for target location over the width of

the coding interval. Due to this factor which is analogous to angular instrumental error, the minimum range error would be

$$\left. \begin{array}{l} \tau_{RC} \\ \text{DIG} \end{array} \right\} = \frac{\tau_c C}{2\sqrt{12}} \approx 0.3 \text{ meters} .$$

The parameters and general radar system characteristics have been synthesized. They are as follows:

1. Transmitter

- Pulse Width; 0.6 microseconds
- Pulse Repetition Frequency; 10 KHz
- Peak Power; 100 KW
- Frequency; 16 GHz
- Phase Coding for Pulse Compression
- Pulse-to-Pulse Frequency Agility

2. Receiver

- Noise Figure; 6 dB
- Bandwidth; 150 MHz

3. Antenna

- Gain; 38.5 dB
- Electronic Scan Rate; 10,000 pulse positions/sec, 3 pulses per beamwidth
- Horizontal Beamwidth
- Vertical Beamwidth
- Diameter

4. Special Processing

- Pulse Compression (50 - 1)
- Post Detection Integration and Correlation Discrimination
- Search, False Alarm Investigation, and Track Mode Control Processing

The above parameters imply certain hardware. For the transmitter, a TWT power amplifier approach is called for. The phase coding of the transmitted signal could conceivably be accomplished in several different ways including the use of a balanced mixer. A tunable continuous duty cycle

oscillator could be used to generate the transmitted waveform. (See Figure IV-3.)

The receiver would be of conventional superhet design with a low noise r-f pre amp. The coherent LO reference signal would be heterodyned with the return signal to produce the fixed intermediate frequency which contains the phase coding information. After amplification, the phase coded i-f would be phase detected against the master oscillator frequency, producing the phase coded in-phase and quadrature bipolar video signals.

Special processing would include the A/D conversion of each video signal and a series of digital processing stages. These stages would include

- Correlation with a replica of the transmitted waveform and compression
- Vector addition of the resultant quadrature correlated, compressed videos.
- Clutter discrimination processing
- Pulse integration.

The antenna design would be of the ULTRA configuration with modifications suggested.

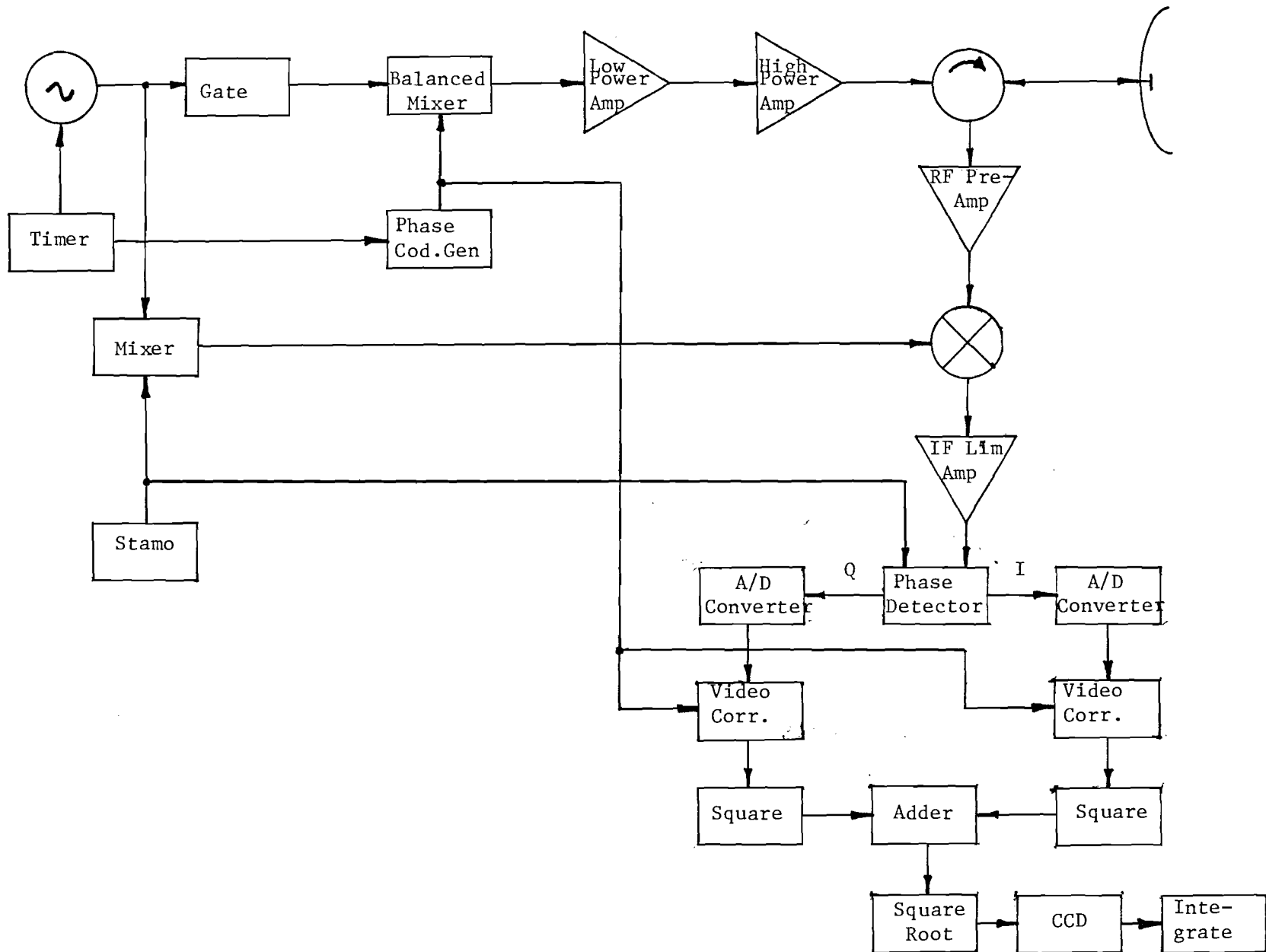


Figure IV-3. Radar system block diagram.

PART V

## A. ROUND TRACKING

The GE phased array concept has the potential capability for round tracking in a very sophisticated manner. The concept is more flexible and potentially more accurate than boresight, target vicinity, closed loop type systems. This section shows that with proper bullet design, round tracking capability may be based on tracking a single bullet and therefore need not be dependent on the number of bullets per resolution cell.

The uniqueness of the GE phased array concept lies in its capability to track rounds in most portions of their trajectory rather than only in the vicinity of the target. This capability provides the potential for correction of errors such as:

- Gun pointing offsets and misalignments
- Atmospheric conditions along the line-of-flight (LOF)
- Permanent changes in initial velocity (iv) due to bore erosion and powder temperature
- Some erroneous ballistic computation data.

The round tracking concept is based on enhancing the effective radar cross section of the 30 mm projectile. The following paragraphs describe one technique for accomplishing the enhancement. A 30 mm diameter circular surface is assumed for the rear of the projectile in the calculations.

A concept which could be employed to enhance the radar return signal from a 30 mm projectile is a redesign of the rear end of the projectile itself so that its radar cross section is increased over a significant range of projectile-to-radar aspects. The flat end of a conventional projectile will exhibit a specular backscatter having a narrow beamwidth

confined about normal incidence. Thus relatively little energy will be scattered back to the radar when the projectile's aspect is such that its near face is not at normal incidence to the illuminating energy. If the rear end were configured so as to increase the reflected power, over a range of projectile aspects, then more effective round tracking could be obtained from the resulting signal-to-noise improvement.

A geometry well suited to this goal is the trihedral corner reflector, a configuration of three mutually perpendicular flat surfaces as shown in Figure V-1. The nature of this reflector design is that a beam incident into the corner will be reflected backward toward the original source over a wide range of incidence angles, with regard to scattering beamwidth.

For normal incidence into a trihedral corner reflector having triangular sides, the radar cross section  $\sigma$  is given by the expression

$$\sigma = \frac{4\pi a^4}{3\lambda^2}$$

where  $a$  is the dimension of a leg of the triangular reflector and  $\lambda$  is the wavelength of the incident energy. It will be assumed that larger reflector dimensions are preferable to smaller ones, since these wavelengths will already be within the so-called resonance region of the projectile. However, we should extrapolate the expression for  $\sigma$  to this resonance region as at least a decent approximation pending actual measurement of radar cross section.

As shown in Figure V-2, the largest inscribed trihedral corner reflector within the projectile's circular boundary (30 mm diameter) will have a base dimension of 18.37 mm and a maximum radar cross section of -33.3 dB sm (X-band:  $\lambda = 3.20$  cm) and -28.7 dB sm (Ku-band:  $\lambda = 1.875$  cm). The cross

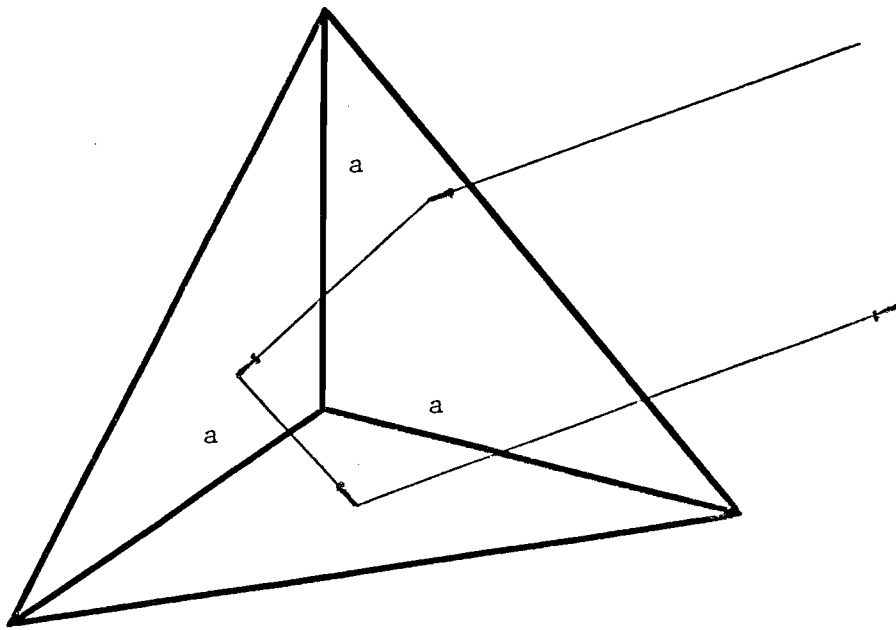


Figure V-1. Trihedral corner reflector.

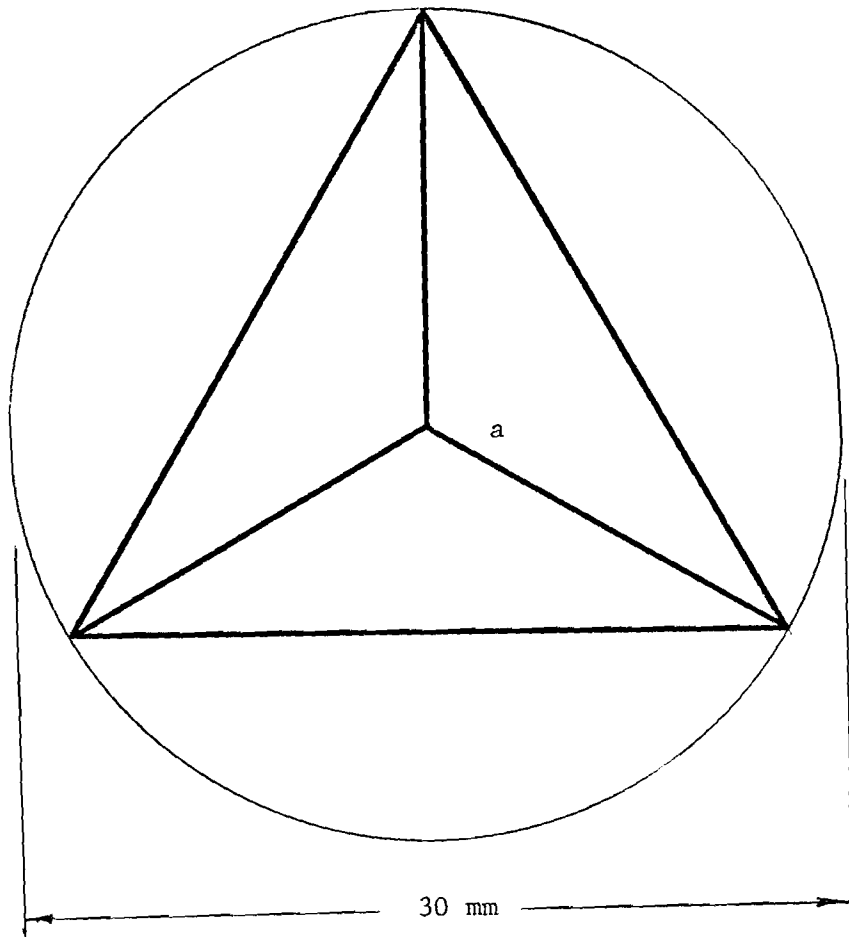


Figure V-2. Largest inscribed trihedron.

section of the entire projectile and must also include that contribution from the flats and will be approximately equal to -22.1 dB sm (X-band) and -17.5 dB sm (Ku-band) at normal incidence only. Again diffraction effects are omitted from these calculations.

The radar cross section of the projectile rear at aspects off the normal may be increased at the expense of retroreflection beamwidth by increasing the dimensions of the trihedral corner reflector toward the limit shown in Figure V-3.

The cross sections then are -22.1 dB sm (X-band) and -17.5 dB sm (Ku-band) as upper bound approximations at normal incidence. Off-normal incidence reflectivity will be less than that of the previously described geometry due to the loss of the "corners" of the trihedral reflector, resulting in a decreased retroreflection beamwidth.

As can be seen from the above calculations, the expected radar cross section for a round manufactured with the stated characteristics is  $0.02 \text{ m}^2$ . The range performance for round tracking should be to  $1 \times 10^4 \text{ m}$  with a single pulse. This is adequate performance considering the maximum effective range of the GAU-8 fired round.

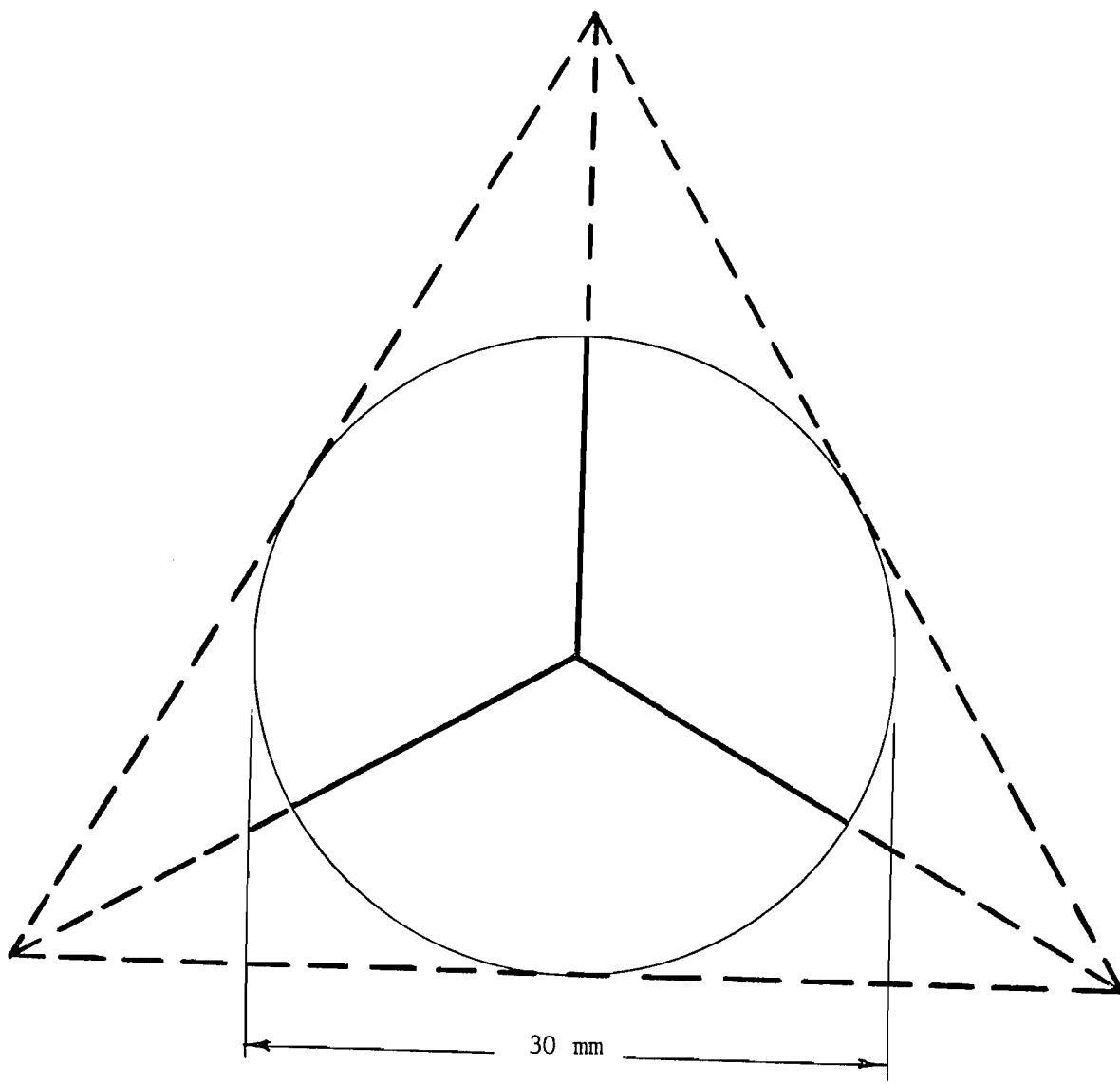


Figure V-3. Increased size trihedral.

## B. LOW ELEVATION TRACKING

Low elevation angle tracking can introduce relatively large tracking errors and even loss of track. The troublesome region for monopulse trackers is usually at elevation angles less than  $1.5 \theta_{e1}$ , where  $\theta_{e1}$  is the elevation 3 dB beamwidth. Barton has summarized the effectiveness of various techniques for different tracking regions. [13] Table V-1 shows the summary.

The synthesized system has three techniques which provide some low angle tracking improvement over conventional systems:

- Narrow Beamwidth
- Range Resolution
- Frequency Agility

The extent of the tracking errors to be realized due to multipath phenomena at low elevation angles is a complex subject, which is dependent on many factors and is deserving of a special analysis. Such analysis is highly recommended.

TABLE V-1

## LOW ELEVATION TRACKING TECHNIQUES

Techniques	Sidelobe Region, $\theta_t > 1.5 \theta_e$ $\sigma_E^t < 0.03 \theta_e$	Mainlobe Region, $0.3\theta_e < \theta_t < 1.5\theta_e$ $0.03\theta_e < \sigma_E^t < 0.3\theta_e$	Horizon Region $\theta_t < 0.3 \theta_e$ Peak Error $\Rightarrow \theta_c$
Narrow Beamwidth	Error = $C\theta_e/\sqrt{G_{se}}$	Error and region proportional to $\theta_e$	Region of large error proportional to $\theta_e$
Range Resolution with Signal Band Width B	Effective for $\frac{h_r h_t}{R} > \frac{c}{2B}$	Effective only if $h_r \theta_e > \frac{c}{2B}$	Ineffective
Data Smoothing or Doppler Resolution	Effective for $\frac{2h_r \theta}{\lambda} > \frac{1}{t_0}$	Effective for $\frac{2h_r \theta}{\lambda} > \frac{1}{t_0}$	Ineffective
Frequency Agility or Diversity	Effective for $\frac{h_r h_t}{R} > \frac{c}{2\Delta f}$	Effective only if $h_r \theta_e > \frac{c}{2\Delta f}$	Permits track on centroid at horizon but no height data
Off-Axis Monopulse Tracking	Ineffective	Provide stable track with $\sigma_E \Rightarrow 0.2\theta_e$ as $\theta_e \Rightarrow 0.3\theta_e$	Provides stable track with increasing error until loss of signal
Double-Null Tracker	Degenerates to normal monopulse	Effective giving $0.02 < \sigma_E/\theta_e < 0.1$	Provides stable track with minimum error
Symmetrical $\Delta/\Sigma$ Pattern	Inapplicable	Effective for smooth and medium surfaces	Relatively large diffuse error and deep fades limit applicability
Assymmetrical Monopulse	Inapplicable	Effective, giving $0.05 < \sigma_E/\theta_e < 0.2$	Provides stable track with increasing error until loss of signal
Complex Angles	Ineffective	Effective for specular reflector at low sites	Possible data over calibrated surface until loss of signal

Table V-1  
(Continued)

Techniques	Sidelobe Region	Mainlobe Region	Horizon Region
Multiple-Target Estimation	Ineffective	Effective for smooth and medium surfaces	Impractical except as implemented with asymmetrical beams
Radar Fences	Effective	Effective when mainlobe clears fence	Detrimental extends horizon to top of fence
Circular Polarization	Ineffective unless $\theta_t$ for narrow beams	$\gg$ brewster angle; not applicable	
Use of <u>a priori altitude</u>	Inapplicable	Poor tracking is better than <u>a priori</u> data	Permits continued range and azimuth track until loss of signal

### C. AIM POINT CRITERIA

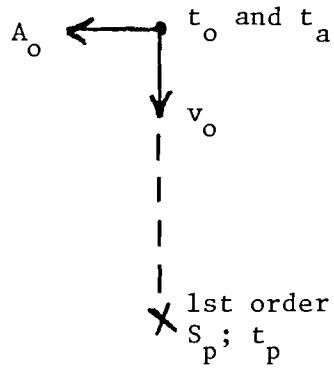
Part III, Section E of this report discussed the systems error budget. It was shown that significant errors could be developed during the TOF of the projectile. It was also shown that in some cases, a second order prediction could cause greater errors than a first order prediction. This raises the question "What is the optimal aim point?"

This section addresses the question raised above for the case of point defense against missiles. In the following paragraphs, questions dealing with what we know about the target's state will be addressed since these pertain to the optimal aim point question.

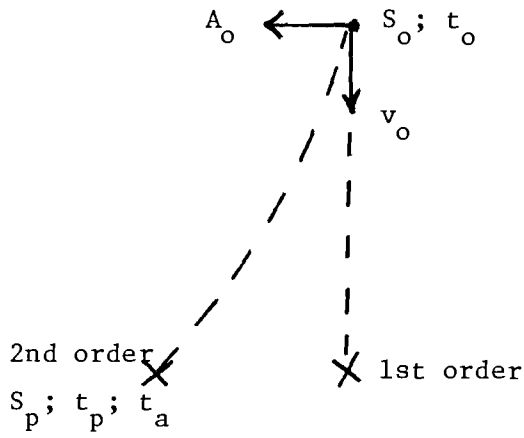
We will define a time interval,  $t_a$ , which represents the time interval required for the target to change its acceleration. For a time interval  $t_a - t_\epsilon$ , where  $t_\epsilon$  is extremely small, the target's acceleration hasn't time to change. For an interval  $t_a + t_\epsilon$ , the target's acceleration can change to any value defined by its maneuverability.

We know that  $t_a > 0$  and that  $t_a < t_p$  where  $t_p$  is the prediction time interval. Yet the first and second order prediction techniques inherently assume that  $t_a = 0$  and  $t_a = t_p$  respectively and in the case of the first order, predicts that no acceleration is expected after time  $t_a$ . These two cases are represented in Figure V-4.

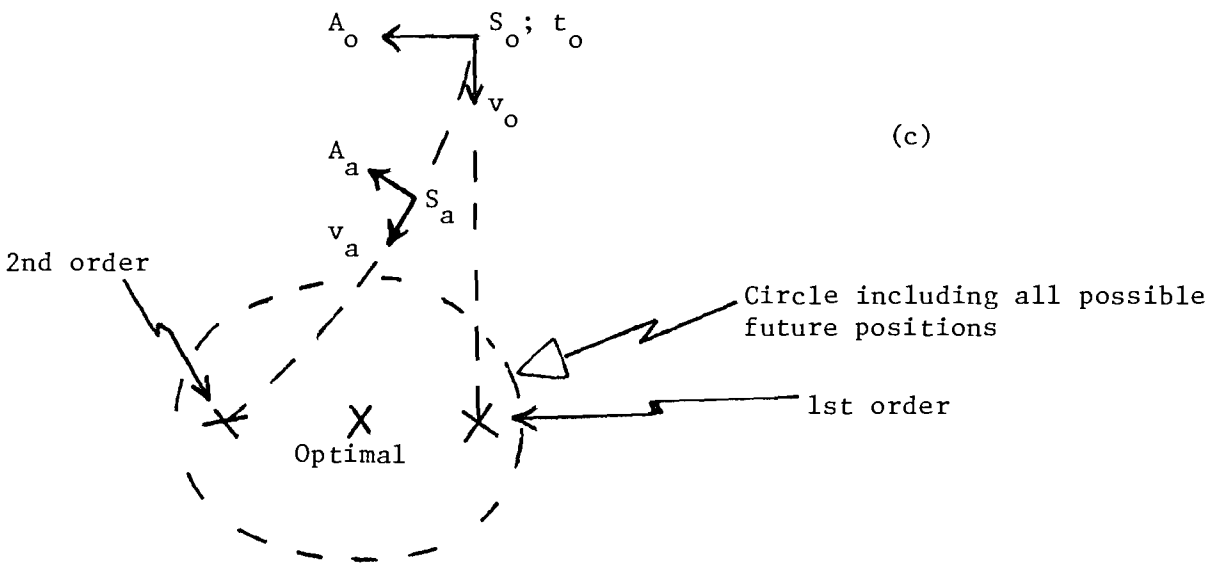
Since, in general,  $t_a$  is neither 0 nor  $t_p$ , then both the first and second order predictors are generally in error. In fact, as was pointed out in Part III, Section E, there are cases when each order predictor is better than the other. The obvious solution to this apparent dilemma is to select an aim point model which will approach the second order predictor



(a)



(b)



(c)

Figure V-4. (a) First order aim point criteria; (b) Second order aim point criteria; (c) Optimal Aim Point Criteria

as  $t_a$  approaches  $t_p$  and approaches the first order predictor as  $t_a$  becomes small in comparison with  $t_p$ . Furthermore, the model should have the correct behavior between the two extremes.

It is not difficult to derive a model which will satisfy the criterion for the extremes. A simple switching function which would switch from a first order to a second order predictor at some point where  $0 < \frac{t_a}{t_p} < 1$ , say 0.5, could accomplish this. Such a predictor would be of little help between the two extremes for  $t_a$  however.

By making use of additional a priori knowledge we can synthesize a model which will have the above characteristics and which will transition from one model toward the other in a smooth and monotonic manner. As will be seen later, this model also has other advantages. The model may be defined by the following equations:

$$\vec{S}_p = \vec{S}_o + \vec{v}_o t_a + \frac{\vec{A}_o}{2} t_a^2 + \vec{v}_a (t_p - t_a)$$

$$\vec{v}_a = \vec{v}_o + \vec{A}_o t_a$$

$$\vec{S}_p = \vec{S}_o + \vec{v}_o t_p - \frac{\vec{A}_o t_a^2}{2} + \vec{A}_o t_a t_p$$

or

$$\vec{S}_p = \vec{S}_o + \vec{v}_o t_p + \frac{\vec{A}_o t_a^2}{2} \left( \frac{2t_p}{t_a} - 1 \right)$$

or

$$\vec{S}_p = \vec{S}_o + \vec{v}_o t_p + \vec{A}_o t_a \left( t_p - \frac{t_a}{2} \right)$$

or

$$\vec{S}_p = \vec{S}_o + \vec{v}_o t_p + \frac{\vec{A}_o}{2} t_p^2 \left[ \frac{2t_a}{t_p} - \frac{t_a^2}{t_p^2} \right]$$

The final form of this equation is probably the easiest form to envision from a physical viewpoint. In this form, the equation appears to represent a second order prediction where the weight given to the acceleration term is exponentially related to the size of the ratio  $t_a : t_p$ .

Further examination shows that if  $t_a$  is a valid number, then the prediction resulting from the equation represents the center of a circle which encompasses all possible future positions of the target. This is represented in Figure V-4. Table V-2 shows the value of the weighting function as a function of the ratio  $t_a/t_p$ .

In the real world, the target's ability to accelerate or decelerate linearly along its flight path will not in general be equal to its ability to turn; hence, the area encompassing all future positions will not be a simple circle or the volume a sphere in the 3-D case, but rather a more complex shape. Likewise, the prediction equation would also be somewhat different. The principle should remain basically the same, however.

Going back to the simple example, we find another interesting characteristic of this model. The size of the circle diminishes toward 0 radius as the centroid approaches the second order prediction for  $t_a/t_p = 1$ . This is in agreement with reality since a ratio of 1 represents a physical situation where the target cannot change its acceleration during a prediction interval and hence the second order prediction is perfect. This characteristic is shown in Figure V-5.

Again, getting back to the real world, the target could probably be expected to vary its acceleration in a manner different from that assumed in this simple example. For example, the acceleration may change in an exponential manner until a new value is reached and then become constant at that value until another change is called for. In such a case, the time interval  $t_a$  would become a time constant representing a time period of measurement of the change and the prediction equation would be modified as necessary.

TABLE V-2

SECOND ORDER WEIGHTING FUNCTION FOR OPTIMAL AIM POINT CRITERIA

$\frac{t_a}{t_p}$	$\frac{2 t_a}{t_p} - \frac{t_a^2}{t_p^2}$
.001	0.002
.01	0.02
.05	0.10
.1	0.19
.5	0.75
.75	0.94
.9	0.99
$\approx 1.0$	$\approx 1.00$

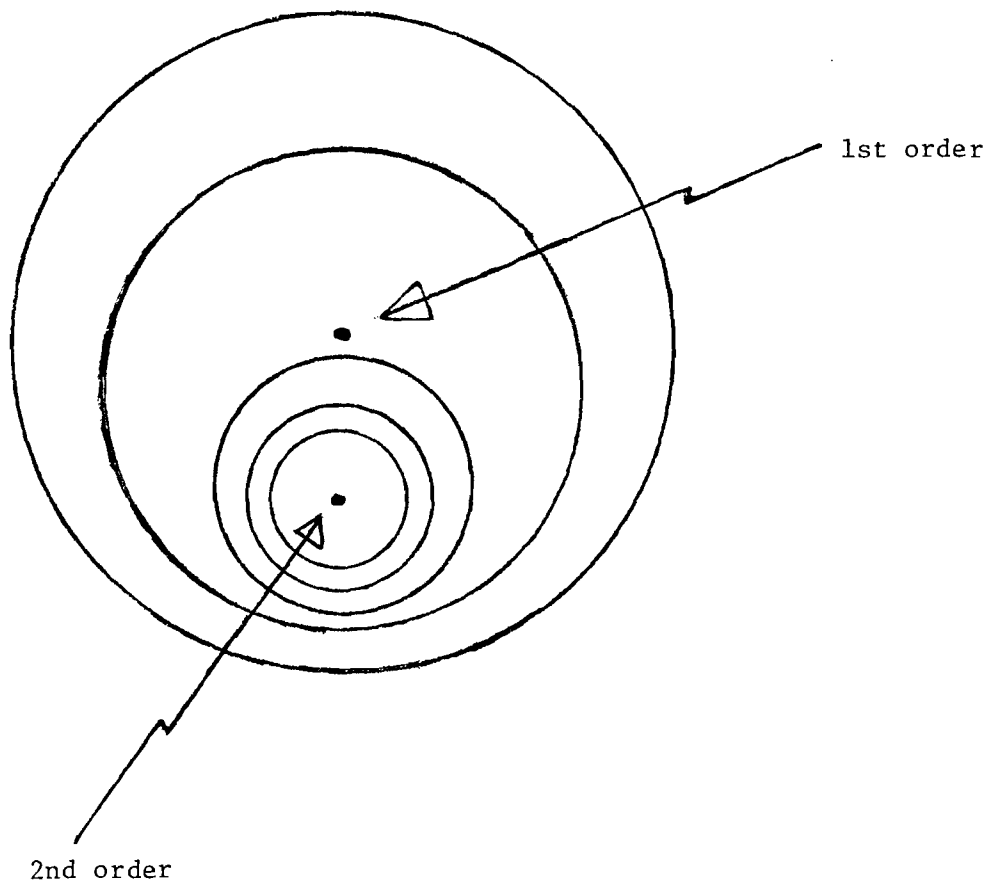


Figure V-5. Convergence to second order solution.

Assumptions that have been made in the synthesis of this model, aside from simplifying assumptions for purposes of explanation, include the assumption that  $t_a \neq 0$  and  $t_a < t_p$

A second aim point criterion that will only be mentioned here involves the correction of gun orders as the result of bullet tracking information. It is believed that most closed loop type techniques attempt to reduce the measured error between where the bullets went and where the target was instead of eliminating the error between where the bullets went and where they were intended to go. It seems that the former technique could contribute errors under some circumstances, whereas the latter technique would always result in error reduction.

A third aimpoint criterion involves the a priori knowledge, in the point defense case, that an attacking missile is restricted in its present maneuverability to those maneuvers that it can undergo and still hit our ship, which is its target. It was shown in Part II, Section C that given a particular maximum maneuverability on the part of the target, it is possible to define velocity-range-aspect angle phase space which the target cannot occupy if it is to be a threat to us.

Suppose that the spatial area resulting from the allowable phase space should be laid over Figure V-5. The results might resemble a situation such as that depicted in Figure V-6. In such a case, where should we aim? In some situations the potential hit area may not include the first, second or centroid aim points. Where should the aim point then be? It is conceivable that the potential hit area does not even intersect the area including all future positions. Deductive reasoning would lead us to the conclusion that we needn't even bother firing in such a circumstance since the

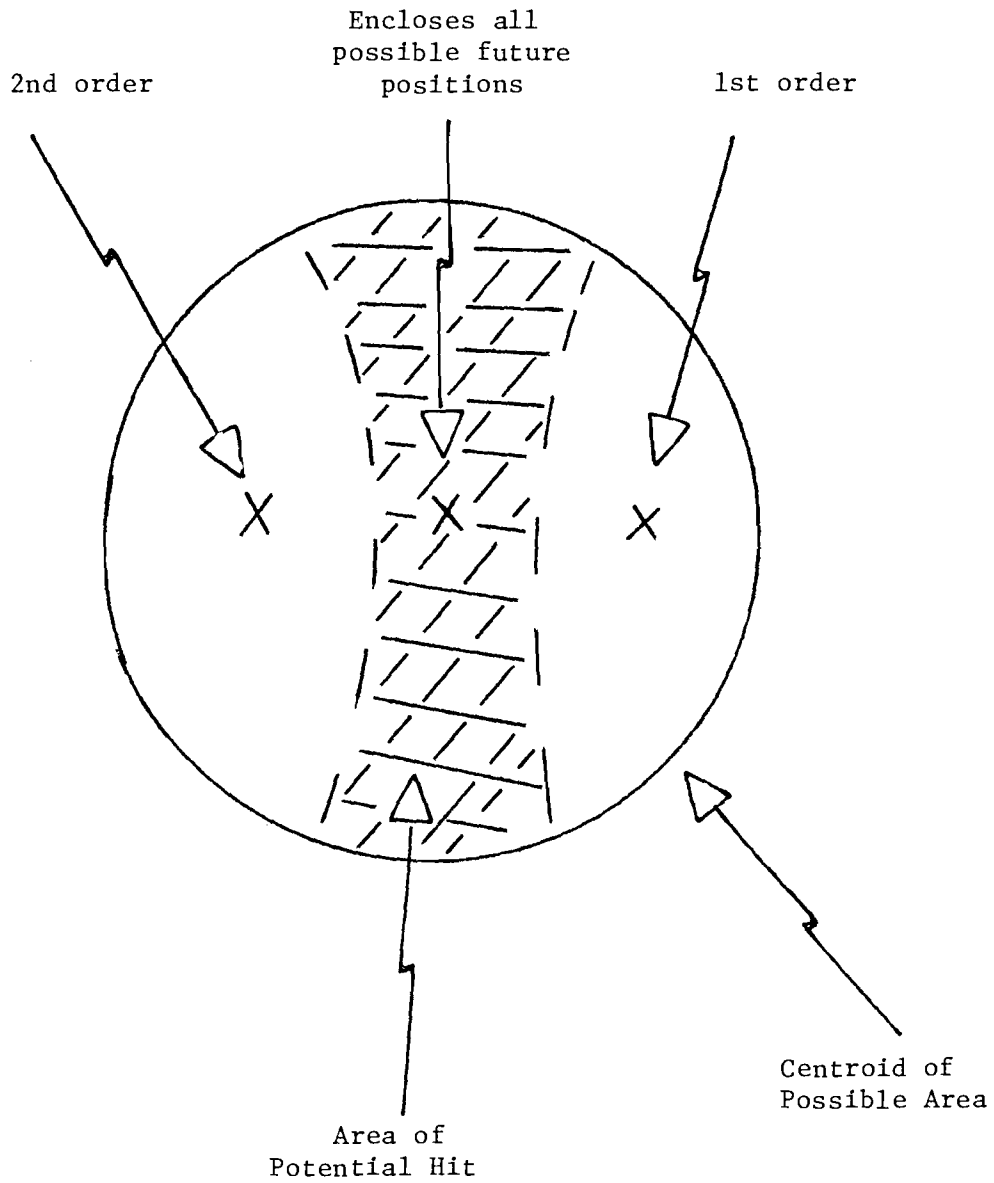


Figure V-6. Aim point reasonableness criteria for point defense.

missile cannot hit our ship/ These considerations and others could revolutionize gun fire control philosophy and they deserve further investigation.

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