AD-A015 238

ANALYSIS OF AIRCRAFT EVASION STRATEGIES IN AIR-TO-AIR MISSILE EFFECTIVENESS MODELS

G. Carpenter, et al

Grumman Aerospace Corporation
Bethpage, New York

August 1975

RE-506

ANALYSIS OF AIRCRAFT EVASION STRATEGIES IN AIR-TO-AIR MISSILE EFFECTIVENESS MODELS

August 1975

RESEARCH DEPARTMENT

GRUMMAN AEROSPACE CORPORATION
BETHPAGE NEW YORK

Grumman Research Department Report RE-506

ANALYSIS OF AIRCRAFT EVASION STRATEGIES IN AIR-TO-AIR MISSILE EFFECTIVENESS MODELS

by

G. Carpenter and M. Falco

System Sciences

August 1975

Approved by: *[signature]*
Charles E. Mack, Jr.
Director of Research

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Grumman Aerospace Corporation	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

Analysis of Aircraft Evasion Strategies in Air-to-Air Missile Effectiveness Models

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Research Report

5. AUTHOR(S) (First name, middle initial, last name)

G. Carpenter and M. Falco

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
August 1975	87	4

8a. CONTRACT OR GRANT NO. b. PROJECT NO. N/A c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) RE-506 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None

10. DISTRIBUTION STATEMENT

Approved for Public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	None

13. ABSTRACT

This report presents a new methodology with which to quantify missile effectiveness and aircraft vulnerability. The approach is a blend of applications of optimal control theory, stochastic learning theory, and simulation. This methodology permits an evaluation of aircraft evasive maneuvering and countermeasures deployment strategy as an integral part of the effectiveness/vulnerability measurements. The strategy determination is a form of feedback control policy based upon a discretized set of information thresholds in the relative coordinate space as would be available to an evading aircraft pilot. The optimization criteria of an evading aircraft is that of maximizing the survival probability for all relative coordinates. The representative model chosen for illustration is evasion from a close range air-to-air IR guided missile. The effectiveness/vulnerability results as well as sample trajectories illustrating the optimal evasive maneuvering are given for several studies conducted with the model. One study illustrates how optimal maneuvering can degrade IR missile effectiveness by taking advantage of the close-range, narrow-field-of-view "saturation" properties of the seeker sensor. Other studies concern the effects of optimal maneuvering on off-boresight launch effectiveness and on effectiveness sensitivity with warhead lethality variations.

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

ABSTRACT

This report presents a new methodology with which to quantify missile effectiveness and aircraft vulnerability. The approach is a blend of applications of optimal control theory, stochastic learning theory, and simulation. This methodology permits an evaluation of aircraft evasive maneuvering and countermeasures deployment strategy as an integral part of the effectiveness/vulnerability measurements. The strategy determination is a form of feedback control policy based upon a discretized set of information thresholds in the relative coordinate space as would be available to an evading aircraft pilot. The optimization criteria of an evading aircraft is that of maximizing the survival probability for all relative coordinates. The representative model chosen for illustration is evasion from a close range air-to-air IR guided missile. The effectiveness/vulnerability results as well as sample trajectories illustrating the optimal evasive maneuvering are given for several studies conducted with the model. One study illustrates how optimal maneuvering can degrade IR missile effectiveness by taking advantage of the close-range, narrow-field-of-view "saturation" properties of the seeker sensor. Other studies concern the effects of optimal maneuvering on off-boresight launch effectiveness and on effectiveness sensitivity with warhead lethality variations.

TABLE OF CONTENTS

Preceding page blank

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF SYMBOLS

a	Aircraft longitudinal acceleration
C_{D_0}	Zero-lift drag coefficient
C_{D_I}	Induced drag coefficient
g_{LIM}	Maneuvering g limit due to structural constraint
K_{ap}	Autopilot closed loop gain
K_g	Guidance gain
m	Missile mass
n_{yc}	Yaw acceleration command
P_K	Kill probability
p_{ij}	Decision table element - probability of selecting the j^{th} control in the i^{th} observed state
R	Missile-to-aircraft range
R_A	Aircraft turn radius
R_{min}	Minimum relative range
R_S	Seeker saturation range
r	Missile/autopilot yaw rate
r_1	Line-of-sight turning rate
r_s	Seeker line-of-sight turning rate
$r_{s_{LIM}}$	Seeker rate limit
S	Aerodynamic reference area
T	Thrust
t_B	Engine burn time
t_{DL}	Control activation delay time

Preceding page blank

t_G	Total guidance time
u_i	Elemental maneuver controls
v_i	Elemental countermeasure controls
V_A	Aircraft velocity
V_M	Missile velocity
V_{SS}	Aircraft steady-state maneuver velocity
V_x, V_y	Relative velocity components
x_i	Relative states determined by aircraft observable decomposition
x_A, y_A	Inertial components of aircraft position
x_M, y_M	Inertial components of missile position
	Outcome description
$_c$	Track crossing angle
	Aircraft control parameter
	Missile inertial heading
	Off-boresight angle (gimbal angle)
$_{LIM}$	Seeker gimbal angle limit
( )	Learning algorithm reinforcement weights
	Atmospheric density
$_{ap}$	Autopilot time constant
$_s$	Seeker time constant
	Aircraft inertial heading
	Inertial line-of-sight angle
	Missile angle-off relative to aircraft velocity vector

I. INTRODUCTION

Quantifying missile effectiveness and aircraft vulnerability by using air-to-air and surface-to-air simulation models is of considerable value in 1) developing more lethal missile systems and improving their operational deployment and 2) determining operational tactics to enable an evading aircraft to increase its survivability. However, the use of such simulation models is frequently criticized because:

1) The missile capability results (which are given by launch envelope data predicted by simulation models with limited maneuvering targets) are overly optimistic in view of real-world statistics

2) Few approaches exist that can determine an evading aircraft's best maneuvering and countermeasures deployment strategies (in terms of maximizing survivability) as a "closed-loop" feedback control over all relative coordinates

Our approach, described later in this introduction, overcomes these objections.

References 1 and 2 outline the methodology that has been adopted to date by many investigators concerned with missile effectiveness. This methodology is characterized by an extensive model that simulates in detail missile trajectory, warhead detonation, and associated aircraft structure damage to determine aircraft survivability. The evading aircraft generally performs prescribed "open loop control" maneuvers such as maximum "g" turns or sinusoidal weaving maneuvers during the trajectory portion of the simulation. The missile effectiveness determination is then made by a statistical sampling over many possible launch conditions as in Ref. 1, or a selected set of conditions as in Ref. 2. The methodology in Ref. 3 is a departure from that of Refs. 1 and 2 in that aircraft evasive maneuvers that maximize the missile miss distance are computed by gradient methods for selected initial conditions. This approach moves in the direction of optimizing the aircraft maneuvering strategy, but has associated with it many mathematical and computational restrictions. An important restriction is that the payoff function must be a continuously differentiable function of the relative coordinates. This mathematical difficulty implies a computational problem in solving for the optimal feedback control for the aircraft over all relative coordinates. Thus, only an open loop control maneuver can be computed for the aircraft for each launch condition.

The approach taken in this report provides a new methodology with which to consider the effectiveness/vulnerability quantification problem. The approach is basically a blend of applications of optimal control theory and stochastic learning theory. The first application of this methodology to one-on-one dogfight game models with gun weapons was reported in Ref. 4. In this setting the best aircraft maneuvering strategies (as a discretized feedback control which maximizes kill probability) for each combatant were computed by a learning algorithm. The domains of effectiveness of each system were then quantified by simulation. That same approach can easily be extended to the missile combat model considered here, with the two-sided game model aspect being replaced by a one-sided control problem for the evading aircraft. This methodology permits model realism not generally considered in other optimization approaches: developing maneuver and countermeasure strategies based upon the pilot's available "information thresholds" in the relative coordinate space and using survival probability in place of miss distance criteria as an optimization criteria. Thus the methods shown here provide one means of resolving criticism No. 2 and offer at the same time a means of accounting for the real world versus computational model differences of criticism No. 1 by having the optimal evasive strategy as an integral part of the effectiveness determination.

The representative evasion model chosen for study in this report is the close-range air-to-air IR guided missile in its launch and postlaunch flight phases employed against aircraft with performance attributes of current day fighters. The problem has been arbitrarily limited to two dimensional flight in the horizontal plane with the evading aircraft employing only its maneuvering control capability to increase its survival probability. The choice of model was quite arbitrary as the methodology can easily accommodate radar guided missiles, countermeasures strategy analysis, and three dimensional flight. In the last case, computer running times can be expected to increase fourfold over the two dimensional case for corresponding levels of model detail. The surface-to-air missile evasion problem would be as easily resolved by the methodology as the air-to-air case.

Four sets of results involving the IR close-range missile model are obtained to illustrate the effect of aircraft employing optimal maneuvering versus nonmaneuvering control on missile effectiveness and aircraft vulnerability measures. The first result set essentially provides an effectiveness/vulnerability data baseline for a standardized missile configuration. The second result set deals with the saturation of the missile seeker field of view for very close target ranges. In this case the seeker field of view is saturated and guidance neutralized at relative target ranges determined by the track crossing angle between the missile/aircraft trajectories. In the first result set the saturation range is a constant independent of track crossing angle. The third set shows effectiveness/vulnerability sensitivity to target off-boresight error at launch. The last result set shows the sensitivity to improvements in warhead lethality. Sample trajectories depicting the optimal maneuvering are given along with the effectiveness/ vulnerability results for each of the four cases.

The authors wish to acknowledge the computational assistance rendered by Mr. Arthur Kaercher of the Grumman Data Systems Corporation in the course of obtaining the numerical results.

II. AIR-TO-AIR MISSILE MODEL

This section presents the mathematical models for the evading aircraft and attacking missile employed in the maneuvering tactics determination and system capability analyses. For the models described, we have limited the analyses to combat in the horizontal plane to simplify presentation. The same modeling technique without alteration in solution methodology can be straightforwardly applied to three dimensional combat problems without reservation.

AIRCRAFT MANEUVERING STRATEGY DEVELOPMENT

The maneuvering strategy construction relies on the specification of which relative coordinates (positions, rates) and what threshold levels for these coordinates will approximate the aircraft pilot's observable information during the engagement. The motivation for the construction and interpretation of the aircraft observable data in terms of relative coordinate decompositions has been described in Section 4 of Ref. 1. The decompositions lead to a finite number of relative coordinate contingencies or regions for consideration in the strategy development The horizontal plane model considered here assumes the aircraft can observe range (R) and angle-off (ω) information with the thresholds shown in the decomposition of Fig. 2-1.

When crossing a threshold for any of the regions making up the decomposition, the aircraft will be permitted to select an elemental control as outlined in the hypothetical case below. In the vectorgram of Fig. 2-2 the elemental controls u_1 and u_5 could correspond to maximum performance turns that decelerate the aircraft to a low steady-state velocity; u_2 and u_4 are maximum performance turns at a high steady-state velocity; and u_3 is a

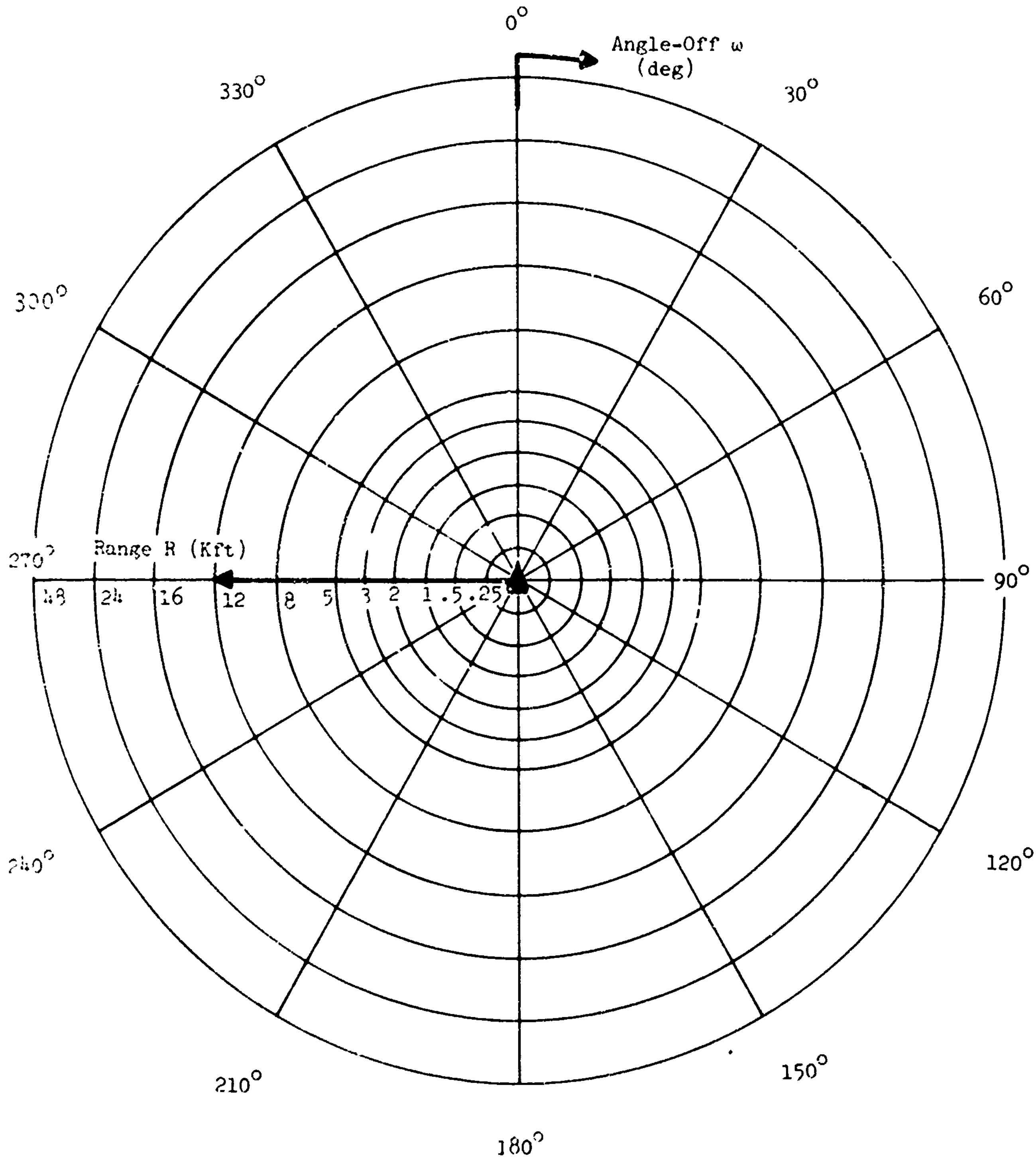


Fig. 2-1 Aircraft Observable State, R, ω

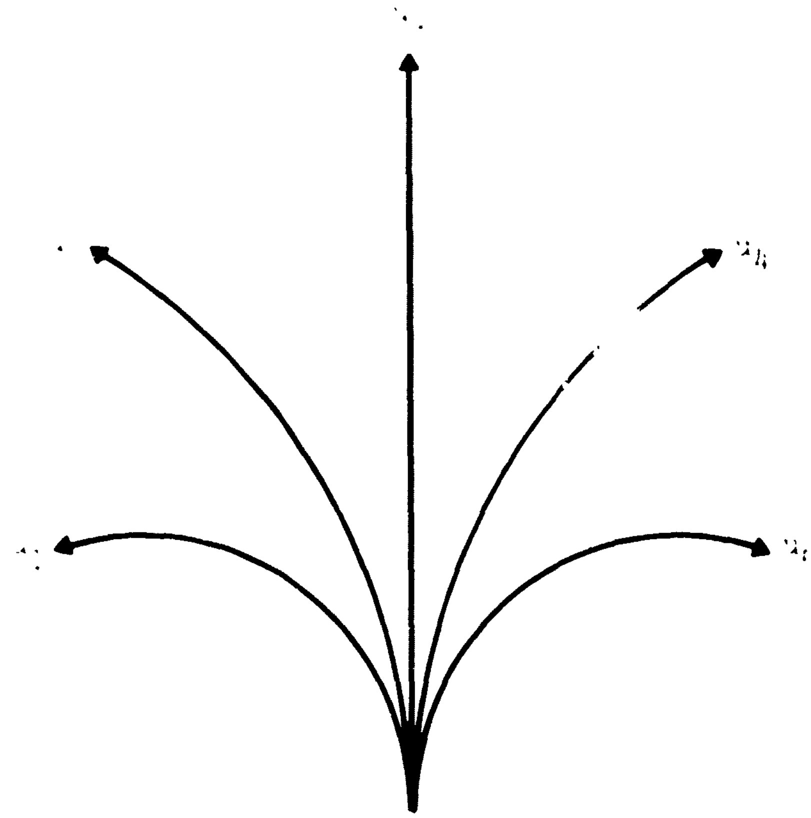


Fig. - Elemental Maneuver Choices

straight ahead dash policy. In the case of countermeasures deployment, the elemental control choices might be:

v_1 - jettison flare decoy

v_2 - illuminate arc-lamp

v_3 - jettison and ignite fuel charge

v_4 - no countermeasures deployment

In this illustration the aircraft would select a pair of controls (u, v) within each region. The specification of a (u, v) pair for all regions as shown in Fig. 2-1 would constitute a maneuvering/countermeasures strategy in our terminology.

DYNAMICAL MODEL

The dynamical equations for a representative air-to-air infrared guided missile in its postlaunch maneuvering phase is presented in this section. In addition, the evading aircraft dynamical equations are also given. The missile systems sensor characteristics, guidance constraints, aerodynamic constraints, and warhead properties as incorporated in the model are explained.

The coordinate nomenclature employed with the trajectory dynamics description is given in Fig. 2-3. The symbol nomenclature is presented in the front of this report.

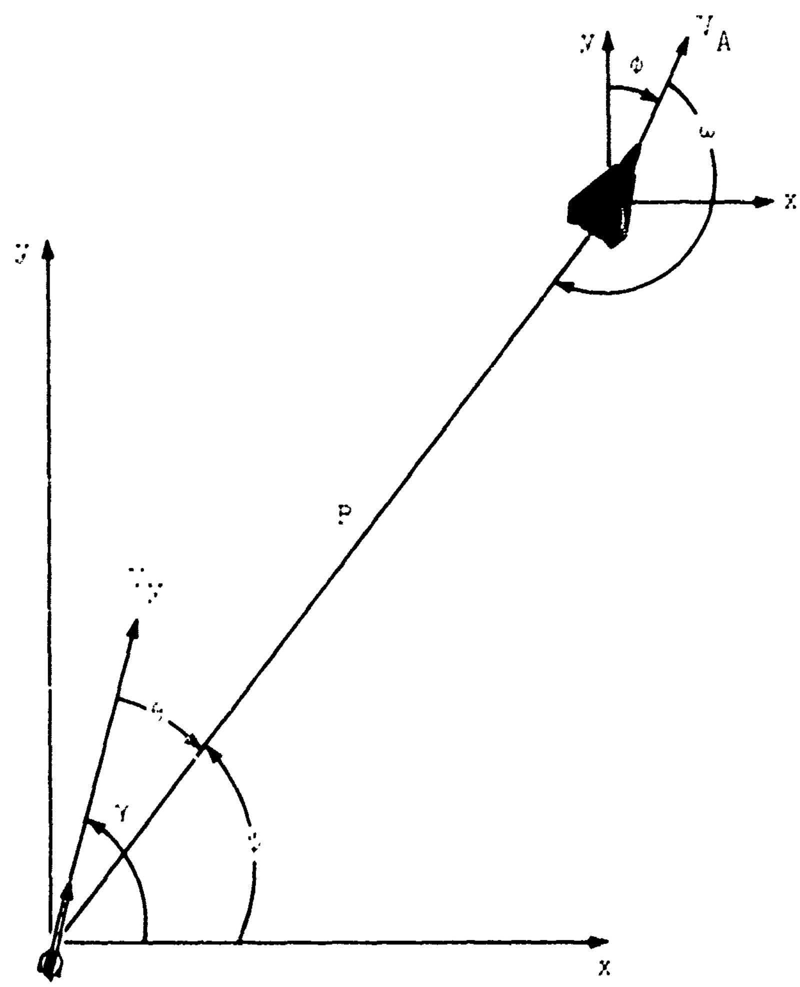


Fig. 2-3 Coordinate Nomenclature

Missile Equations of Motion in Inertial Coordinates

$$\dot{x}_M = V_m \cos \gamma$$

$$\dot{y}_M = V_M \sin \gamma$$

$$\dot{\gamma} = r$$

$$\dot{V}_M = - \frac{\rho V_M^2}{2m} S C_{D_O} - \frac{2m}{\rho S V_M^2 C_{D_I}} (n_{yc})^2 + \frac{T}{m}$$

Aircraft Equations of Motion in Inertial Coordinates

$$\dot{x}_A = V_A \sin \psi$$

$$\dot{y}_A = V_A \cos \psi$$

$$\dot{\psi} = \frac{V_A}{R_A} \varepsilon$$

$$\dot{V}_A = a$$

The values for the control variable ε and the steady-state velocity V_{SS} associated with five representative elemental maneuver choices are as follows:

Maneuver	u_1 Left Turn Deceleration to Low V	u_2 Left Turn High Sustainable V	u_3 Dash	u_4 Right Turn High Sustainable V	u_5 Right Turn Deceleration to Low V
Control ε	-1	-1	0	+1	+1
V_{SS}	V_{T_1}	V_{T_2}	V_D	V_{T_2}	V_{T_1}
R_A	R_{T_1}	R_{T_2}	—	R_{T_2}	R_{T_1}

The longitudinal acceleration/deceleration parameter, a, is determined by the following scheme:

1) Determine V_{SS} according to the selected maneuver u_i from the above table.

2) If

$$V_A > V_{SS} \qquad a = a^-$$

$$V_A < V_{SS} \qquad a = a^+$$

$$V_A = V_{SS} \qquad a = 0$$

The dynamical capability of the aircraft can be specified then by the set of parameters $(V_{T_1}, V_{T_2}, V_D, R_{T_1}, R_{T_2}, a^+, a^-)$, which are given for a representative aircraft in Table 4-1. The aircraft trajectory dynamics also requires the quantities R and ω for the strategy development. These quantities are made available by the following computations:

$$R = \left[(x_A - x_M)^2 + (y_A - y_M)^2\right]^{\frac{1}{2}}$$

$$\omega = \frac{3\pi}{2} - \theta - \psi$$

where

$$\psi = \tan^{-1} \frac{(y_A - y_M)}{(x_A - x_M)}$$

Missile Guidance Considerations

The equations corresponding to the line of sight geometry as employed in the missile guidance are as follows:

- Relative velocity components

$$V_x = V_A \sin \xi - V_M \cos \psi$$

$$V_y = V_A \cos \xi - V_M \sin \psi$$

- Line of sight yaw rate

$$r_1 = \frac{(V_x \sin \vartheta - V_y \cos \vartheta)}{R}$$

with R and ϑ as computed on page 10.

The equations corresponding to the seeker and autopilot response and associated constraints are:

- Seeker line of sight rate response

$$\dot{r}_s = \frac{(r_1 - r_s)}{\tau_s}$$

with the seeker rate limited by $|r_s| \leq r_{s_{LIM}}$

- Missile/autopilot yaw rate response

$$\dot{r} = \frac{1}{\tau_{ap}} \left(\frac{K_{ap} n_{yc}}{V_M} - r \right)$$

where $n_{y_c} = K_g r_s V_M$ is the commanded acceleration.

The commanded acceleration is restricted in magnitude to correspond to a maximum allowable maneuvering g limit required by structural considerations. In this case the constraint $n_{yc} \leq g_{LIM}$ is imposed.

Other guidance constraints are considered in the model:

- A control activation delay at launch of t_{DL} seconds. In this case $n_{yc} = 0$ when $0 \leq t \leq t_{DL}$; n_{yc} as above for $t > t_{DL}$.

- A maximum guidance time of t_G seconds after which $n_{yc} = 0$
- A gimbal angle limit corresponding to seeker line of sight and boresight axis limitations. In this case if $|\theta| > \theta_{LIM}$, then the commanded acceleration $n_{yc} = 0$ corresponds to centering the controls. The seeker is modeled to require the correct line of sight when excursions lead back to within the allowable angle range. Two limits are employed: θ_{LIM_L} a lower limit angle value at launch, and θ_{LIM_F} a higher value of flight.

The thrust (T) and burn rate ($\dot{m}$) are specified as functions of time in the model, and data for the representative problem considered are given in Section IV. Along with this the aerodynamic drag coefficients C_{D_O} and C_{D_I} are incorporated as functions of Mach number and the air density computed from an exponential atmosphere model. These aerodynamic data for a representative missile configuration operated at a specific altitude are also given in Section IV.

MISSILE SEEKER PROPERTIES

It is important to note that the above model developed for simulation of the seeker response has made use of the assumption that perfect geometric line of sight information (with a time constant of τ_S) was made available to the autopilot whenever the target was in the gimbal angle range of the seeker head. Line of sight rate errors due to detector signal/noise properties at various ranges, atmospheric properties, multiple sources, countermeasures, etc. can easily be incorporated in the model in a straight forward manner without any alteration of the basic solution methodology. An example showing how a specific type of line of sight rate information error can be modeled is treated in this report. Briefly, the error modeled deals with the seeker detectors field of view being "filled" by the nonzero size source at very close target ranges in comparison to the generally assumed point source property. This blooming error is dependent upon the target aircraft track relative to the missile boresight axis as well as relative range. A more detailed discussion of this error model is given in Section IV.

MISSILE WARHEAD DETONATION AND KILL DETERMINATION

The problem of terminating the missile trajectory with detonation of the warhead and subsequent damage assessment of the target aircraft is tremendously complex and is generally analyzed separately from the manuevering problem. These analyses seek the determination of kill† probability given relative flight conditions sufficient to activate the fusing and detonation sequence. This probability is empirically derived by detailed simulation of the fusing and detonation procedures and study of the warhead blast and/or fragment interaction with all known vulnerable areas of the specific target aircraft. Moreover, this assessment is made for all the various dynamical aspects, range, azimuth angle, elevation angle, velocity magnitude, and orientation at detonation. As this report is concerned with aircraft evasive tactic methodology, the kill determination phase is much simplified in scope, but sufficiently realistic to be representative of the lethality data typically associated with small close-range infrared-missile warheads detonated near current fighter aircraft.

---

†By "kill" one assumes at least to disable the aircraft so that its primary mission capability is eliminated, but not necessarily to render catastrophic destruction.

The simplification employed relies upon computing the minimum relative range R_{min} (from the equation on page 10) between the centers of mass for any missile/aircraft trajectory pair. The minimum range value is used to determine a kill probability from a lethality plot, as shown in Fig. 2-4. This typical function represents "average" data over all missile/aircraft orientations and relative velocities at detonation. It is assumed that detonation occurs at precisely the minimum relative range point. The numerical P_K value is utilized to specify the kill/no-kill outcome distribution employed subsequently in the learning and statistics phases of the computational approach.

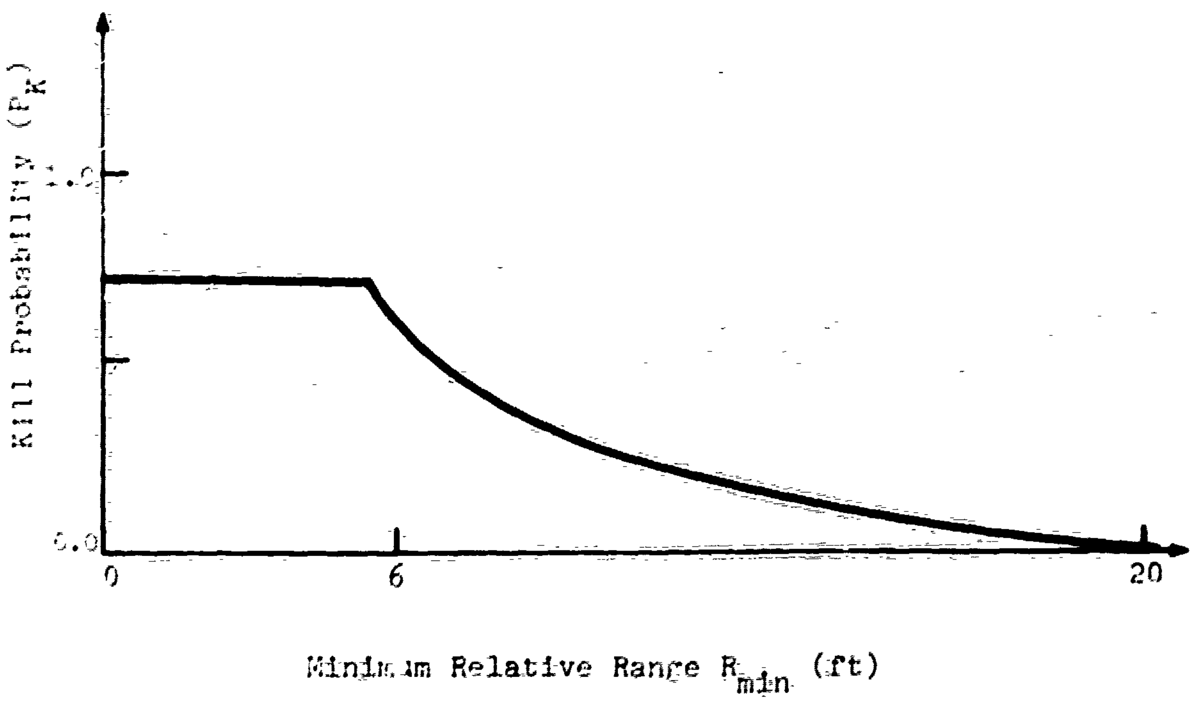


Fig. 2-4 Warhead Lethality

III. COMPUTATIONAL APPROACH

The computational method is presented in two phases: a "learning" phase, which is associated with the optimal strategy development for the aircraft, and a statistics phase associated with the determination of the aircraft vulnerability and missile effectiveness measures.

LEARNING PHASE

Strategy Initialization

A stochastic learning algorithm has been developed for strategy resolution in two-player, one-on-one duels in Ref. 1. That methodology is applied to the aircraft/missile problem in a similar manner. In this case one player (missile) employs a prespecified guidance policy while the second player (aircraft) has its strategy resolved by the algorithm in accordance with a survival goal. Section II outlines the aircraft maneuvering strategy definitions in terms of the observable relative coordinate data and elemental controls. The countermeasures strategy development, although not described in this report, would be treated in a manner similar to the maneuvering case. One initially begins with the aircraft strategy represented by the decision table:

	.	.	u_j	.	.
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
x_i	.	.	p_{ij}	.	.
.	.	.	.	.	.
.	.	.	.	.	.

where the x_i, $i = 1, \ldots, N$ represent the observable coordinate decomposition given in Fig. 2-1 and where u_j, $j = 1, \ldots, 5$ represent the elemental maneuver choices as shown in Fig. 2-2. Initially the table begins with $p_{ij} = 0.2$ for all $i = 1, \ldots, N$ and $j = 1, \ldots, 5$; that is, the elemental control choices are selected at random in an equally likely manner for each visited coordinate region x_i.

<u>Trajectory and Outcome Simulation</u>

With the initial strategy for the aircraft selected as given previously, the simulation of a trajectory, outcome determination, and strategy modification cycle of the learning phase are begun. The trajectory simulation begins with an initial condition, relative range R, angle-off , and boresight angle being chosen at random in a uniform manner over the allowable space of initial conditions. A control choice u_j is then selected for the aircraft in accordance with the assumed starting strategy for the specific region x_i given by the range (R) and angle-off (ω) thresholds. The missile and aircraft trajectories are then integrated until the next aircraft threshold is crossed and a new aircraft control decision selected. This process continues until one of the following events occurs, a minimum miss distance (R_{min}) is obtained, $R > 48{,}000$ ft, or $t > t_G$. The region/control sequence employed by the aircraft meanwhile is temporarily stored for reference.

The outcome of any trajectory sample is determined in the following manner: For a given R_{min} a kill or miss is obtained by consulting the distribution for P_K given as a function of R_{min}, as shown in Fig. 2-4. If $R > 48{,}000$ or $t > t_G$, the outcome is classified as a miss.

Strategy Modification

For each of the two outcomes (α) we employ the following weightings $\mu(\alpha)$ in the strategy modification portion of the learning phase.

Outcome α	$\mu(\alpha)$
Kill	$\frac{1}{2}$
Miss	2

These weightings are consistent with a survival rationale as a goal in the combat for the aircraft (see Chapter 4 of Ref. 1). If the aircraft is in region i using control u_k and outcome α occurs, then the strategy table is modified from p_{ij} to $\bar{p}_{ij}$ by first modifying p_{ij} to p_{ij}^* where

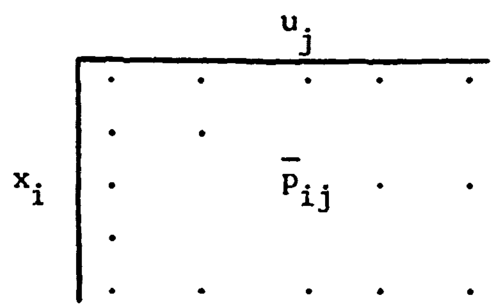
$$p_{ij}^* = \mu(\alpha) p_{ij} \qquad j = k$$

$$p_{ij}^* = p_{ij} \qquad j \neq k$$

The p_{ij}^* is then renormalized to form $\bar{p}_{ij}$

$$\bar{p}_{ij} = \frac{p_{ij}^*}{\sum_j p_{ij}^*}$$

This process is carried out over all x_i, u_j pairs temporarily stored for that trajectory resulting in an updated strategy table for the aircraft, as follows:



Approximately 100 trajectories with initial conditions selected at random within each region are simulated to obtain a converged decision table that represents the "optimized" survival strategy for the aircraft.

STATISTICS PHASE

The statistics phase of the computations now fixes the converged decision table and computes the aircraft vulnerability and missile effectiveness measures in Monte Carlo fashion. For the vulnerability data approximately 100 trajectory computations with initial conditions in each observable region were obtained. The quantitative measure of vulnerability is the kill probability of the missile as a function of all range (R) and angle-off (ω) thresholds relative to the aircraft as outlined in the observable set description of Fig. 2-1. The missile effectiveness data are obtained in a similar way, except here the initial conditions are chosen at random from an arbitrarily chosen set of launch regions that comprise the totality of all possible launch coordinates for the missile (see Fig. 3-1). The effectiveness data is given as a kill probability for target range (R) and target heading relative to missile boresight axis ([illegible])† for launches within the off-boresight requirement of the missile seeker head for each region

†Without any loss in generality we have assumed that [illegible] = $\pi/2$ at launch; otherwise the aircraft heading relative to missile boresight axis nomenclature on each effectiveness chart should be [illegible] + [illegible] − $\pi/2$.

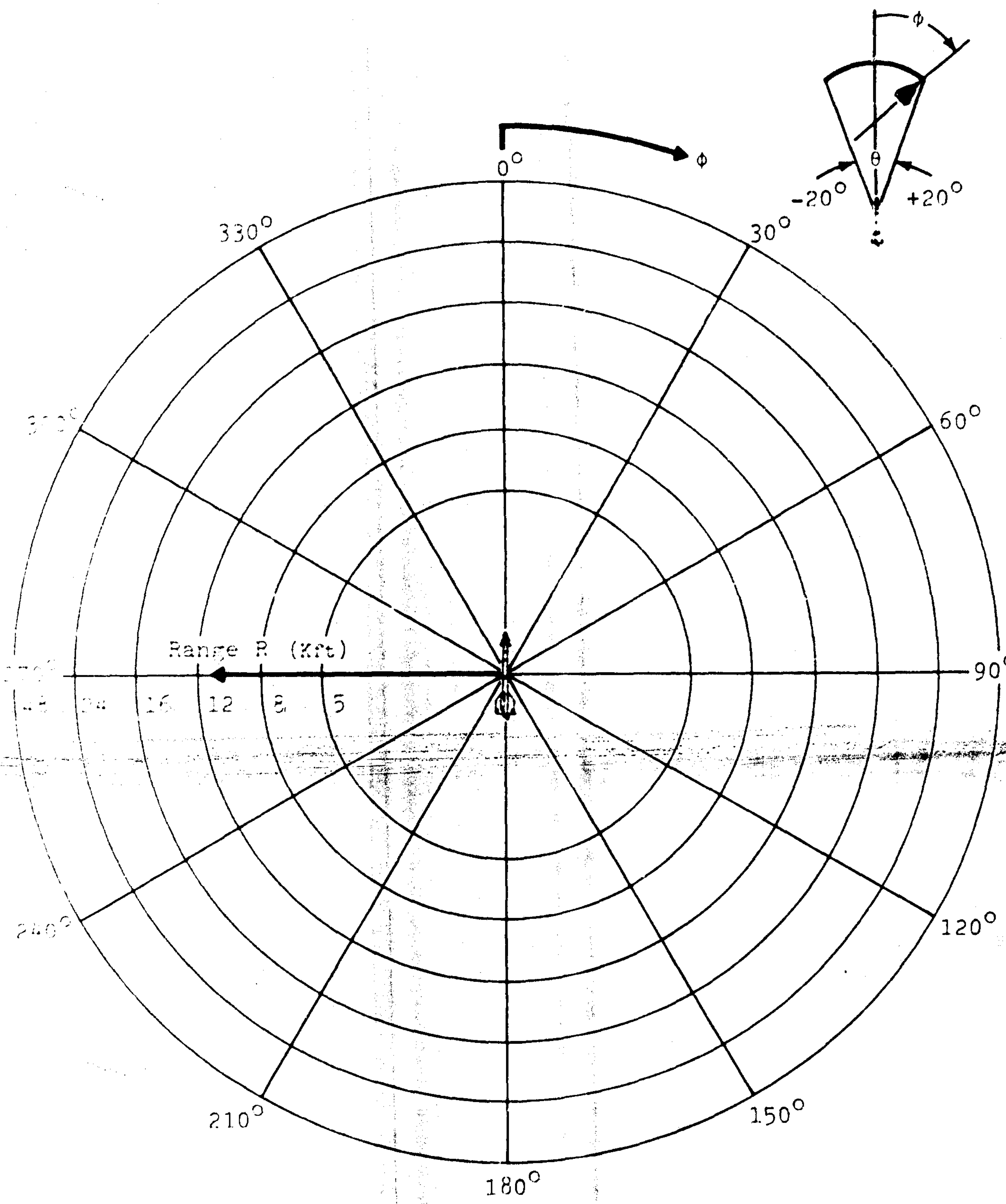


Fig. 3-1 Missile Launch Coordinates

of the decomposition in Fig. 3-1. Within each region the P_K value represents an average of all launches that satisfy the off-boresight requirements $LIM_L = \pm 20°$.

IV. COMPUTATIONAL RESULTS

SUMMARY

The main ingredient in this methodology development, when compared to other missile effectiveness analyses, is the evading aircraft's employment of a maneuvering and/or countermeasures feedback control policy that minimizes the kill probability of the missile over-all launch initial conditions. (Only the maneuvering case is treated in this report.) These optimized policies can in some cases (depending on the specific missile/target aircraft systems design data) seriously degrade missile system effectiveness when compared with system evaluations made with nonmaneuvering or open-loop maximum g turn policies for the target aircraft.

The specific missile and target aircraft data given in Table 4-1 and Fig. 4-1 and employed to obtain the results presented are representative of current-day IR missile systems deployed for close-in air

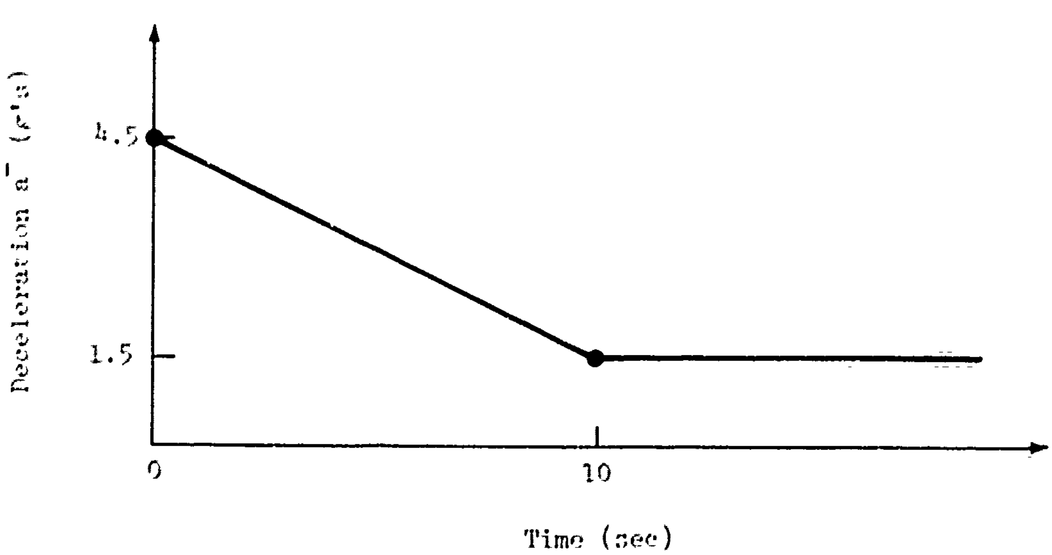


Fig. 4-1 Longitudinal Deceleration Parameter $\bar{a}$

TABLE 4-1 REPRESENTATIVE MISSILE AND AIRCRAFT DATA

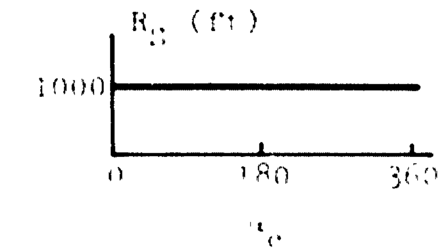
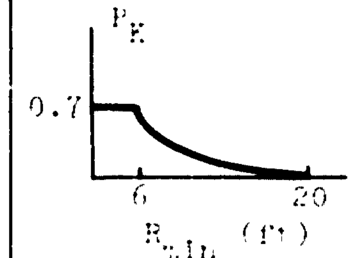
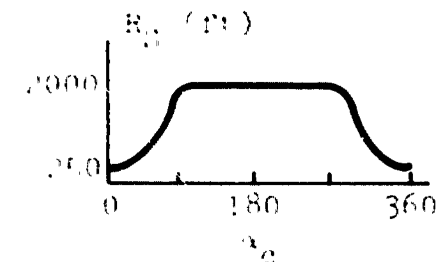
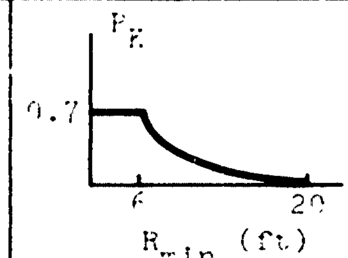
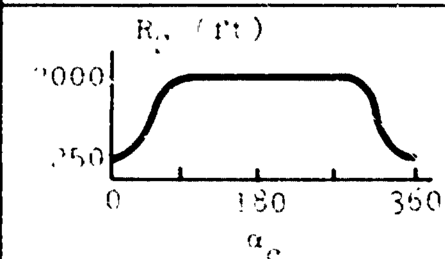
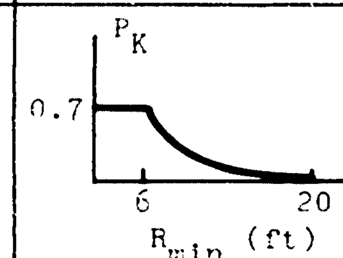
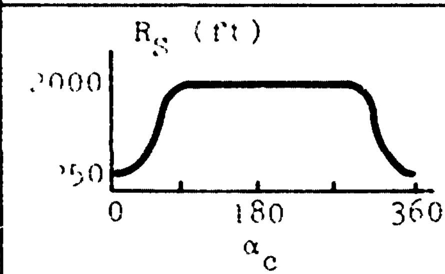
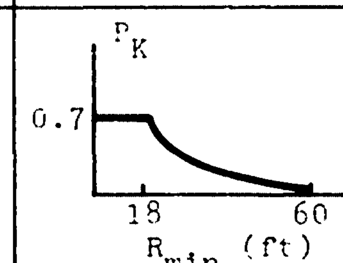
MISSILE DATA			
Aerodynamic Data			
Reference Area	S	(ft^2)	0.01644
Zero-Lift Drag Coefficient	C_{D_0}		0.8 for $M \leq 1$ 1.3 for $M \geq 1$
Induced Drag Coefficient	C_{D_I}		80.0 for $M < 1$ 80.0 - (13.6)(M-1) for $M > 1$
Engine Data			
Thrust (15,000 ft altitude)	T	(lb)	2820.0
Engine Burn Time	t_B	(sec)	5.2
Missile Mass at Launch	m_0	(slugs)	6.211
Engine Mass Flow Rate	$\dot{m}$	(slugs/sec)	-0.3584
Seeker Data			
Field of View		(deg)	2.5
Gimbal Limits during flight		(deg)	±40.0
at launch		(deg)	±20.0
Gimbal Rate Limit		(deg/sec)	20.0
Seeker Output Gain	K_g		4.0
Seeker Time Constant	τ_s	(1/sec)	0.0
Guidance and Control Data			
Launch Delay Time	t_{DL}	(sec)	2.0
Autopilot Gain	K_{ap}		1.0
Autopilot Time Constant	τ_{ap}	(1/sec)	0.1
Commanded Turning Acceleration Limit	$n_{yc}V_M$		30.0 g's
Guidance Time	t_G	(sec)	20.0
AIRCRAFT DATA			
Maneuver Data			
Dash Velocity	V_D	(fps)	900.0
Steady State Turn Velocity	V_{T_1}	(fps)	900.0
Deceleration Turn Limit Velocity	V_{T_2}	(fps)	500.0
Steady-State Turn Radius	R_{T_1}	(ft)	5000.0
Deceleration Turn Radius	R_{T_2}	(ft)	3555.0
Longitudinal Acceleration	a^+	(ft/sec^2)	+22.0
Longitudinal Deceleration	a^-	(ft/sec^2)	see Fig. 4-1

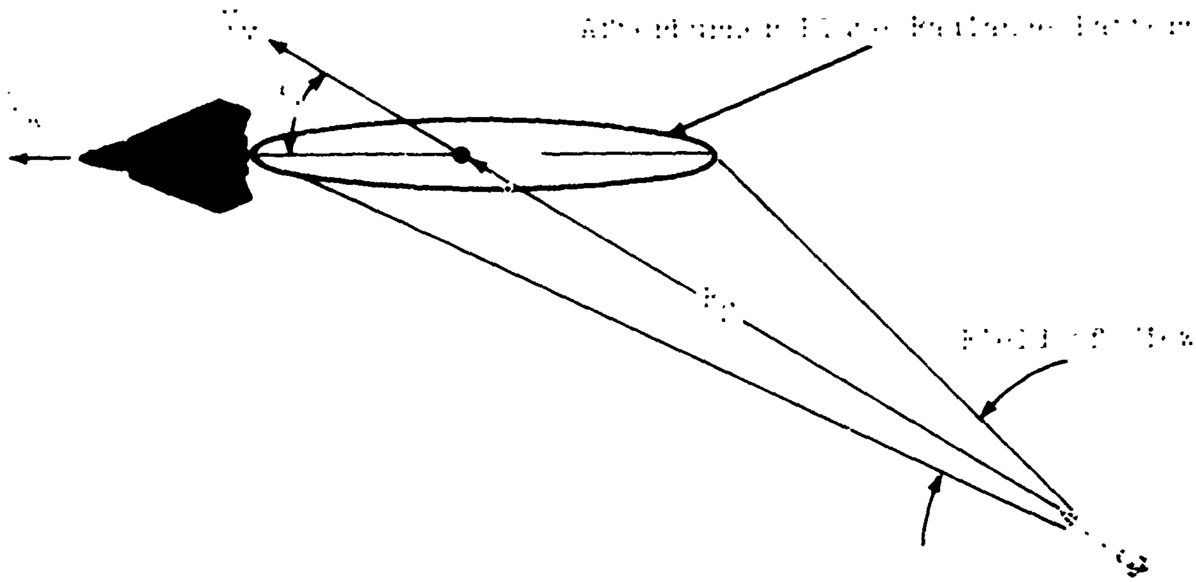
duels and current-day fighter aircraft maneuvering capability. The representative launch condition selected is at a 15,000 ft altitude with the target and launch aircraft flying at the initial speed of 900 ft/sec.

The results obtained in this report, which illustrate the levels of degradation achievable by optimal maneuvering control, fall essentially into four study categories as outlined in Table 4-2. Studies 1 and 2 focus on the blooming error property of narrow field of view sensors at close target ranges. Study 1 examines the case where the sensor field of view becomes saturated at a nominal relative range $R_s = 1000$ ft from the target independent of the missile/target aspect specified by the track crossing angle γ_c. In this case, the missile guidance command is neutralized $(n_{yc} = 0)$ at the $R_s = 1000$ ft point until detonation. The missile warhead lethality model as assumed for study 1 is given in Table 4-2. In this case, the maximum P_K value of 0.7 is maintained for a mininum miss distance R_{min} of between zero and 6 ft, and quadratically decreases to $P_K = 0$ at a distance of 20 ft. Study 2 considers the case where the saturation range R_s is dependent upon the track crossing angle γ_c. The functional dependence on γ_c for this case is shown in Table 4-2. This particular R_s versus γ_c relationship is derived in a geometric way from a simplified afterburner plume radiance pattern and sensor field of view limit consideration, as shown in Fig. 4-2. The $2\frac{1}{2}°$ field of view limit gives an $R_s =$ 250 ft for the tail aspect, increasing to 2000 ft for the beam aspect for a typical afterburner plume pattern. The 2000 ft value of R_s is maintained constant throughout the beam to head-on aspects for the sake of simplicity.†

†The methodology is not limited to these simplified saturation effect cases as presented in this section, and, in fact, if extensive model detail in terms of seeker characteristics is available it can be easily incorporated.

TABLE 4-2 MISSILE EFFECTIVENESS AND AIRCRAFT VULNERABILITY STUDIES

Study No.	Description	Results	Missile Seeker Saturation Model	Missile Warhead Lethality Model
1	Constant Saturation Range Seeker	Fig. 4-3 to 4-11		
2	Aspect Dependent Saturation Range Seeker	Fig. 4-12 to 4-17		
3	Off-boresight Launch Sensitivity	Fig. 4-18 to 4-23		
4	Warhead Lethality Sensitivity	Fig. 4-24		



Study 3 deals with quantifying the off-boresight launch angle impact on aircraft vulnerability. Two special cases are considered in this study: the on-boresight case and the 15-20 off-boresight case representative of launches at the edge of the boresight launch envelope. In this study, the saturation property of the seeker and warhead lethality model are identical to those employed in study 2. Study 4 deals with quantifying the change in kill effectiveness with increased warhead lethality. In this study, the saturation property of the seeker is maintained as employed in studies 2 and 3.

The computational results for studies 1 through 4 are presented with the following format: In each of the studies the missile effectiveness results are presented first, the aircraft vulnerability measures second, followed by sample evasion trajectories. The effectiveness and vulnerability results are given for both the non-maneuver and "optimal" learned maneuver cases.

STUDY NO. 1 – CONSTANT SATURATION RANGE SEEKER

The missile effectiveness results for study 1 are presented in Fig. 4-3. Three levels of P_K have been arbitrarily selected as shown to simplify the results presentation.* The actual P_K values, however, are available in the computational results for more detailed appraisals. The diagram at left shows the kill effectiveness in the launch coordinate space nomenclature of Fig. 3-1, when the aircraft does not employ evasive maneuvering but is in straightline flight. The diagram at the right shows the degradation in effectiveness made possible with optimal learned maneuvers. Note

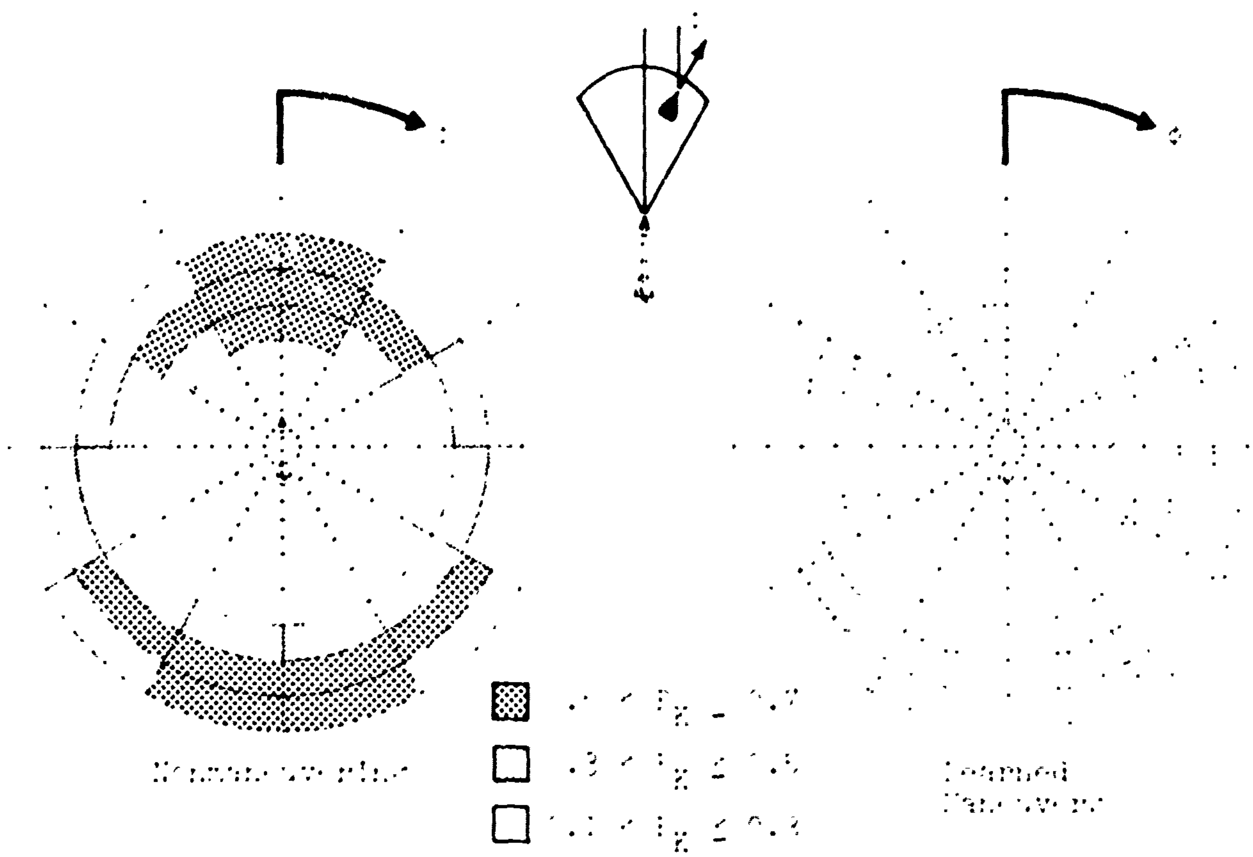


Fig. 4-3 Missile Effectiveness Results, Constant Saturation Range = 1000 Feet (Nonmaneuvering vs. Optimal)

---

*All regions shown in white, in all missile effectiveness, and aircraft vulnerability results, correspond to levels of $P_K \leq 0.1$.

that no missile launches were considered at ranges $R < 5000$ ft in any of the results reported here. This was an arbitrarily imposed criterion in light of the missile guidance delay parameter $t_{DL} = 2$ sec and was implemented only for the purpose of reducing the computer running time by limiting the simulation to fewer initial conditions. One can see the degree of degradation in kill effectiveness in the tail aspect ($\phi = \pm 60°$) and head-on aspect ($\phi = 120$ to $240°$) brought about by the learned maneuvers. Figure 4-4 shows the missile effectiveness comparison between an aircraft employing

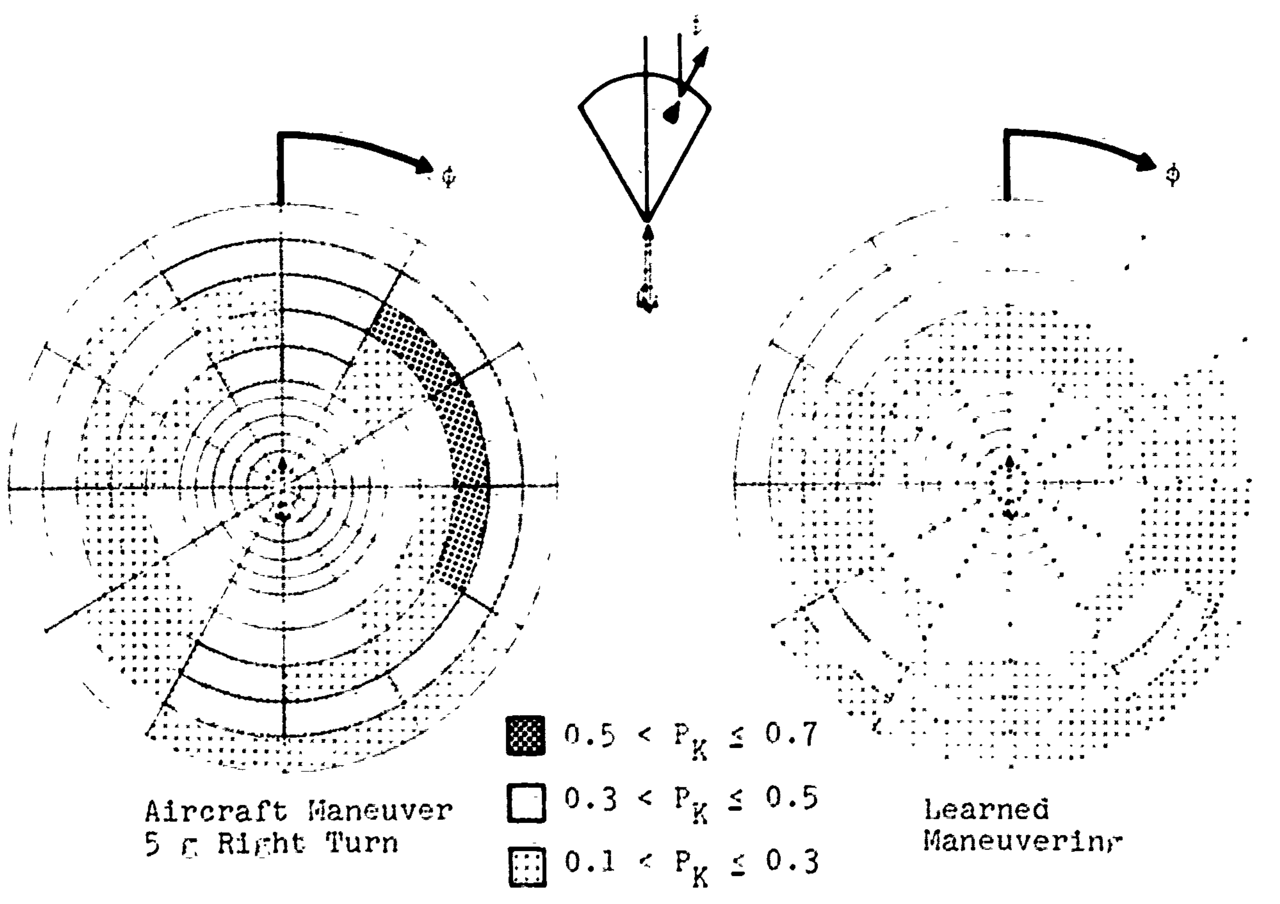


Fig. 4-4 Missile Effectiveness Results, Constant Saturation Range = 1000 Feet (5g Turn vs. Optimal)

a 5 g right turn and one employing the learned maneuvers. The 5 g right turn case represents the kind of "open loop" maneuvering usually consider-d in missile effectiveness analyses (see Refs. 1 and 2). For relative headings in the right hemisphere, $\phi = 0°$ to $180°$, the learned maneuvers markedly reduce the $P_K \leq 0.3$ level for all but one region in contrast to the 5 g turn. In the left hemisphere, the reduction is less marked. The head-on and tail aspect cases where $P_K \geq 0.3$ for the 5 g turn case have been reduced to levels < 0.3 for the maneuvering case. On the other hand, some regions now appear in the ≥ 0.1 range for the learned maneuvers as contrasted with the ≤ 0.1 values in the 5 g turn case. This particular situation is brought on by the discrete levels chosen for plotting; e.g., the 5 g turn case has regions for which the P_K values are between 0.09 and 0.1, while the corresponding regions in the maneuvering case have values between 0.10 and 0.11. Moreover, the sensitivity of the learning algorithm is such that it could not differentiate between maneuver sequences that produced P_K levels having those small differences. At the risk of these small data abnormalities in some of the results, the P_K levels were plotted as computed without adjustment for solution variability.

The aircraft vulnerability results are presented in Fig. 4-5 for the nonmaneuvering versus learned maneuvering cases. In these cases, the P_K data are given with respect to the aircraft observable state description in Fig. 2-1. One can see the marked P_K degradation possible in the head-on and tail apsects by employing the learned maneuvers as contrasted with the straight ahead flight policy.

We now turn to the illustrations of strategy and trajectory sample results. The results were generated from hard copies of

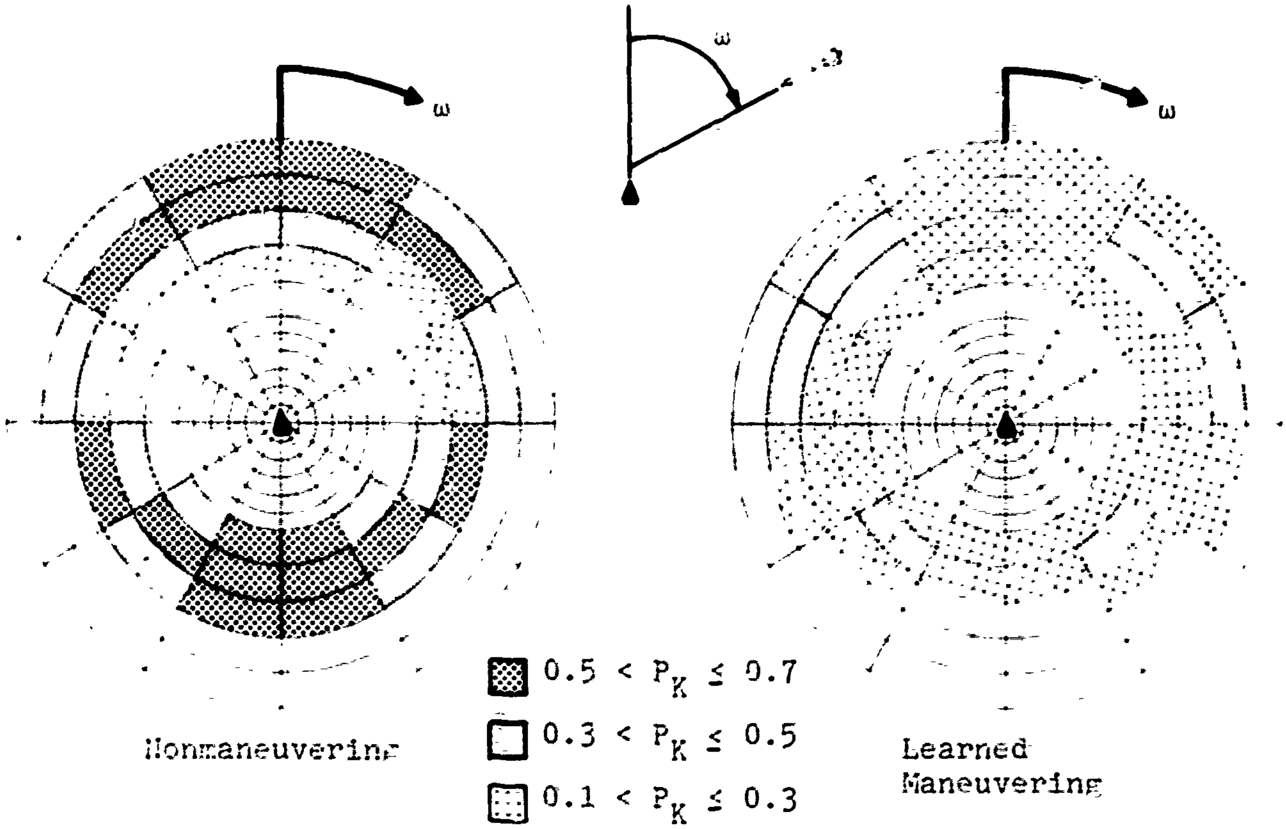


Fig. 4-5 Aircraft Vulnerability Results, Constant Saturation Range = 1000 Feet

solutions made available by a computer-driven CRT display. Two forms of trajectory plot are illustrated for each trajectory sample. The first shows motion in coordinates relative to the evading aircraft and is useful in demonstrating the learned aircraft maneuvering strategy. The second is the normally drawn plot in absolute coordinates showing the motion of both vehicles during the engagement. The optimal learned strategy data, though available, is not presented for each result in its entirety (viz, with regard all regions in Fig. 2-1) because the general characteristics of the derived strategies are more easily inferred from selected sample trajectories. Table 4-3 supplies an outline for the sample results

TABLE 4-3 SAMPLE RESULTS – EVASIVE STRATEGIES AND TRAJECTORIES

Study No.	Study Description	Sample Result No.	Figure No.	Aircraft Maneuvering Comparisons	Launch Initial Conditions* Range R (ft)	Angle-Off (deg)	Boresight Angle (deg)	P_k Level Comparison	Minimum Miss Distance (ft)
1	Constant Seeker Saturation Range	1A	4-6 and 4-7	Nonmaneuvering Versus Learned Maneuvering	11900	200	0	Versus	4.0 Versus 22.7
		1B	4-8 and 4-9	Nonmaneuvering Versus Learned Maneuvering	20000	10	0	Versus	2.3 Versus 24.9
		1C	4-10 and 4-11	5g Right Turn for Counterpart Initial Conditions	14000	255 Versus 105	0 Versus 0	Versus	47.1 Versus 6.7
2	Aspect Dependent Seeker Saturation Range	2A	4-14 and 4-15	Nonmaneuvering Versus Learned Maneuvering	15000	145	0	Versus	0.8 Versus 28.5
		2B	4-16 and 4-17	Nonmaneuvering Versus Learned Maneuvering	7500	110	10	Versus	11.4 Versus 2400
3	Off-Boresight Launch	3A	4-20 and 4-21	On Boresight	15000	- 40	0		7.5
		3B	4-22 and 4-23	Boresight Error Lag Versus Lead	15000	40 - 40	18 Versus 18	Versus	22.9 Versus 7.4
4	Warhead Lethality	None	...	...	...	...	...	...	...

*Aircraft Relative Coordinates

corresponding to studies 1 through 3. For study 1, the constant saturation range case, a typical "tail shot" example is given by result 1A in Figs. 4-6 and 4-7. Figure 4-6 shows the motion in coordinates relative to the aircraft and illustrates the weaving maneuver (control reversals at sequential range thresholds) developed by the learning algorithm to minimize the kill probability against the constant saturation range type missile seeker. For this specific launch initial condition the minimum miss distance comparison is 4 and 23 ft for the straight and learned strategy, respectively. Figure 4-7 shows the absolute coordinate trajectory comparison for the same initial condition. Result 1B, shown in Figs. 4-8 and 4-9, depicts the case "head-on" initial conditions for the nonmaneuvering and learned maneuvering comparisons. Figure 4-8 again shows the weaving maneuver developed by the learning technique in relative coordinates, and Fig. 4-9 shows the maneuvering comparison in absolute coordinates. Result 1C shows the effect of a steady 5 g right turn for two counterpart initial conditions representative of a "beam" launch aspect for the constant saturation range seeker. The dashed trajectory in Figs. 4-10 and 4-11 shows the turn into the missile approach heading, and the solid trajectory shows the turn away for the counterpart initial condition. These typify the kinds of "open loop" maneuvering control given the evading aircraft in most effectiveness evaluations (see Ref. 1 and 2). One can see from the difference in the miss distance results of 6.7 and 47 ft for the counterpart initial conditions that a single open loop control policy (whether a maximum g turn or straight flight) may not furnish the evading aircraft with its best defensive policy when compared to closed loop control over all relative coordinates. The effectiveness results associated with the open loop cases tend to overestimate missile capability.

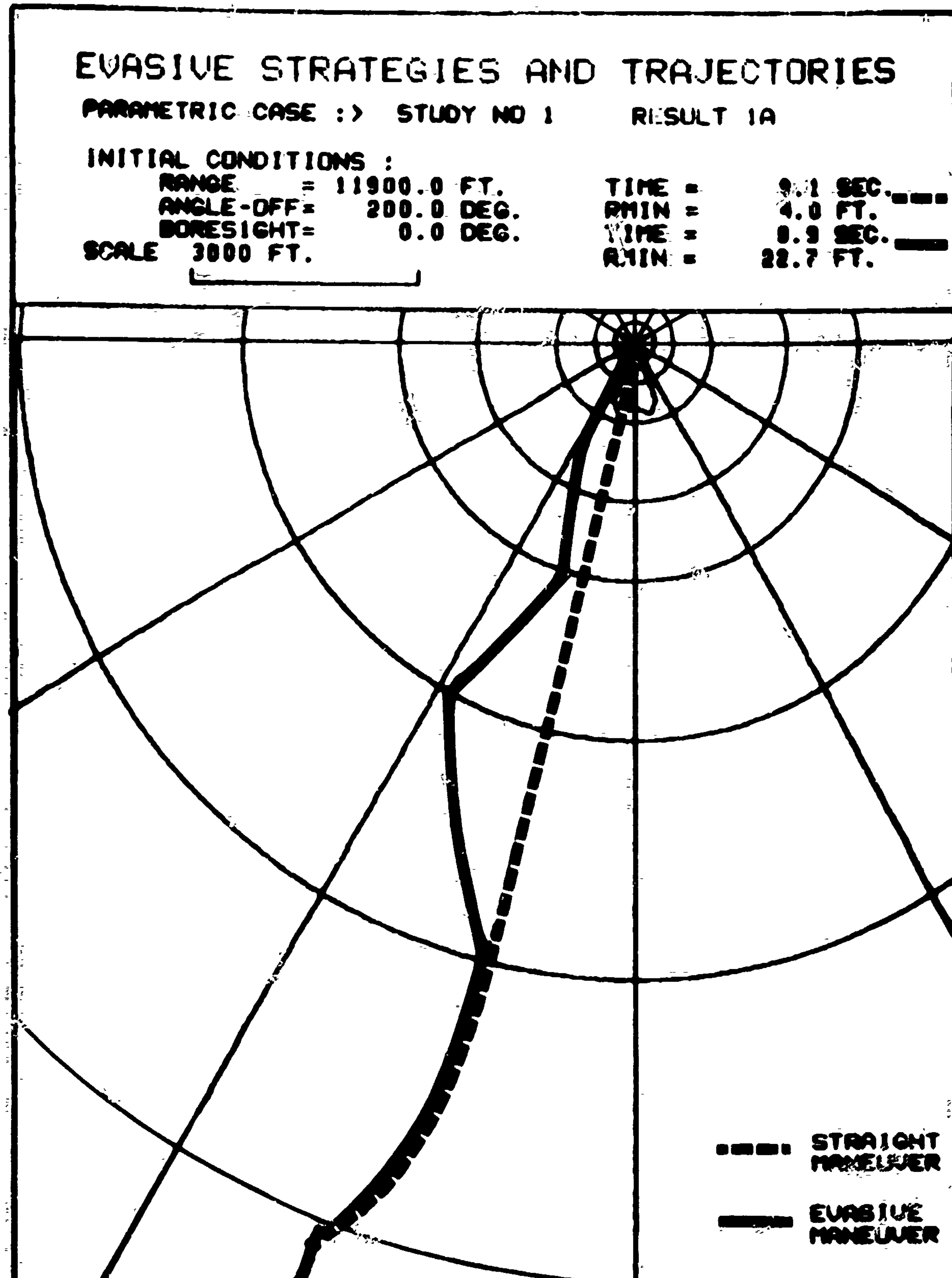


Fig. 4-6 Evasive Strategies and Trajectories, Study No. 1, Result 1A (Relative)

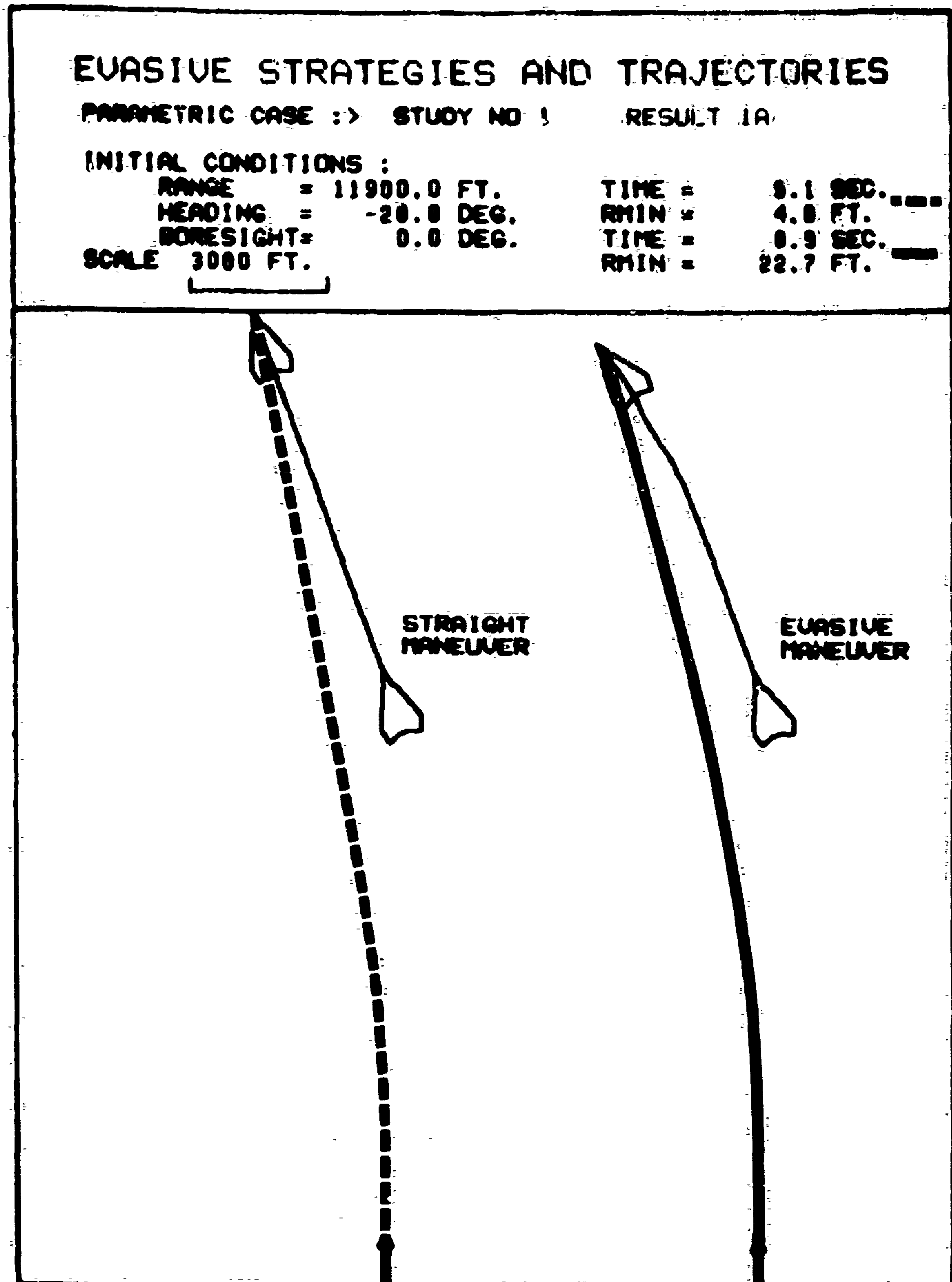


Fig. 4-7 Evasive Strategies and Trajectories, Study No. 1, Result 1A (Absolute)

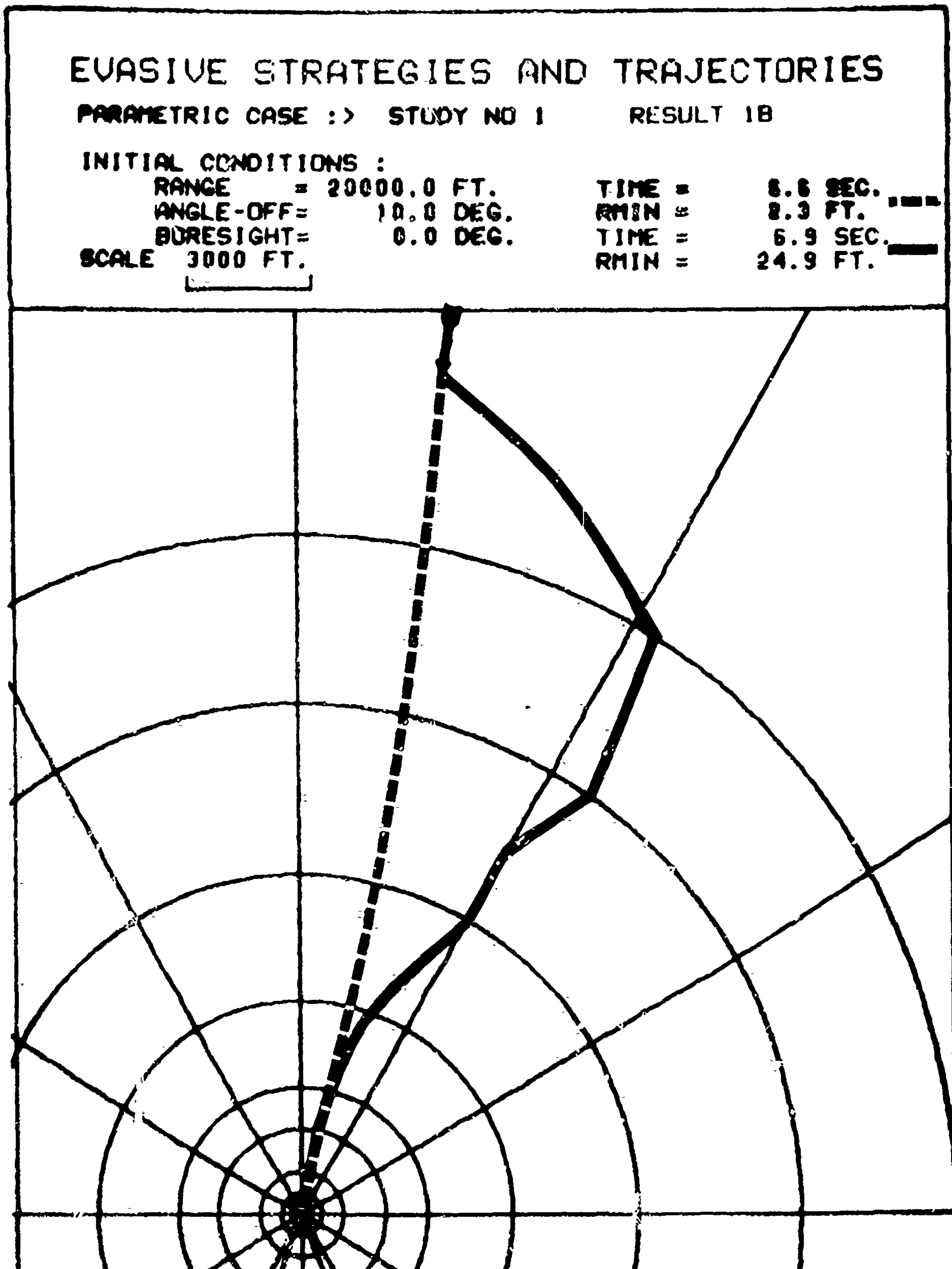


Fig. 4-8 Evasive Strategies and Trajectories, Study No. 1, Result 1B (Relative)

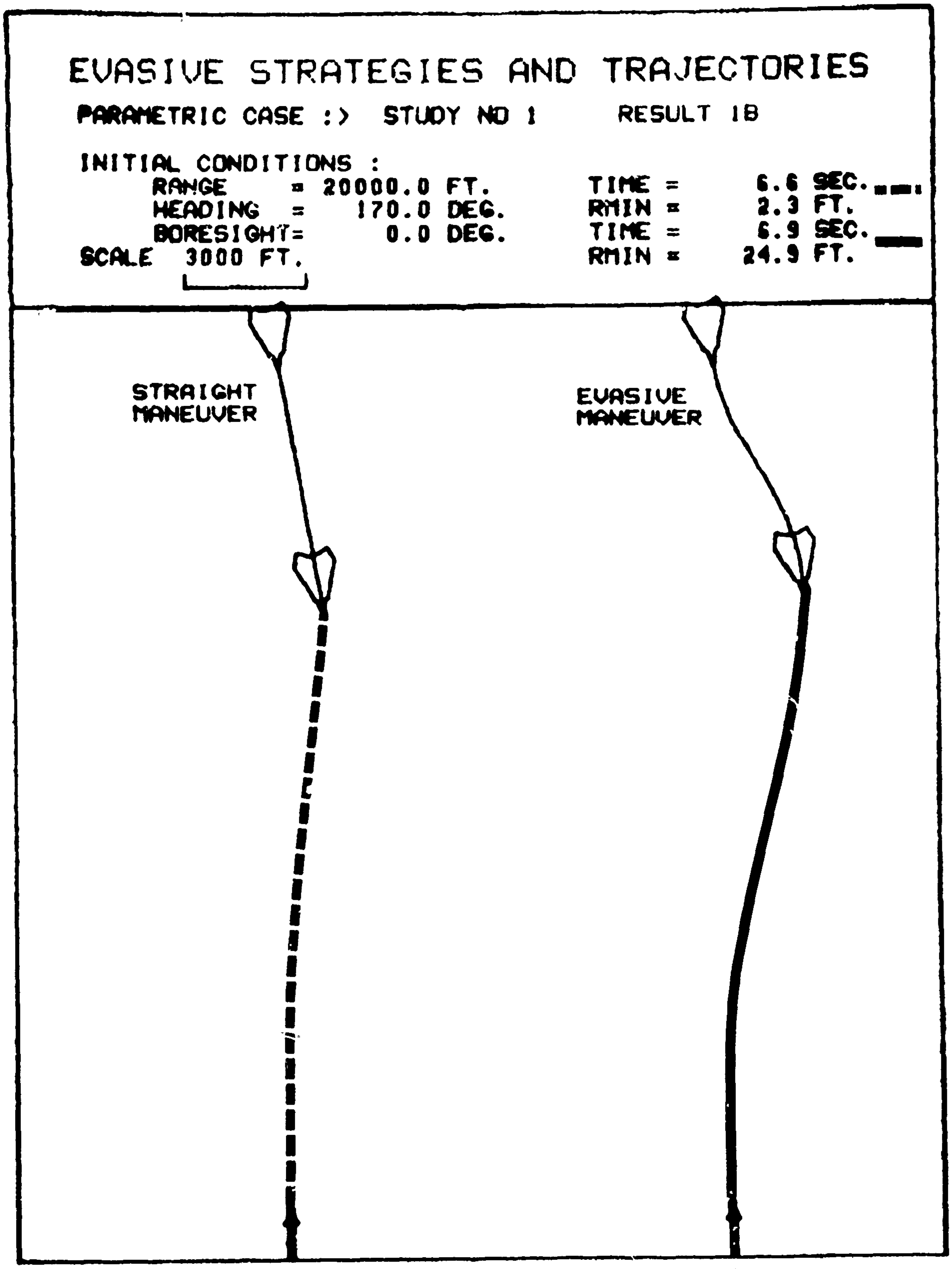


Fig. 4-9 Evasive Strategies and Trajectories, Study No. 1, Result 1B (Absolute)

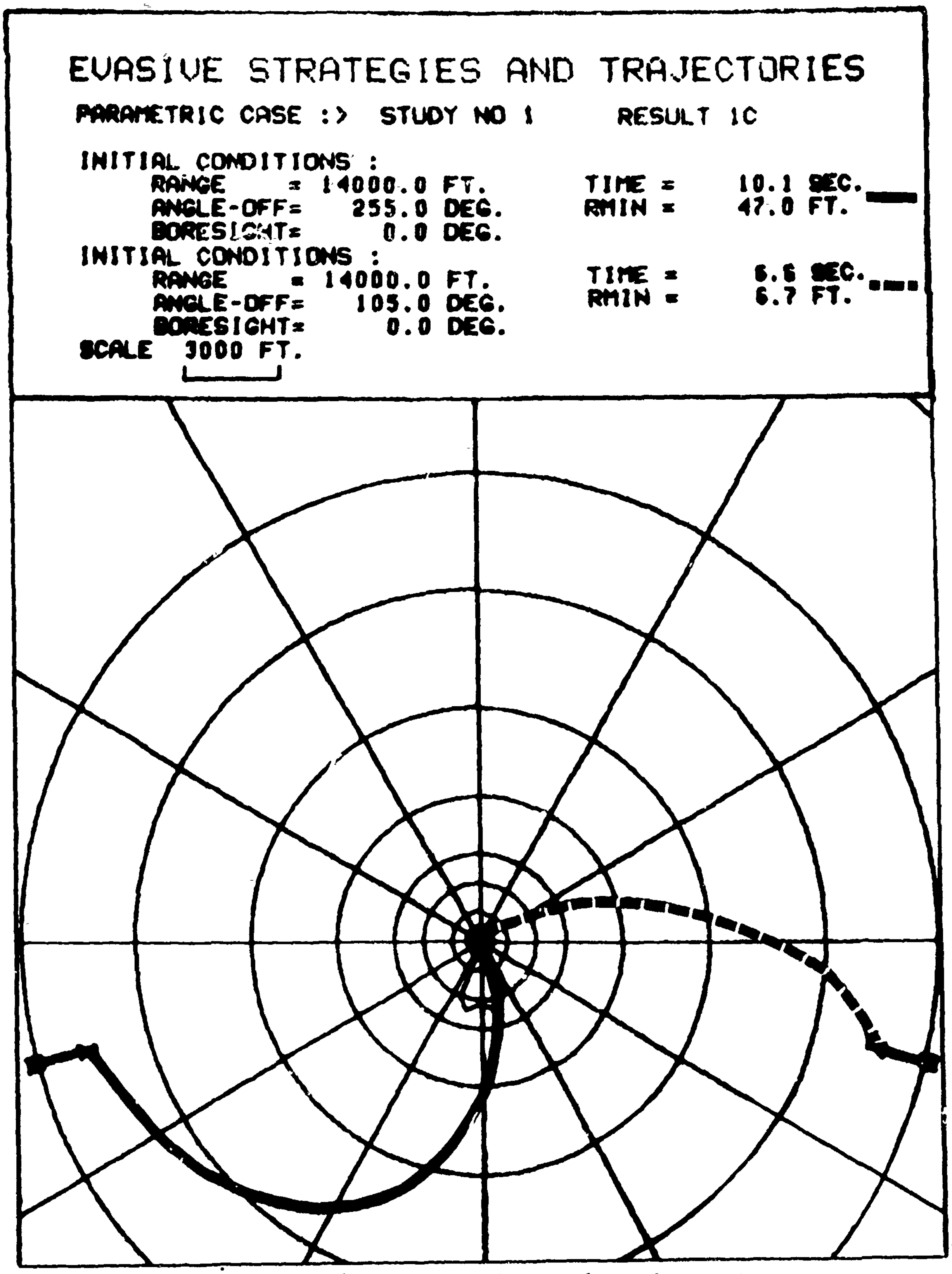


Fig. 4-10 Evasive Strategies and Trajectories, Study No. 1, Result 1C (Relative)

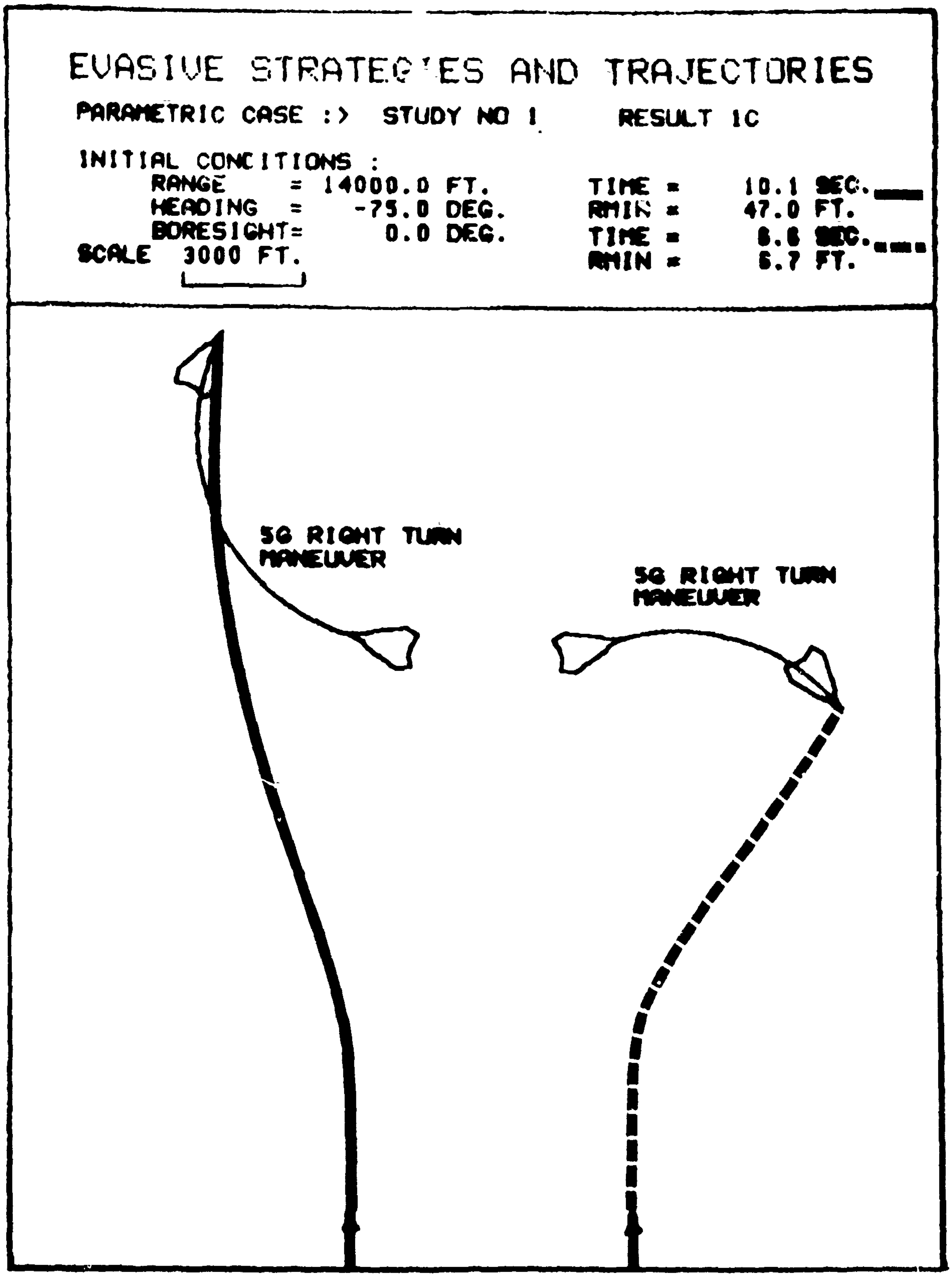


Fig. 4-11 Evasive Strategies and Trajectories, Study No. 1, Result 1C (Absolute)

STUDY No. 2 — ASPECT DEPENDENT SATURATION RANGE SEEKER

The missile effectiveness results for study 2, the aspect dependent seeker case, are presented in Fig. 4-12. The diagram at the left shows the kill effectiveness in the launch coordinate space for a nonmaneuvering aircraft. The diagram at the right shows the degradation in effectiveness possible with the optimal learned maneuvers. A marked reduction exists in the tail and beam launch orientations in the 5-16 K ft ranges and elimination of the head-on capability in the 16 to 48 K ft ranges. The aircraft vulnerability results for this study are presented in Fig. 4-13 in coordinates relative to the aircraft. One can see by comparison

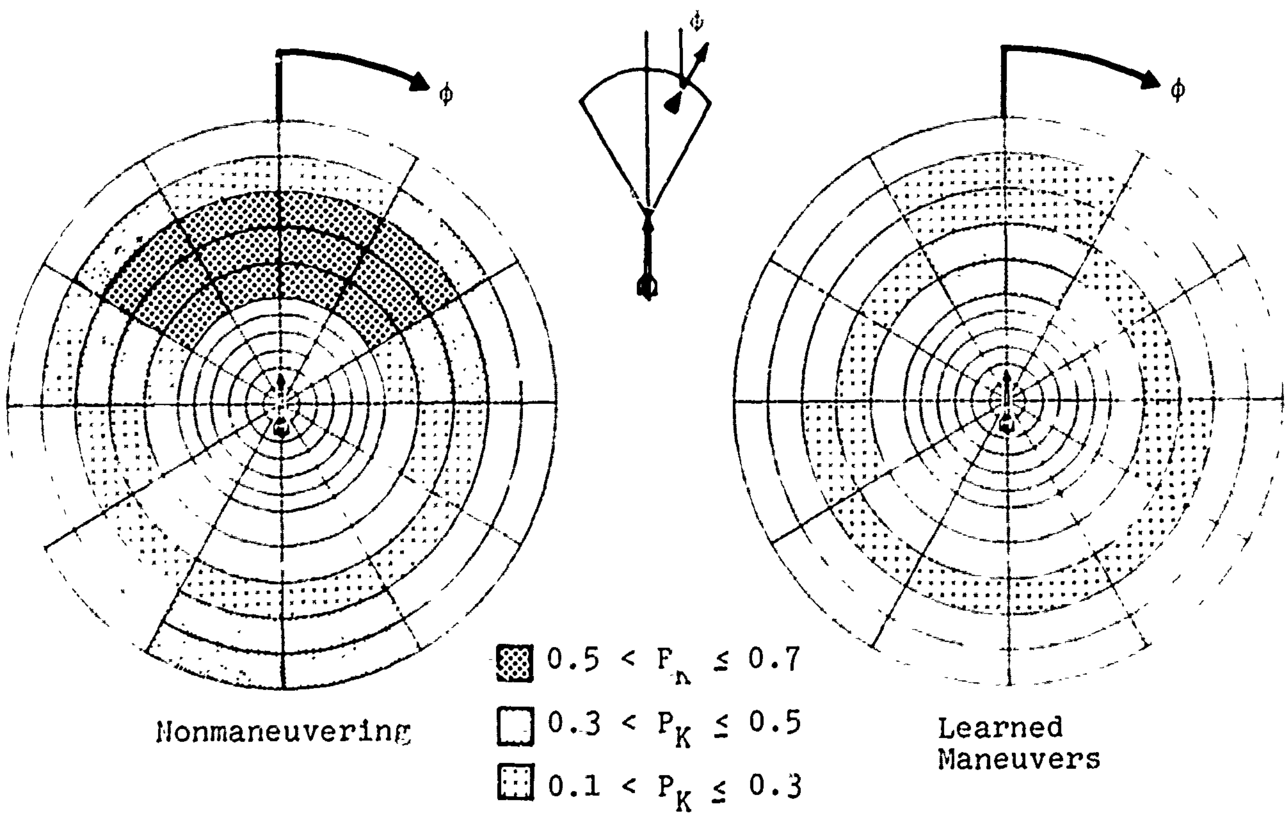


Fig. 4-12 Missile Effectiveness Results, Aspect Dependent Saturation Range = 250-2000 Feet

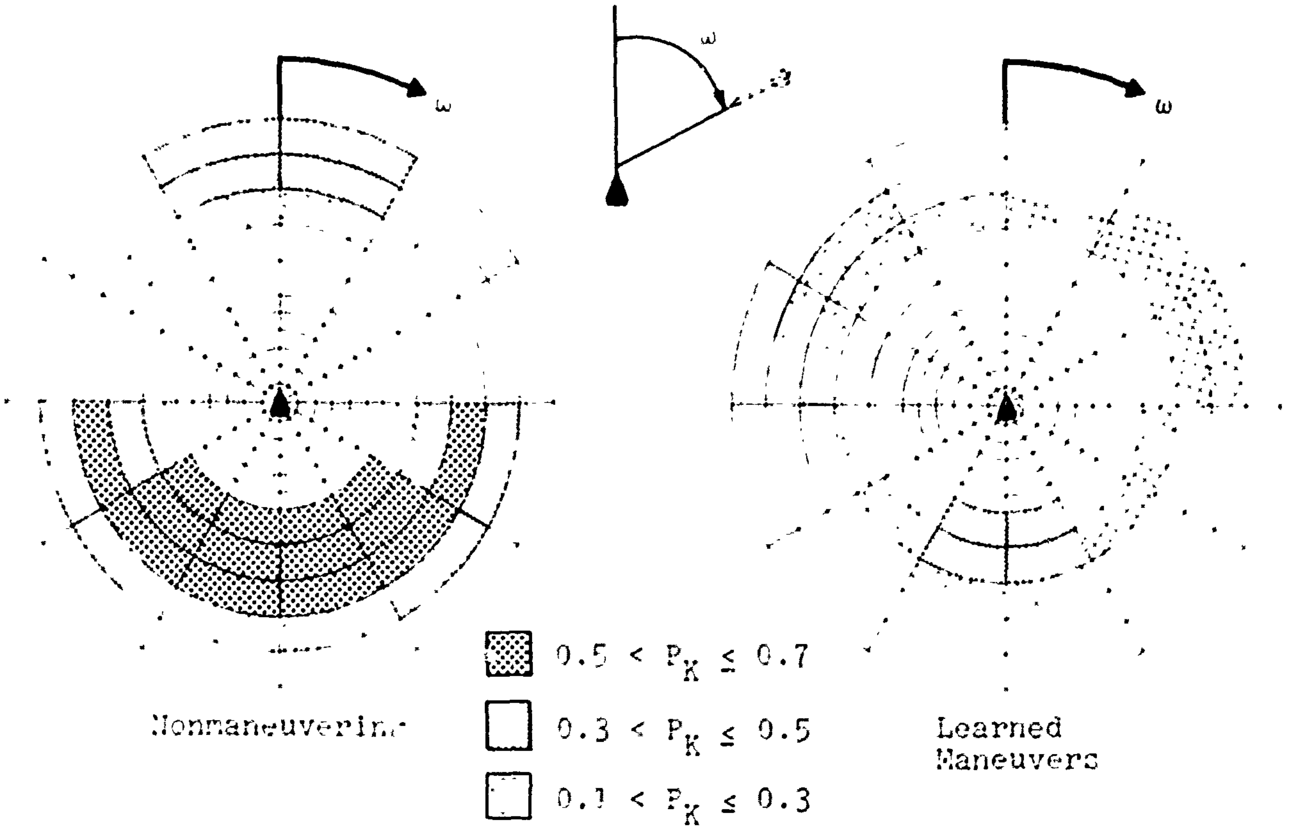


Fig. 4-13 Aircraft Vulnerability Results, Aspect Dependent Saturation Range = 250-2,000 Feet

with the results in Fig. 4-5, the constant saturation range case, that optimal maneuvering plays a stronger role in achieving vulnerability reductions for the aspect dependent case. Two sets of comparison trajectory results are given to illustrate the optimal maneuvering for study 2 (see Table 4-3). Sample result 2A given in Figs. 4-14 and 4-15 illustrates the nonmaneuvering/maneuvering comparisons for a tail shot initial condition at medium range. One can see the maneuvering strategy of the aircraft is to turn hard to obtain a beam aspect at the longer relative ranges followed by a turn reversal at the saturation range threshold of 2000 ft

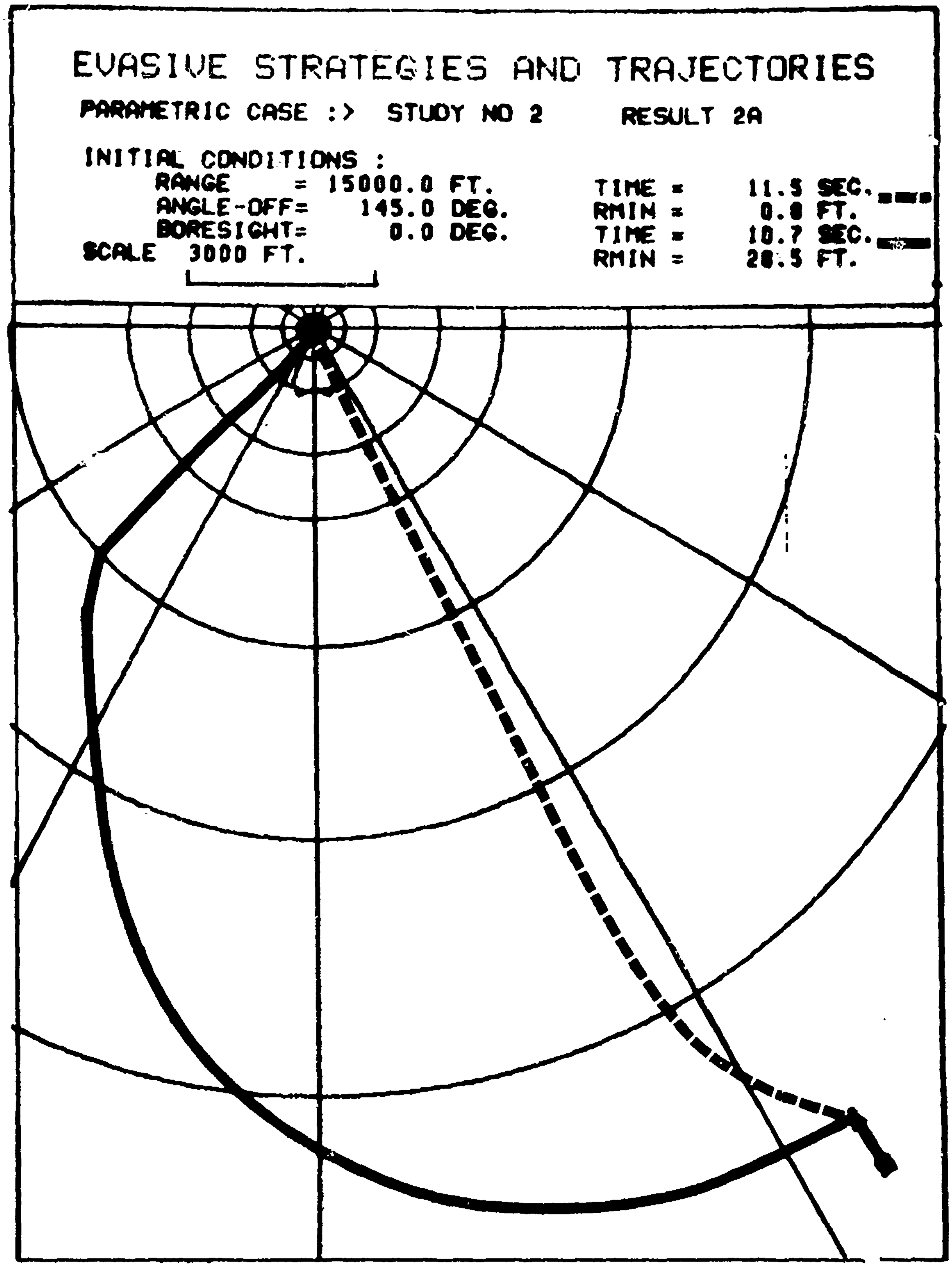


Fig. 4-14 Evasive Strategies and Trajectories, Study No. 2, Result 2A (Relative)

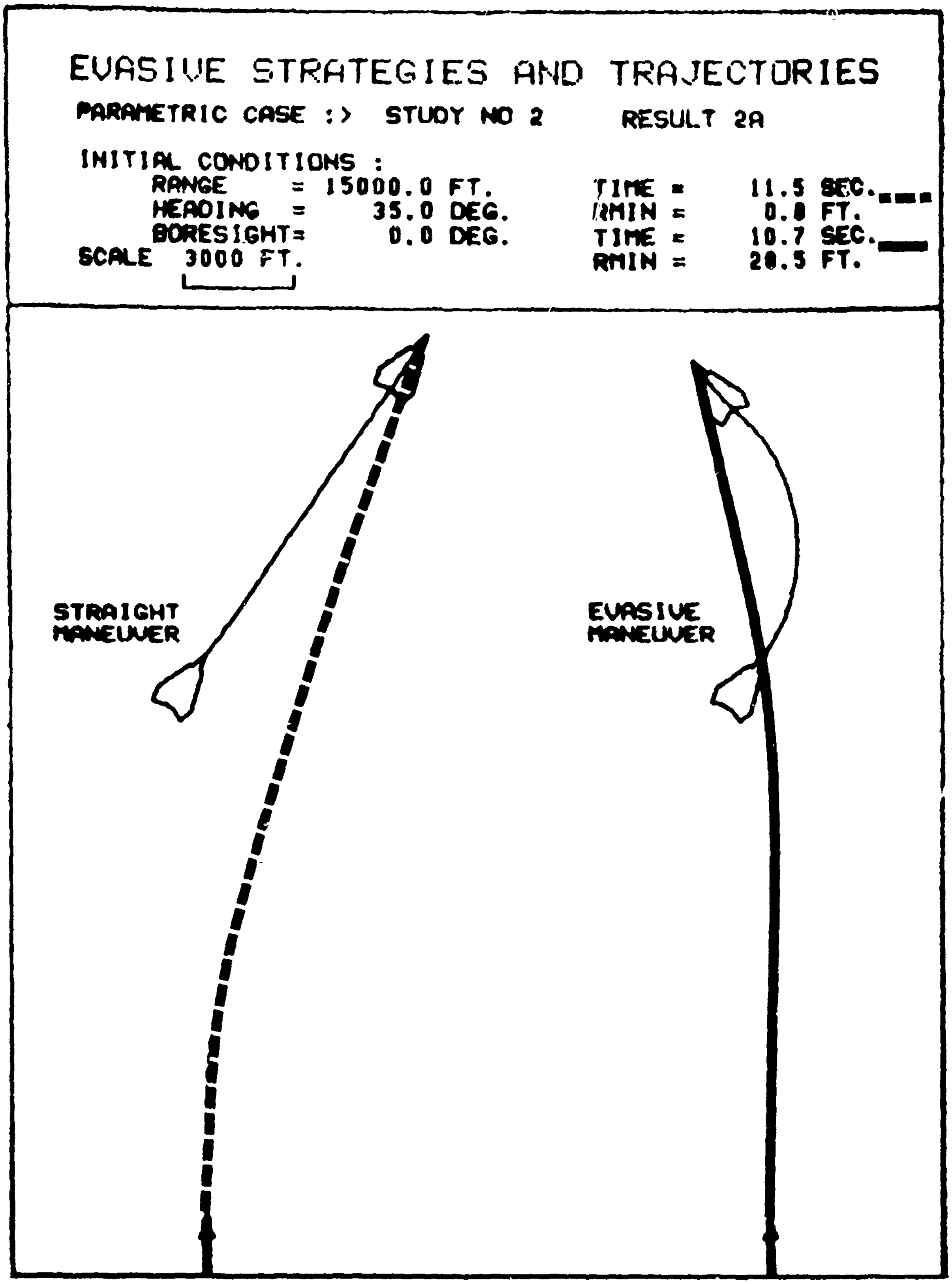


Fig. 4-15 Evasive Strategies and Trajectories, Study No. 2, Result 2B (Absolute)

to open the miss distance. It is important to note that in the interpretation of the optimal learned maneuvers the criterion for "optimality" is not maximizing the minimum miss distance for the evader, but maximizing the survival probability. This criterion, for example, has the effect of rating control sequences that achieve miss distances of say 20 ft and 2500 ft for this warhead lethality as equally desirable. Therefore, the learning technique may show optimal maneuvering sequences that defy intuition for certain portions of the relative coordinate space, yet satisfy the stated criteria for optimality. Sample result 2B illustrates the maneuvering comparisons for a close range beam launch initial condition. The trajectory result comparisons are depicted in Figs. 4-16 and 4-17 for both the nonmaneuvering and learned maneuver cases. The guidance delay parameter t_{DL} is a particularly important missile characteristic for this launch condition, and the execution of a proper maneuver sequence by the evading aircraft can definitively degrade missile effectiveness at these close ranges.

STUDY No. 3 - OFF-BORESIGHT LAUNCH SENSITIVITY

The results for study 3, which is aimed at illustrating the sensitivity of target aircraft vulnerability to off-boresight launch conditions, are presented in Fig. 4-18. The plot on the left shows the vulnerability for the on-boresight launch case. One may compare this plot with the averaged result obtained for -20° to +20° boresight error spread as shown in the right hand plot of Fig. 4-13. The comparison shows the vulnerability to be basically the same for tail aspect launches and slightly reduced in the beam and head-on situations for the on-boresight launch case. These vulnerabilities can be compared with data for the 15° to 20° off-boresight errors at launch are restricted to the +15 to +20° edge of boresight condition; therefore the right half plane depicts results for

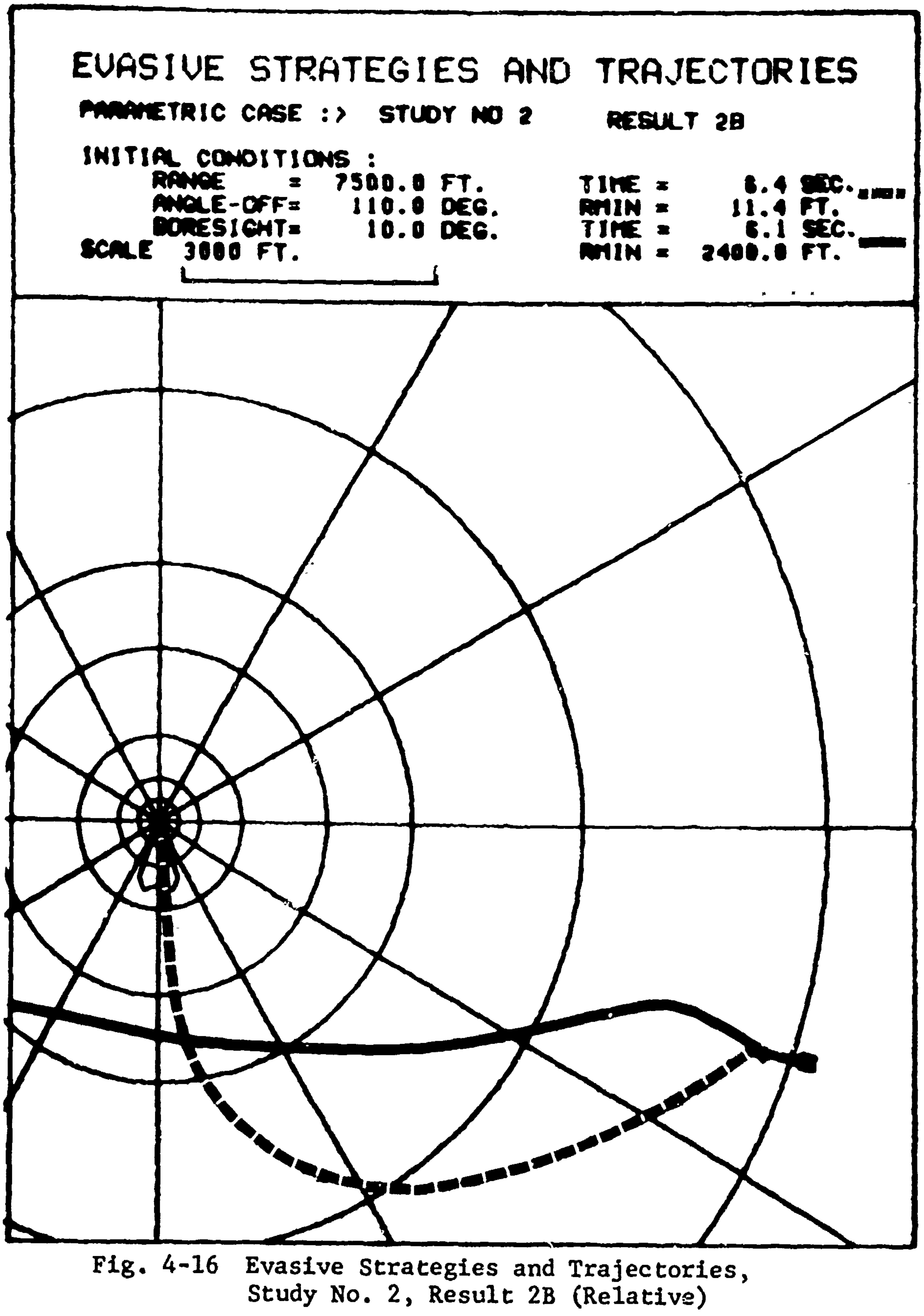


Fig. 4-16 Evasive Strategies and Trajectories, Study No. 2, Result 2B (Relative)

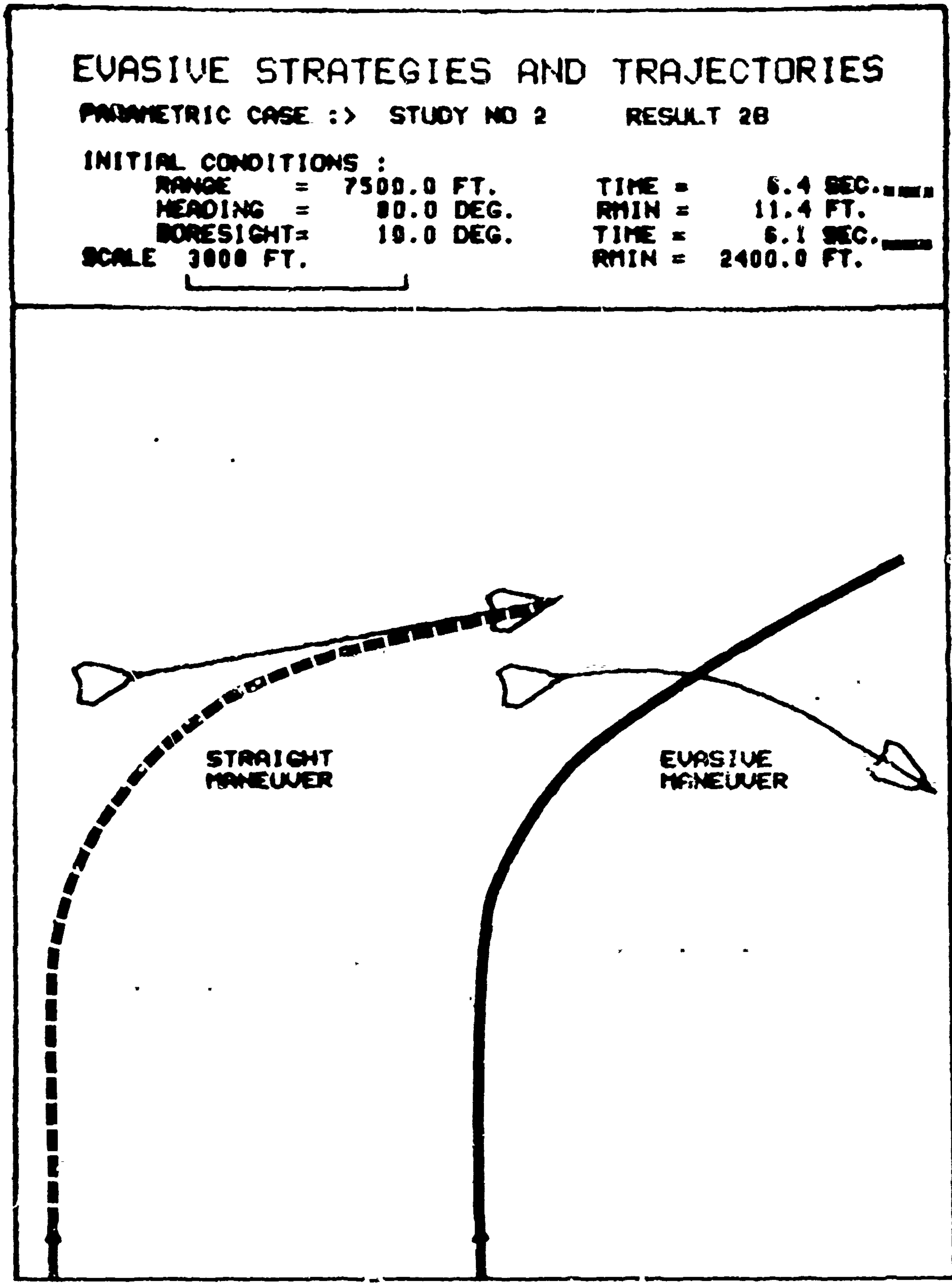


Fig. 4-17 Evasive Strategies and Trajectories, Stud·· No. 2, Result 2B (Absolute)

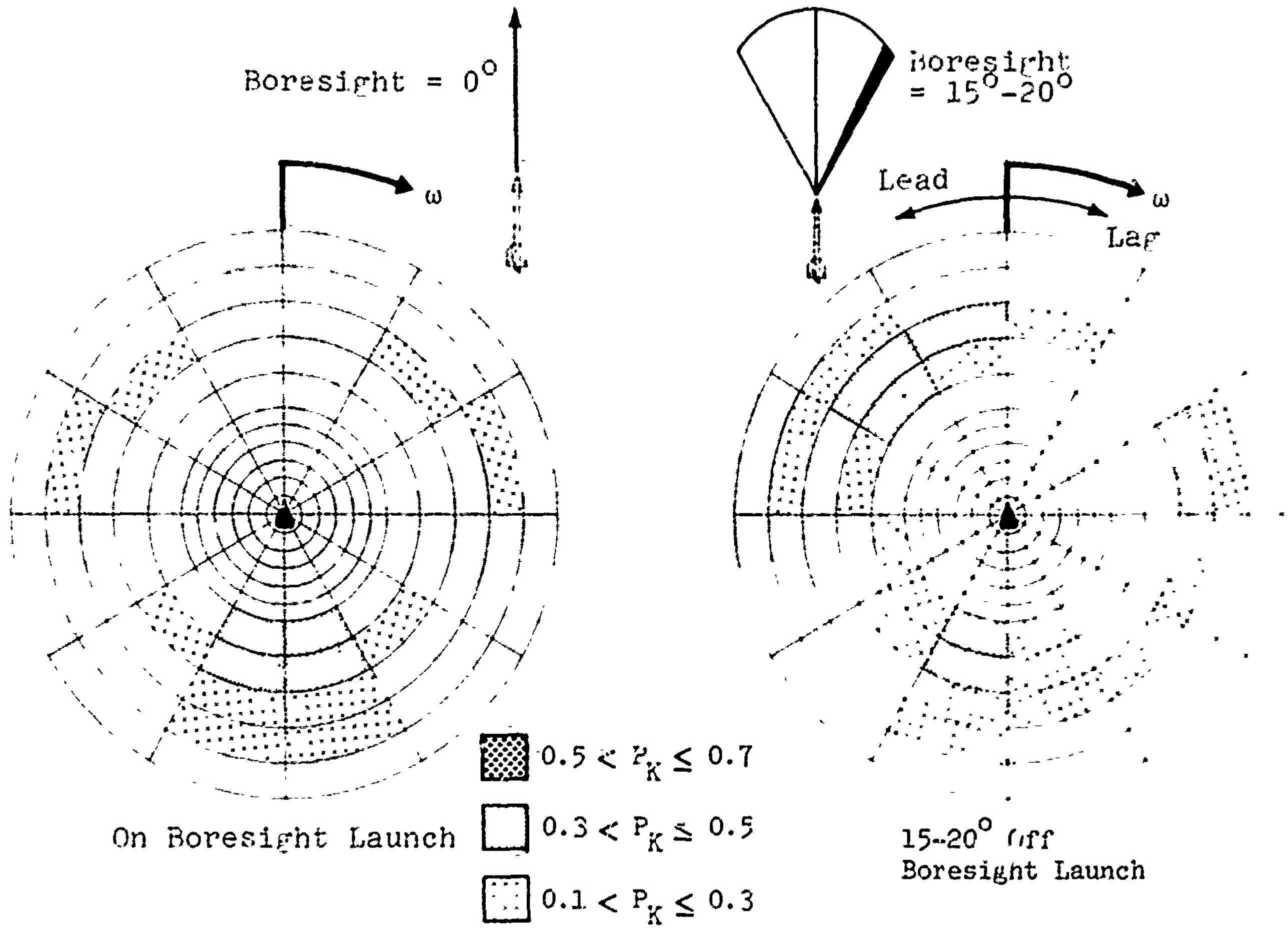


Fig. 4-18 Aircraft Vulnerability Results, Off-Boresight Launch Sensitivity Study

a 15° to 20° lag, and the left half plane a 15° to 20° lead with respect to target line of sight (see Fig. 4-19). One can see that when compared to the on-boresight data that the lead effect, generally, increases target vulnerability, while the lag effect diminishes it. It is important to note that the optimized maneuvers for these statistical results were restricted to be the same as those computed for the -20° to +20° off-boresight study, thereby allowing straightforward comparison between all three boresight launch cases. Sample trajectories depicting the evasive

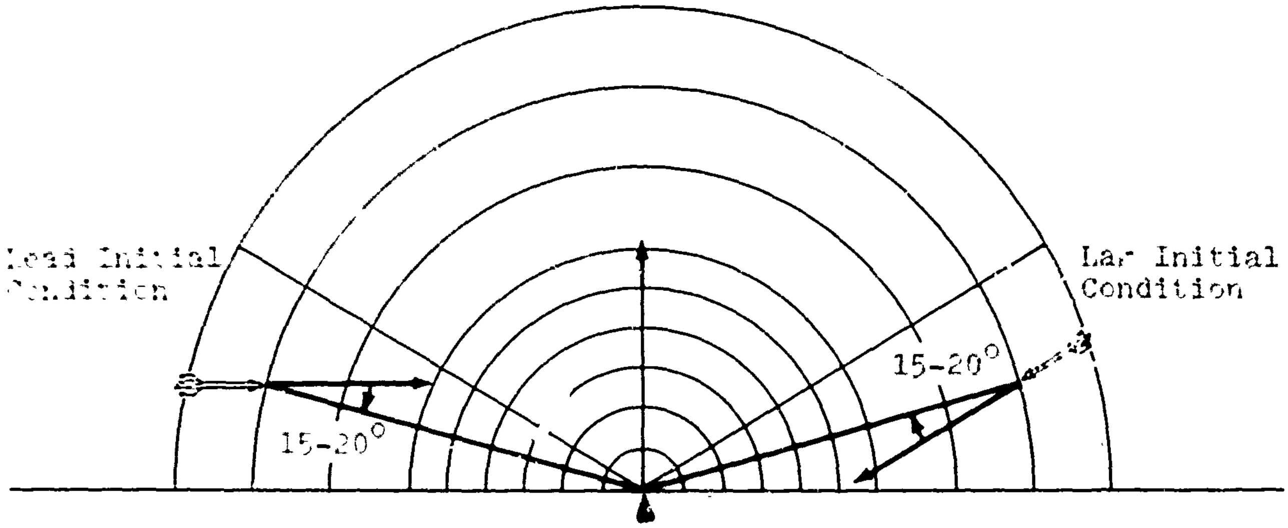


Fig. 4-19 Lead/Lag Initial Condition Nomenclature

maneuvering for the boresight sensitivity analysis are shown in Figs. 4-20 through 4-23. Figures 4-20 and 4-21 depict the on-boresight case for a sample head-on type launch condition in terms of relative and absolute coordinates, respectively. Figures 4-22 and 4-23 show the "edge" of boresight launch conditions and subsequent maneuvering representing the lead and lag cases.

STUDY No. 4 — WARHEAD LETHALITY SENSITIVITY

We now move on to study 4 and show the sensitivity of aircraft vulnerability with change in warhead lethality. Table 4-2 describes the improved warhead model of study 4 as assumed in the comparison with the baseline warhead of studies 1 through 3. The improved warhead described as the P_K (18,60) warhead is as lethal as the baseline warhead called P_K (6,20) at three times the minimum range. Figure 4-24 shows the vulnerability results for the baseline and improved warhead for both the nonmaneuvering and learned maneuvering

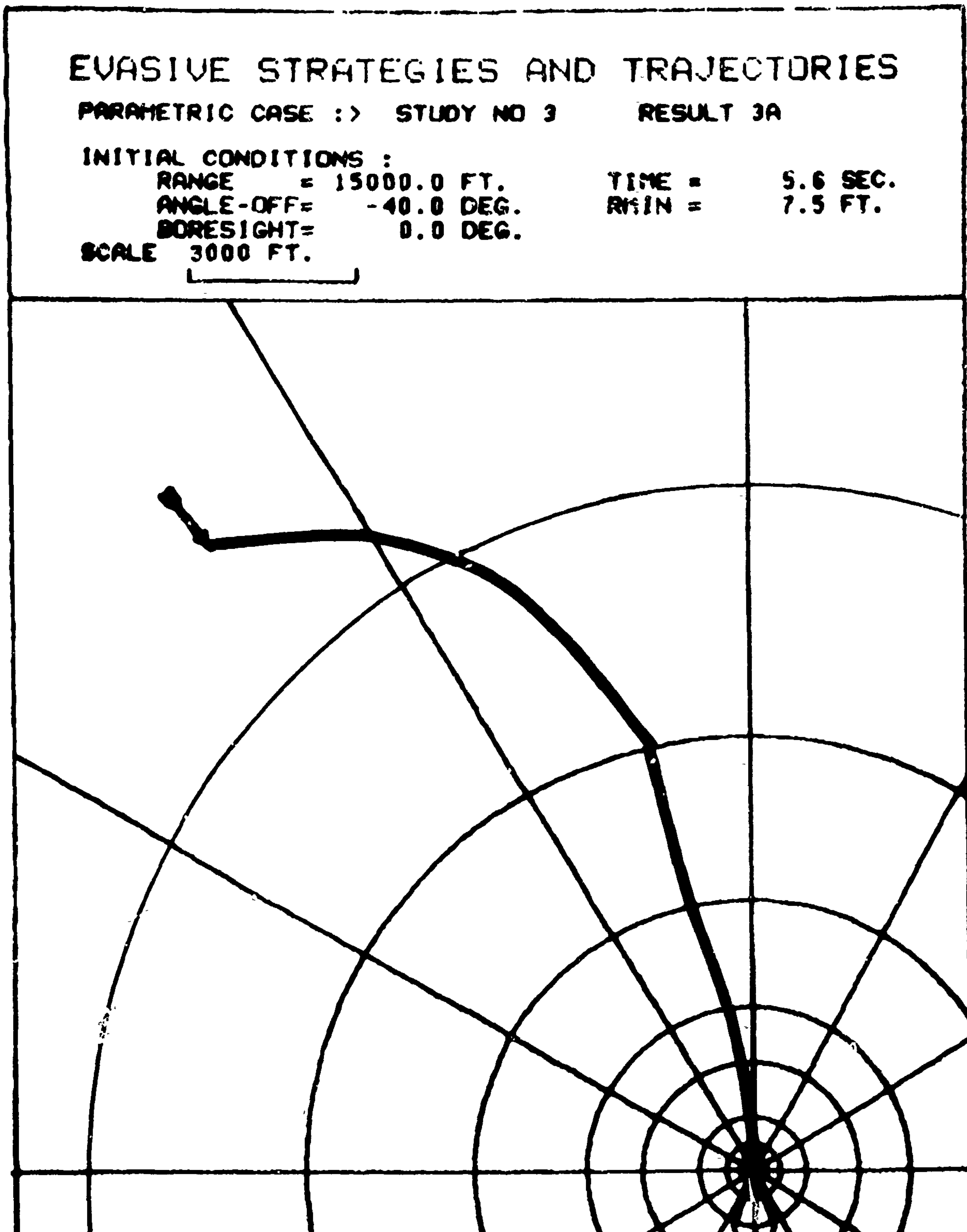


Fig. 4-20 Evasive Strategies and Trajectories, Study No. 3, Result 3A (Relative)

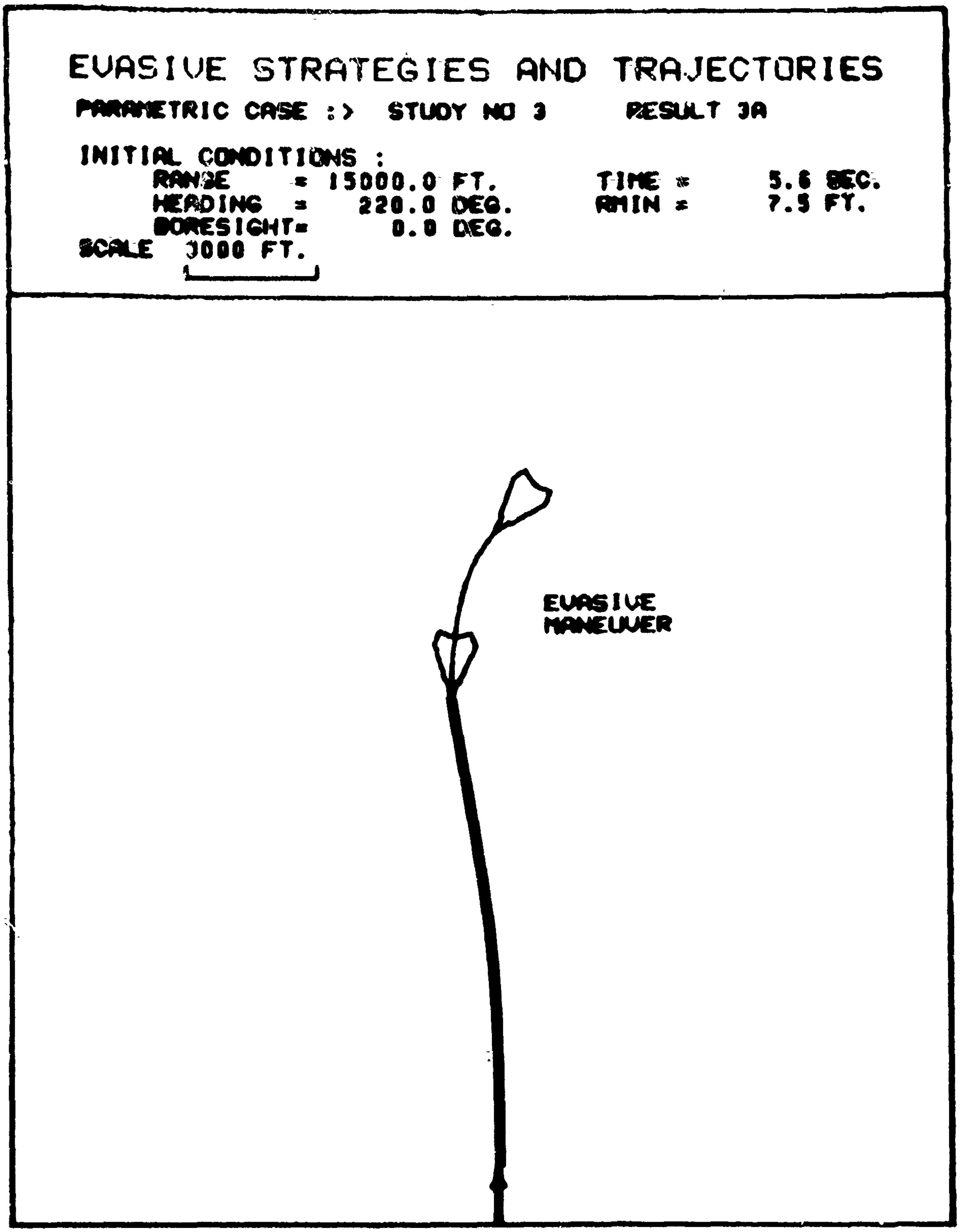


Fig. 4-21 Evasive Strategies and Trajectories, Study No. 3, Result 3A (Absolute)

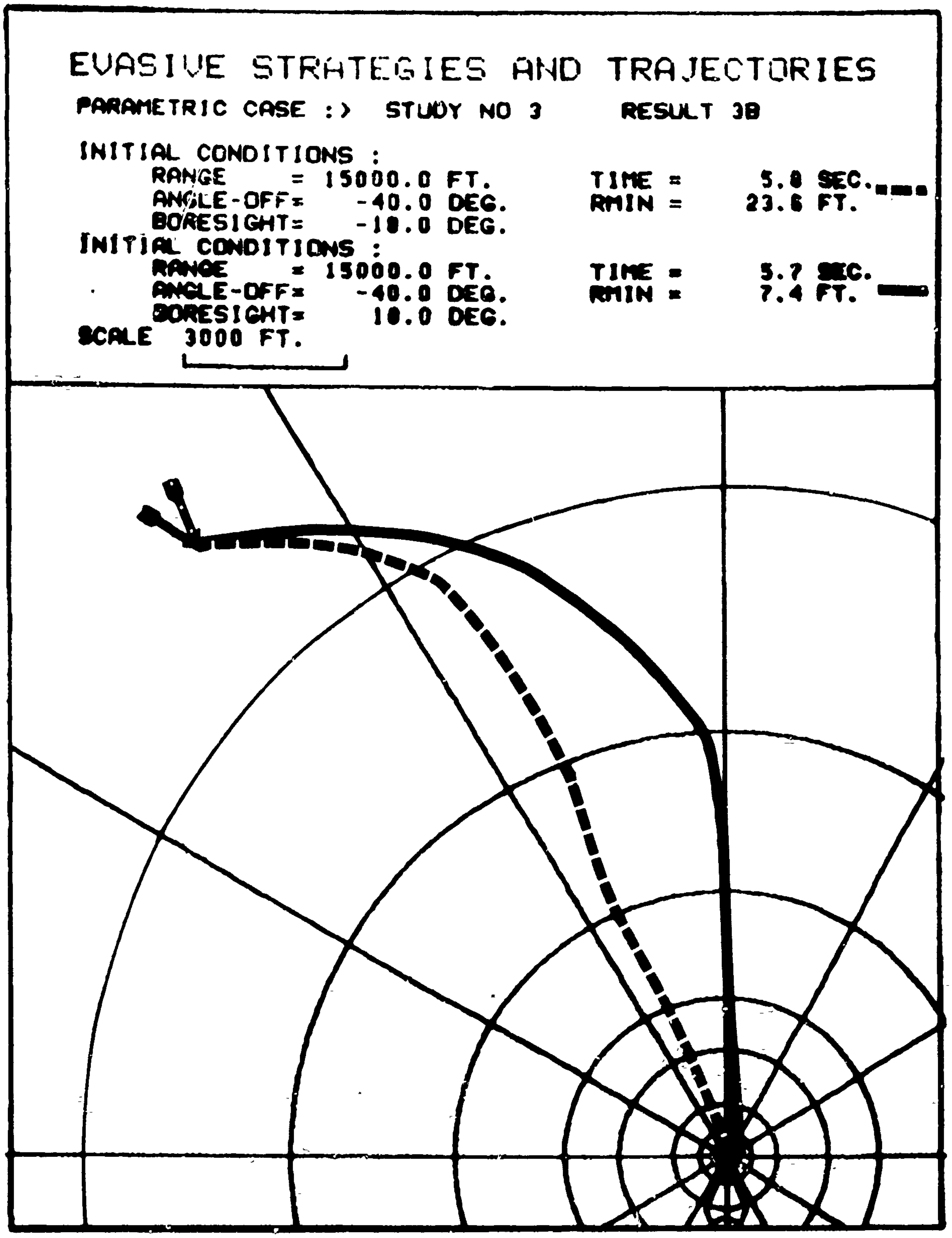


Fig. 4-22 Evasive Strategies and Trajectories, Study No. 3, Result 3B (Relative)

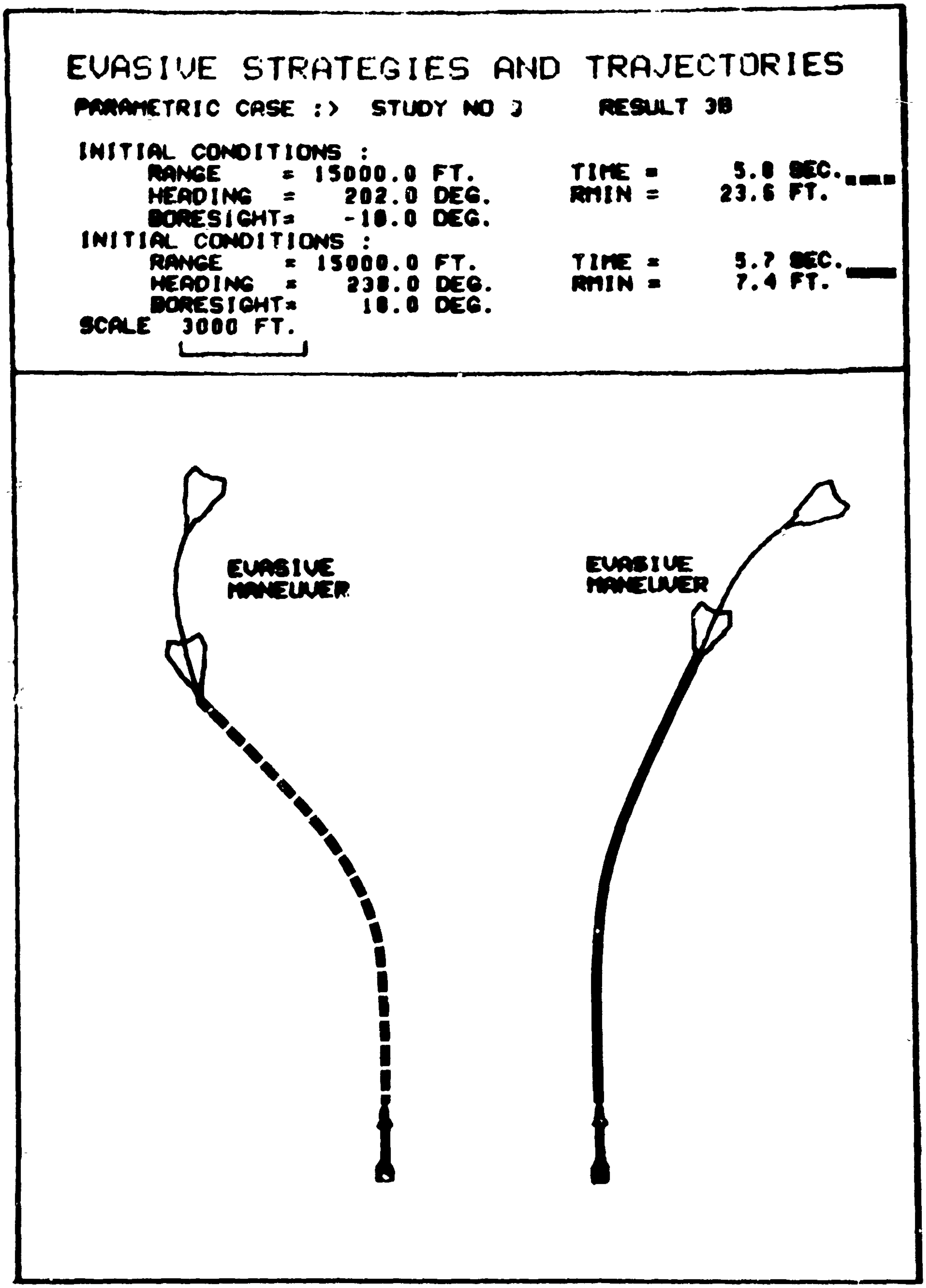


Fig. 4-23 Evasive Strategies and Trajectories, Study No. 3, Result 3B (Absolute)

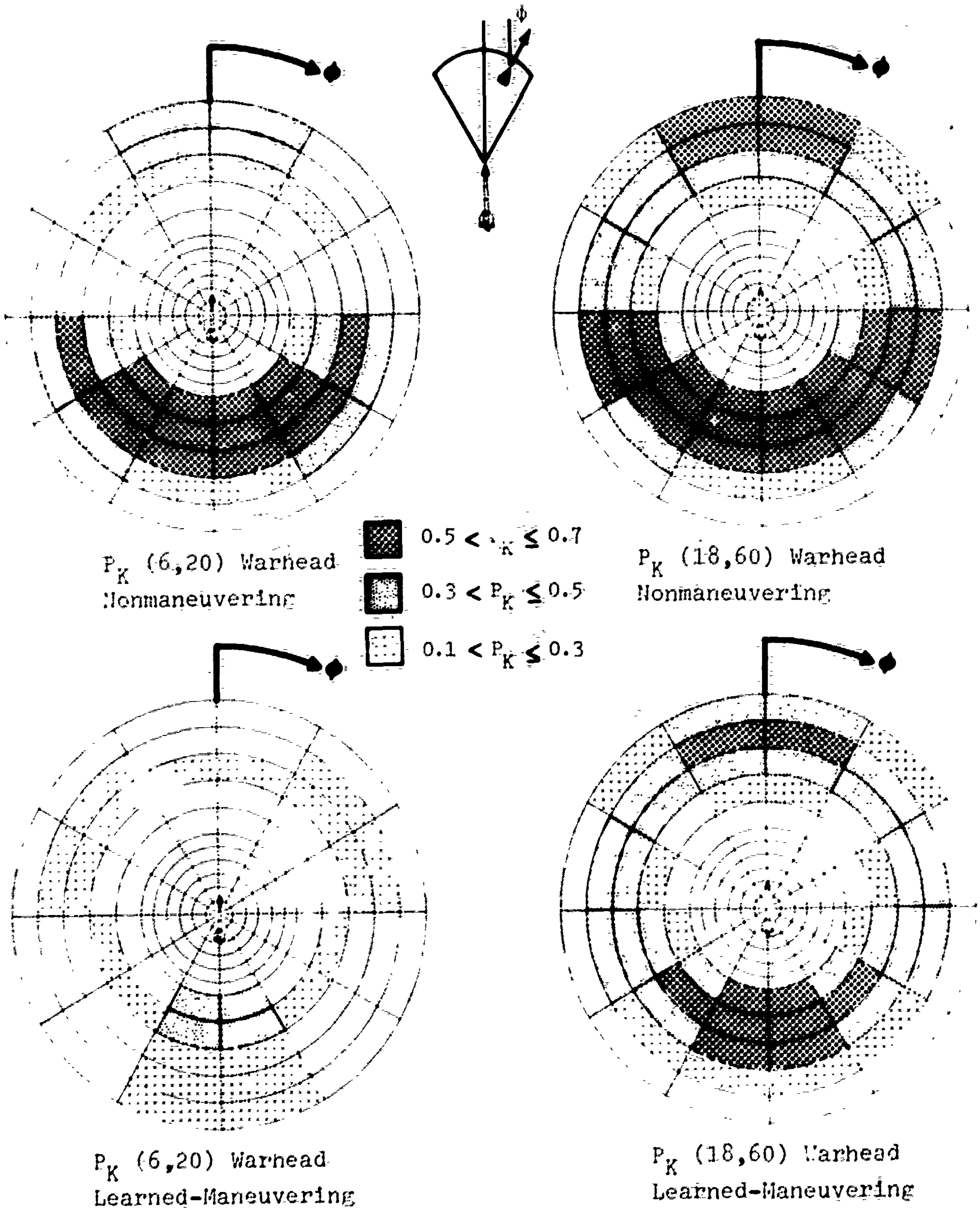


Fig. 4-24 Missile Effectiveness Results, Warhead Lethality Study

cases. The improved warhead model, as the results show, allows much less of a vulnerability reduction with optimal maneuvering than did the baseline warhead. With such an improved system, a tactics analyst would perhaps divert more of his effort into the countermeasures policy area rather than rely upon maneuvering to achieve vulnerability reductions.

This study concludes the computational results portion of this report. The studies illustrated were intended to furnish a small sampling of the type of result that is available to the system designer and tactics analyst in system effectiveness studies using the described methodology.

V. CONCLUSIONS

The important relationship of aircraft evasive maneuvering within the analysis of missile effectiveness has been made clear with the numerical studies conducted here. The first three result sets clearly show marked reductions in missile effectiveness achieved by the optimal "closed loop" maneuvering over the non-maneuvering and other open loop control cases for typical close range IR missile combat. In the constant seeker saturation range case, the optimal evasive policy for most launch coordinates is essentially a weaving maneuver whose control reversal points are dependent upon the relative range coordinate thresholds. In the aspect dependent case, the aircraft policy is essentially a maximum rate turn to present a beam aspect to the oncoming missile followed by a maximum rate turn reversal at the seeker saturation range threshold. The off-boresight launch results show that optimal maneuvering can achieve considerable reductions in missile effectiveness at close ranges when launch off-boresight angle lags the line of sight. The last of the results configured the improved missile warhead to be sufficiently lethal so as to obtain negligible effectiveness reductions with optimal maneuvering. It indicates that the major burden of the evasion problem should be placed in the domain of countermeasures deployment. The optimal maneuvering data (particularly in the first three result sets for the baseline missile warhead lethality) when averaged over all of the launch coordinates corresponds numerically to those statistical levels achieved in actual combat firings. The computational costs are reasonable, requiring one-half hour for the complete solution set for the 2-D problem with projected running times of two hours for comparably detailed 3-D models on IBM 370/168 type computers.

The technique as described can be incorporated in existing simulation programs where the evasive maneuver optimization can be programmed to become an integral part of the trajectory simulation process and where the fusing, detonation, and warhead damage assessment portion would be maintained and computed in its original detail. On the other hand, the methodology here can be easily augmented to include summary statistics of the detailed warhead damage effects to provide a self-contained program in its own right, which might offer shorter computer running times per problem than the former modification. The methodology also is easily extendable to countermeasures strategy determination and to problems of three dimensional flight. If necessary, the methodology can permit analysis of missile effectiveness to be achieved with in-flight alteration of missile guidance or counter-countermeasures policies. This is tantamount to reverting back to a two-sided game model for the combat in place of the one-sided control problem as analyzed here.

VI. REFERENCES

1. Drane, R. B., Capt. and Duffey, J. G. Jr., Capt., "A Digital Simulation Model for Evaluating System Effectiveness of Air-to-Air Missiles (U)," Air to Air Combat Analysis and Simulation Symposium Proceedings AFFDL-TR-72-57, Vol. II, Air Force Armament Laboratory, Eglin AFB, Florida, May 1972 (SECRET).

2. Chandler, W. E., "Survivability of Maneuvering F-4 Aircraft in Air-to-Air Combat (U)," NMC-TP-74-39, DDC AD-531-557L, Naval Missile Center, Pt. Mugu, California, September 1974 (SECRET).

3. Hyde, J. P., Lt. Col (F. J. Seiler Research Laboratory, AFSC) and Hines, J., Capt. (Department of Aeronautics, USAF Academy), "Application of a Computer Simulation and Optimization of a 3-D Engagement Between a SAM and Tactical Aircraft to Determine Optimum Evasive Tactics for AC-130 Gunships (U)," Air to Air Combat Analysis and Simulation Proceedings AFFDL-TR-72-57, Vol. II, Air Force Armament Laboratory, Eglin AFB, Florida, May 1972 (SECRET).

4. Falco, M., Carpenter, G., and Kaercher, A., "The Analysis of Tactics and System Capability in Aerial Dogfight Game Models," Grumman Research Department Report RE-474, May 1974 (prepared for Air Force Office of Scientific Research under Contract F44620-72-C-0032).

APPENDIX

COMPUTER PROGRAM LISTING

```
              C     CONTINUOUS TWO DIMENSIONAL MISSILE VS. AIRCRAFT COMBAT MODEL.
              C         OCTOBER 1974
0001                COMMON  /BLK1/TMAX,ACC1,T1Z,V1Z,V1F,U1,V1,D1,RMIN,KILL,I20
0002                DIMENSION DEC1(150,5),TEM(8),RT12(150,5),KTEM(10),
                   1U(500,2),SWU(500),MI(11,12,1),
                   2X(12),XINTAL(12),VEL1(5),PBS(5),ACC1(2,2)
0003                INTEGER U,V
0004                DATA PI/3.14159265358979 3/,D80/180.0/,DT/.25/
0005                DATA  TST/5.0E-04/
0006                DATA WC/1.E0/, SMAX/0.5E0/
              C INITIAL STATE /XM,YM,GAMMA,VM,RANGE,PSI,RS,R,TIME,XT,YT,HEADING/
0007                DATA XINTAL/0.E0,0.E0,0.F0,9.F2,0.F0,0.F0,0.E0,0.E0,0.E0,0.E0,
                   1  0.E0,0.E0/
0008                DATA NOREG/132/
0009                TWOPI = 2.E0*PI
0010                ITIME=ICHRON(3)
0011                KNTOUT = 1
0012                RD = D80/PI
0013                DO 100 I=1,2156
0014            100 YXY=RDM(DUM)
              C     SUBROUTINE IN1 ORDERS REGIONS 1/2
0015                CALL IN(MI)
0016            110 READ(5,99)IDEN
0017             99 FORMAT(I10)
0018             98 FORMAT(4E15.0)
0019                READ(5,98)ACC1(1,1),ACC1(1,2),ACC1(2,1),ACC1(2,2)
0020                READ(5,98)(VEL1(I),I=1,3)
0021                VEL1(4)=VEL1(2)
0022                VEL1(5)=VEL1(1)
0023                READ(5,98)DIS,DIF
0024                READ(5,98)WWIN,WLOSS
0025                READ(5,98)DT,TMAX
0026                READ(5,97)LOOP,MODE,KB1,KB2,NPLS
0027             97 FORMAT(5I5)
0028                IF(MODE.EQ.1)  NPLS = 1
              C     IDEN IS RUN NUMBER FOR IDENTIFICATION PURPOSE ONLY
              C     ACC1 ARE ACCELERATION COEFF FOR PLAYER 1
              C     VEL1 ARE STEADY STATE VELOCITIES FOR PLAYER 1
              C     DIS, DIF ARE THE TWO TURN RADII FOR PLAYER 1
              C     WWIN,WLOSS ARE WEIGHTS FOR PLAYER 1 FOR WIN AND LOSS
              C     DT IS DELTA TIME USED IN THE INTEGRATION COMPUTATION OF THE TRAJEC
              C     TMAX IS THE MAXIMUM TIME ALLOWED  FOR ANY TRAJECTORY
              C     SMAX IS WEIGHT FACTOR , USUALLY AVG. NO. SAMPLES PER REGION PER RU
              C     LOOP IS NUMBER OF SAMPLES FOR THIS RUN
              C     MODE = 1 FOR LEARNING  MODE = 2 FOR STATISTICS (NO LEARNING) RUN
              C     KB1 = 1 DECISION TABLE WILL BE INPUT, KB1 = 0 IT IS NOT INPUT
              C     KB2 = 1 STATISTIC TABLE WILL BE INPUT, KB2 = 0 IT IS NOT INPUT
              C     NOTE  THE ENTIRE TABLE (376 CARDS) WILL BE INPUT OR NOT. THE ENTIR
```

```
                C      TABLE WILL BE PUNCHED OUTPUT AT THE END OF THE RUN                MIS00480
                C      WHEN MODE = 2 THE STATISTICS CAN BE GENERATED RELATIVE TO EITHER  MIS00490
                C      THE AIRCRAFT OR MISSILE BY SETTING NPLS                           MIS00500
                C      NPLS = 1   STATISTICS USING THE AIRCRAFT INITIAL CONDITION SPACE  MIS00510
                C      NPLS = 2   STATISTICS USING THE MISSILE  INITIAL CONDITION SPACE  MIS00520
 0029                  WRITE(6,96)IDEN,ACC1(1,1),ACC1(1,2),ACC1(2,1),ACC1(2,2),          MIS00530
                      1(VEL1(I),I=1,5)                    ,DIS,DIF                       MIS00540
 0030               96 FORMAT(23H1INPUT FOR RUN NUMBER    ,I10//                         MIS00550
                      127H ACCELERATION COEFFICIENTS   ,1P4E18.6 /                       MIS00560
                      225H0 STEADY STATE VELOCITIES/                                     MIS00570
                      311H PLAYER 1   ,1P5E18.6/                                         MIS00580
                      511H TURN RADII,1P3E18.6)                                          MIS00590
 0031                  WRITE(6,95) WWIN,WLOSS                                            MIS00600
 0032               95 FORMAT(31H   WEIGHTS FOR PLAYER 1 WIN,LOSS,2F10.4)                MIS00610
 0033                  WRITE(6,94)DT,TMAX,SMAX                                           MIS00620
 0034               94 FORMAT(10H0DELTA T =, F12.4 ,   9H   TMAX =, F12.4/               MIS00630
                      1 7H SMAX =,F12.4 )                                                MIS00640
 0035                  WRITE(6,93)LOOP,MODE,KB1,KB2,NPLS                                 MIS00650
 0036               93 FORMAT( 1H0,I10,26H SAMPLES REQUESTED  MODE =,I5,                 MIS00660
                      110H KB1,KB2 =,2I5, 9H   NPLS =,I5,//                              MIS00670
                      2 67H  MODE = 1 FOR LEARNING, MODE = 2 FOR STATISTICS ONLY - NO LEAMIS00680
                      3RNING /                                                           MIS00690
                      4 52H  KB1 = 1 DEC. TABLE WILL BE INPUT,  = 0 IT WILL NOT  /       MIS00700
                      5 53H  KB2 = 1 STAT. TABLE WILL BE INPUT,  = 0 IT WILL NOT  ///)   MIS00710
 0037                  IF(KB1 .EQ. 0)GO TO 135                                           MIS00720
 0038              115 CONTINUE                                                          MIS00730
 0039                  READ(5,92)K,(TEM(L),L=1,5)                                        MIS00740
 0040               92 FORMAT(I5,5F9.6)                                                  MIS00750
 0041                  IF(K .LE. 0)GO TO 125                                             MIS00760
 0042                  DO 120 J=1,5                                                      MIS00770
 0043              120 DEC1(K,J)=TEM(J)                                                  MIS00780
 0044                  GO TO 115                                                         MIS00790
 0045              125 CONTINUE                                                          MIS00800
 0046                  WRITE(6,91)IDEN                                                   MIS00810
 0047               91 FORMAT(45H1DECISION TABLE INPUT          DEC1 FOR RUN NO. ,I10//) MIS00820
 0048                  DO 130 I=1,NOREG                                                  MIS00830
 0049              130 WRITE(6,90)I,(DEC1(I,J),J=1,5)                                    MIS00840
 0050               90 FORMAT(I5,5F10.6)                                                 MIS00850
 0051              135 IF(KB2 .EQ. 0)GO TO 160                                           MIS00860
 0052              137 CONTINUE                                                          MIS00870
 0053                  READ(5,81)K,(TEM(L),L=1,5)                                        MIS00880
 0054               81 FORMAT(I5,1P5E14.7)                                               MIS00890
 0055                  IF(K .LE. 0)GO TO 145                                             MIS00900
 0056               89 FORMAT(6I5)                                                       MIS00910
 0057                  DO 140 J=1,5                                                      MIS00920
 0058              140 RT12(K,J)=TEM(J)                                                  MIS00930
 0059                  GO TO 137                                                         MIS00940
 0060              145 CONTINUE                                                          MIS00950
```

```
0061           WRITE(6,88)IDEN                                                   MIS00960
0062        88 FORMAT(34HISTATISTIC TABLE INPUT FOR RUN NO. ,I10)                MIS00970
0063           IF(NPLS.EQ.1)  WRITE(6,70)                                        MIS00980
0064           IF(NPLS.EQ.2)  WRITE(6,71)                                        MIS00990
0065        70 FORMAT(5X,24HRELATIVE TO THE AIRCRAFT.//)                         MIS01000
0066        71 FORMAT(5X,24HRELATIVE TO THE MISSILE .//)                         MIS01010
0067           DO 150 I=1,NOREG                                                  MIS01020
0068       150 WRITE(6,81)I,(RT12(I,J),J=1,5)                                    MIS01030
0069        87 FORMAT(I5,2X,5I5)                                                 MIS01040
0070       160 IF(KB1 .NE. 0)GO TO 175                                           MIS01050
0071           DO 170 I=1,NOREG                                                  MIS01060
0072           DO 170 J=1,5                                                      MIS01070
0073           DEC1(I,J) = 0.2E0
0074   170     CONTINUE
0075       175 IF(KB2 .NE. 0)GO TO 190                                           MIS01090
0076           DO 180 I=1,NOREG                                                  MIS01100
0077           DO 180 J=1,5                                                      MIS01110
0078       180 RT12(I,J)=0.E0                                                    MIS01120
0079       190 CONTINUE                                                          MIS01130
      C        MAIN LOOP FROM 1 TO NUMBER OF SAMPLES STARTS HERE                 MIS01140
0080           DO 500 IJKL = 1,LOOP                                              MIS01150
0081           FRAN = 73 + 60*RDM(DUM)                                           MIS01160
0082           KRAN = FRAN                                                       MIS01170
      C        ROT WILL DEFINE INITIAL CONDITION WHICH WILL BE RANDOMLY CHOSEN  MIS01180
      C        INSIDE REGION 2/1  NUMBER KRAN                                    MIS01190
0083           CALL ROT(KRAN,M1,ROE,OME,THE)                                     MIS01200
0084           INCBR = 1                                                         MIS01210
0085           IF(MODE.EQ.1)  GO TO 200                                          MIS01220
0086           IF(NPLS.EQ.1)  GO TO 200                                          MIS01230
0087           DO 195 I=1,12                                                     MIS01240
0088       195 X(I) = XINTAL(I)                                                  MIS01250
0089           PHI = OME/RD                                                      MIS01260
0090           THE = THE/RD                                                      MIS01270
0091           X(3) = PI/2.E0                                                    MIS01280
0092           X(5) = ROE                                                        MIS01290
0093           X(6) = (PI/2.E0) - THE
0094       196 IF(X(6).GT.TWOPI)  X(6) = X(6) - TWOPI                            MIS01310
0095           IF(X(6).LT.0.E0)   X(6) = TWOPI + X(6)                            MIS01320
0096           IF(X(6).LT.0.E0.OR.X(6).GT.TWOPI)  GO TO 196                      MIS01330
0097           X(10) = X(5)*COS(X(6))                                            MIS01340
0098           X(11) = X(5)*SIN(X(6))                                            MIS01350
0099           X(12) = PHI                                                       MIS01360
0100           V1 = VEL1(3)
0101           XR = X(10) - X(1)
0102           YR = X(11) - X(2)
0103           RC = SQRT(XR**2 + YR**2)
0104           VXL = V1*SIN(X(12)) - X(4)*COS(X(3))
0105           VYL = V1*COS(X(12)) - X(4)*SIN(X(3))
```

```
          PSIC = ATAN2(YR,XR)
          PSIDOT = (-VXL*SIN(PSIC) + VYL*COS(PSIC))/RC
          X(7) = PSIDOT
          GO TO 215                                                    MIS01370
      200 CONTINUE                                                     MIS0138C
          DO 201 I=1,12                                                MIS01390
      201 X(I) = XINTAL(I)                                             MIS01400
          OME = OME/RD                                                 MIS01410
          THE = THE/RD                                                 MIS01420
          X(6) = 3.E0*PI/2.E0 - OME                                    MIS01430
      205 IF(X(6).GT.TWOPI)  X(6) = X(6) - TWOPI                       MIS01440
          IF(X(6).LT.0.E0)   X(6) = TWOPI + X(6)                       MIS01450
          IF(X(6).LT.0.E0.OR.X(6).GT.TWOPI)  GO TO 205                 MIS01460
          X(5) = ROE                                                   MIS01470
          X(3) = X(6) + THE                                            MIS01480
      210 IF(X(3).GT.TWOPI)  X(3) = X(3) - TWOPI                       MIS01490
          IF(X(3).LT.0.E0)   X(3) = TWOPI + X(3)                       MIS01500
          IF(X(3).LT.0.E0.OR.X(3).GT.TWOPI)  GO TO 210                 MIS01510
          X(10) = X(5)*COS(X(6))
          X(11) = X(5)*SIN(X(6))
          VI = VEL1(3)
          XR = X(10) - X(1)
          YR = X(11) - X(2)
          RC = SQRT(XR**2 + YR**2)
          VXL = VI*SIN(X(12)) - X(4)*COS(X(3))
          VYL = VI*COS(X(12)) - X(4)*SIN(X(3))
          PSIC = ATAN2(YR,XR)
          PSIDOT = (-VXL*SIN(PSIC) + VYL*COS(PSIC))/RC
          X(7) = PSIDOT
      215 DO 225 J=1,500                                               MIS01540
          SWU(J) = 0.                                                  MIS01550
          U(J,1)=0                                                     MIS01560
      225 U(J,2)=0                                                     MIS01570
C         SWU WILL STORE WEIGHTS, U(I,J) REGION,STATEGY FOR PLAYERS 1  MIS01580
C         NU IS A COUNTER FOR U SUBSCRIPT I                            MIS01590
          NU = 0                                                       MIS01600
          NS1 = -99                                                    MIS01610
          T = 0.                                                       MIS01620
          KILL = 0                                                     MIS01630
      230 CONTINUE                                                     MIS01640
          XR = X(10) - X(1)
          YR = X(11) - X(2)
          RI = SQRT(XR**2 + YR**2)
          O1 = ((3.E0*PI/2.E0) - X(12) - X(6))*RD                      MIS01660
      235 IF(O1.GT.360.E0)  O1 = O1 - 360.E0                           MIS01670
          IF(O1.LT.0.E0)   O1 = 360.E0 + O1                            MIS01680
          IF(O1.LT.0.E0.OR.O1.GT.360.E0)  GO TO 235                    MIS01690
      242 CONTINUE                                                     MIS01700
```

```
FORTRAN IV G LEVEL  21                    MAIN                DATE = 75101          21/37/03

                  C      REGI SUBROUTINE  PACKS THE SUBCRIPTS OF M1(I1,I2,I3)                    MIS01710
                  C      INTO N1 FOR PLAYER 1                                                    MIS01720
                  C      NOTE  THE REGION NUMBER FOR PLAYER 1 IS ACTUALLY REGION 2/1             MIS01730
                  C      IF REGION FOR PLAYER 1 HAS NOT CHANGED NS1 = N1.  IF IT HAS CHANGEMIS01740
                  C      NEW REGIS OBTAINED USING N1, M1, THEN A NEW STRATEGY IS PICKED ANDMIS01750
                  C      REGION NO. AND STRATEGY ARE STORED                                      MIS01760
 0152                    CALL REG(N1,R1,O1,T1)                                                   MIS01770
 0153                    IF(N1 .EQ. NS1)GO TO 275                                                MIS01780
 0154                    NS1 = N1                                                                MIS01790
 0155                    NU = NU+1                                                               MIS01800
                  C      TEST FOR CHATTER - MAX. OF 450 REG. MAY BE VISITED BY  PLAYER 1         MIS01810
                  C      NO REINFORCEMENT FOR CHATTER                                            MIS01820
 0156                    IF(NU .GE. 450)GO TO 500                                                MIS01830
 0157                    I1 = N1/1000                                                            MIS01840
 0158                    NN = N1 - I1*1000                                                       MIS01850
 0159                    I2 = NN/10                                                              MIS01860
 0160                    I3 = NN - I2*10                                                         MIS01870
 0161                    IF(I3 .EQ. 0)I3=1                                                       MIS01880
 0162                    I = M1(I1,I2,I3)                                                        MIS01890
 0163                    U(NU,1)=I                                                               MIS01900
 0164                    R = RDM(DUM)                                                            MIS01910
 0165                    T1Z = T                                                                 MIS01920
                  C      KS1=1 SLOW LEFT, =2 FAST LEFT, =3 STRAIGHT, =4 FAST RIGHT, = 5 SLOMIS01930
 0166                    KS1=5                                                                   MIS01940
 0167                    D1=DIS                                                                  MIS01950
 0168                    V1F=VEL1(5)                                                             MIS01960
 0169                    U1=1.0                                                                  MIS01970
 0170                    IF(R .LE. DEC1(I,1))GO TO 260                                           MIS01980
 0171                    TEMP = DEC1(I,1)+DEC1(I,2)                                              MIS01990
 0172                    IF(R .LE. TEMP)GO TO 261                                                MIS02000
 0173                    TEMP = TEMP + DEC1(I,3)                                                 MIS02010
 0174                    IF(R .LE. TEMP)GO TO 262                                                MIS02020
 0175                    TEMP = TEMP + DEC1(I,4)                                                 MIS02030
 0176                    IF(R .LE. TEMP)GO TO 263                                                MIS02040
 0177                    GO TO 270                                                               MIS02050
 0178                260 KS1 = 1                                                                 MIS02060
 0179                    D1=DIS                                                                  MIS02070
 0180                    U1 = -1.0                                                               MIS02080
 0181                    V1F = VEL1(1)                                                           MIS02090
 0182                    GO TO 270                                                               MIS02100
 0183                261 KS1 = 2                                                                 MIS02110
 0184                    D1=D1F                                                                  MIS02120
 0185                    U1 = -1.0                                                               MIS02130
 0186                    V1F = VEL1(2)                                                           MIS02140
 0187                    GO TO 270                                                               MIS02150
 0188                262 KS1 = 3                                                                 MIS02160
 0189                    D1=D1F                                                                  MIS02170
 0190                    U1 = 0.                                                                 MIS02180
```

```
0191          VIF = VELI(3)                                                  MIS02190
0192          GO TO 270                                                      MIS02200
0193      263 KSI = 4                                                        MIS02210
0194          DI=DIF                                                         MIS02220
0195          UI = 1.0                                                       MIS02230
0196          VIF = VELI(4)                                                  MIS02240
0197      270 U(NU,2)=KSI                                                    MIS02250
        C     THIS RUN INITIALIZES V TO VMAX                                 MIS02260
0198          IF(INCBR .EQ. 1)VIZ=VELI(3)                                    MIS02270
0199          IF(INCBR .EQ. 1)VI=VIZ                                         MIS02280
0200          IF(INCBR .NE. 1)VIZ = VI                                       MIS02290
0201          INCBR = 2                                                      MIS02300
0202          IZO=2                                                          MIS02310
0203          IF(VI .GT. VIF)IZO=1                                           MIS02320
0204      275 TI = T                                                         MIS02330
0205          TF = T + DT                                                    MIS02340
0206          CALL RKI(X,TI,TF,DT)                                           MIS02350
0207          T = TF                                                         MIS02360
        C     DYNAMIC EQUATIONS                                              MIS02370
        C           KILL = 0   DEFAULT                                       MIS02380
        C           KILL = 1   AIRCRAFT WINS  (EXCEEDED TMAX)                MIS02390
        C           KILL = 2   AIRCRAFT WINS  (WARHEAD MISS )                MIS02400
        C           KILL = 3   AIRCRAFT LOSS  (WARHEAD HIT   )               MIS02410
0208          IF(KILL.EQ.0)  GO TO 230                                       MIS02420
0209          IF(MODE .EQ. 2)GO TO 475                                       MIS02430
0210          IF(KILL.NE.3)  CALL BIGI(SWU,WWIN,NU,WC)                       MIS02440
0211          IF(KILL.EQ.3)  CALL SMALLI(SWU,WLOSS,NU,WC)                    MIS02450
0212          DO 400 I=1,NU                                                  MIS02460
0213          IR = U(I,1)                                                    MIS02470
0214          IU = U(I,2)                                                    MIS02480
0215          DECI(IR,IU)=DECI(IR,IU)*SWU(I)                                 MIS02490
0216          DEN = DECI(IR,1)+DECI(IR,2)+DECI(IR,3)                         MIS02500
             1 + DECI(IR,4) + DECI(IR,5)                                     MIS02510
0217          DO 395 J=1,5                                                   MIS02520
0218      395 DECI(IR,J)=DECI(IR,J)/DEN                                      MIS02530
        C     NO ELEMENT OF THE DEC. TABLE CAN BE LESS THAN TST              MIS02540
        C     TST IS DEFINED IN DATA STATEMENT                               MIS02550
0219          IF(DECI(IR,1) .LT. TST .OR. DECI(IR,2) .LT. TST                MIS02560
             1 .OR. DECI(IR,3) .LT. TST .OR. DECI(IR,4) .LT. TST)GO TO 396   MIS02570
0220          IF(DECI(IR,5) .LT. TST)GO TO 396                               MIS02580
0221          GO TO 400                                                      MIS02590
0222      396 KD = 1                                                         MIS02600
0223          IF(DECI(IR,2).GT.DECI(IR,1))KD=2                               MIS02610
0224          IF(DECI(IR,3).GT.DECI(IR,KD))KD=3                              MIS02620
0225          IF(DECI(IR,4) .GT. DECI(IR,KD))KD=4                            MIS02630
0226          IF(DECI(IR,5) .GT. DECI(IR,KD))KD=5                            MIS02640
0227          DO 397 J=1,5                                                   MIS02650
0228          IF(DECI(IR,J).GE.TST)GO TO 397                                 MIS02660
```

```
0229            TM1 = TST - DECI(IR,J)                                        MIS02670
0230            DECI(IR,J)=TST                                                MIS02680
0231            DECI(IR,KD)=DECI(IR,KD)-TM1                                   MIS02690
0232      397   CONTINUE                                                      MIS02700
0233      400   CONTINUE                                                      MIS02710
0234      475   CONTINUE                                                      MIS02720
0235            IU = KRAN
          C          RT12(I,1) ----   RECORD OF THE NO. OF WINS DUE TO TMAX   MIS02740
          C          RT12(I,2) ----   RECORD OF THE NO. OF WINS DUE TO MISS   MIS02750
          C          RT12(I,3) ----   RECORD OF THE NO. OF LOSSES DUE TO A HIT MIS02760
          C          RT12(I,4) ----   THE AVERAGE MISS DISTANCE FOR RT12(I,2)  MIS02770
          C          RT12(I,5) ----   THE AVERAGE MISS DISTANCE FOR RT12(I,3)  MIS02780
0236            RT12(IU,KILL) = RT12(IU,KILL) + 1.E0                          MIS02790
0237            IF(KILL.EQ.2)  RT12(IU,4) =((RT12(IU,2)-1.E0)*RT12(IU,4) +    MIS02800
               1  RMIN)/RT12(IU,2)                                            MIS02810
0238            IF(KILL.EQ.3)  RT12(IU,5) =((RT12(IU,3)-1.E0)*RT12(IU,5) +    MIS02820
               1  RMIN)/RT12(IU,3)                                            MIS02830
0239            ITIME=ICHRON(0)                                               MIS02840
0240            FTIME=ITIME                                                   MIS02850
0241            FTIME=FTIME/600.                                              MIS02860
0242            IF(FTIME .GE. 50.)GO TO 502
0243            IF(IJKL .EQ. LOOP)GO TO 500
0244            IF(IJKL .NE.  2000*KNTOUT)GO TO 500                           MIS02880
0245            K= 2000*KNTOUT
0246            KNTOUT=KNTOUT+1
0247            WRITE(6,79)K                                                  MIS02910
0248       79   FORMAT(18H1 DEC TABLES AFTER      ,I7,9H SAMPLES   //)        MIS02920
0249            DO 505 I=1,NOREG                                              MIS02930
0250      505   WRITE(6,90)I,(DECI(I,J),J=1,5)                                MIS02940
0251            WRITE(6,78)K                                                  MIS02950
0252       78   FORMAT(25H1 STATISTC TABLES AFTER         ,I7,9H SAMPLES   //) MIS02960
0253            DO 507 I=1,NOREG                                              MIS02970
0254      507   WRITE(6,81)I,(RT12(I,J),J=1,5)                                MIS02980
0255      500   CONTINUE                                                      MIS02990
          C     THIS ENDS MAIN LOOP                                           MIS03000
0256            GO TO 503                                                     MIS03010
0257      502   WRITE(6,501)IJKL                                              MIS03020
0258      501   FORMAT(30HOTIME EXCEEDED NO. SAMPLES =       ,I7)             MIS03030
0259      503   CONTINUE                                                      MIS03040
          C     KT12 CONTAINS COUNT OF THE OUTCOMES WIN(TMAX),WIN(MISS),LOSS  MIS03050
          C     FOR PLAYER 1   PER  INITIAL REGION                            MIS03060
0260            WRITE(6,86)IDEN                                               MIS03070
0261       86   FORMAT(62H1  DECISION TABLE    PLAYER 1           AT THE END OFMIS03080
               1RUN       ,I10/45HOSLEFT, FLEFT, STRAIGHT, FRIGHT, SRIGHT     //)MIS03090
0262            DO 510 I=1,NOREG                                              MIS03100
0263            WRITE(6,90)I,(DECI(I,J),J=1,5)                                MIS03110
0264      510   WRITE(7,92)I,(DECI(I,K),K=1,5)                                MIS03120
0265            WRITE(6,85)IDEN                                               MIS03130
                                                                              MIS03140
```

```
FORTRAN IV G LEVEL  21                   MAIN                  DATE = 75101          21/37/03

0266         85 FORMAT(96H1   STATISTIC TABLE                   WIN(TMAX),WIN(MISS),LOSS   MIS03150
               1                            AT THE END OF RUN   ,I10)                       MIS03160
                                                                                            MIS03170
0267            IF(NPLS.EQ.1)  WRITE(6,70)                                                  MIS03180
0268            IF(NPLS.EQ.2)  WRITE(6,71)                                                  MIS03190
0269            DO 520 I=1,NORFG                                                            MIS03200
0270            WRITE(6,81)I,(RT12(I,J),J=1,5)                                              MIS03210
0271        520 WRITE(7,81)I,(RT12(I,K),K=1,5)                                              MIS03220
0272            WRITE(6,84)IDEN                                                             MIS03230
0273         84 FORMAT(54H1 PROBABILITIES   WIN(TMAX),WIN(MISS),WIN(TOTAL),LOSS    ,MIS03240
               1I10,//)                                                                     MIS03250
0274            WRITE(6,74)                                                                 MIS03260
0275         74 FORMAT(37H FOR PLAYER 1                                   ///)              MIS03270
0276            DO 550 K=1,NOREG                                                            MIS03280
0277            DEN1 = 0.                                                                   MIS03290
0278            DO 535 I=1,3                                                                MIS03300
0279        535 DEN1 = DEN1 + RT12(K,I)                                                     MIS03310
0280            IF(DEN1 .EQ. 0.)DEN1=1.                                                     MIS03320
0281            PBS(1) = RT12(K,1)/DEN1                                                     MIS03330
0282            PBS(2) = RT12(K,2)/DEN1                                                     MIS03340
0283            PBS(3) = (RT12(K,1)+RT12(K,2))/DEN1                                         MIS03350
0284            PBS(4) = RT12(K,3)/DEN1                                                     MIS03360
0285        550 WRITE(6,83)K,(PBS(I),I=1,4)                                                 MIS03370
0286         83 FORMAT(I5,4F9.5)                                                            MIS03380
0287        555 CONTINUE                                                                    MIS03390
0288            WRITE(6,96)IDEN,ACC1(1,1),ACC1(1,2),ACC1(2,1),ACC1(2,2),                    MIS03400
               1(VEL1(I),I=1,5),                          DIS,DIF                           MIS03410
0289            WRITE(6,95) WWIN,WLOSS                                                      MIS03420
0290            CALL EXIT                                                                   MIS03430
0291            END
```

```
FORTRAN IV G LEVEL  21                   OUTCOM              DATE = 75101          21/37/03

  0001                 SUBROUTINE OUTCOM(X,T,TF,IOC)                                         RKI01360
  0002                 COMMON  /BLK1/TMAX,ACC1,T1Z,V1Z,V1F,U1,V1,D1,RMIN,KILL,I20             RKI01370
  0003                 DIMENSION  X(12), ACC1(2,2)                                           RKI01380
  0004                 DATA  A/0.70E0/, R1/06.0E0/, R2/12.E0/
  0005                 IOC = 0                                                               RKI01400
  0006                 IF(ABS(X(7)).GT.3.4907E-1)  X(7) = ABS(X(7))/X(7)* 3.4907E-1          RKI01410
  0007                 VXL = V1*SIN(X(12)) - X(4)*COS(X(3))                                  RKI01420
  0008                 VYL = V1*COS(X(12)) - X(4)*SIN(X(3))                                  RKI01430
  0009                 XR = X(10) - X(1)                                                     RKI01440
  0010                 YR = X(11) - X(2)                                                     RKI01450
  0011                 RC = SQRT(XR**2 + YR**2)                                              RKI01460
  0012                 PSIC = ATAN2(YR,XR)                                                   RKI01470
  0013                 RDOT = (VXL*COS(PSIC) + VYL*SIN(PSIC))                                RKI01480
              C            KILL = 0   DEFAULT                                                RKI01490
              C            KILL = 1   AIRCRAFT WINS  (EXCEEDED TMAX)                         RKI01500
              C            KILL = 2   AIRCRAFT WINS  (WARHEAD MISS )                         RKI01510
              C            KILL = 3   AIRCRAFT LOSS  (WARHEAD HIT  )                         RKI01520
  0014                 KILL = 0                                                              RKI01530
  0015                 IF(RC.LT.48.E3)  GO TO 4
  0016                 KILL = 1
  0017                 GO TO 900
  0018        4        IF(T.LT.TMAX)  GO TO 5
  0019                 KILL = 1                                                              RKI01550
  0020                 GO TO 900                                                             RKI01560
  0021        5        IF(RC.LT.1.E3.AND.RDOT.GT.0.E0)  GO TO 10
  0022                 GO TO 900                                                             RKI01580
  0023       10        CONTINUE                                                              RKI01590
  0024                 DEN = VXL**2 + VYL**2                                                 RKI01600
  0025                 IF(DEN.EQ.0.E0)  GO TO 20                                             RKI01610
  0026                 TMIN = (-VYL*YR - VXL*XR)/DEN                                         RKI01620
  0027                 XM = X(1) + TMIN*X(4)*COS(X(3))                                       RKI01630
  0028                 YM = X(2) + TMIN*X(4)*SIN(X(3))                                       RKI01640
  0029                 XT = X(10) + TMIN*V1*SIN(X(12))                                       RKI01650
  0030                 YT = X(11) + TMIN*V1*COS(X(12))                                       RKI01660
  0031                 RMIN = SQRT((XT-XM)**2 + (YT-YM)**2)                                  RKI01670
  0032                 TMIN = T + TMIN                                                       RKI01680
  0033                 IF(RMIN.LT.R1)  PK = A                                                RKI01690
  0034                 IF(RMIN.GE.R1.AND.RMIN.LE.R2)  PK = (A*(R2-RMIN)**2)
                     1     /((R2-R1)**2)                                                     RKI01710
  0035                 IF(RMIN.GT.R2)  PK = 0.E0                                             RKI01720
  0036                 RNUM = RDM(DUM)                                                       RKI01730
  0037                 KILL = 2                                                              RKI01740
  0038                 IF(RNUM.LE.PK)  KILL = 3                                              RKI01750
  0039                 GO TO 900                                                             RKI01760
  0040       20        KILL = 1                                                              RKI01770
  0041                 WRITE(8,200)                                                          RKI01780
  0042      200        FORMAT(5X,'NO COLLISION     PARALLEL COURSES WITH EQUAL SPEED')       RKI01790
  0043      900        IF(KILL.NE.0)  IOC = 1                                                RKI01800
```

```
0044      RETURN                                   RK101810
0045      END                                      RK101820
```

```
      SUBROUTINE FUNC(F,X,T)                                            RK100740
      COMMON  /BLK1/TMAX,ACC1,T1Z,V1Z,VIF,U1,V1,D1,RMIN,KILL,IZO        RK100750
      DIMENSION F(12),X(12),ACC1(2,2)                                   RK100760
      DATA OLDC/0.E0/                                                   RK100770
      DATA PI/3.1415926E0/, TWOPI/6.2831853E0/
      DATA RHO/1.518E-3/, S/0.1644E0/
      TIME = T                                                          RK100800
      AMACH = X(4)/1.058E3                                              RK100830
      TYME=T-T1Z                                                        RK100840
      V1=.5*ACC1(IZO,1)*TYME**2+ACC1(IZO,2)*TYME+V1Z                    RK100850
      IF(IZO .EQ. 2  .AND.  V1 .GT. VIF)V1=VIF                          RK100860
      IF(IZO .EQ. 1  .AND.  V1 .LT. VIF)V1=VIF                          RK100870
      V1OR1 = V1/D1                                                     RK100880
      TERM1 = U1 * V1OR1                                                RK100890
      XR = X(10) - X(1)                                                 RK100900
      YR = X(11) - X(2)                                                 RK100910
      RC = SQRT(XR**2 + YR**2)                                          RK100920
      VXL = V1*SIN(X(12)) - X(4)*COS(X(3))                              RK100930
      VYL = V1*COS(X(12)) - X(4)*SIN(X(3))                              RK100940
      PSIC = ATAN2(YR,XR)                                               RK100950
      PSIDOT = (-VXL*SIN(PSIC) + VYL*COS(PSIC))/RC                      RK100960
      X(5) = RC
      X(6) = PSIC
      X(7) = PSIDOT
      THRUST = 2820.E0                                                  RK100970
      IF(TIME.GT.5.2E0)  THRUST = 0.E0                                  RK100980
      AMASS = 6.211E0 - 0.3584E0*TIME                                   RK100990
      IF(TIME.GT.5.2E0)  AMASS = 4.347E0                                RK101000
      CD0 = 8.E-1                                                       RK101010
      IF(AMACH.GT.1.0E0)  CD0 = 1.3E0                                   RK101020
      CDI = 80.E0                                                       RK101030
      IF(AMACH.GT.1.E0)  CDI = 80.E0 - 13.6E0*(AMACH-1.0E0)             RK101040
      IF(ABS(X(7)).GT.3.4907E-1)  X(7) = ABS(X(7))/X(7)* 3.4907E-1      RK101050
      CACEL = 4.E0*X(7)                                                 RK101060
      CACELV = CACEL*X(4)                                               RK101070
      IF(ABS(CACELV).GT.9.66E2)  CACEL = ABS(CACEL)/CACEL*(9.66E2/X(4)) RK101080
      IF(TIME.LE.2.E0)  CACEL = 0.E0                                    RK101090
      IF(PSIC.LT.0.E0)  PSIC = PSIC + TWOPI                             RK101110
      GAMMA = X(3)                                                      RK101120
   10 IF(GAMMA.GT.TWOPI)  GAMMA = GAMMA - TWOPI                         RK101130
      IF(GAMMA.LT.0.E0)   GAMMA = TWOPI + GAMMA                         RK101140
      IF(GAMMA.LT.0.E0.OR.GAMMA.GT.TWOPI)  GO TO 10                     RK101150
      AOFF = ABS(GAMMA - PSIC)                                          RK101160
      IF(AOFF.GT.PI)  AOFF = TWOPI - AOFF                               RK101170
      IF(AOFF.GT.0.69813E0)  CACEL = 0.E0                               RK101180
      PHI = X(12)
   15 IF(PHI.GT.TWOPI)  PHI = PHI - TWOPI
      IF(PHI.LT.0.E0)  PHI = TWOPI + PHI
```

FORTRAN IV G LEVEL 21   FUNC   DATE = 75101   21/37/03

```
                  IF(PHI.LT.0.E0.OR.PHI.GT.TWOPI)  GO TO 15
                  ALPHAC = PI/2.0E0 - PHI - GAMMA
         20       IF(ALPHAC.GT.TWOPI)  ALPHAC = ALPHAC - TWOPI
                  IF(ALPHAC.LT.0.E0)  ALPHAC = TWOPI + ALPHAC
                  IF(ALPHAC.LT.0.E0.OR.ALPHAC.GT.TWOPI)  GO TO 20
                  SAT = 1125.0E0 + 875.E0*SIN(2.E0*(ALPHAC-(PI/4.E0)))
                  IF(ALPHAC.GT.1.5708E0.AND.ALPHAC.LT.4.71239E0)  SAT = 2000.E0
                  IF(RC.LT.SAT)  CACEL = 0.E0
                  OLDC = CACEL                                                RKI01190
                  F(1) = X(4)*COS(X(3))                                       RKI01200
                  F(2) = X(4)*SIN(X(3))                                       RKI01210
                  F(3) = X(8)                                                 RKI01220
                  F(4) = (-(RHO*S*X(4)**2*CD0/(2.E0*AMASS)) -(2.E0*AMASS*CACEL**2 RKI01230
                 1 /(RHO*S*CDI)) +(THRUST/AMASS))                             RKI01240
                  F(5) = 0.E0
                  F(6) = 0.E0
                  F(7) = 0.E0
                  IF(ABS(X(7)).GT.3.4907E-1)  F(7) = 0.E0                     RKI01280
                  F(8) = (1.E0/0.3E0)*(1.0E0*CACEL-X(8))                      RKI01290
                  F(9) = 1.0E0                                                RKI01300
                  F(10) = V1*SIN(X(12))                                       RKI01310
                  F(11) = V1*COS(X(12))                                       RKI01320
                  F(12) = TERM1                                               RKI01330
                  RETURN                                                      RKI01340
                  END                                                         RKI01350
```

```
FORTRAN IV G LEVEL  21                  RKI                    DATE = 75101          21/37/03
 0001              SUBROUTINE RKI(X,TI,TF,HSTEP)                                          RKI00010
             C                                                                            RKI00020
             C   THIS SUBROUTINE INTEGRATES THE FOLLOWING EQUATIONS                       RKI00030
             C                                                                            RKI00040
             C            XDOT = F(X,T)              = F                                  RKI00050
             C                                                                            RKI00060
             C   WHICH PROVIDES THE VALUE OF THE FUNCTIONS AT THE                         RKI00070
             C   FINAL TIME ,TF,                                                          RKI00080
             C                                                                            RKI00090
             C            X(TF)   SOLUTION TO THE NONLINEAR EQU.                          RKI00100
             C                                                                            RKI00110
             C   THE FUNCTION  F MUST BE SUPPLIED BY A SUBROUTINE WITH                    RKI00120
             C   THE NAME     SUBROUTINE FUNC(F,X,T)                                      RKI00130
             C                                                                            RKI00140
             C   DEFINITION OF THE ARGUMENTS IN THE CALL STATEMENT                        RKI00150
             C                                                                            RKI00160
             C            X = X(TI)                                                       RKI00170
             C           TI - INITIAL TIME                                                RKI00180
             C           TF - FINAL TIME                                                  RKI00190
             C           HS - INTEGRATION STEPSIZE                                        RKI00200
             C                                                                            RKI00210
             C   AFTER THE INTEGRATION IS COMPLETED THE OUTPUT IS                         RKI00220
             C                                                                            RKI00230
             C            X = X(TF)                                                       RKI00240
             C                                                                            RKI00250
             C                                                                            RKI00260
             C   THE LENGTH OF THE STATE VECTOR MUST BE SPECIFIED BY                      RKI00270
             C      THE STATEMENT  ML =   OR PUT IN THE CALL STATEMENT.                   RKI00280
             C                                                                            RKI00290
             C                                                                            RKI00300
 0002              DIMENSION F(12), QX(12,4), X(12), YX(12)                               RKI00310
 0003              ML = 12                                                                RKI00320
 0004              H = HSTEP                                                              RKI00330
 0005              H2 = H/2.0E0                                                           RKI00340
 0006              T = TF - TI                                                            RKI00350
 0007              IF(T.EQ.0.0E0)  GO TO 900                                              RKI00360
 0008              TNS = ABS(T/H) + 1.0E-4                                                RKI00370
 0009              JS = TNS                                                               RKI00380
 0010              TJ = JS                                                                RKI00390
 0011              TT = TI                                                                RKI00400
 0012              KZ = 0                                                                 RKI00410
 0013              IF(JS.EQ.0) GO TO 200                                                  RKI00420
 0014           12 KZ = KZ + 1                                                            RKI00430
 0015              TIME = TT                                                              RKI00440
 0016              DO 70  IA=1,4                                                          RKI00450
 0017              KA = IA - 1                                                            RKI00460
 0018              GO TO (20,30,30,40), IA                                                RKI00470
 0019           20 HA = 0.0E0                                                             RKI00480
```

```
      KA = 1
      GO TO 50
   30 HA = H2
      GO TO 50
   40 HA = H
   50 DO 60  I=1,ML
   60 YX(I) = X(I) + HA*QX(I,KA)
      TT = TIME + HA
      CALL FUNC(F,YX,TT)
      DO 70  I=1,ML
   70 QX(I,IA) = F(I)
      DO 80  I=1,ML
   80 F(I) = (QX(I,1)+2.0E0*QX(I,2)+2.0E0*QX(I,3)
     1           +QX(I,4))/6.0E0
      DO 100  I=1,ML
  100 X(I) = X(I) + H*F(I)
      CALL OUTCOM(X,TT,TF,IQC)
      IF(IQC.EQ.1)  GO TO 900
      IF(KZ.EQ.JS+1)  GO TO 900
      IF(KZ.NE.JS)    GO TO 12
  200 H = T - IJ*H
      H2 = H/2.0E0
      GO TO 12
  900 RETURN
      END
```

```
 0001              SUBROUTINE SMALL1(S,W,N,WC)                                MIS04240
 0002              DIMENSION S(500)                                           MIS04250
 0003              IF(N .LE. 0)GO TO 30                                       MIS04260
 0004              C = N                                                      MIS04270
 0005              C = W/C                                                    MIS04280
 0006              C=C*WC                                                     MIS04290
 0007              DO 100 I=1,N                                               MIS04300
 0008              F = I                                                      MIS04310
 0009              IF(W .EQ. 1.)C=0.                                          MIS04320
 0010          100 S(I) = 1. - F*C                                            MIS04330
             C                                         )N,1=I,)I(S()99,6(ETIMIS04340
 0011           99 FORMAT(10H SMALL S =/(1P6E20.7))                           MIS04350
 0012           30 RETURN                                                     MIS04360
 0013              END                                                        MIS04370
```

FORTRAN IV G LEVEL 21 BIG1 DATE = 75101 21/37/03

```
      SUBROUTINE BIG1(S,W,N,WC)                                        MIS04110
      DIMENSION S(500)                                                 MIS04120
      IF(N .LE. 0)GO TO 30                                             MIS04130
      C = N                                                            MIS04140
      C =(W-1.)/C                                                      MIS04150
      C=C*WC                                                           MIS04160
      DO 100 I=1,N                                                     MIS04170
      F = I                                                            MIS04180
  100 S(I) = 1. + F*C                                                  MIS04190
C                                               )N,1=I,)I(S()99,6(ETIMIS04200
   99 FORMAT( 9H  BIG S =/(1P6E20.7))                                  MIS04210
   30 RETURN                                                           MIS04220
      END                                                              MIS04230
```

```
      SUBROUTINE ROT(N,M,ROE,OMG,THE)
      DIMENSION M(11,12,1),R(12),O(13),T(2)
      DATA R/0.,250.,500.,1000.,2000.,3000.,5000.,8000.,
     112000.,16000.,24000.,48000./
      DATA O/0.,30.,60.,90.,120.,150.,180.,210.,240.,270.,
     1300.,330.,360./
      DATA T/0.,0./
      I3 = 1
      DO 100 I1=1,11
      DO 100 I2=1,12
      K = M(I1,I2,I3)
      IF(K .EQ. N)GO TO 110
  100 CONTINUE
  110 ROE = R(I1) + RDM(DUM) * (R(I1+1)-R(I1))
      OMG = O(I2) + RDM(DUM) * (O(I2+1)-O(I2))
      THE = T(I3) + RDM(DUM) * (T(I3+1)-T(I3))
      RETURN
      END
```

```
0001              SUBROUTINE REG(N,ROE,OMG,THE)                                          MISO3620
0002              DIMENSION R(12),O(13)                                                  MISO3630
0003              DATA R/0.,250.,500.,1000.,2000.,3000.,5000.,8000.,                     MISO3640
                 112000.,16000.,24000.,48000./                                           MISO3650
0004              DATA O/0.,30.,60.,90.,120.,150.,180.,210.,240.,270.,                   MISO3660
                 1300.,330.,360./                                                        MISO3670
0005              IF(R(1) .GT. ROE .OR. ROE .GT. R(12)                                   MISO3680
                 1.OR. O(1).GT. OMG  .OR. OMG .GT. O(13))GO TO 30                        MISO3690
0006              IF(ROE.NE.0.E0)  GO TO 90                                              MISO3700
0007              NR = 1000                                                              MISO3710
0008              GO TO 110                                                              MISO3720
0009           90 DO 100 I=1,11                                                          MISO3730
0010              IF(ROE .LE. R(I) .OR. ROE .GT. R(I+1))GO TO 100                        MISO3740
0011              NR = I * 1000                                                          MISO3750
0012              GO TO 110                                                              MISO3760
0013          100 CONTINUE                                                               MISO3770
0014          110 IF(OMG .NE. O(1))  GO TO 115                                           MISO3780
0015              NO = 10                                                                MISO3790
0016              GO TO 130                                                              MISO3800
0017          115 DO 120 I=1,12                                                          MISO3810
0018              IF(OMG .LE. O(I) .OR. OMG .GT. O(I+1))GO TO 120                        MISO3820
0019              NO = I * 10                                                            MISO3830
0020              GO TO 130                                                              MISO3840
0021          120 CONTINUE                                                               MISO3850
0022          130 NT = 1                                                                 MISO3860
0023              N = NR + NO + NT                                                       MISO3870
0024              RETURN                                                                 MISO3880
0025           30 WRITE(6,99)ROE,OMG                                                     MISO3890
0026           99 FORMAT(1H0///19H ERROR IN REG,ROE =,1PE18.5,  6H OMG =,1PE18.5)        MISO3900
0027              CALL EXIT                                                              MISO3910
0028              END                                                                    MISO3920
```

```
FORTRAN IV G LEVEL  21                    IN                    DATE = 75101          21/37/03

0001              SUBROUTIN   ,N(M)                                                     MISO3440
0002              DIMENSIO    (I1,I2,1)                                                 MISO3450
0003              I3 = 1                                                                MISO3460
0004              K = 0                                                                 MISO3470
0005              DO 100 I1=1,I1                                                        MISO3480
0006              DO 100 I2=1,I2                                                        MISO3490
0007              K = K + 1                                                             MISO3500
0008          100 M(I1,I2,I3) = K                                                       MISO3510
0009              IF(K .NE. 0)GO TO 120                                                 MISO3520
0010              WRITE(6,99)K                                                          MISO3530
0011           99 FORMAT(52H1 SUBROUTINE INI DEFINES THE FOLLOWING ORDER FOR THE ,      MISO3540
                 1I4,10H ROWS OF M //29H  I1, I2, I3        M(I1,I2,I3) // )            MISO3550
0012              DO 110 I1=1,I1                                                        MISO3560
0013              DO 110 I2=1,I2                                                        MISO3570
0014          110 WRITE(6,98)I1,I2,I3,M(I1,I2,I3)                                       MISO3580
0015           98 FORMAT(10X,3I5,15X,I5)                                                MISO3590
0016          120 RETURN                                                                MISO3600
0017              END                                                                   MISO3610
```