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HEURISTIC APPROACH TO THE
DEVELOPMENT OF RATINGS AND TACTICS APPLICABLE TO THE
ONE-ON-ONE AERIAL COMBAT (DOGFIGHT) ENCOUNTER

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Summary

Computer simulation of the one-on-one aerial combat encounter is now a routine performance assessment tool for advanced air-superiority fighters. These simulations are generated under the control of specified guidance laws. Given an initial state, the vehicle and atmospheric characteristics, and the guidance laws the aerial combat encounter, or dogfight, is then simulated by forward integration of the two vehicles' motion. Many guidance laws tend to develop "scissor-like" aircraft maneuvers as each vehicle seeks to obtain a firing opportunity in the shortest elapsed time. When one vehicle is advantaged it is possible that a delay in achieving a firing opportunity will result in the achievement of a better firing opportunity as measured by success probability. Generally these improved firing opportunities occur when the attacker achieves a tail position on his opponent.

This report describes the development of a combat guidance law which converts positional advantage into an improved firing opportunity by delaying the time at that opportunity. A combination of lag, line-of-sight, and lead pursuit steering paths are followed in the guidance law. Generally, the guidance law is based on the use of parameters which are familiar to the combat pilot. These parameters include steering error, target angle-off and the relative velocities. The guidance law is therefore in a form which can readily be automated either as an on-board aid to manned aircraft pilots or as a combat guidance law for unmanned vehicles.

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PREFACE

This report was prepared under Contract NAS 2-9223, A Study into the Applicability of Three-Dimensional Combat Analysis and Differential Game Theory to Advanced Weapon Systems. The report discusses several rating functions which may be applied to the analysis of aerial combat encounters and develops a heuristic guidance law developed to achieve a tail attack position on an opponent.

The tail attack guidance law is applied to an encounter involving an advanced manned fighter aircraft and a remotely piloted vehicle (RPV) having superior maximum load factor capability. It is shown that the new guidance law allows the RPV to achieve and hold a tail attack position in thirty seconds from an initial position of geometric and kinematic equality. For comparison using the same initial position, a straight-forward line-of-sight attack results in a series of high angle-off low kill probability passes of the scissors type. The newly developed tail attack guidance law involves a combination of lead pursuit, line-of-sight, lag pursuit, and throttle control laws with control law selection dependent on a partitioning of state space primarily in the angle-off/steering error plane.

Mr. Michael E. Tauber of NASA Ames Research Center acted as the government technical monitor for the study and assisted in evaluation of the new control law. Mr. D. S. Hague was the Aerophysics Research Corporation principal investigator for this work.

HEURISTIC APPROACH TO THE
DEVELOPMENT OF RATINGS AND TACTICS APPLICABLE TO THE
ONE-ON-ONE AERIAL COMBAT (DOGFIGHT) ENCOUNTER

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Introduction

Various combat rating functions can be used to measure the outcome of a one-on-one dogfight, for example, time to first firing opportunity or time within weapon system firing constraints. However, a given vehicle may be equipped with a variety of weapon systems; hence, there is a need for a dogfight rating which measures the intrinsic maneuver capability of the vehicle independent of the particular weapon system being employed. The construction of such a criteria is discussed in this report.

The simplest criteria provides a measure of the relative time each of the two combatants maintains his opponent within a cone of specified angle. It is thus an integral measure of combat performance over a given encounter or series of encounters. The measure is non-dimensionalized to provide a combat rating for each vehicle. This measure varies in the range

$$0 \leq R_C \leq 100 \quad (1)$$

where R_C is the combat rating.

This measure provides only a qualitative indicator for vehicle performance. The actual outcome of a dogfight depends on many additional factors which are not included in the combat rating, for example,

1. Pilot skill in flight control, weapon system usage, and initial condition control together with pilot determination and will to succeed.
2. Detailed weapon system characteristics.
3. Luck with regard to the actual initial conditions experienced in an encounter or the quality of an opposing pilot.

A combat encounter in the "Combat Optimization and Analysis Program," COAP, ref. 1 occurs between two vehicles in three-dimensional space. Pilot and vehicle characteristics are specified independently for each vehicle, Figure 1. The manner in which the COAP program

generates a dogfight is illustrated in Figure 2. An instantaneous steering vector is defined on the basis of vehicle state and the opponent's state. Given instantaneous steering vectors each vehicle first banks to maximize acceleration along this vector. Then, second pitches to maximize steering vector acceleration. This process has the approximate effect of maintaining the steering vectors in each vehicle's plane of symmetry through the canopy. It also tends to produce maximum angle-of-attack maneuvers for large steering errors subject to pilot and vehicle flight limitations.

Figure 3 illustrates some typical steering vectors which may be employed to produce a simulated dogfight. They include lag, line of sight, and lead vectors. Selection of a particular vector should depend on the relative state of each vehicle. Steering vector selection will be discussed later in this report.

Typical Dogfight

A typical dogfight between two vehicles is presented in Figure 4. Vehicle characteristics and capabilities are representative of a remote piloted vehicle and an advanced manned fighter. The highly dynamic nature of the dogfight is readily apparent. Total flight time is forty seconds. The periods of low steering error conditions, which must be satisfied for an attack, are shown by the hatched regions of the combat.

Some very significant parameters from the pilot's viewpoint are separation distance, closing rates, cone angle to target, and target aspect angle. These parameters are illustrated in Figure 5. It is well known that pilots prefer a tail attack; that is, with $\phi_{\text{off}} \approx 0.0$; however, many of the combat aces were expert deflection shots with machine gun or cannon. Hence, it is assumed that the most important angle from the pilot's aspect is the steering error to the target, or better still, the steering error to the firing vector.

A history of the four combat parameters, illustrated in Figure 5. for each vehicle during the dogfight of Figure 4 are presented in Table I. This dogfight is generated by both vehicles locally maximizing the line of sight acceleration throughout the dogfight. Several points are worth noting. First, the firing opportunities as measured by minimum steering error conditions all occur at large angle-off values; that is, neither vehicle can achieve a tail attack. This behavior is typical of combative encounters generated by line of sight steering. This tactic tends to generate a series of scissor-like maneuvers. Second, it may be noted that the range is moderate for all firing opportunities. Third, all firing opportunities occur at high closing velocities.

Combat parameter values for each opportunity are illustrated in Table II. This figure also contains path integrals of the time that each vehicle is able to maintain his opponent within a given steering error. These path integrals are defined by

$$I_{\bar{\theta}} = \int dt; \quad \theta_c \leq \bar{\theta} \quad (2)$$

Integrals for a 10°, 20°, and 30° steering error are included in Table II.

VEHICLE 1				VEHICLE 2			
ANGLE-OFF	STEERING ERROR	SEPARATION DISTANCE	CLOSING VELOCITY	ANGLE-OFF	STEERING ERROR	SEPARATION DISTANCE	CLOSING VELOCITY
90.00000	90.00000	7313.428	0.0	90.00000	90.00000	7313.428	0.0
87.93857	84.86401	7372.592	-45.32890	95.13599	92.06143	7372.592	-45.32890
75.10096	85.89341	7335.794	143.3095	94.10659	104.88990	7335.794	143.3095
61.26468	88.48879	7093.234	339.8992	91.51121	118.7353	7093.234	339.8992
47.31051	92.08274	6661.854	521.9207	87.91727	132.8895	6661.854	521.9207
33.13033	96.89423	6055.813	688.1812	83.15777	146.8697	6055.813	688.1812
18.75527	102.8290	5295.071	829.2855	77.17096	161.2447	5295.071	829.2855
4.165422	110.2481	4410.325	934.2153	69.75186	175.8342	4410.325	934.2153
8.91722	117.6193	3429.766	1018.518	62.58074	171.0803	3429.766	1018.518
8.232126	120.4373	2393.793	1045.710	59.56274	171.7679	2393.793	1045.710
12.14210	115.7578	1364.089	992.4842	64.24219	167.8579	1364.089	992.4842
50.78761	72.01684	571.7985	335.2688	107.9832	129.2124	571.7985	335.2688
111.3165	7.181642	975.4675	-770.3486	172.6184	68.68347	975.4675	-770.3486
111.6054	25.42894	1741.833	-710.8825	154.5711	68.39462	1741.833	-710.8825
99.85798	45.43168	2334.737	-459.3209	134.5683	80.14202	2334.737	-459.3209
83.66290	66.15891	2630.045	-108.5851	113.8401	96.33710	2630.045	-108.5851
64.85308	84.83027	2247.909	272.8509	95.16973	115.1469	2247.909	272.8509
43.78359	99.50695	2098.190	614.0011	80.49305	136.2104	2098.190	614.0011
19.59888	104.6929	1354.841	815.6494	75.30709	160.4011	1354.841	815.6494
42.29184	74.25988	644.0096	404.6605	105.7401	137.7082	644.0096	404.6605
109.2537	14.62133	933.2484	-714.2630	165.3787	70.74633	933.2484	-714.2630
107.9794	30.50943	1653.854	-645.5545	149.4906	72.02061	1653.854	-645.5545
93.38291	52.61304	2158.022	-337.6333	127.5870	86.61709	2158.022	-337.6333
84.1473	72.90837	2319.854	-62.17446	107.0916	95.85527	2319.854	-62.17446
99.48929	92.14462	2442.486	-117.2636	87.85538	80.51001	2442.486	-117.2636
109.7841	112.5162	2555.958	-112.2735	67.48376	70.21588	2555.958	-112.2735
108.8879	135.3974	2604.490	55.04712	44.60258	71.11210	2604.490	55.04712
100.8648	162.0904	2416.251	305.5006	17.90957	79.13515	2416.251	305.5006
99.57604	166.4967	2058.259	366.7775	13.50527	80.42396	2058.259	366.7775
110.3156	132.3747	1803.807	80.82078	47.62529	69.68440	1803.807	80.82078
126.5486	101.5920	1970.741	-396.3898	78.40805	53.45145	1970.741	-396.3898
134.0004	88.83289	2492.821	-599.8380	91.16711	45.99957	2492.821	-599.8380
133.7816	59.83636	3214.746	-867.8933	120.1636	46.21840	3214.746	-867.8933
126.7712	52.73787	4089.996	-830.9986	127.2621	53.22883	4089.996	-830.9986
124.2444	58.19525	4910.926	-769.1505	121.8047	50.75559	4910.926	-769.1505
117.1215	64.49829	5583.232	-580.9955	115.5017	62.87866	5583.232	-580.9955
102.6560	70.65280	6060.675	-347.6488	109.3472	77.34401	6060.675	-347.6488
83.72939	76.73167	6265.995	-60.89572	103.2683	96.27061	6265.995	-60.89572
63.89613	82.75752	6182.144	228.9994	97.24248	116.1033	6182.144	228.9994
43.43292	89.26661	5813.268	504.7494	90.73319	136.5671	5813.268	504.7494

TABLE I. HISTORY OF COMBAT PARAMETERS

VEHICLE 1 (RPV)				VEHICLE 2 (VEH. Z)			
Opportunity	Time	Steering Error	Target Angle-Off	Opportunity	Time	Steering Error	Target Angle-Off
1	7.0	4.2	110.2	1	9.0	59.6	171.8
2	18.0	19.6	104.7	2	18.0	75.3	160.4
3	28.0	99.6	166.5	3	28.0	13.5	80.4
4	40.0	24.8	97.1	4	40.0	82.9	155.2
$\int dt = 2.33$ $\int dt = 5.67$ $\int dt = 6.67$				$\int dt = .67$ $\int dt = 1.67$ $\int dt = 1.83$			
10° 20° 30°				10° 20° 30°			
DESCRIPTION: RPV versus VEHICLE Z: THROTTLE DOWN AT M = .7 (BOTH)							

TABLE II. TYPICAL COMBAT RATING PARAMETERS

Combat Rating

Based on Steering Error. It can be seen that for the type of dogfight considered in the previous section, the line of sight attack, that steering error is the dominant factor in assessing combat outcome. Now, the actual steering error values at a given opportunity are sensitive to initial conditions; however, the integral of the time within a given steering error is less dependent on the selected initial conditions but remains an effective measure of the dogfight outcome. Thus, a global combat rating, applicable to a wide range of encounters, could be based on the steering error integrals.

In the encounter of Table II the steering error integrals for $\bar{\theta} = 10^\circ$, 20° , and 30° are roughly in proportion to each other for each vehicle. This has been found to be usually true on a wide range of encounters. It seems reasonable to assume that the $\bar{\theta} = 30^\circ$ integral will be a less sensitive measure of combat performance than the integrals within the smaller steering error cones. Hence, the following definition may be employed for producing a combat rating for each vehicle

$$R_{C1} = 100 \times \frac{\int dt_2}{T_c} ; \bar{\theta}_1 < 30^\circ \quad (3)$$

$$R_{C2} = 100 \times \frac{\int dt_2}{T_c} ; \bar{\theta}_2 < 30^\circ \quad (4)$$

where each integration extends only over the period in which the corresponding inequality is satisfied and T_c is the total combat duration; R_{C1} and R_{C2} therefore measure the per cent time each vehicle satisfies its inequality function during the dogfight.

The vehicle having the highest combat rating is assumed to be the winner in a given encounter.

Based on Steering Error and Angle-Off. While a low steering error is essential to obtain a firing opportunity, it is not the only desirable characteristic. Weapon system firing constraints and the dynamics of an encounter both indicate the desirability of also obtaining a tail position

(low angle-off) on the opponent. The advantage of simultaneously achieving low steering error and low angle-off is graphically illustrated in Figure 6. Here, the diagonal line defines the locus of points in which a vehicle and its opponent have equality in the angle-off/steering error plane when steering error is measured from the line of sight vector. In the shaded half plane a vehicle has the advantage; in the other half plane a vehicle is disadvantaged. The amount of advantage or disadvantage may be measured by perpendicular distance from the diagonal line of equality to any point in the plane.

The advantage of simultaneously attaining low steering error and angle off can be incorporated into the rating function integrals of Equations (3) and (4) by replacing the inequalities $\bar{\theta}_1$ and $\bar{\theta}_2 < 30^\circ$ by the simultaneous inequalities

$$\theta_{c1} \text{ and } \phi_{\text{off}1} < 30^\circ$$

$$\theta_{c2} \text{ and } \phi_{\text{off}2} < 30^\circ$$

This is the rating currently being used in combat studies for Ames Research Center. Other inequalities could be imposed on the period of integration without difficulty. Some additional possibilities are discussed in the next section.

An alternative approach to rating the outcome of an aerial combat encounter is to employ actual kill probability estimates. This approach is discussed in some detail in reference 2 where encounters involving cannon, missiles, and advanced wide field of fire weapons are considered. This more detailed approach involves determination of "co-kill probabilities" where each vehicle exchanges fire with the other.

Other Combat Rating Functions

Since one object of the combative encounter is to reduce the steering error as much as possible, it could be argued that the more sensitive 10° cone integral should be employed; that is,

$$C_{Rj} = \frac{\int dt_j}{\int dt_1 + \int dt_2} \quad \theta_c \leq 10^\circ \quad (5)$$

A more sophisticated approach would be to employ a rating of the form

$$C_{Rj} = \frac{W_1 I_{1j} + W_2 I_{2j} + W_3 I_{3j}}{W_1 (I_{11} + I_{12}) + W_2 (I_{21} + I_{22}) + W_3 (I_{31} + I_{32})} \quad (6)$$

where $I_{ij} = \int dt_j$; $\theta < \bar{\theta}_i$.

The improved performance available at low steering errors can then be reflected through the weighting constants. Again, it could be argued that the steering error at the first opportunity is more significant than that at the second opportunity, etc. This can be recognized by creating a rating function of the form

$$R_{cj} = \frac{W_1 \theta_{c1j} + W_2 \theta_{c2j} + W_3 \theta_{c3j}}{W_1 (\theta_{c11} + \theta_{c12}) + W_2 (\theta_{c21} + \theta_{c22}) + W_3 (\theta_{c31} + \theta_{c32})} \quad (7)$$

where θ_{cij} is the steering error at i^{th} opportunity for the j^{th} vehicle.

Finally, the combat rating could, of course, be based on the actual weapon system firing constraints and probabilities of success at each opportunity. This approach requires information which is not always available with reliability at the preliminary design stage. When this approach is deemed advisable, it should be noted that Aerophysics Research Corp. (ref. 2) has constructed a series of computer programs which allow a given combat encounter to be "played back" with various weapon systems. However, in using this approach it should be borne in mind that the optimal steering

vector for each weapon would tend to differ. Thus, for example, the line of sight acceleration maximization tactic used in the Figure 4 dogfight could be more appropriate to one weapon than to another.

Tactics to Achieve Improved Combat Rating

It has been noted previously that line of sight steering tends to produce a sequence of scissor-like maneuvers. These maneuvers do not necessarily lead the advantaged vehicle to the low steering error, low angle-off condition discussed in the combat rating section. Tactics which do lead to this condition could readily be devised by employing the multi-variable search capability of the COAP program; however, the preliminary nature of the present studies and the relatively high cost of computer time required for tactic optimization studies dictated a trial and error approach to tactic selection.

Throttle Control. Early in the development of improved tactics, it became obvious that a throttling logic must be developed; otherwise, the vehicle having the acceleration advantage would achieve a higher velocity than its opponent. At the higher speed it could become out-turned by its slower opponent if both have the ability to reach and pull the same normal acceleration, \bar{g}_n . For turning rate, σ , is

$$\dot{\sigma} = \frac{F_n}{mV} = \frac{\bar{g}_n}{V}$$

and for two vehicles pulling the same normal acceleration

$$\frac{\dot{\sigma}_1}{\dot{\sigma}_2} = \frac{V_2}{V_1}$$

More generally

$$\frac{\dot{\sigma}_1}{\dot{\sigma}_2} = \left(\frac{\bar{g}_{n1}}{\bar{g}_{n2}} \right) \left(\frac{V_2}{V_1} \right)$$

On the other hand, when the vehicles are not \bar{g} limited, speed becomes an advantage, for then

$$F_N \propto V^2$$

and

$$\dot{\sigma} \propto V$$

Thus, up to the speed at which the maximum load factor, or buffet angle of attack schedule is achieved, the turn rate is improved by speeding up.

These considerations and those of the following subsection lead to the following rules for throttling:

1. Don't throttle back unless advantaged in the steering error angle-off plane
2. Throttle to match opponent's velocity when advantaged.

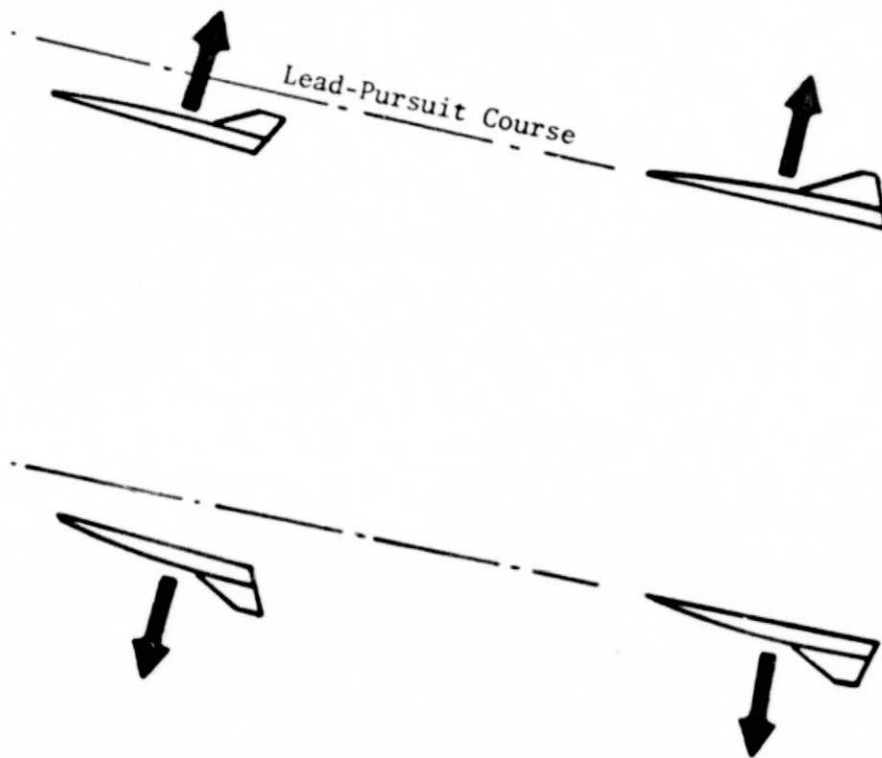
These simple rules appeared sufficient for the studies undertaken. In more detailed studies the effect of CL_{max} versus Mach number would have to be considered. CL_{max} is usually smallest in the transonic region. Thus, a supersonic aircraft throttling back may or may not improve its turn rate depending on the rate at which CL_{max} decreases with falling Mach number. (Again, an accelerating subsonic aircraft which is not g limited may or may not improve its turn rate depending on how rapidly CL_{max} falls with increasing Mach number.

Steering Vector Selection to Attain a Tail Position. The key to achieving a tail position is the judicious use of lag pursuit steering. This is illustrated in Figure 7 where the encounter of Figure 4 is rerun with the RPV using lag pursuit steering. Within 31 seconds the RPV achieves and maintains a tail position on vehicle Z. It should be noted that in the simulations of Figures 4 and 7, both vehicles are initially equally placed in the angle-off/steering error plane. The normal g advantage lies with the RPV and this allows it to perform a successful conversion onto vehicle Z's tail using simple lag pursuit.

With more evenly matched vehicles lag pursuit must be used with discretion. Figure 8 illustrates the approach developed. When a vehicle is disadvantaged a line of sight pursuit is followed; however, a "lag bucket" is introduced in the advantaged half of the angle-off/steering error plane. This bucket stretches from the equality boundary to the 90° advantage line. Thus, whenever a vehicle finds that it has achieved a superior position, an attempt is made to trade this advantage for a more rearward approach on the opponent. If a vehicle has a great enough performance advantage on an opponent, this can be done without sacrificing the advantage. Otherwise when the line of equality is again crossed, the vehicle will revert to line of sight pursuit.

In initial studies, once the 90° line of advantage was successfully crossed, the vehicle would revert to line of sight pursuit for closure. This tactic worked well until small steering error angle-off condition was reached. At that point the disadvantaged vehicle could often throw off a pursuer due to failure of the pursuer to react to a build up of velocity normal to the line of sight by his opponent. This problem was largely eliminated by the introduction of a lead pursuit tactic in this region of the angle-off/steering error plane, Figure 9.

It should be noted that such a region must be introduced when cannon or machine guns are employed. The introduction of lead pursuit, however, does allow the defender to limit the firing time in the lead situation; for a half roll places the pursuer on the outside again, and the lead pursuit tactic must be maintained until lead is gained again. With air to air missiles this defensive tactic is not so effective.



The combined throttle/tactic selection logic outlined above was applied to a wide range of reattack situations varying from one leading to an initial head on pass following the initial turn to situations in which the RPV could immediately turn inside his opponent, Figure 10. In all cases the logic placed the RPV on its opponent's tail within one minute of combat time.

SUMMARY

A variety of rating procedures and flight tactics suitable for evaluating aircraft relative performance in the one-on-one encounter at the preliminary design level have been discussed. Methods for achieving tail attack positions have been presented and the advantage of such tactics over line-of-sight attacks which lead to scissoring maneuvers have been outlined. In particular, a method for determining steering vector as a function of position in the angle-off/steering error plane is suggested. Rating methods applicable to more detailed design studies are presented in reference 2.

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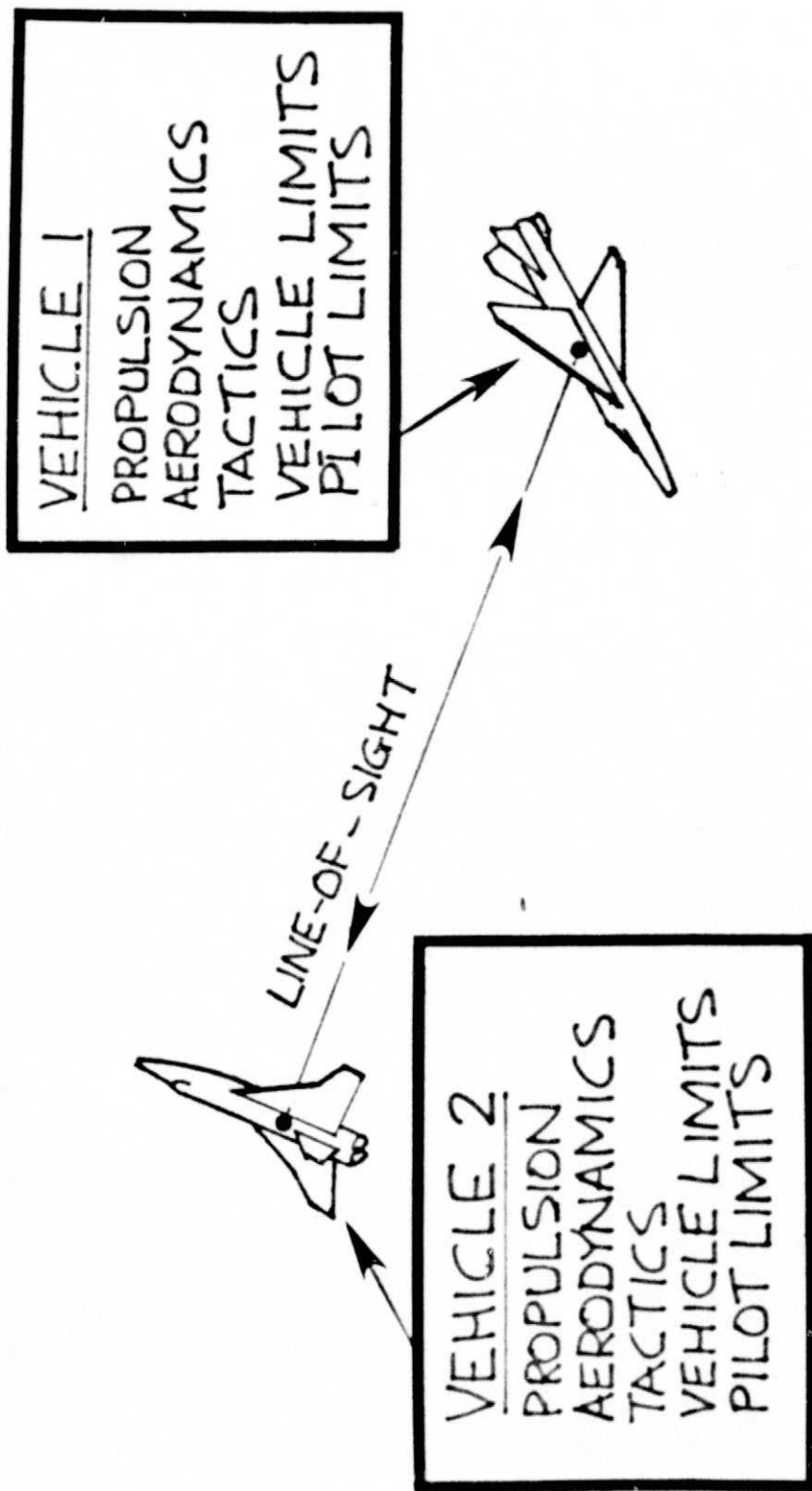


FIGURE 1. THREE-DIMENSIONAL ONE-ON-ONE
COMBAT SIMULATION

INSTANTANEOUS STEERING VECTOR

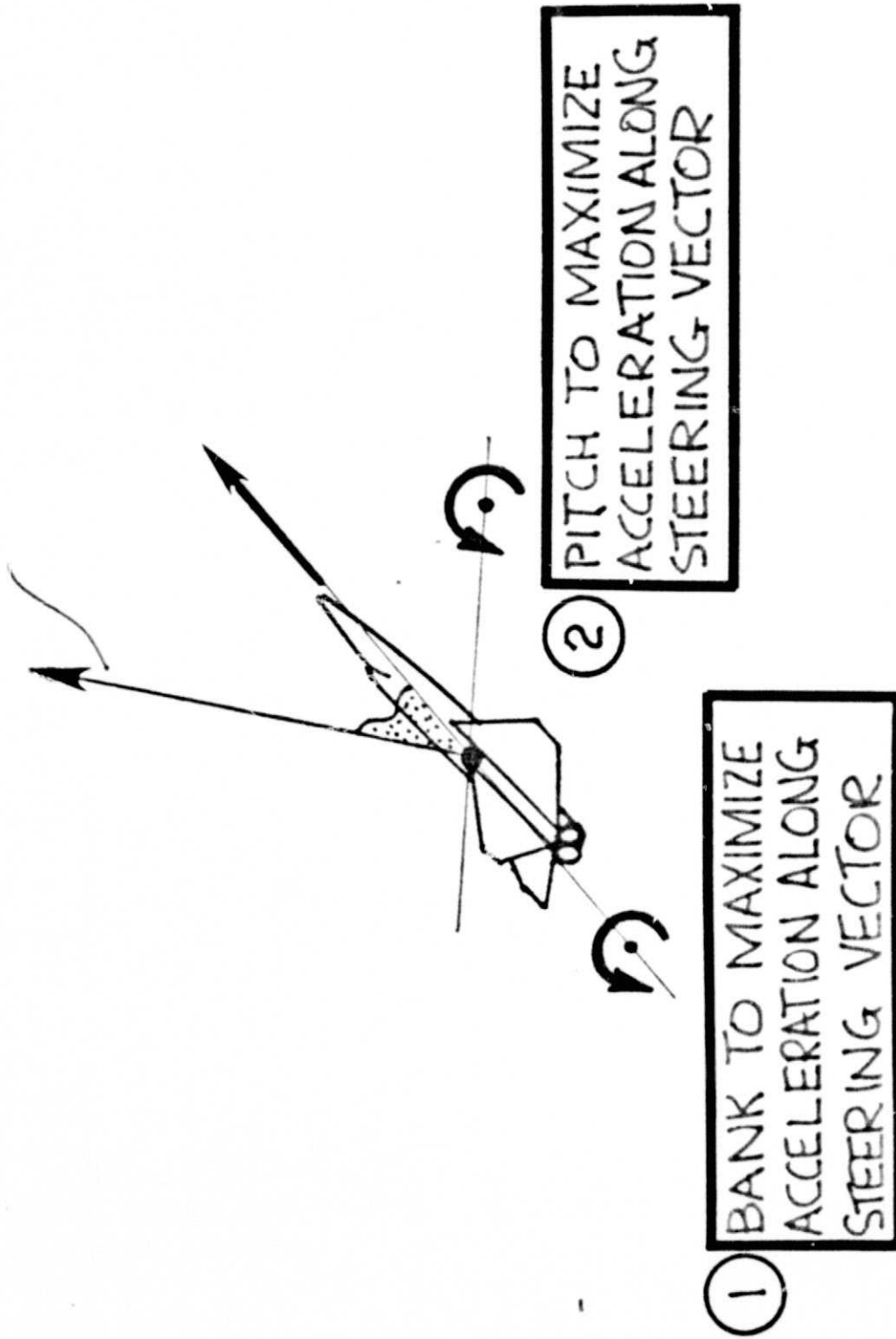


FIGURE 2. CONTROL SELECTION

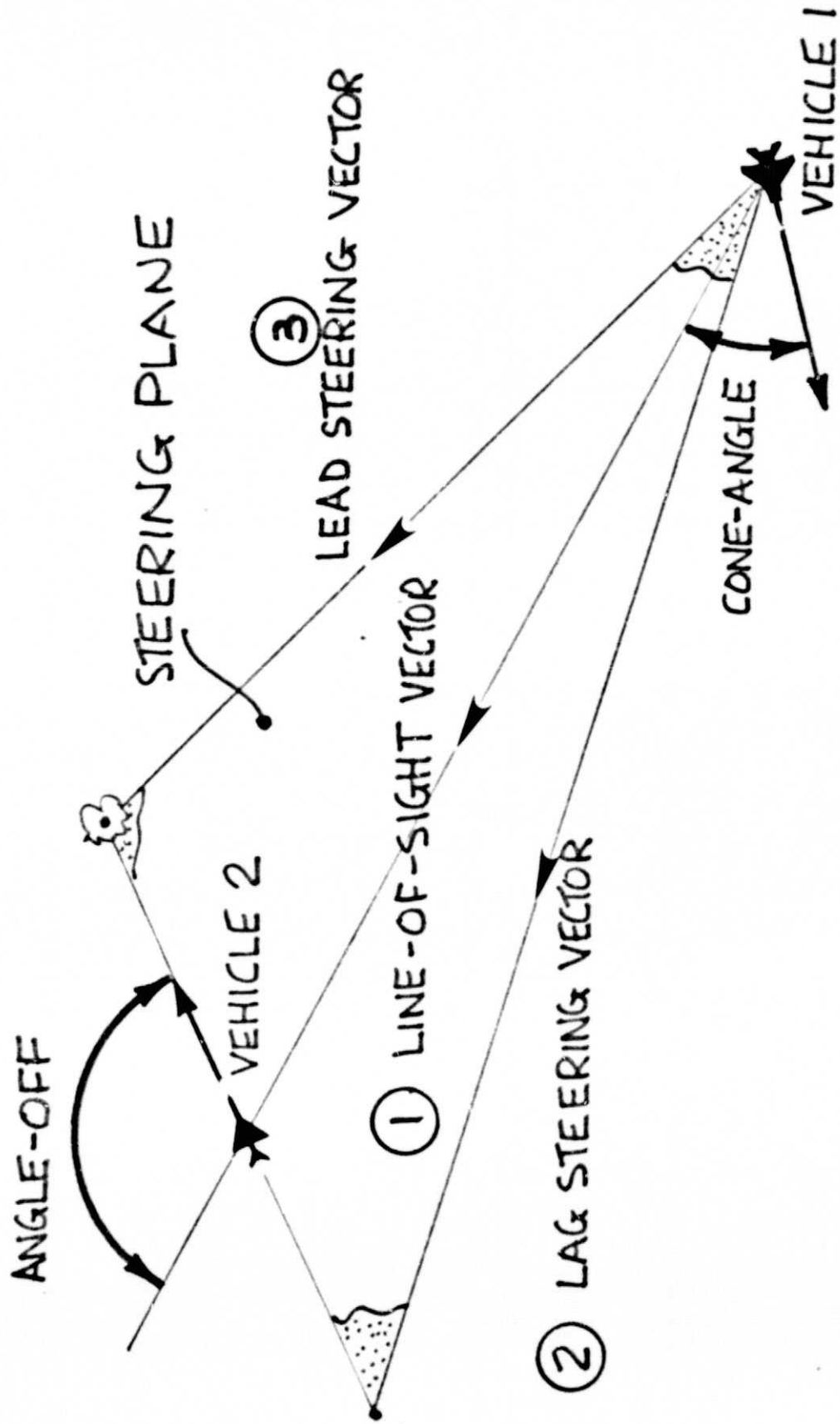


FIGURE 3. STEERING VECTORS

FIGURE 4(A). TYPICAL DOGFIGHT IN PLAN VIEW
(RPV vs. "Z")

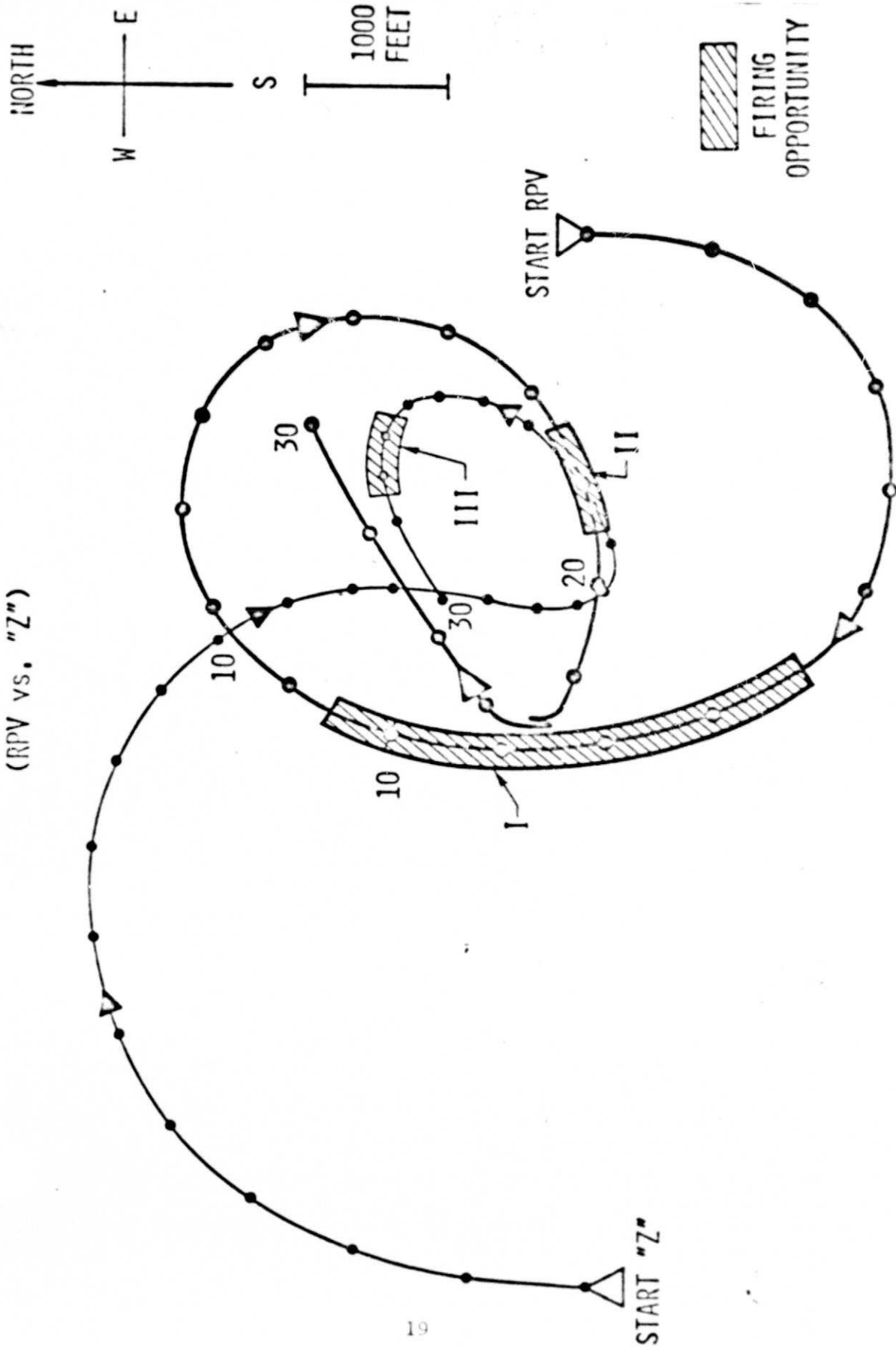
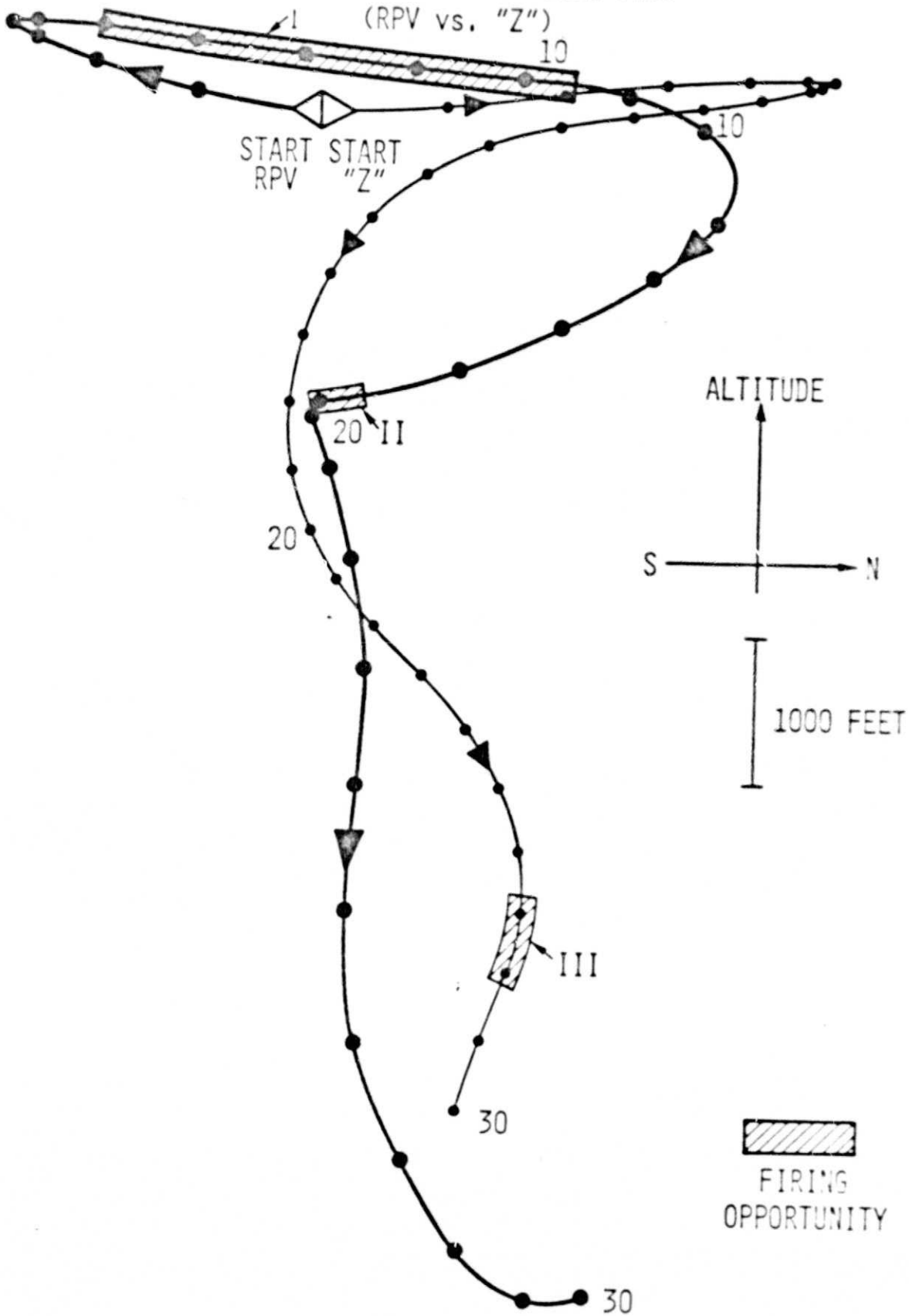


FIGURE 4(B).
TYPICAL DOGFIGHT IN SIDE VIEW
(RPV vs. "Z")



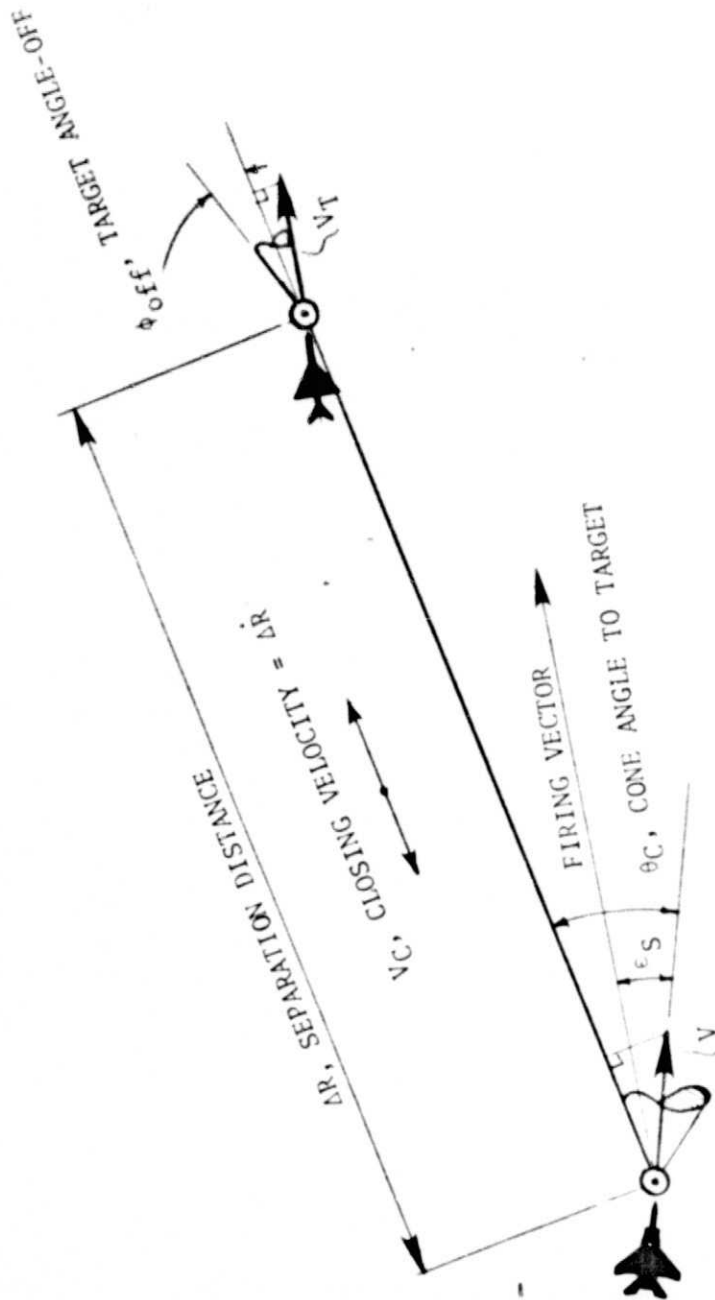
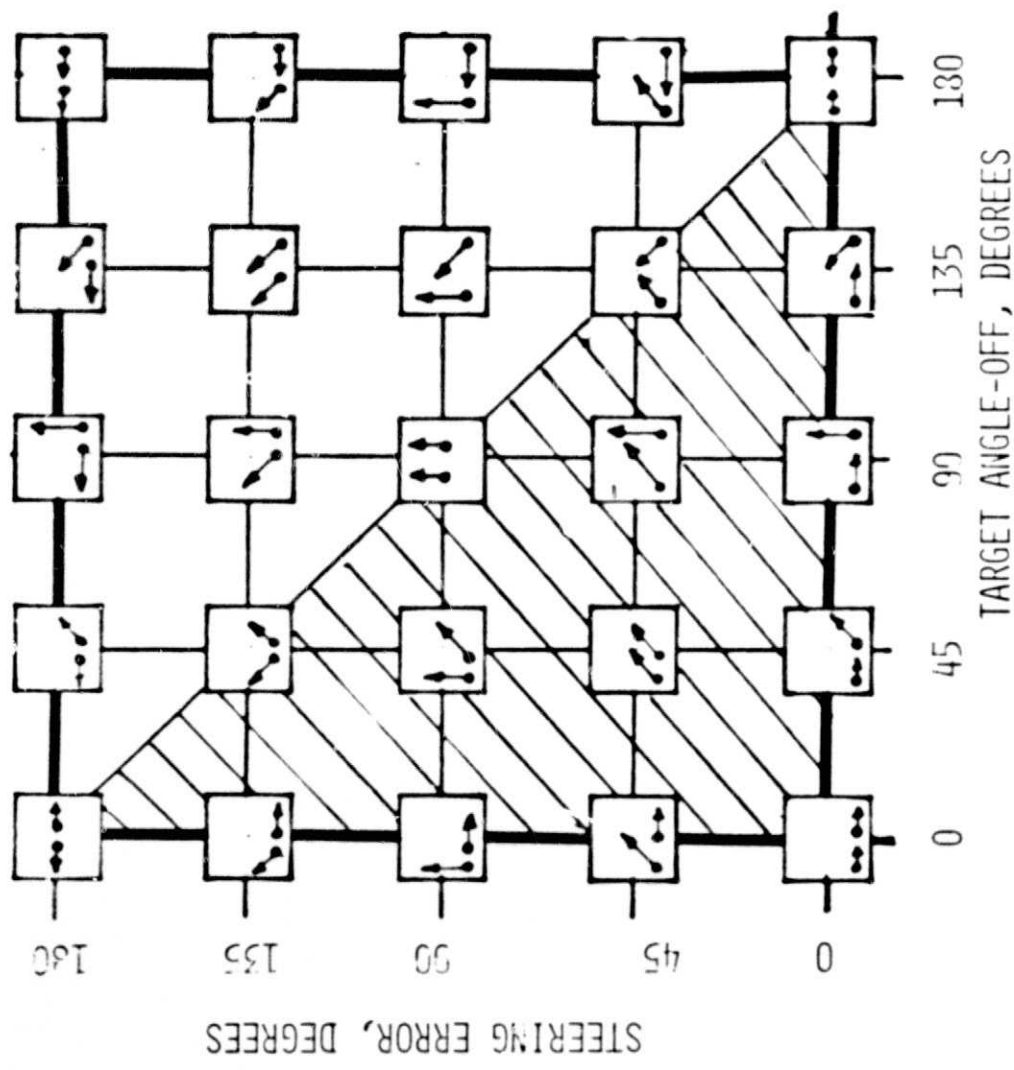


FIGURE 5. COMBAT PARAMETERS

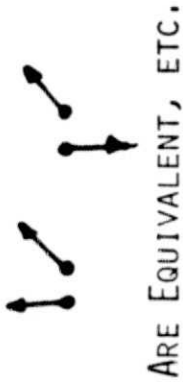


NOTE:

1. LEFT VEHICLE IS YOU
2. RIGHT VEHICLE, TARGET



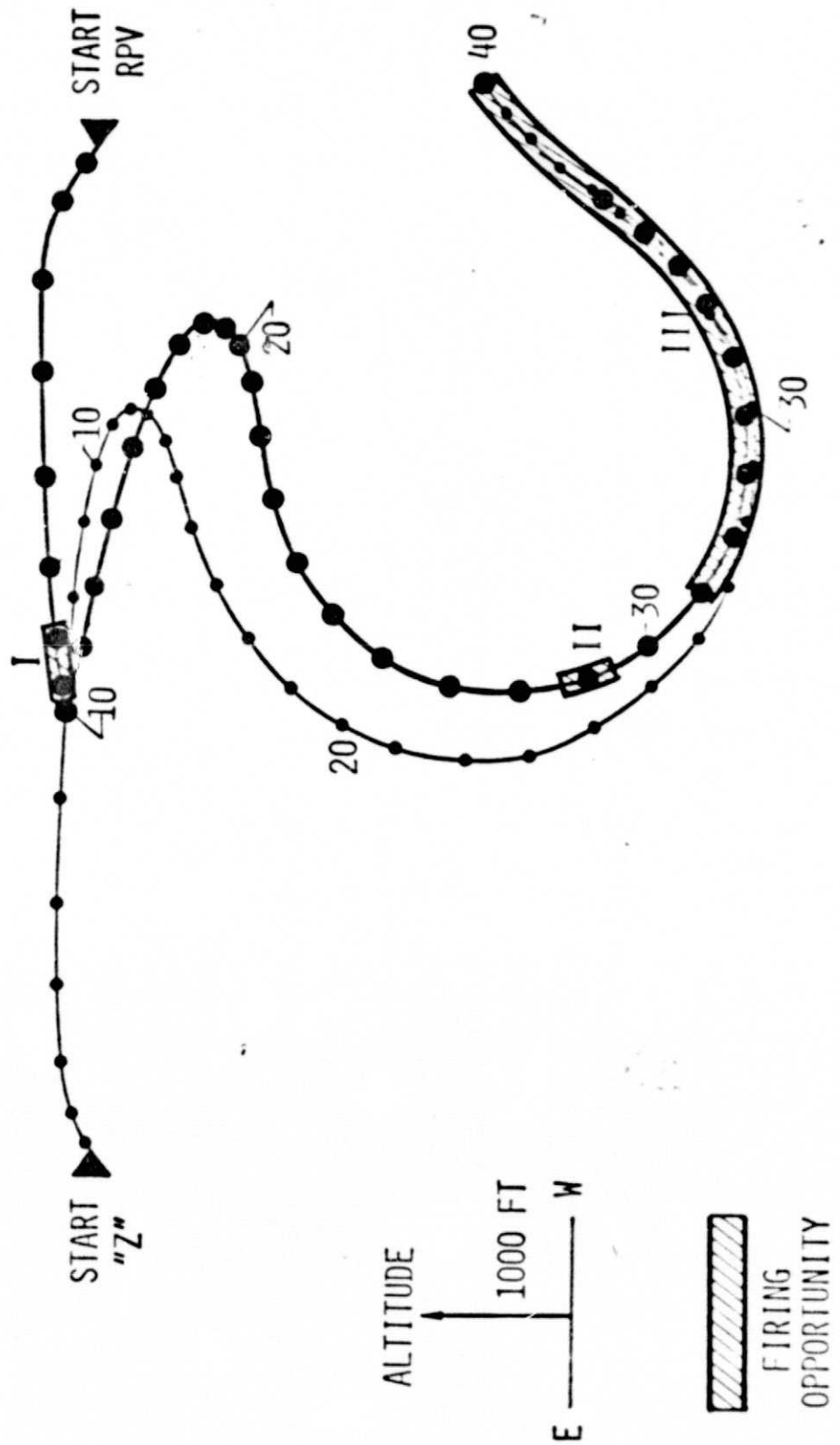
3. FROM SYMMETRY



ARE EQUIVALENT, ETC.

FIGURE 6. TYPICAL RELATIVE ORIENTATION

FIGURE 7. TYPICAL DOGFIGHT IN SIDE VIEW
10g RPV USING LAG PERSUIT VS "Z"



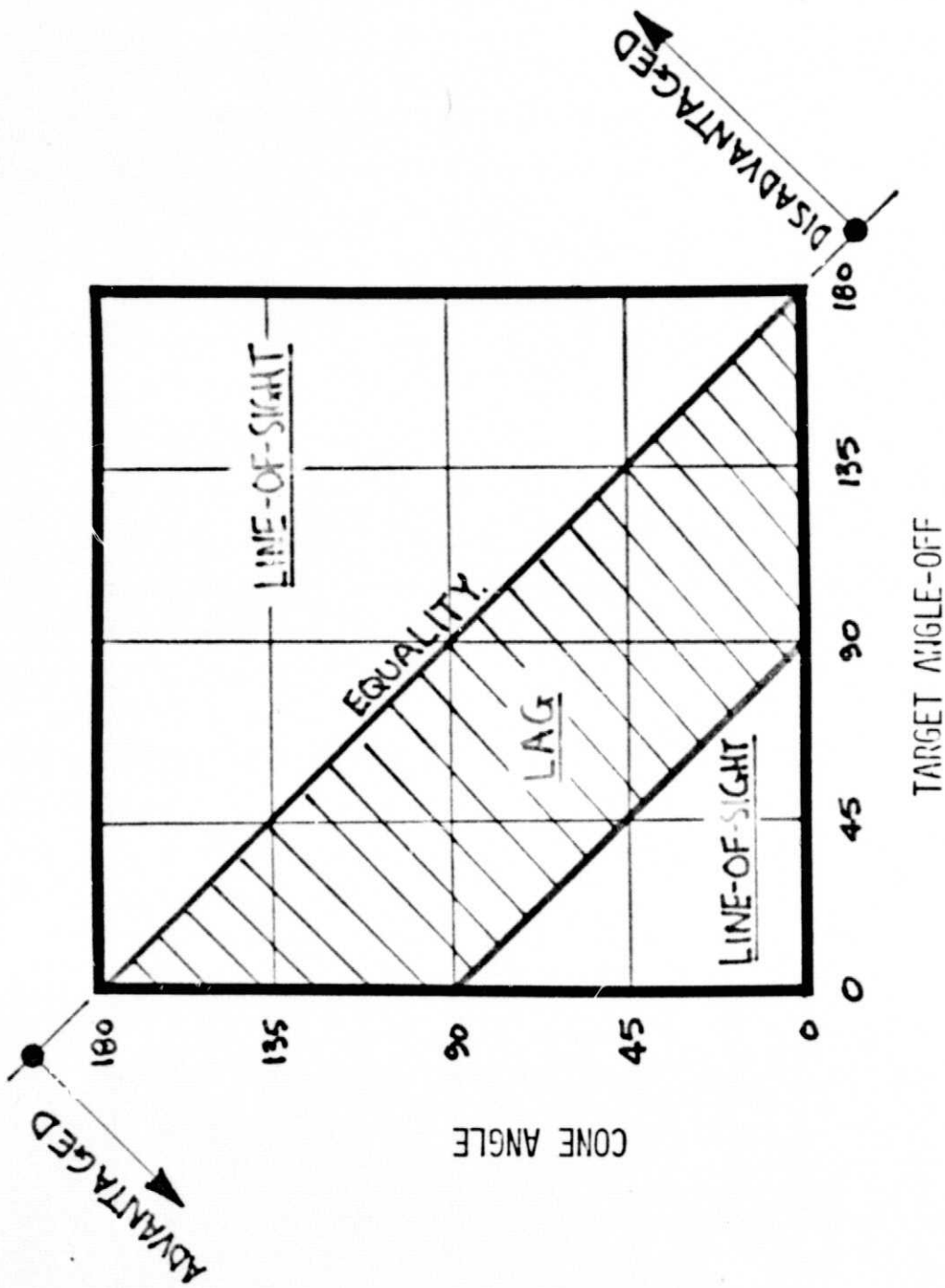


FIGURE 8. LAG BUCKET PURSUIT

LINE-OF-SIGHT STEERING

LAG STEERING

LEAD STEERING

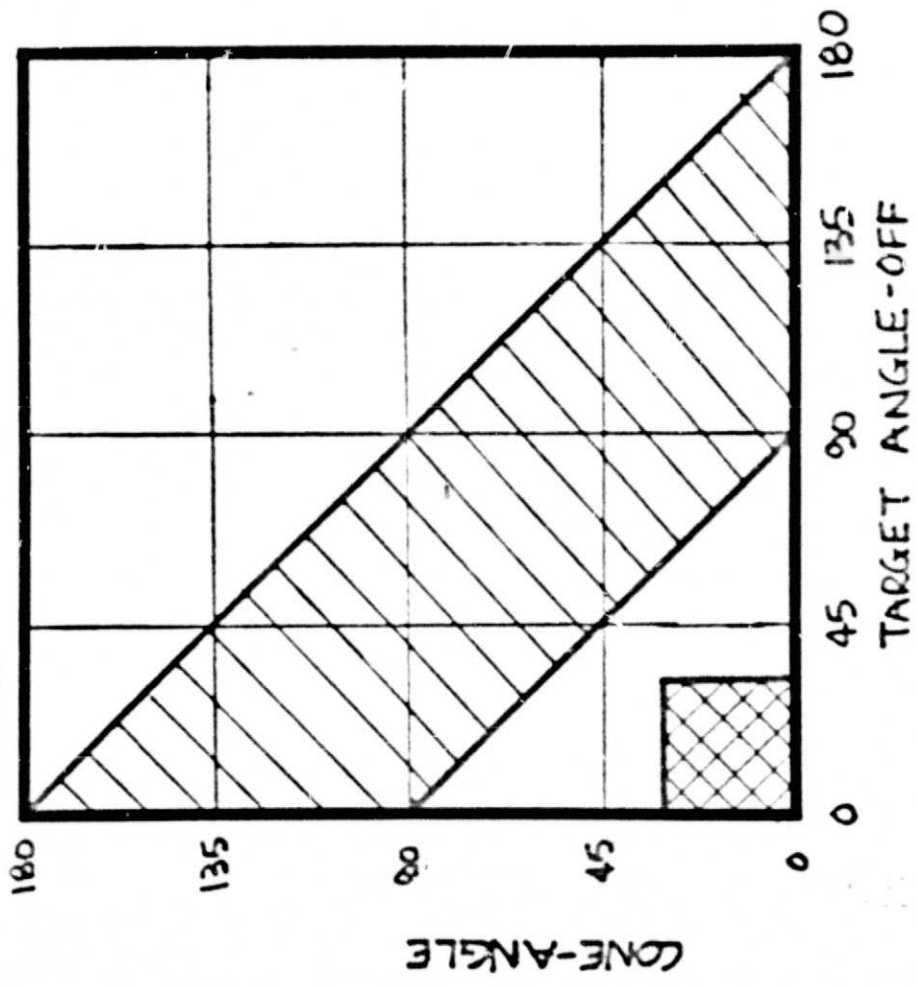


FIGURE 9. PRESENT STEERING LAW

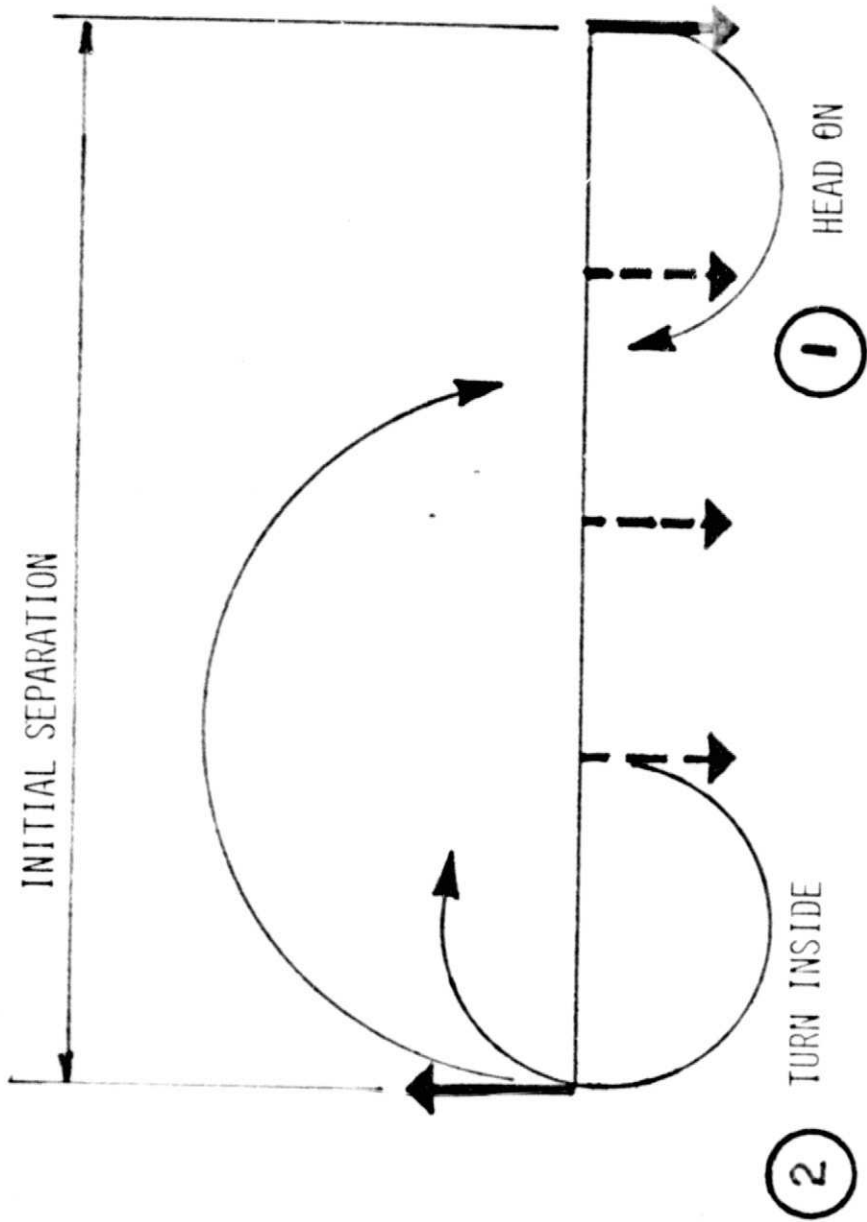


FIGURE 10. RE-ATTACK ENCOUNTER