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AN ADAPTIVE MANEUVERING LOGIC COMPUTER PROGRAM FOR THE SIMULATION OF ONE-ON-ONE AIR-TO-AIR COMBAT

Vol. I: General Description

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16. Abstract

A novel technique for computer simulation of air combat is described. Volume I describes the computer program and its development in general terms. Two versions of the program exist. Both incorporate a logic for selecting and executing air combat maneuvers with performance models of specific fighter aircraft. In the batch processing version the flight paths of two aircraft engaged in interactive aerial combat and controlled by the same logic are computed. The real-time version permits human pilots to fly air-to-air combat against the Adaptive Maneuvering Logic (AML) in Langley Differential Maneuvering Simulator (DMS). Volume II consists of a detailed description of the computer programs.

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PREFACE

The work reported herein was authorized under Contract NAS1-9115 in April 1969. This study was conducted under the direction of P. Gainer and W. Hankins, Simulation and Human Factors Branch, Langley Research Center, NASA.

This study was performed at Decision Science, Inc., San Diego with G. Burgin acting as principal investigator. Numerous Navy and Air Force fighter pilots contributed freely of their time to make significant suggestions to this study. NASA pilots and engineers flew numerous missions on the DMS and made essential suggestions for improvement of the program.

This report reflects the status of this program at the end of 1973. Since then, important improvements have been added to the program under the guidance of W. Hankins at the Langley Research Center, NASA.

The report is divided into two volumes, Volume I providing a general description of the Adaptive Maneuvering Logic, and Volume II describing in some detail the computer program, its structure and its mathematical foundations.

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AN ADAPTIVE MANEUVERING LOGIC COMPUTER PROGRAM FOR THE SIMULATION OF ONE-ON-ONE AIR-TO-AIR COMBAT

Vol. I General Description

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SUMMARY

This report describes a novel technique for computer simulation of dogfights between two fighter aircraft. The complex decision process, combining dynamic, psychological and physiological factors in air combat is simulated. The method developed here is new in that the goal seeking behavior of the pilot is modeled by mapping the relative physical situation between the two combatants into a finite, abstract situation space. Control variables are then determined so that they maximize a certain performance index in this situation space.

Such an approach provides the capability to determine the basic control variables (bank angle, load factor and thrust) for an arbitrary relative situation without relying on a prior knowledge of the performance characteristics of the two aircraft or on pilot experience. The technique therefore adapts itself automatically to the physical characteristics of the two aircraft as well as to human factors influencing the tactics of the two opponents.

Two computer programs implement this Adaptive Maneuvering Logic (AML). One operates in a batch processing mode on a digital computer. Both aircraft are driven by the same logic. The other program is used on the Langley Research Center's Differential Maneuvering Simulator (DMS), where it replaces one of the human pilots. Engagements between human pilots and the AML program demonstrated that it is a highly competent adversary. In fact, it

"wins" most of the engagements against experienced fighter pilots.

The off-line program is useful for aircraft and weapons combinations studies. It is also used successfully for postflight analysis of dogfights to detect and to identify tactical mistakes of the participating pilots.

INTRODUCTION

Control of a fighter aircraft in air combat involves a complex combination of dynamic, psychological and physiological variables. In the past, it has been thought that the human pilot, with his capacity for learning and judgment, would excel any machine in the performance of this task. The present state-of-the-art of computers, however, has enabled the programming of highly complex logical decisions to be executed in real-time in a form not subject to the possible inconsistencies or errors of a human pilot.

The purpose of this investigation was to develop a digital computer program, based on an Adaptive Maneuvering Logic (AML), which may be used in one of two basic modes. In real-time, it provides an opponent for human pilots on the NASA Langley Research Center's (LRC) Differential Maneuvering Simulator (DMS). In the off-line mode, both aircraft are controlled by the AML, and parametric studies concerning aircraft and/or weapons systems parameters may be made relatively inexpensively.

Although the logic and geometry from which the program makes control decisions are intricate and complex, the basic concepts are simple. The attacking aircraft predicts the future position and velocity of its opponent by extrapolating along a flight path determined by curve fitting through past positions along the opponent's flight path. Having determined the opponent's expected position, the attacker predicts its own position for several elemental trial maneuvers. A value is placed on each of the candidate maneuvers by answering questions about the state of each candidate maneuver relative to the predicted state of the opponent. That maneuver having the highest value is chosen as the next to be performed.

The AML program is presently being used as an invariant opponent against DMS pilots in advanced fighter technology studies. Pilot acceptance of the AML program has been enthusiastic and complimentary.

The batch program will be used to predict the results of parametric evaluations of aircraft prior to conducting studies on the DMS.

GLOSSARY OF TERMS

Load Factor: The ratio of aerodynamic lift to weight.

Specific Energy: The sum of the kinetic and potential energy of the aircraft divided by its weight.

Specific Energy Rate: Time derivative of specific energy.

Sustained g Turn: A turn with a load factor so that specific energy rate is zero; i.e., no gain or loss of energy occurs during the turn.

Maximum g Turn: A turn in which the load factor is the maximum available.

Maneuver Plane: A plane containing the aircraft's velocity and acceleration vectors. All AML maneuvers are performed in maneuver planes. All net forces acting on the aircraft lie in this plane.

Rotation Angle:	The angle, ρ, from a vertical plane through the velocity vector to the maneuver plane; positive for clockwise rotations, negative for counter-clockwise rotation looking in the direction of the velocity vector. Maximum and minimum values are $+\pi$ and $-\pi$, respectively.
Situation Matrix:	A finite matrix into which the physical situation between two opposing aircraft is mapped.
Cell Value:	A measure of relative worth associated with a particular element (cell) of the situation matrix.
Performance Index:	Same as cell value.
Cycle Time:	The integration step size for the numerical solution of the equations of motion.
Decision Interval:	The time between two tactical decisions.
Decision Point:	The time at which a tactical decision is made.
Prediction Time:	The time increment between the present time and some future time over which the AML controlled aircraft predicts the state of its aircraft and the opponent aircraft for various trial maneuvers.
Dive Recovery Angle:	The maximum angle at which an aircraft may dive at a given speed and altitude and still be able to pull out without hitting the ground.

Line-of-Sight Angle:	The angle between the x- body axis and the line-of-sight vector to the opponent.
Deviation Angle:	The angle between own velocity vector and line-of-sight vector.
Angle Off:	The angle between the line-of-sight vector and the opponent's velocity vector.
Offensive Time:	The accumulated time during which the opponent was in front of the wing line of the reference aircraft.
Offensive Time with Advantage: (DMS - Definition OTA-DMS)	The accumulated time during which the opponent was in front of the reference aircraft's wing line and the reference aircraft was behind the opponent's wing line.
Offensive Time with Advantage: (AML - Definition OTA-AML)	The accumulated time during which the reference aircraft's deviation angle was less than 60 degrees and its angle off was less than 60 degrees.

SYMBOLS

A	attacker
C_L	lift coefficient
E_S	specific energy
g	acceleration due to earth gravity (32.2 ft/sec^2)
g_{max}	maximum permissible load factor
h	altitude ($h = -z_e$)
M	Mach number

P_s	specific energy rate, specific excess power
p, q, r	angular velocities about the x- body, y- body and z- body axes, respectively
T	target
x_e y_e z_e	earth fixed coordinates x_e positive north y_e positive east z_e positive down
x_b y_b z_b	body axes system coordinates x_b along longitudinal axis, positive towards the nose y_b pointing toward right wingtip z_b pointing down
x_m y_m z_m	maneuver plane coordinates x_m aligned with velocity vector y_m normal to maneuver plane z_m towards concave side of flight path
α	angle of attack
β	sideslip angle
δ_a δ_e δ_r	aileron, elevator and rudder deflection angles, respectively
ρ	rotation angle (of the maneuver plane)
$\Delta\rho$	incremental change in maneuver plane rotation angle
ψ, θ, ϕ	Euler angles of yaw, pitch and roll, respectively

BACKGROUND

Development of the DMS began in 1966, and the system was put into operation in the spring of 1971. The DMS is a flight simulator which makes possible the study of two vehicles as they maneuver with respect to one another and with respect to the earth. Either one or both vehicles may be piloted by a human pilot. Figure 1 depicts in schematic form the major elements of the DMS. Each of the two 40-foot diameter projection spheres houses a single-seat cockpit, a projection system, and two image generators (one for the opposing aircraft, the other for the sky-earth image). The projection systems are controlled by digital computer programs operating on a CDC 6600 computer. The DMS is, in the opinion of the pilots who have flown in it, the most advanced and most realistic flight simulator today for differential maneuvering of two vehicles. Additional information about the DMS may be found in Reference 1.

LRC recognized during the early design and construction phases of the DMS the utility which could be derived from an interactive, computer driven opponent. A requirement for an invariant opponent, which can be used to reduce the influence of pilot variability from DMS research studies was then anticipated.

In 1968, LRC awarded a contract to Decision Science, Inc. to design a computer program which would provide a realistic opponent for the DMS pilot. Two important features were required: First, the program had to be capable of performing the calculations required for a tactical maneuver and driving an aircraft to perform it in real-time. Secondly, arbitrary aircraft had to be simulated realistically and the tactical decisions derived by the program had to be adapted to the characteristics of the driven aircraft as well as the opposing aircraft.

Such a program not only provides an invariant opponent on the DMS, but it may also be used for:

- aircraft and weapons systems design studies
- development of new tactical maneuvers for existing and postulated aircraft - weapons systems combinations
- pilot training.

A survey of the state-of-the-art in air-to-air combat simulation at that time indicated that no interactive, real-time program with the above-required capabilities was available. The non-real-time air-to-air combat simulations could be grouped into three classes: Programs which represented two aircraft, flying interactively, with the decision process preprogrammed according to pilot opinion and the aircraft type simulated (TACAVENGER (ref. 2) was typical of this group); Programs which simulated the flight of two aircraft, operating from a tactical decision logic formulated by the user as a subprogram. The user could command either of the aircraft to perform classical air combat maneuvers, such as a split S or a barrel roll (the Rand TACTICS PROGRAM (ref. 3) typically represented this group); Finally, programs which applied modern control theory, optimization methods, and the theory of differential games to obtain control laws. These programs could not operate in real-time under realistic conditions because of the large computational requirements.

The required level of generality and adaptability ruled out the use of pilot opinion as the primary input for formulating tactical control laws. The limited number of computations which could be performed in real-time made a game theoretical approach clearly unsuitable. Therefore, a distinctly different approach was called for.

THE ADAPTIVE MANEUVERING LOGIC SUMMARIZED

It has been pointed out earlier that the decision logic of the AML program is complex; however, the underlying concept is simple. At certain discrete intervals of time (decision interval), the AML decides what its next maneuver will be. This maneuver is defined by three basic control variables which characterize the flight of any aircraft engaged in air combat.

These are:

- bank angle
- load factor (or lift)
- thrust.

A maneuver defined by a set of values for these three control variables will be called an "elemental maneuver"; a sequence of elemental maneuvers may then be interpreted in terms of classical air combat maneuvers, such as "scissors" or "high speed yo-yo".

At each decision point, a number of elemental maneuvers are selected as candidates for the next tactical maneuver. These maneuvers, called "trial maneuvers", are evaluated as follows: The opponent's position and attitude are extrapolated to some point in the future. This extrapolation interval is called the "forward prediction time". For each set of control variables, the position and attitude of own aircraft are predicted for this same time period. For each trial maneuver, a unique relative situation between own aircraft and the opponent is predicted. This situation in the three-dimensional physical space is then mapped into a situation space with a finite number of different possible states. This space can be represented in the form of a matrix. Any physical situation therefore corresponds to a unique cell in that situation matrix. Each of these cells has a value associated with it; consequently, each trial maneuver has a certain expected value. The program then chooses that trial maneuver with the highest expected (predicted) value for actual execution.

Figure 2 shows how the AML program interfaces with the other elements of the DMS. The CDC 6600 digital computer and one sphere with its projection equipment form the major hardware components of the system; the Real-Time Monitor, the basic DMS program, and the AML program constitute the major software elements. A number of peripheral devices perform functions for data storage, retrieval and display. Most noteworthy among these is a cathode ray tube (CRT) display, which permits an outside observer to view in a perspective real-time display, the engagement between the two aircraft.

THE CONCEPT OF THE SITUATION SPACE

When pilots are instructed in air combat maneuvering (ACM), they first learn to fly certain classical air combat maneuvers, such as a high and low speed yo-yo, a barrel roll, and so forth. They are then taught the relative situations which call for one of these maneuvers; and, through their sense of timing, they learn to initiate these maneuvers at the right point in time. It seemed reasonable, therefore, to develop a computer simulation for air combat with a similar logic. To do this, it would be necessary to define a number of ACM maneuvers, define a number of physical situations, and devise a decision logic to decide what maneuver should be performed under a given geometrical condition. It was soon realized, however, that such an approach had several severe drawbacks. First, it lacked generality because the decision tree would have been strongly aircraft-performance dependent. It would have been necessary to change the program for each new aircraft driven by it as well as for each new opponent. Secondly, an accurate definition of situations requiring one of the classical maneuvers is almost impossible to obtain. To quote from an ACM instructional text: "...when it becomes apparent that it will be impossible to stay inside the defender's turn radius, employ the high-speed yo-yo." To formulate a computer program based on statements such as this is practically impossible. Finally, in discussions with fighter pilots, it was learned that a complete classical maneuver is rarely completed in a dogfight because of continuous interaction and changes in the relative situation.

A technique was therefore devised which attempts to determine the next tactical maneuver as it contributes to the goals of the pilot. The goal or purpose of each pilot is defined in terms of quantized physical variables. Note that the purpose of the pilot includes certain aspects of the other aircraft's status. Questions such as "Am I ahead or behind the other aircraft?" "Is he ahead or behind me?" "Can I see him?" "Can he see me?" and so forth, once answered, identify the cell in the situation matrix into which this physical situation is mapped. Figure 3 illustrates the concept of the situation matrix; it shows two aircraft, labeled "I" and "HE", in relative positions and attitudes, where, for simplicity of presentation, the longitudinal axes of the two aircraft are assumed to lie in a plane. A plane, defined by the body y and z axes, divides the space of the aircraft into an ahead and a behind region. Consider the plane defined by the aircraft longitudinal axis and the wing axis (x_b, y_b axes). Now rotate this plane 30 degrees about the y_b axis toward the positive z_b axis. Everything above this plane is assumed to be visible and everything below it to be not visible. A more complex geometrical definition of visibility, as a function of a particular aircraft cockpit geometry, could be programmed. The situation depicted in Figure 3 shows that "I" am not visible to "HIM", and "I" am behind "HIM" while "HE" is visible to "ME", but he is also behind "ME". The discussion of the tactical decision process will show how this basic four-by-four situation matrix is expanded to more realistically represent the pilot's goals in a dogfight.

In order to use the situation matrix for the tactical decision process, a value has to be assigned to each cell. The decision process will then select that maneuver which is expected to maximize this value. Consider first a slightly different description of the situation space, in which the situation is described in the form of a situation state vector. This vector consists simply of the answers to questions describing the situation. Assume that a one corresponds to a "YES" while a zero corresponds to a "NO". Consider a second vector containing a weight factor for each one of these questions. One possible way of obtaining a value for a given situation is to form the scalar product of these two vectors. Computationally, this is a very efficient way of calculating the value of a given situation, and the AML program obtains cell values in this manner. The weights associated with the individual questions are input data to the AML program, giving the user freedom to vary them from run to run. Thus, he cannot only change the priority of the questions; but, by assigning a weight of zero, he may effectively delete one or more questions.

AIRCRAFT DEFINITIONS AND DYNAMICS

The primary consideration in modeling the aircraft was to represent an arbitrary aircraft with dynamics which would be consistent with that aircraft's performance. Realistic maneuvering constraints, such as maximum rotational rates, were imposed. No attempt, however, has been made to represent the aircraft dynamics in terms of handling qualities. Otherwise, every effort has been made to constrain the AML program to those maneuvers which the pilot-aircraft combination could conceivably perform. These constraints include "g" limitations corresponding to pilot blackout.

The primary variables defining the AML aircraft are weight, wing area, thrust, maximum load factor as a function of Mach number and altitude, drag as a function of Mach number and coefficient of lift (C_L), maximum lift coefficient as a function of Mach number, and maximum rotational rates about the three aircraft body axes (p_{max}, q_{max}, r_{max}). The effects of speed brakes are included in the thrust function because it is assumed that speed brakes and idle thrust will be used simultaneously.

An important and fundamental concept in the AML program is the maneuver plane. Between decision points, the aircraft flies generally in such a way that its velocity vector lies in a plane, called the "maneuver plane". This presents no practical limitation of the AML method since any three-dimensional curve can be approximated by a sequence of piece-wise plane curves.

The primary advantage of having the aircraft fly in a maneuver plane is the reduction in computer time, this because:

- prediction of aircraft position and attitude is straightforward
- the aircraft equations of motion are simplified.

For the real-time application of the AML program on the DMS, it is crucial to use as little computational time as possible; therefore flying in maneuver planes makes real-time execution possible.

To define a maneuver plane, consider first a plane containing the velocity vector and perpendicular to the x_e-y_e plane. This plane is called the unrotated maneuver plane or a maneuver plane with rotation angle $\rho = 0$. Arbitrary maneuver planes are those planes obtained by rotating the unrotated maneuver plane about the velocity vector in integer multiples of an angle $\Delta\rho$ whose value is specified as an input parameter (typical values for $\Delta\rho$ are 10 degrees or 15 degrees). A clockwise rotation of the maneuver plane (looking in the direction of the velocity vector) is considered positive, a counter-clockwise rotation negative. Consider now a turn in a given maneuver plane. Since the maneuver plane contains the velocity vector at all times, the flight path lies in the maneuver plane. An orthogonal right-handed maneuver plane coordinate system (x_m, y_m, z_m) is now introduced, such that its x axis is aligned with the velocity vector, its negative z axis is in the maneuver plane pointing toward the concave side of the flight path, and its y axis being normal to the maneuver plane. The aircraft is then oriented in such a way that the resultant net force acting on it (aerodynamic, propulsive and gravity forces) lie in the maneuver plane at all times. Note that the aircraft's right wing is on the same side of the maneuver plane as the maneuver plane y axis. The aircraft longitudinal axis forms an angle α with the velocity vector. To illustrate, consider the maneuver plane required for a climbing right turn. Let the velocity vector initially be at an angle of, say, 30 degrees from the x_e-y_e plane. A positive rotation angle of, say, 45 degrees may define the desired maneuver plane. The positive y_m axis would point down (the unit vector along the positive y_m axis has a positive component along the z_e axis) and the aircraft's right wing points down.

To illustrate further, consider now what maneuver plane is required to initiate a left diving turn given the same initial velocity vector as above. This maneuver requires a rotation angle of -135 degrees which leads to the "same plane" as in the first example, but with the y_m axis now pointing upwards (a unit vector along the positive y_m axis has a negative component along the z_e axis). The aircraft's right wing points upwards.

For straight flight (climbing, level or descending), the maneuver plane is a vertical plane, perpendicular to the x_e-y_e plane, the wing line of the aircraft being parallel to the x_e-y_e plane. If the cockpit is pointed away from the earth, the aircraft flies straight upright; if it is pointed toward the earth, the aircraft performs a straight inverted flight maneuver. Straight flight is a special case of flying in a maneuver plane (ρ = 0 degrees (upright) or ρ = 180 degrees (inverted)), with zero acceleration normal to the velocity vector.

The program checks whether it is physically possible for the aircraft to fly in a particular plane at a given Mach-altitude combination. First, the maneuver plane is always defined so that the present velocity vector lies in it. Next, the program determines whether it is possible to orient the aircraft such that the net forces acting on the aircraft (aerodynamic, propulsive and gravity forces) lie in the maneuver plane. Planes for which it is not possible to generate net forces so that they lie in that plane are rejected as possible maneuver planes. This situation arises in very low speed flight conditions where enough lift cannot be obtained to compensate for the gravity component normal to the maneuver plane.

A problem arises at the transition from one maneuver plane to another. Each maneuver plane, at the time of its definition, contains the velocity vector. This, of course, guarantees that there will be no discontinuities in the trajectory nor in its first derivative. But if the maneuver plane changed its orientation instantaneously at a decision point, the resulting trajectory would have a point of discontinuity in torsion* at that point. In an earlier study of air-to-air combat, this discontinuity in torsion, which physically corresponds to an instantaneous change in bank angle, was tolerated (ref. 4). For the AML program, however, in which a human pilot flies against the AML driven aircraft, instantaneous changes in bank angle are unacceptable because the maneuvering performance of the aircraft would be misrepresented by such a model and the displayed aircraft motion would appear unrealistic and therefore unacceptable to human pilots. To overcome this difficulty, the AML program inserts a transition period between flight in different maneuver planes. During this period, the aircraft rolls from its present bank angle to a bank angle required for flight in the desired new maneuver plane. The roll maneuver is performed with realistic roll rates, the forces acting on the aircraft are determined, and the aircraft's accelerations and velocities are integrated to obtain a realistic trajectory. The resulting trajectory includes both curvature and torsion and is continuous in its two first derivatives.

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*The torsion of a space curve is defined as the rate of change of the osculating plane with respect to the length of the curve.

Maneuver planes and trial maneuvers.- The tactical decision process, which is the heart of the AML program, has been summarized in a previous section of this report. Here, additional details and explanations are given.

Tactical decisions are made at discrete intervals of time. The time between these decisions will be called the (tactical) decision time interval. This time interval is an input parameter to the program and remains fixed during each engagement. However, the selected maneuver may be changed before the present decision time interval has elapsed if there is a chance of the aircraft being on a flight path for which a crash on the ground could not be avoided. This situation is discussed in the section "Dive Recovery and Low Speed Recovery". Perhaps the tactical decision time should always be a function of the situation. Such a study, however, was beyond the scope of this investigation. Suitable decision times for the DMS were found to be on the order of one-half second to two seconds. When a decision point occurs, the AML program goes through the following steps:

- extrapolation of opponent's flight path and attitude
- prediction of its own flight path and attitude for a situation-dependent number of trial maneuvers
- evaluation of the trial maneuvers and selection of the most promising one for actual execution.

The difference between current time and the time point in the future at which the trial maneuvers are evaluated is called "forward prediction time". Note that during the following discussion, the process by which the opponent's situation is estimated at the forward prediction time will be called extrapolation (because it is simply a mathematical extrapolation of his past flight path), while the situation of the driven aircraft at this time is obtained by prediction.

Since the three basic control variables are load factor, bank angle and thrust (a different way of defining these same control variables would be: magnitude of lift, direction of lift, and magnitude of thrust), one might, in principle, set up the different trial maneuvers directly in terms of these control variables. Considerable computer time, however, may be saved by defining trial maneuver planes and certain load factors for flight in these trial maneuver planes. Since, by definition, a trial maneuver plane contains the present velocity vector, one degree of freedom is left for the definition of a trial maneuver plane. Consider a vertical plane through the velocity vector. Every possible trial maneuver plane can now be obtained by a rotation of this plane about the velocity vector. The angle by which the plane is rotated is called "rotation angle" and denoted by ρ (it should be noted that the same symbol is also used for air density). Trial maneuver planes are allowed to exist at discrete increments of rotation angle; 5, 10 or 15 degrees are the increments usually selected for $\Delta\rho$ (see Figure 4).

Trial maneuvers are defined in these trial maneuver planes. The set of trial maneuvers depends on the existing relative situation and on the presently flown maneuver. Consider first the situation in which the aircraft is in straight flight. Then, the first trial maneuver is a continuation of the existing flight mode. The second maneuver is straight flight again, but with the aircraft rolled 180 degrees from its present attitude. The third and fourth maneuvers are maximum g turns in the two adjacent maneuver planes that bracket the plane, defined by the velocity vector and the opponent's extrapolated position.

Consider next the situation where the aircraft is presently flying along a curved trajectory in a maneuver plane. The first trial maneuver is a continuation of the present maneuver. The second and third trial maneuvers are maximum g turns in the two maneuver planes adjacent to and on opposite sides of the one in which the aircraft flies presently. The fourth trial maneuver is straight flight, upright if the opponent is above the aircraft, inverted if the opponent is below.

Under certain conditions, additional trial maneuvers will be added. If, among the four standard trial maneuvers, none was executed in the trial maneuver plane which is closest to the plane through the velocity vector and the opponent's extrapolated position (this maneuver plane will be called "the plane closest to the opponent"), a maximum g turn in this plane is added to the set of trial maneuvers. If the AML aircraft has a deviation angle less than 90 degrees, a trial maneuver is added which will approximately result in a trajectory intercepting the opponent at its extrapolated position. This maneuver is added only if the load factor required for this intercept trajectory is less than the permissible load factor.

Finally, if the tactical position deteriorates; that is, the cell value falls below a certain threshold, a defensive trial maneuver is added. The maneuver plane for this defensive trial maneuver is perpendicular to the plane closest to the opponent.

Dive Recovery

Avoiding maneuvers which would cause the AML driven aircraft to crash on the ground is of highest priority in the tactical decision process. Two precautionary steps to avoid ground crashes are taken as follows:

Assigning low values to maneuvers with predicted altitudes less than 300 feet.- In the evaluation of the worth of the trial maneuvers, a question about the altitude at the end of the prediction time is added. This question is answered by "Yes" if the predicted altitude is less than 300 feet. The weight factor for this question is chosen to be -13, which drastically reduces the value of maneuvers bringing the aircraft too close to the ground. An additional trial maneuver is added regardless of the value of all other trial maneuvers. This maneuver consists of a max g pullup in an unrotated maneuver plane. This trial maneuver has a good chance for not breaking the 300 foot ground avoidance level.

Test for exceeding a certain dive recovery angle.- At every integration step, a check is made whether the dive angle exceeds a certain dive recovery angle. This dive recovery angle is tabulated as function of Mach numbers and of altitude between zero and 12,000 feet, in steps of 3,000 feet for the altitude. Should the present dive angle exceed 80 percent of the dive recovery angle, the program executes a new tactical decision immediately. The trial maneuvers now depend on the magnitude of the dive angle and the present altitude. If the dive angle is greater than the recovery angle, only one trial maneuver; that is, straight pullup, is allowed. If the dive angle is less than 90 percent of the recovery angle and the altitude still greater than 4,000 feet, normal maneuver selection is performed. Otherwise, three trial maneuvers are set up, pullup in a vertical plane and pullup in maneuver planes with a rotation angle of plus or minus $\Delta\rho$.

Low Speed Recovery

Of second highest priority in the tactical decision process is the avoidance of flying too slowly to maintain effective maneuvering. The low speed recovery process is more complex than dive recovery because corrective action depends on the flight path climb angle when low speed problems arise. Primary goal of this process is to start flying in such a manner so that speed will be built up again before there is a danger of the aircraft stalling. It was beyond the scope of this contract to investigate flying characteristics of fighter planes close to a stall condition. As long as the aircraft has enough speed to pull 1.5 or more g's, the previously-described trial maneuvers are used. As soon as the maximum permissible load factor (g max) is less than 1.5 g, different sets of trial maneuvers are investigated, depending on flight path angle and g max. The "pitch angle" of the velocity vector is defined by:

$$\bar{\theta} = \tan^{-1} [-\dot{z}_e / \sqrt{\dot{x}_e^2 + \dot{y}_e^2}]$$

The program now differentiates between the following situations and sets up corresponding trial maneuvers:

Situation 1.- This situation is defined if $\bar{\theta} < 0$; that is, a descending flight path. In this situation, a sustained turn rate guarantees no loss of specific energy and altitude will continue to be traded for speed. The program sets up six trial maneuvers, all turns with sustained g, in six maneuver planes with the following rotation angles: $\rho = 0$, $\rho = \pi$, $\rho = \pm\Delta\rho$, $\rho = \pi\pm\Delta\rho$.

Situation 2.- In this situation, the flight path angle $\bar{\theta}$ is between 0 degree and +80 degrees and g_{max} between 1.0 and 1.5 g's. The trial maneuvers are the same as in situation 1 except for the load factor, which is set to 90 percent of sustained g.

Situation 3.- Here, the flight path angle $\bar{\theta}$ is again between 0 degree and +80 degrees; however, g_{max} is less than 1 g. Two trial maneuvers are allowed, both with a load factor of zero; that is, an angle of attack which produces minimum drag. The maneuver plane rotation angles are zero degrees or 180 degrees. In either case, the gravity force will eventually cause the flight path to descend.

Situation 4.- This situation prevails if the flight path angle $\bar{\theta}$ is greater than 80 degrees. In this case, the only maneuver allowed is a maximum g turn in the plane closest to the opponent. The purpose is to let the aircraft continue its loop through the 90 degree point as quickly as possible because it is already close to that point. Once the aircraft gets past the 90 degree point, it will have its nose pointed in a tactically desirable direction, its pitch angle will be reduced, and airspeed may be regained.

Thrust Control

The underlying logic of the thrust control algorithm is the assumption that, unless certain specific conditions require rapid deceleration, the throttle is set to full afterburner. Currently, the only other throttle position used is idle. Speedbrake effects are coupled with idle thrust under the assumption that the control logic will select idle thrust only when maximum deceleration is desired.

Two situations are identified in which slowing down is required. In tne first, deceleration is desirable to prevent overshooting an opponent which is being tracked. This situation is specified in terms of the line-of-sight angle of the tracking aircraft, the closure rate, and the distance between the two aircraft.

In the second situation, deceleration is desirable in attempting to force the opponent to overshoot. In principle, the conditions are the same as those stated above, but with the roles of the two aircraft reversed.

Possible improvements in the thrust control logic would include military thrust in addition to idle and full afterburner thrust.

Prediction and Extrapolation

The prediction of future situations plays a critical role in the evaluation of trial maneuvers and, thus, represents a cornerstone of the decision process which selects the next action to be taken. Obviously, the reliability of these predictions has a direct bearing on the progress of the engagement. Two distinctly different processes are used to forecast the situation arising from trial maneuvers. The process used for the opponent will be called extrapolation while that for the AML controlled aircraft will be called prediction.

The estimation of the opponent's trajectory uses a second-order extrapolation based on three past coordinates recorded at equal time intervals (typically one second apart). In a polynomial approximation, this provides a linear approximation of the velocity vector and a quadratic extrapolation of position. In terms of the equations of motion, this means a constant acceleration vector and a planar flight path. Trial and error was used to estimate a suitable extrapolation time interval. Assuming a continuous decision process for the opponent, reliable extrapolation is possible if his motion remains approximately planar for the combined time of sample accumulation and extrapolation period. It is expected, and simulations confirm, that for two aircraft which are far apart, it is permissible to extrapolate over a relatively long period of time, on the order of five to ten seconds. To obtain about the same extrapolation accuracy during close-range maneuvering, shorter extrapolation times are required. The program compromises by using a constant extrapolation time, typically two to four seconds.

The extrapolation of the opponent's attitude at the end of the extrapolation time interval is relatively difficult, particularly with the limited information about the opponent assumed available to the AML program. Note that it is only assumed that the AML program receives data about the opponent's position at the sampling points; no information about his velocity or his attitude is required by this program. To simplify the process of attitude extrapolation, it is assumed that the wings of the opponent's aircraft are perpendicular to the plane determined by the three sample points. This assumption results in attitude errors for the x-body axes which remain, in most situations, within 20 degrees.

The prediction of an aircraft's own trajectory could, in principle, be made accurately, at least for one decision time interval. Computer cycle time limitations, however, require compromise in this area for real-time simulation. A reasonable balance must be achieved between the number of trial maneuvers executed and the accuracy of their analysis. Therefore, a simplified prediction is made by assuming the trajectory to be a segment of a circle corresponding to a particular normal acceleration characteristic of the particular trial maneuver being analyzed. Acceleration tangential to the flight path is neglected. Although the effects of thrust and drag are not included in the prediction, their inclusion might provide a possible improvement in the program.

Since the decision determining the next maneuver is based on the forecast situation, the extrapolation time must be the same as the prediction time. Intuitively, it is necessary to forecast at least as far ahead as the next tactical decision point. It may be desirable to forecast even further ahead. Times for prediction and decision intervals were determined empirically on the DMS.

Value Assignment to Individual Cells

The final step in the tactical decision process consists of selecting for actual execution that trial maneuver which promises the greatest benefit. The assessment of the worth of a particular relative situation between own aircraft and the opponent is the most important function in the AML program. The value of a particular situation is obtained by summation of the weighted answers (a "Yes" answer being represented by a one, a "No" answer by a zero) to a set of questions about the relative situation between the two opponents. These questions were obtained from several sources. ACM instruction manuals implicitly suggested several questions. Discussions with fighter pilots provided additional questions. Analysis of engagements between the AML program and human pilots indicated the need for additional questions. Finally, in order to accommodate different weapon types and weapon-type combinations, engineering judgment was used to formulate the remaining questions.

The method of assessing the value of a particular situation by answering a set of pertinent questions greatly contributes to the flexibility of the AML program. These questions reflect the present knowledge about air combat for particular aircraft and weapons combinations. They should not be considered as an unalterable part of the AML program but rather as a tool available to the AML program user to adapt the program to his specific needs.

The following set of 15 questions is provided as an illustration of typical questions used in the AML program. All questions are formulated in such a way that a "Yes" answer reflects a favorable condition.

The first four questions are the basic questions about who is behind or in front and about visibility.

1. Is the opponent in front of me?
2. Am I behind the opponent?
3. Can I see the opponent?
4. Can the opponent not see me?

The next two questions are concerned with the possibility that either aircraft could fire a weapon. It is assumed that weapons are fired only if the opponent is visible to the firing aircraft.

5. Is the opponent within my weapons envelope, and is he visible to me?
6. Am I outside the opponent's weapons envelope, or can the opponent not see me?

The next two questions determine whether the situation is such that the opponent is within a certain cone in front of one's aircraft and the own aircraft behind the opponent.

7. Is the opponent within a certain cone in front of me, and am I behind the opponent?
8. Am I outside of a certain cone in front of the opponent, or is the opponent ahead of me?

The next four questions deal with range rate; that is, whether the two aircraft are closing or separating. The underlying assumption is that, under certain conditions (offensive), closing with a certain closure rate is desirable; while, under certain conditions (defensive), separating appears to be more desirable. Since the answer to question 9 is always "Yes" if the answer to question 10 is "Yes", question 10 is explained first.

10. In order to obtain a "Yes" to question 10, the opponent must be within my weapons delivery envelope and visible, or he must be within a certain cone in front of me, and I must be behind my opponent; that is, the answer to question 5 and/or question 7 must be "Yes". In addition, the opponent must be within a range which lies between my minimum and my maximum weapons delivery range. Furthermore, the range rate must remain such that this condition will stay true for at least five decision time intervals.

9. As in question 10, the answer to question 5 or question 7 or both must be "Yes". The opponent, however, does not have to be within my weapons delivery range; if the range is greater than the maximum weapons delivery range, the two aircraft must be closing; if their range is less than the minimum weapons delivery range, they must be separating. Furthermore, the separating or closing rate must be of such a magnitude that it would take between two and ten decision time intervals to pass through the entire weapons delivery range.

If the aircraft finds itself in a defensive situation, it wants to avoid a closure or a separation rate which would bring it into the weapons range of the opponent.

Questions 11 and 12 will be answered by "Yes" as long as the aircraft is not in a defensive situation; that is, as long as questions 6 and 8 are both answered with "Yes". Assuming now that the aircraft finds itself in a defensive situation (question 6 or 8 or both being answered by "No"), it may still get "Yes" answers for questions 11 and 12 if the following conditions are satisfied: If the opponent is within weapons delivery range but the range rate is so that he is not expected to be able to stay within that range for more than five decision time intervals, question 12 will be answered with "Yes". If the opponent is outside the range, question 11 will be answered with "Yes" if one of the following conditions is true:

a. The range rate has the wrong sign; that is, the range is shorter than the minimum weapons delivery range and the two aircraft are closing or the range is greater than the maximum weapons delivery range and the two aircraft are separating.

b. If the range rate is of the right sign, but its magnitude is such that it would take the opponent less than two decision intervals to traverse the entire weapons range (closing or separating too fast), or it would take more than ten decision time intervals to reach the weapons delivery range (closing or separating too slowly).

Question 13 is answered by "Yes" if the line-of-sight angle from own aircraft to the opponent is less than a certain constant; for instance, 60 degrees.

Question 14 is answered by "Yes" if the rate of change of the line-of-sight angle lies within certain desirable limits. Figure 15 illustrates what that desirable region is. One straight line separates the desirable line-of-sight rates from those which are undesirable because the absolute value of the rate is so high that it is to be expected that the two aircraft just pass each other. A second straight line separates the desirable region from line-of-sight rates whose absolute values are considered to be too low and where it would take too long to obtain a favorable line-of-sight angle for weapons delivery. For instance, for a line-of-sight angle of 90 degrees, it is desirable to have a rate of the line-of-sight angle between -10 degrees/second and -30 degrees/second, which means that, if that rate continues, the line-of-sight angle reaches zero between 3 and 9 seconds.

The last question, 15, deals with the difference in specific energy between the opponents. It is answered by "Yes" if own specific energy, predicted five decision intervals from now, will be within certain limits of the opponent's present specific energy. This reflects the goal to obtain a specific energy slightly greater than that of the opponent. Energy conservation is not only not needed, but is actually undesirable if the opponent is at a significantly lower energy state than own's aircraft.

Each one of the 15 questions has a positive weight. The weight factors are input to the program and may therefore be varied from run to run. Weight factors may also be changed during the run under program control. This feature permits accounting for expended weapons. For instance, if no more missiles are available to the pilot, the weight to the questions pertaining to missile envelopes may be set to zero, which then forces the program to attempt to reach a gun firing position. No systematic investigation has yet been made to optimize these weight factors; they are usually all set to one.

The AML program is written in such a form that questions may easily be changed or added. For instance, by adding a question and assigning a strongly negative weight to it, the AML program can be prevented from operating in certain flight regimes.

DISCUSSION OF THE OFF-LINE PROGRAM

Program Capabilities

This section is intended to help the user of the off-line program make efficient use of the program and properly interpret the results. The program capabilities are quite extensive and permit sophisticated simulation of combat engagements. Any two aircraft may be paired against each other as long as the necessary input data for each aircraft are provided. The choice of initial conditions for combat simulation is practically unlimited, and any sequences of them involving the same two aircraft can be executed on the computer in a single job.

Pilot limitations are simulated with realistic consequences; for example, blackout occurs as a result of prolonged high load factor. More important, however, in this category is the simulation of imperfections in the decision process and of the situation judgments. During a dogfight, the human pilot can only estimate the range of the opposing aircraft within certain accuracy limits. To simulate these effects, certain random variables have been incorporated, and the program user is given six options for each pilot which he can exercise in any desired combination. The following variables can be perturbed randomly about their nominal values:

- decision time
- prediction time
- range
- line-of-sight angle
- load factor for first trial maneuver
- opponent's specific energy.

The randomization is made by generating a uniformly distributed random variable, in most cases in the range between 80 percent and 120 percent of the nominal value.

Generally, strict and definitively programmed rules are applied with respect to the knowledge each participant has of his opponent's capabilities and actions. One exception exists; the program user can decide whether the opponent's weapons delivery capabilities are known or not. If they are not known, it is assumed that both aircraft have the same weapons capability. Knowledge of the opponent's weapons envelope is reflected in the answer to questions 6 and 8 in the cell determination and may therefore influence the value of the trial maneuvers and consequently the decision process.

The decision processes used by both opponents to select a most desirable maneuver are identical. The program user, however, can alter the grading system for either aircraft through input data. For example, by assigning weight factors of zero, certain decision components can be eliminated from the evaluation process.

The program produces printed output on the progress of both aircraft at selected time intervals and optionally also on the evaluation of trial maneuvers. Certain aspects of an engagement can be graphically displayed, using a CALCOMP plotter. Among these are time histories of the value of the tactical situation, the line-of-sight angles, the Mach numbers, the range, the range rate, and the altitudes. Flight path projections onto a horizontal plane may also be plotted.

The decision process and trial maneuver evaluation could be refined, primarily with the objective of improving the ability to discriminate between closely-resembling situations. Additional logic which overrides the standard maneuver selection process, such as thrust control, dive recovery, evasive maneuvers, and so forth, might be needed to handle different aircraft combinations. The program in its present form is able to handle most recurring situations satisfactorily, and the cell evaluation is a good performance index. But, occasionally, a situation arises in which the program chooses a maneuver which will require a decision reversal after a short time. Such decision reversals do not necessarily impair the tactical performance, however; often in the real-time version, they actually help by confusing the opposing pilot.

Sample Engagement

The narrations of the simulated engagements of both the off-line program and the DMS runs were provided by a VietNam-era combat fighter pilot who possesses subsequent experience in air combat maneuvering against the advanced design fighter aircraft simulated here. These narrations are therefore somewhat typical of a fighter pilot's account and jargon.

A typical engagement between two almost identical fighters of modern design as simulated by the off-line program is illustrated in Figures 5 through 11. The program which generated the plots of Figure 11 was developed by the Langley Research Center and is described in Reference 5, page 20. Summarized, these plots represent a ground trace (x_e-y_e plane) and a perspective three-dimensional representation of the two aircraft and their trajectories as seen from a selected point in space. The aircraft is represented by a 9-point vector figure. The two points representing the wingtips are plotted at one-second intervals using different symbols for the two aircraft to define their trajectories.

In the following description, one aircraft is labeled "Attacker", the other "Target". Since the initial conditions are neutral, these names do not describe the role of the aircraft; they simply differentiate between the two opponents.

The engagement commences with the same initial conditions as will be used in some of the DMS runs described later in this report. Both aircraft are on parallel courses at 25,000 feet, speed .6M, 2-1/2 miles apart, when the attacker turns into the target at Military Rated Thrust (MRT) pulling 2-1/2 g's. The target responds similarly in MRT, initially pulling 3.8 g's but gradually easing back stick and load factor to 2 g's. MRT thrust is permitted by the AML program as initial thrust, but thereafter it uses only afterburner thrust (Combat Rated Thrust - CRT) or idle.

At 20 seconds, the two aircraft pass head-on at the same altitude, but the attacker has a 40 knot speed advantage. Both fighters light afterburners and commence turning back into each other with the target pulling 4 g's for approximately 4 seconds before the attacker begins to pull (increase g) his aircraft. Neither fighter sees an advantage with a vertical maneuver and thus begins a horizontal scissors maneuver that lasts for the next 70 seconds.

At 84 seconds, the attacker's airspeed dissipation, coupled with the target's continued promptness at reapplying g after each scissor reversal, has resulted in the attacker being thrown slightly out in front of the target. Each aircraft has approximately 20 seconds of weapons delivery time to his credit, all during head-on passes during the scissors maneuvers.

After 104 seconds into the run, the attacker commits himself to a dive in an attempt to shake off the target aircraft who has maneuvered himself into a tactically advantageous position. This initiates a tight vertical rolling scissors maneuver which draws the attacker out in front of his target with a 130 knot speed advantage, slightly offset from the target's flight path, pulling up to 6.8 g's.

At 121 seconds, the target has accumulated another 7 seconds of weapons delivery time by dropping back into the attacker's 30 degree tail cone (within 30 degrees of the attacker's longitudinal (x) axis), and possesses a distinct tactical advantage. The attacker's 130 knot speed advantage rapidly dissipates to co-speed due to the heavy loading he maintains in the scissors and upon pullout at 14,000 feet.

The two aircraft remain in a horizontal rolling scissors with the target continuing to improve his advantage and increase his weapons delivery time by slowing and maneuvering behind the attacker. Except during two slight overshoots, the attacker is never able to shake the target from his 30 degree tail cone area.

At about 150 seconds, the two aircraft begin to dive for additional airspeed; however, the scissors terminates with the target dropping back "into the saddle" (that unshakeable position where the lead aircraft cannot shake off the chase aircraft's tail pursuit) on the attacker with a 50 knot speed disadvantage but within missile and gun range (1,600 feet). From time 152 seconds to 176 seconds, the target obtains another 14 seconds of weapons time now that he is established at the attacker's 5:00 to

7:00 o'clock position; thus the engagement must be considered as lost to the target.

The engagement is nearly a perfect draw until time 84 seconds when the two aircraft begin their vertical rolling scissors. The coordinated changes in dive angle and applied g by the target causes the attacker to begin to drift out in front of the target due to an accumulated airspeed advantage. The target makes excellent use of his opponent's airspeed differential by dropping back during the dive to a more tactically advantageous position.

DISCUSSION OF THE REAL-TIME PROGRAM

Program Development

By the summer of 1971, the off-line program had been sufficiently well developed to justify its implementation on the DMS as an opponent against human pilots. Decision Science, Inc. was authorized by NASA to extend the previous work to include a real-time simulation of one-on-one combat on the DMS. The first tests of such a program on the DMS were performed in the summer of 1972. The objective at that time was to properly interface the AML program with the already-existing DMS computer program and to achieve a preliminary evaluation of the performance of the AML program against human pilots.

These tests demonstrated that the AML program provided a competent adversary for human pilots. The following three problems were identified at the end of these tests:

1. The motion of the AML aircraft was too jerky.
2. On rare occasions, the AML program would no longer interact with the opponent but maintained a straight course at constant speed.
3. The AML driven aircraft often flew so slowly that it could not continue to maneuver.

The first problem occurred under normal flight conditions while the second and third were related only to low speed flight. To correct the first problem and ensure smoothness of attitude change, the rotational body rates p, q, and r, as calculated in the equations of motion of the AML program, were passed through a digital filter before being transferred to the DMS program for driving the displayed model aircraft. This produced realistic, smooth attitude changes so that pilots flying against the AML driven aircraft no longer complained about its "jerkiness".

The second problem was resolved through program changes in the equations of motion which would now determine the proper trajectory of the aircraft according to whatever forces were acting on the aircraft at low speeds.

The third problem was solved by extensively modifying the available trial maneuvers once the aircraft has reached a certain low speed status. To prevent loss of controlability, the low speed recovery trial maneuvers, as described in the section on the tactical decision process, were programmed.

A second and final series of experiments under this contract were conducted in December 1973, with the primary objective being to verify proper resolution of the above-referenced problems and to gain additional experience with the AML program operating on the DMS.

After the low speed recovery procedures appeared to produce satisfactory flight conditions in the off-line program, they were checked out on the DMS. First, the AML driven aircraft was engaged against a "canned" trajectory on the DMS so that the AML aircraft was forced into a vertical loop. By adjusting the initial velocity of the AML aircraft, different conditions of the low speed recovery could be replicated. In all situations, the aircraft assumed a downward pointing velocity vector and recovered properly from the low speed condition in a few seconds.

Human pilots then performed sharp pullups with enough initial velocity to complete a vertical loop while the AML driven aircraft pursued with an initial velocity adjusted so it would enter the low speed regime during its pursuit maneuver. Here again, the AML driven aircraft was able to continue to fly and to maneuver effectively in each case.

The following section describes flights against human pilots performed during the month of December 1973. At that time, the AML program differed in several aspects from the version which is described in the rest of this report; that is, several improvements have been added to the program since December 1973. These improvements were made primarily in the area of dive recovery and in the set of questions defining the state and the value of a particular situation. The test whether to pull out of a dive in order to avoid hitting the ground was made only at the tactical decision times rather than at every integration step. This required a criterion for pullout which was more restrictive than the one described in the section "Dive Recovery", because failing to pull out at a given decision point could not be corrected until the next decision point. Indeed, the AML driven aircraft did pull out of dives too early, thus frequently giving an advantage to the opponent. Instead of 15 questions defining the state, only 12 were used; and furthermore, they were of a simpler form than the ones described earlier in this report. The 12 questions at that time were:

1. Is the opponent in front of me?
2. Am I behind the opponent?
3. Can I see the opponent?
4. Can the opponent not see me?
5. Am I within a certain cone behind my opponent?
6. Is the opponent not within a certain cone behind me?
7. Am I in an attitude and position so that I can fire at the opponent?

8. Is the opponent not in an attitude and position so that he can fire at me?
9. Are we closing between zero and 300 feet/seconds?
10. Is the line-of-sight angle from me to the opponent less than 60 degrees?
11. Is the rate of change of the line-of-sight angle from me to the opponent negative?
12. Is my specific energy rate P_S greater than a given constant?

Flights Against Human Pilots

On December 14, 1973, a series of engagements were flown against a highly-qualified Navy pilot. Both aircraft simulated were F-4's. The pilot had flown some 150 missions in the F-4 over VietNam and had several hours of previous experience on the DMS. The first few engagements should, nevertheless, be considered only as familiarization exercises. Table I shows the duration of 15 engagements as well as total offensive time with advantage for the manned aircraft and for the AML driven aircraft. Simply defining the aircraft holding the longer offensive time with advantage as the winner, the score for the AML program would be nine wins, four losses, and two stalemates. It should be pointed out here that, in all the runs of short duration (4, 5, 11, 12, 13), the human-piloted aircraft spun, thus terminating the run.

A second series of engagements were flown on December 19, 1973, the last day of this test series. The human pilot was a highly-qualified NASA engineer who had probably flown more ACM engagements in the F-4 in the DMS than any other person. All engagements started with neutral initial conditions with both aircraft flying straight and level at co-speed, co-altitude, and pointing in the same direction. Altitudes were 20,000, 25,000, and 30,000 feet; velocities Mach 0.6, Mach 0.8, and Mach 1.2. The initial range was 15,000 feet.

The first three runs were against canned trajectories and were not recorded. Between Run 4 and Run 22, some runs were extremely short (because the piloted aircraft spun very early during the engagement), and were therefore also not recorded. The 14 remaining runs were analyzed later by the DMS Data Reduction and Analysis Program (ref. 5); the results of this analysis are summarized in Table II. The score for the AML program was ten wins, three losses, and one stalemate.

It is interesting to note that the outcomes of Runs 4, 5, 7, 15, and 22 were essentially decided during the first 30 seconds of the engagement; Run 20 between 60 and 90 seconds. In all other runs, the critical time occurred between 30 and 60 seconds. Note that time to achieve an offensive position is generally shorter when two opponents start parallel than for a head-on initial conditions.

To complete these examples of the DMS runs, one run out of this series is shown here in detail. Run 12 was selected because it shows a fairly even fight in which the AML program finally emerged as winner when the run was terminated after 102 seconds.

In the figures illustrating this engagement, Sphere A (or aircraft A) was flown by the human pilot; Sphere B was driven by the AML program.

Figures 12 and 13 show time histories of altitude, velocity, load factor, and line-of-sight angle of the two aircraft. These time histories were recorded in real time on Brush Analog Recorders.

Figure 14 illustrates the engagement by perspective views of the two aircraft and by ground traces. The points were recorded in one second intervals, and each frame displays 19.22 seconds of flight time. Engagement 12 commenced with both aircraft heading in the same direction at an altitude of approximately 25,000 feet at Mach 0.6 (approximately 400 knots) with about 2-1/2 miles of separation between the aircraft. Upon the commencement of the engagement, both aircraft turned into each other; the human-piloted aircraft rolled into a tight angle of a bank pulling 2-1/2 g's in an attempt to point his nose at the aggressor AML aircraft. The AML aircraft executed a "tuck under break" (a 270 degree roll to an approximate 90 degree bank angle) and pulled 2-1/2 g's in a level turn into the human-piloted aircraft. The two aircraft passed head-on in a high angle of bank turn, reversed their turns, decreased g slightly, and began a second turn back into each other; the AML aircraft in a shallow climb, the human-piloted aircraft in a shallow dive. At this point, they were approximately a mile apart, with the human-piloted aircraft holding a 70 knot speed advantage due to its loss of altitude subsequent to reversal. The AML aircraft held a 2,000 feet altitude advantage at this point. Thus, at time 19.22, neither aircraft held a distinct tactical advantage; however, the seeds of victory were sown as the AML aircraft held an altitude advantage that would enable it to drop onto the human-piloted aircraft's rear quarter during the next 20 seconds.

The human-piloted aircraft continued his hard left diving turn, pulling as much as 4 g's and dropping 5,000 feet in altitude in order to gain airspeed. The AML aircraft continued his hard right turn, rolled inverted and commenced a tight diving spiral and began to assume an advantage by dropping behind the human-piloted aircraft, decreasing the line-of-sight angle to zero degrees for 3 seconds, at a range of approximately 1,800 feet at co-speed. At time 38.44 seconds, the AML aircraft had assumed a definite advantage over the human-piloted aircraft by flying to a 45 degree tail cone position at a range of 1,700 feet, co-speed at 20,000 feet altitude. The human-piloted aircraft continued his tight left turn and increased his angle of dive almost to the vertical. In a tight rolling dive to escape from the aggressor AML, he increased his airspeed 50 knots but lost an additional 9,000 feet of altitude. The aggressor AML continued his tight diving spiral to the left at maximum g, decreasing the line-of-sight angle to 10 degrees again at 49 seconds while still retaining a 1,500 feet altitude advantage. At 57.66 seconds, the human-piloted aircraft had begun to pull out of his dive at a speed of 478 knots, approximately 5,000 feet in front of the AML aircraft who was back at his 8:00 o'clock position. The human-piloted aircraft continued a tight left 6 g turn and decreased his dive angle in an attempt to slow his loss of altitude. The aggressor AML also slowed his loss of altitude, continuing a 5 g left turn back at the opponent's 7:00 O'clock position. From 62 to 72 seconds, the aggressor AML aircraft held a strict tactical advantage over the human-piloted aircraft in that he was co-speed, co-altitude, and within range of either an AIM-9 Sidewinder or an AIM-7 Sparrow missile shot. From 64 to 72 seconds, the AML aircraft maintained a line-of-sight angle of approximately 10 degrees, placing the opponent within gun range. At 76.88 seconds, the AML aircraft continued to retain its tactical advantage maintaining co-speed and a slight altitude advantage at a range of 4,500 feet at the opponent's 8:00 o'clock position. Both aircraft continued in a port turn tail chase with the AML aircraft decreasing its applied g while increasing its velocity to almost 400 knots. The range between the aircraft increased to approximately one mile while the AML aircraft was building its airspeed back up, both aircraft flying a level turn in an attempt to keep from breaking the 5,000 feet altitude restriction usually imposed in ACM training (96.09 seconds). The engagement concluded with both aircraft in a 4 g level port turn with the AML aircraft utilizing his speed advantage to decrease the range between the aircraft while maintaining the line-of-sight angle of less than 45 degrees. The engagement concluded therefore with the AML aircraft holding a distinct advantage over the opposing aircraft in that he was back at a 7:00 o'clock position at a range of less than a mile with both a speed and altitude advantage. The AML driven aircraft kept his opponent within less than a 40 degree line-of-sight angle, well within the envelope for a Sparrow or Sidewinder launch.

CONCLUSION

These experiments have demonstrated the capability of the AML program to serve as the tactical driver in one-on-one aerial combat engagements. Each day the AML program scored successes more often than the human pilot. It demonstrates a significant adaptability in that it can fly successfully against different types of aircraft. Since nothing in the program is specifically tailored to the F-4 or any other specific aircraft, the program performs maneuvers which are certainly sound when flying an F-4 against any similar aircraft. The same should be true for any two aircraft. One pilot commented that, if he had not known that the opposing aircraft was not driven by a human, he would <u>not</u> have noted this from the way the aircraft flew. Another interesting comment noted that the AML driven aircraft sometimes performed unexpected maneuvers. This tended to confuse the pilot.

It is important to recognize that the AML driven aircraft frequently obtains a positional advantage because of its capability to roll (with relatively high roll rate) while under load. It appears to be the combination of this rapid roll without relieving the g load which makes the AML driven aircraft more maneuverable. This effect is particularly pronounced at low airspeeds. If the human pilot attempts to induce a high roll rate at high angle of attack, he is likely to spin. On the F-4, only a highly-skilled pilot can prevent such a spin by judicious balancing of rudder and aileron commands. Unfortunately, the particular selection of these depends strongly on the type of aircraft involved, so that pilots have to be retrained for flying ACM in different fighter aircraft types. Evidently, the capability of existing fighter aircraft could be significantly improved without changes in the basic airframe design, by improving the stability augmentation system in a manner that enhances the pilot's control of the aircraft at low airspeeds and high loads.

One might ask, "Why does the AML program sometimes lose when the combat is initially in a neutral situation?" The answer is straight-forward: The AML program is not perfect. It occasionally makes one of two kinds of errors:

- It sets up an effective trial maneuver but, because of erroneous evaluation, it does not choose it as the next maneuver to be executed.
- The optimum maneuver in a given situation is not exercised as a trial maneuver.

In principle, it is possible to analyze each run wherein the AML program lost and, with the aid of expert pilots, determine what caused it to lose. If there was an error of the first kind, the question arises as to whether or not the future situation resulting from a trial maneuver was incorrectly predicted. This could happen in two ways: The position, attitude, and energy state of the driven aircraft could be incorrectly predicted, or a similar error could be made in extrapolating that state of the enemy aircraft. The latter error arises if the opponent makes an unexpected maneuver...a move which is beyond the extrapolation technique used in the program. The future situation of the AML driven aircraft could, in principle, be predicted accurately except that certain limitations are implicit from the computational capacity of the simulation. Simplifications used in the prediction technique permit predicting several trial maneuvers in real time, but this simplification may have its cost in terms of prediction accuracy.

If an error of the second type is made and recognized as such, one could, in principle, add that maneuver to the set of trial maneuvers. Once again, the limitation is one of the available computational capacity and memory. It seems reasonable to expect that, with increasing computer capability, there can be a significant improvement in the already remarkable performance of the AML program.

RECOMMENDATIONS FOR FURTHER STUDIES

The current AML program represents a highly-competent adversary in one-on-one dogfights. As one pilot put it: "It makes sound tactical decisions." Pilots losing against the program attempt to find some excuse. Presently, such an excuse can easily be found in that the AML driven aircraft remains perfectly controllable at very low airspeeds. As explained earlier in this report, the equations of motion calculate the forces acting on the center of gravity of the aircraft which, in turn, determine the aircraft's trajectory. Rotational rates about the three aircraft body axes are then calculated such that the aircraft will assume an attitude required for a given velocity vector, angle of attack, and sideslip angle. If the AML program, instead of determining p, q, and r in this way, would command control surface deflections (elevator, aileron, and rudder) to the DMS program, the aircraft dynamics of the aircraft controlled by the AML could be made identical to the aircraft flown by the pilot. Thus, the AML program would have no advantage over the human pilot in controlling the aircraft. To accomplish this task within the AML program requires the design of a feedback control system which would accept as input the desired changes in roll angle and in angle of attack. It would then produce as output elevator, aileron, and rudder deflections such that the desired attitude changes would be obtained. Sideslip would be minimized during the transition and reduced to zero after steady state had been reached.

Decision Science, Inc.
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REFERENCES

1. Meintel, A. J., Jr.; and Pennington, J. E.: Differential Maneuvering Simulator. Air-to-Air Combat Analysis and Simulation Symposium, AFFDL-TR-72-57, Vol. I, U. S. Air Force, May 1972, pp. 187-210.

2. Welch, L. D.; and Pickitt, J. L.: TAC AVENGER - Conception to Maturity. Air-to-Air Combat Analysis and Simulation Symposium, AFFDL-TR-72-57, Vol. II, U. S. Air Force, May 1972, pp. 333-350.

3. Hutcheson, J. H.: A Six-Degrees-of-Freedom Version of the Tactics Intercept Simulation Program. Air-to-Air Combat Analysis and Simulation Symposium, AFFDL-TR-72-57, Vol. II, U. S. Air Force, May 1972, pp. 175-190.

4. Kohlas, J.: Simulation von Luftkampfen (Simulation of Air-to-Air Combat). Ph.D. Thesis, University of Zurich, Juris Publishing Company, Zurich, Switzerland, 1967.

5. Beasley, G. P.; and Sigman, R. S.: Differential Maneuvering Simulator Data Reduction and Analysis Software. NASA Technical Memorandum, TMX-2705, Washington, D. C., July 1973.

TABLE I.- SUMMARY OF THE RUNS OF DECEMBER 14, 1973

AGAINST NAVY PILOT

Run Number	Duration of the Engagement Seconds	Human Pilot Offensive Time With Advantage Seconds (OTA-DMS)	AML Driven Aircraft Offensive Time With Advantage Seconds (OTA-DMS)
4	37	0	2.92
5	27	0	0
6	160	7.6	20.50
7	230	16.13	16.93
8	67.9	0	10.65
9	94.8	0	6.48
10	114.4	0	82.8
11	40.3	0.60	0
12	42.9	0	0.08
13	5.1	0	0
15	125.5	4.36	0.16
16	105.7	0.44	0.08
17	135.2	0	86.20
18	358.0	8.52	37.90
19	310.7	6.76	5.56

TABLE II.- SUMMARY OF RUNS OF DECEMBER 9, 1973

Run No.	Total Seconds of Offense		Total Seconds of Offense With Advantage (OTA-DMS)		Average[a] Cell Value		Seconds of Offense Within First 30 Seconds		Seconds of Offense Within First 60 Seconds	
	Pilot	AML	Pilot	AML	Pilot	AML	Pilot	AML	Pilot	AML
4	91.5	69.0	47.0	24.5	5.3	4.8	30.5	5.5	61.5	15.0
5	30.0	23.0	14.0	7.0	4.9	5.0	28.0	14.5	28.0	14.5
7	94.0	54.0	51.5	11.5	5.9	4.3	29.0	12.0	60.0	14.5
8	19.5	36.5	13.5	30.5	4.1	6.0	19.0	17.5	19.5	36.5
11	37.0	67.0	9.0	39.0	4.4	5.7	23.0	20.5	23.0	51.5
12	32.0	97.5	0.0	65.5	4.2	6.4	17.0	22.0	25.5	53.0
13	29.5	118.5	2.5	91.5	4.1	6.6	19.0	24.0	22.0	55.0
15	13.0	80.0	0.0	67.0	3.7	6.8	12.5	27.5	12.5	57.5
16	39.0	91.0	0.0	52.0	4.3	6.3	14.0	16.5	29.0	38.0
17	31.0	100.5	2.0	71.5	3.7	6.6	22.0	24.0	22.0	55.0
19	27.0	132.0	2.5	107.5	4.0	7.0	21.5	19.5	27.0	50.5
20	123.5	204.0	3.0	83.5	4.6	5.8	22.0	21.5	48.0	45.5
21	16.0	37.0	2.5	23.5	4.1	6.1	15.0	23.5	16.0	37.0
22	34.5	16.5	19.5	1.5	5.6	4.4	27.0	8.5	34.5	16.5

[a]The state vector in these runs was defined such that 12 was the maximum achievable cell value.

TABLE III.- OFFENSIVE TIMES AND CELL VALUES

RUN NUMBER 12

		Seconds Into Flight Time			
		30	60	90	102.3
Seconds on Offense	Pilot	17.0	25.5	25.5	32.0
	AML	22.0	53.0	84.0	97.5
Seconds on Offense With Advantage	Pilot	0.0	0.0	0.0	0.0
	AML	5.0	27.5	59.0	65.5
Accumulated[a] Average Cell Values	Pilot				4.2
	AML				6.4

[a]Based on a maximum achievable cell value of 12.

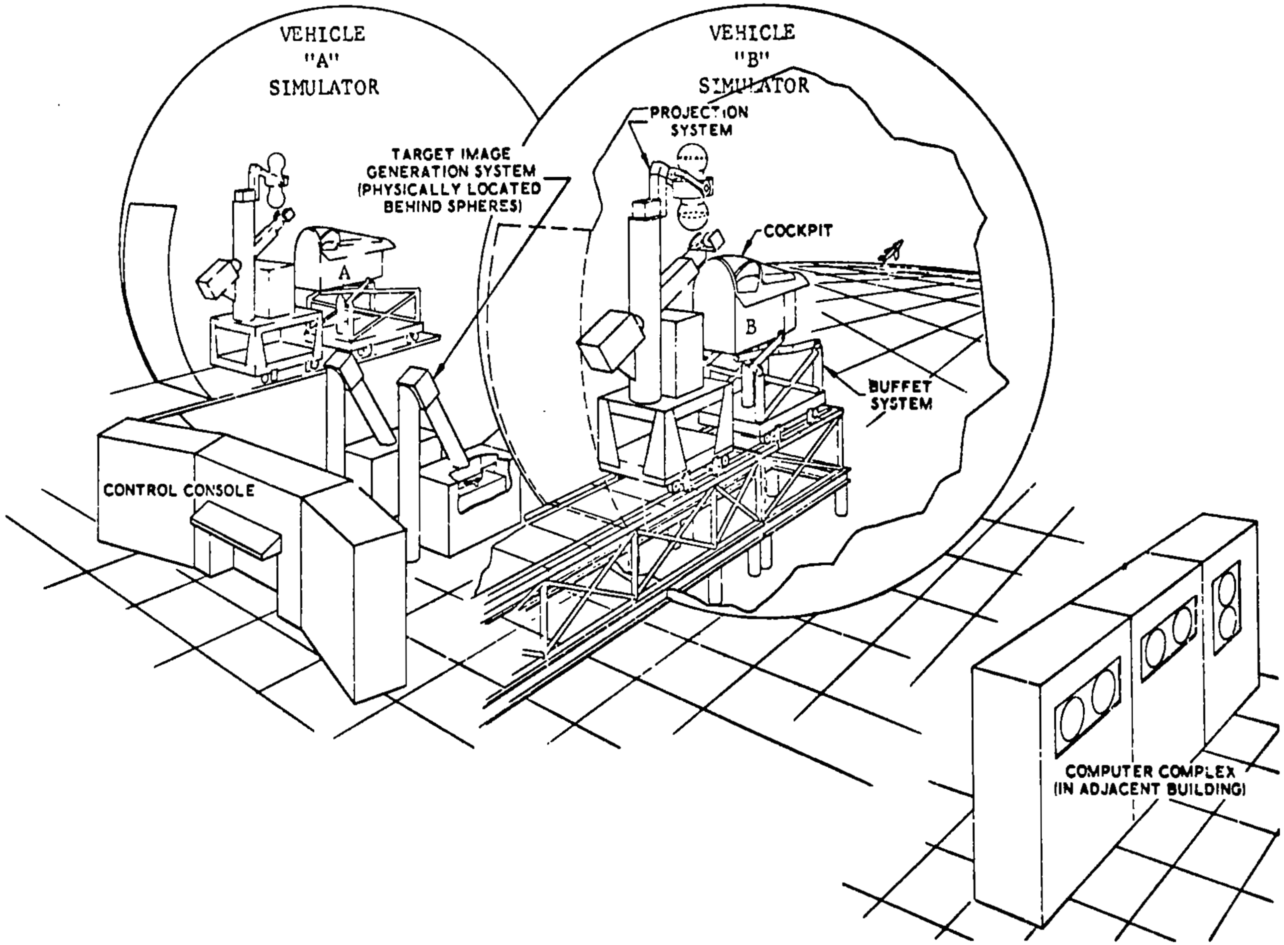


Figure 1.- Differential Maneuvering Simulator

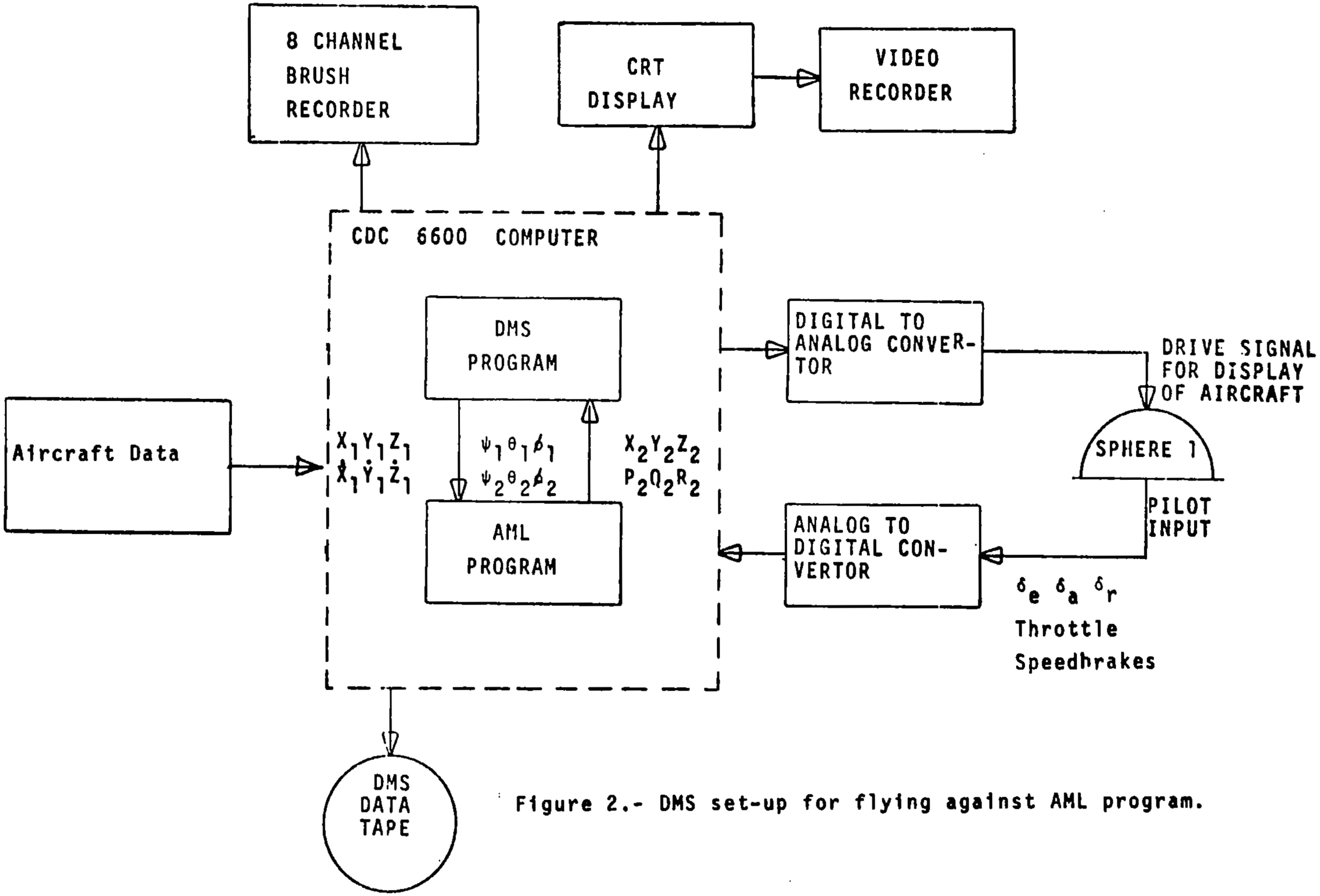
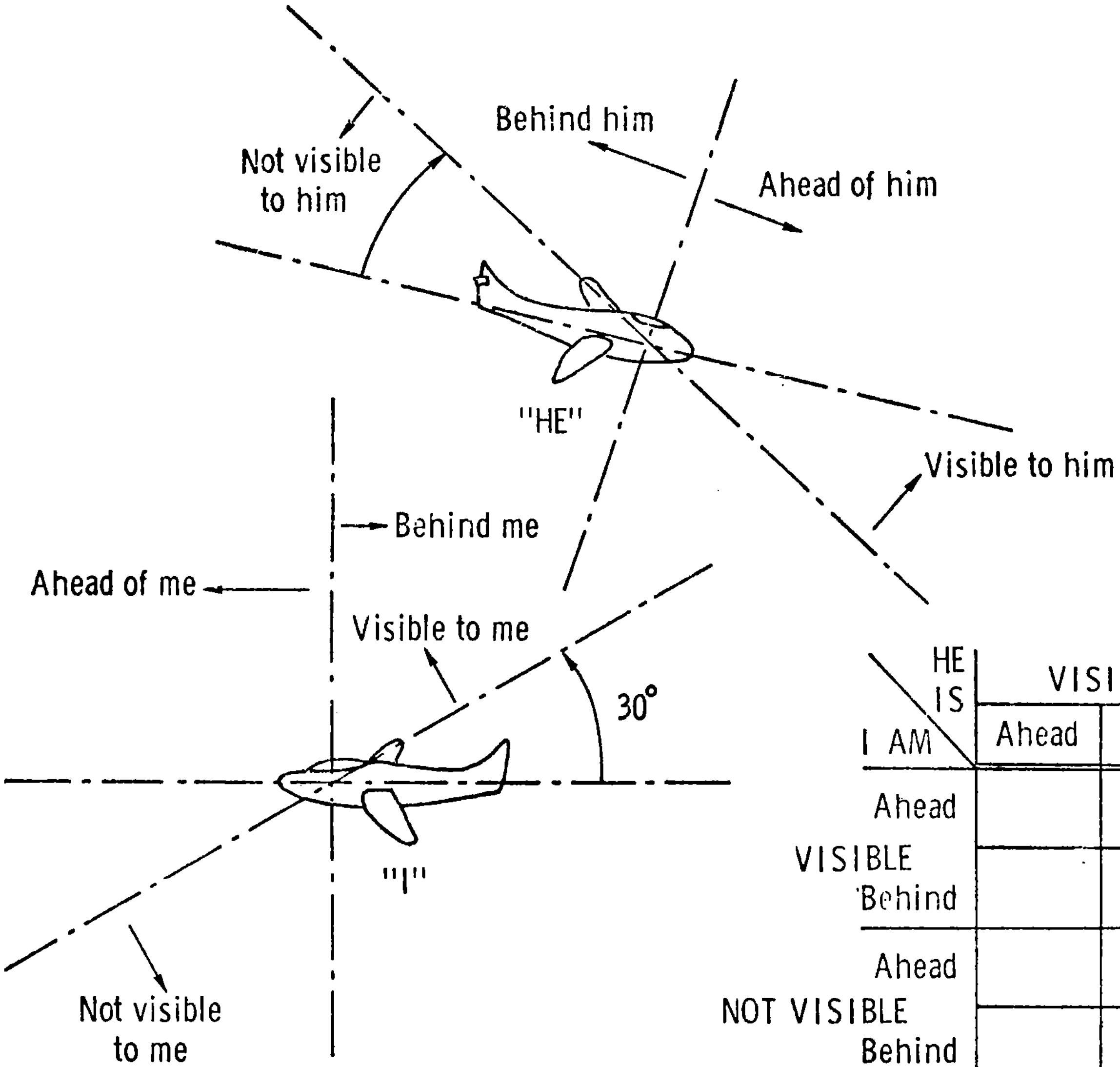


Figure 2.- DMS set-up for flying against AML program.



HE IS / I AM		VISIBLE		NOT VISIBLE	
		Ahead	Behind	Ahead	Behind
VISIBLE	Ahead				
	Behind				
NOT VISIBLE	Ahead				
	Behind		X		

Figure 3.- Basic element of situation matrix.

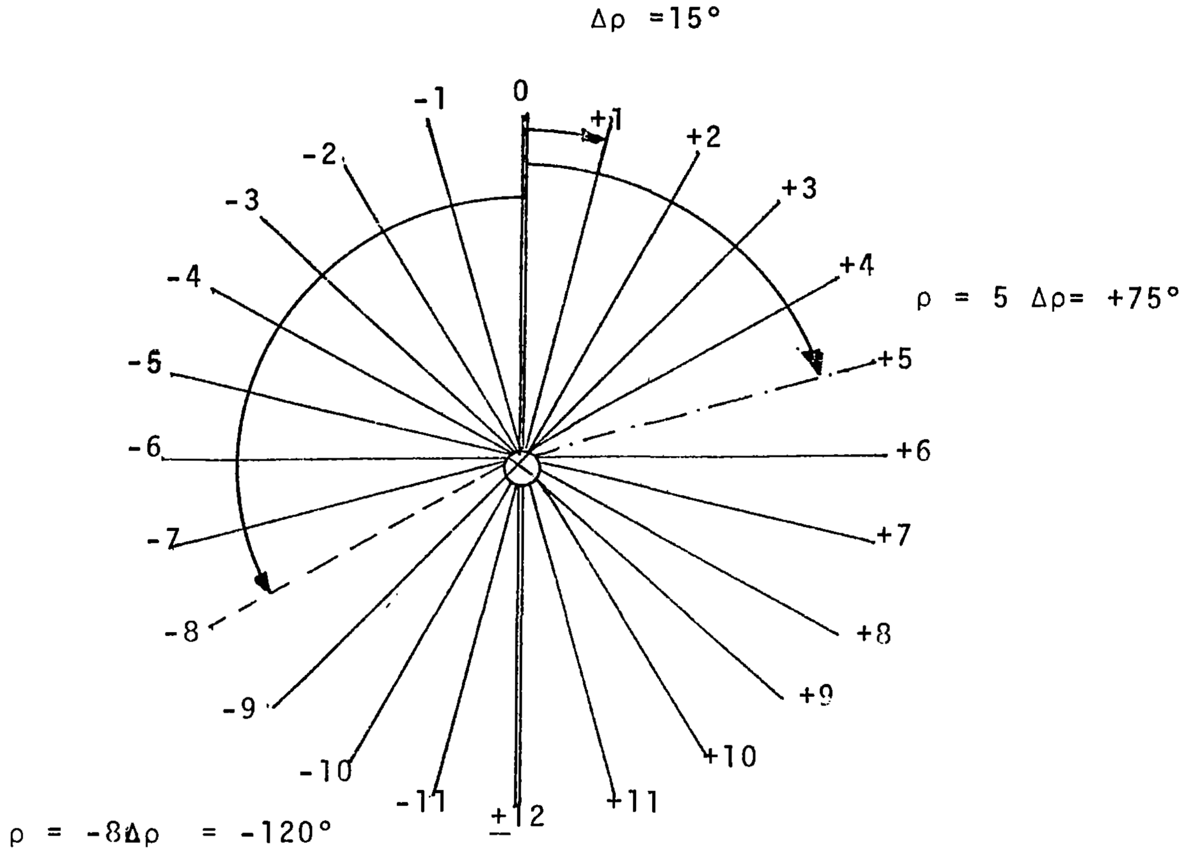


Figure 4.- Orientation of maneuver planes with respect to velocity vector.

Velocity vector is pointing perpendicular into the plane of the drawing. To obtain a maneuverplane with a rotation angle ρ (for example $\rho = 75°$ or $\rho = -120°$), a plane through the velocity vector and perpendicular to the X_e Y_e-plane is rotated by the angle ρ about the velocity vector.

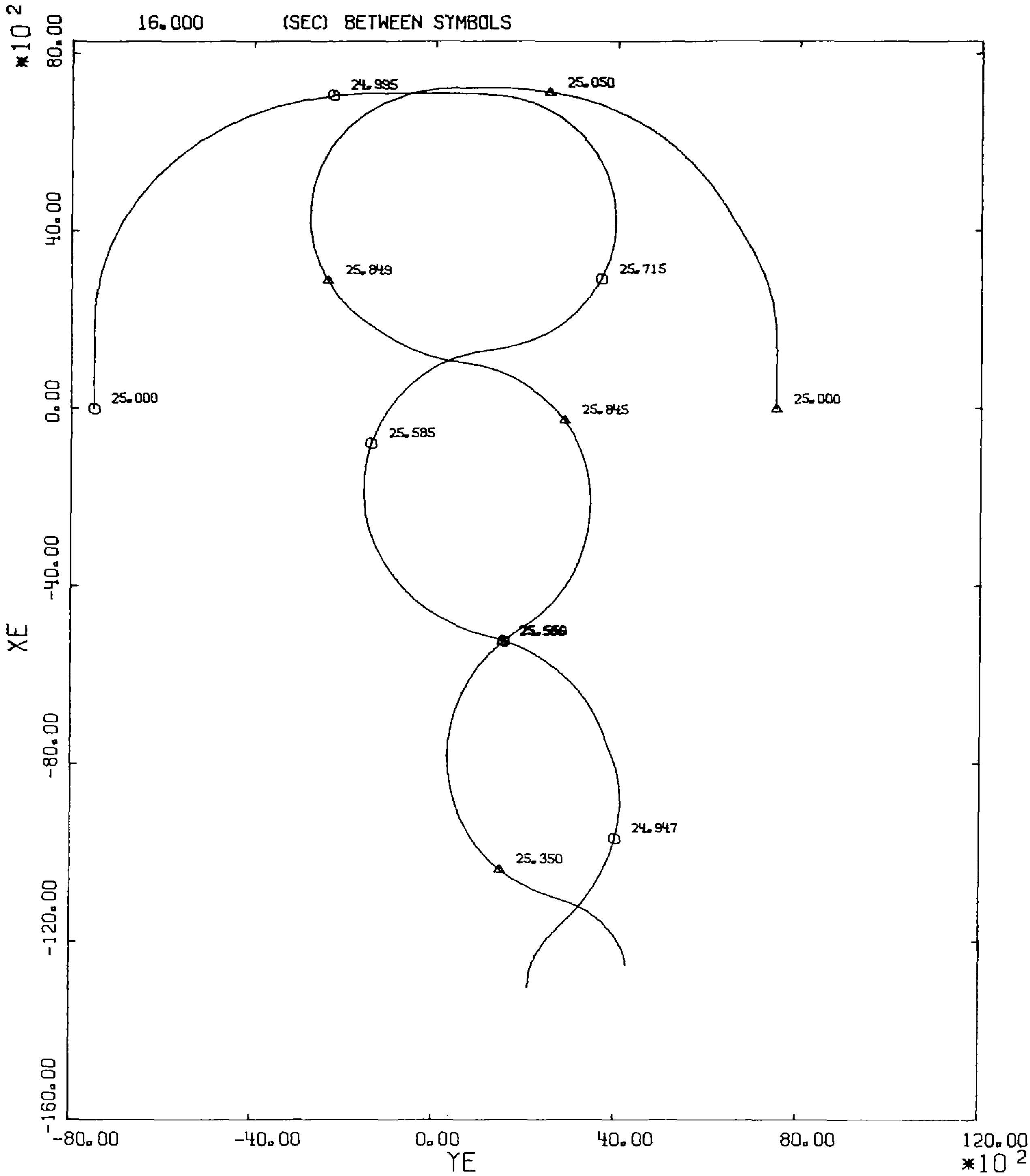


Figure 5.- Ground trace of sample engagement. Altitude is marked in 1,000 feet every 16 seconds.

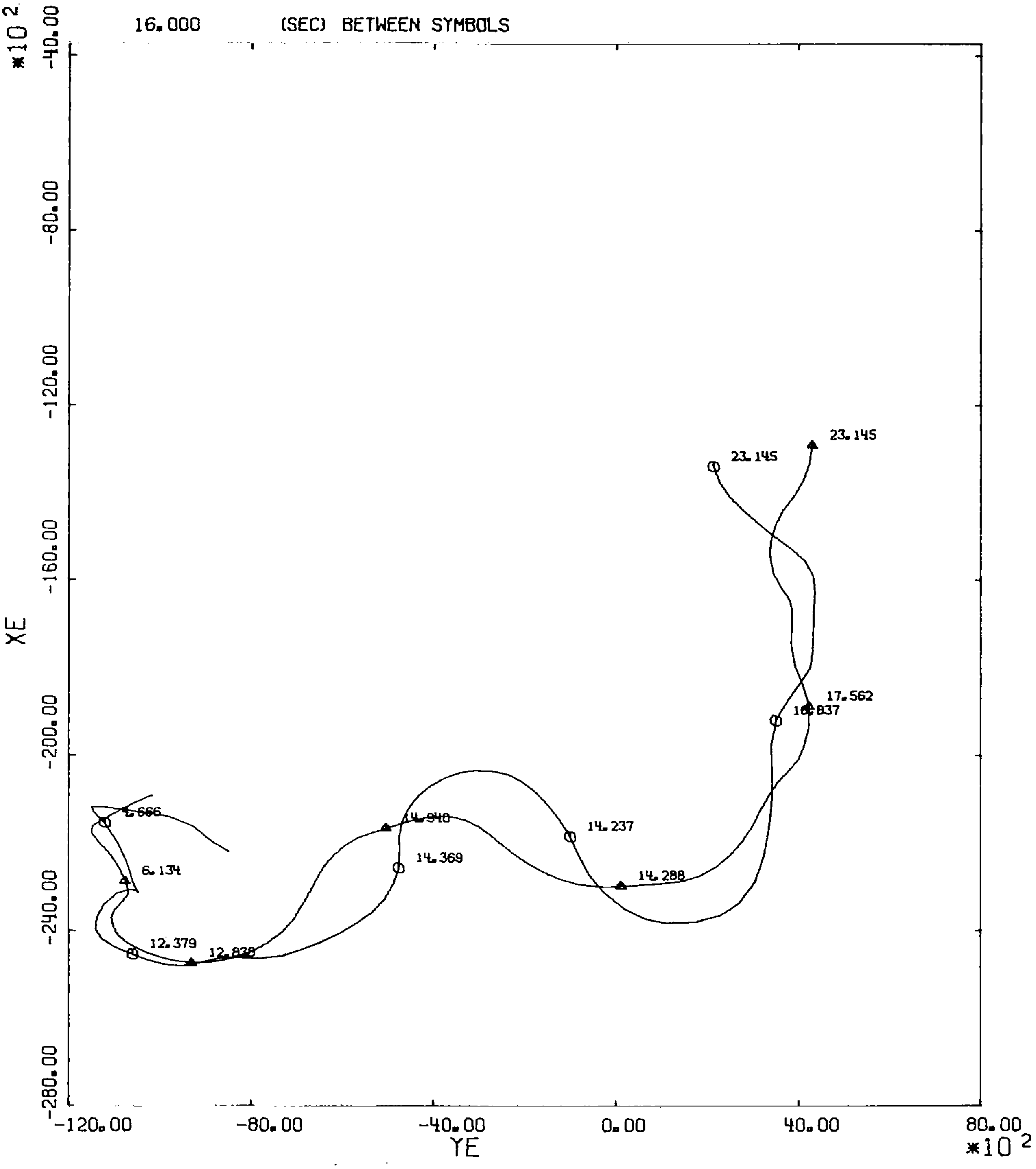


Figure 5.- Concluded

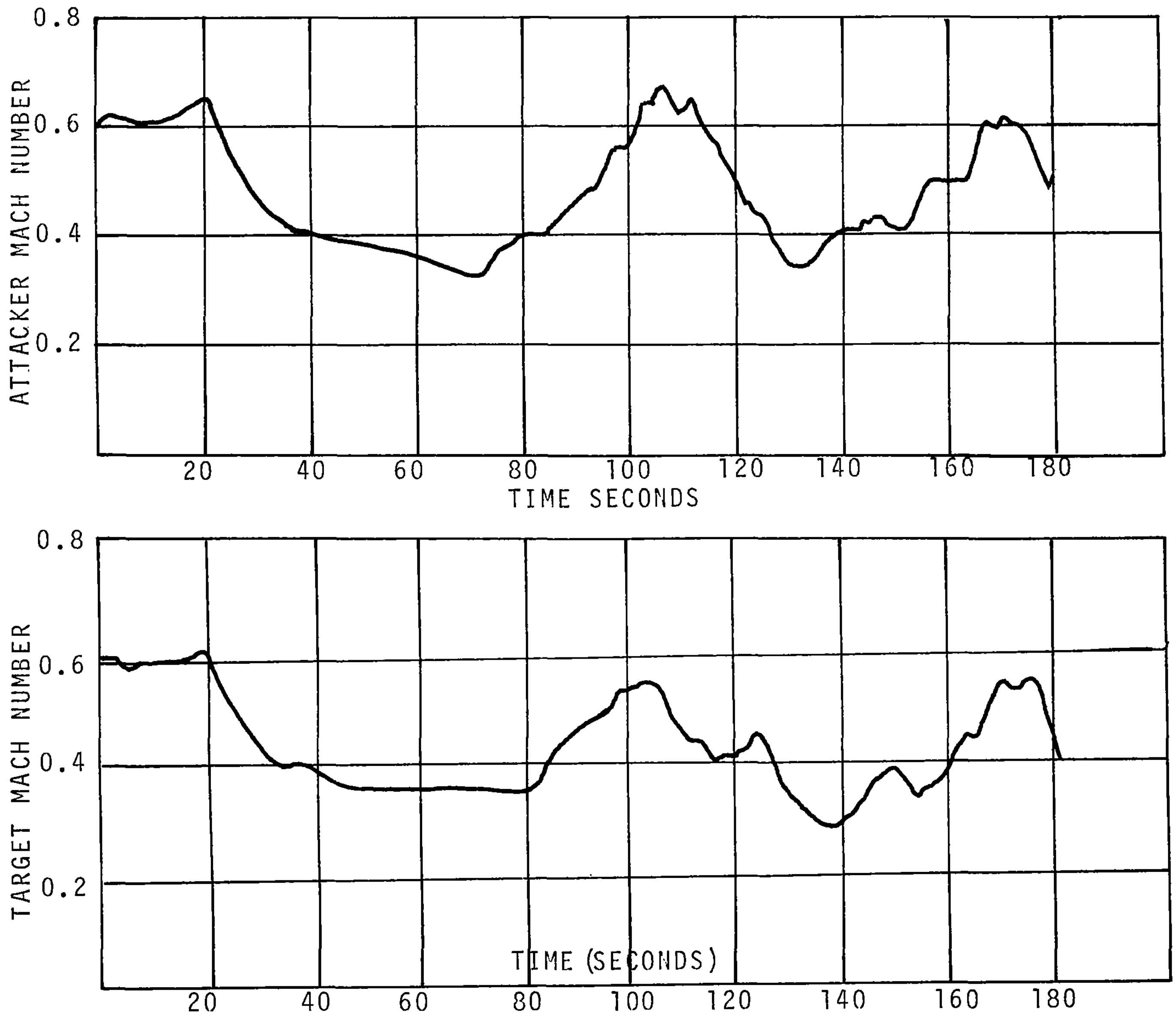


Figure 6.- Mach numbers for off-line sample engagement.

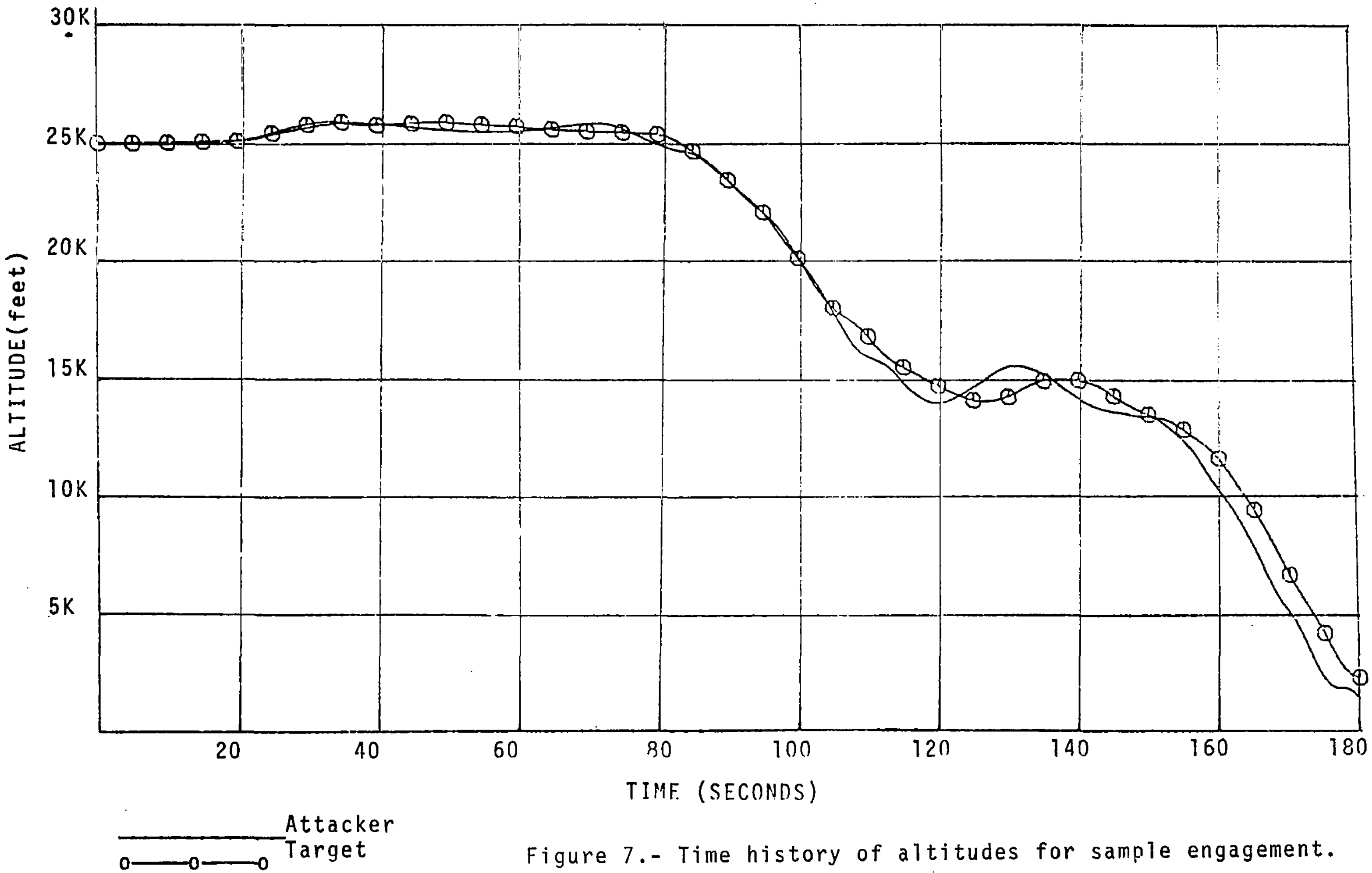


Figure 7.- Time history of altitudes for sample engagement.

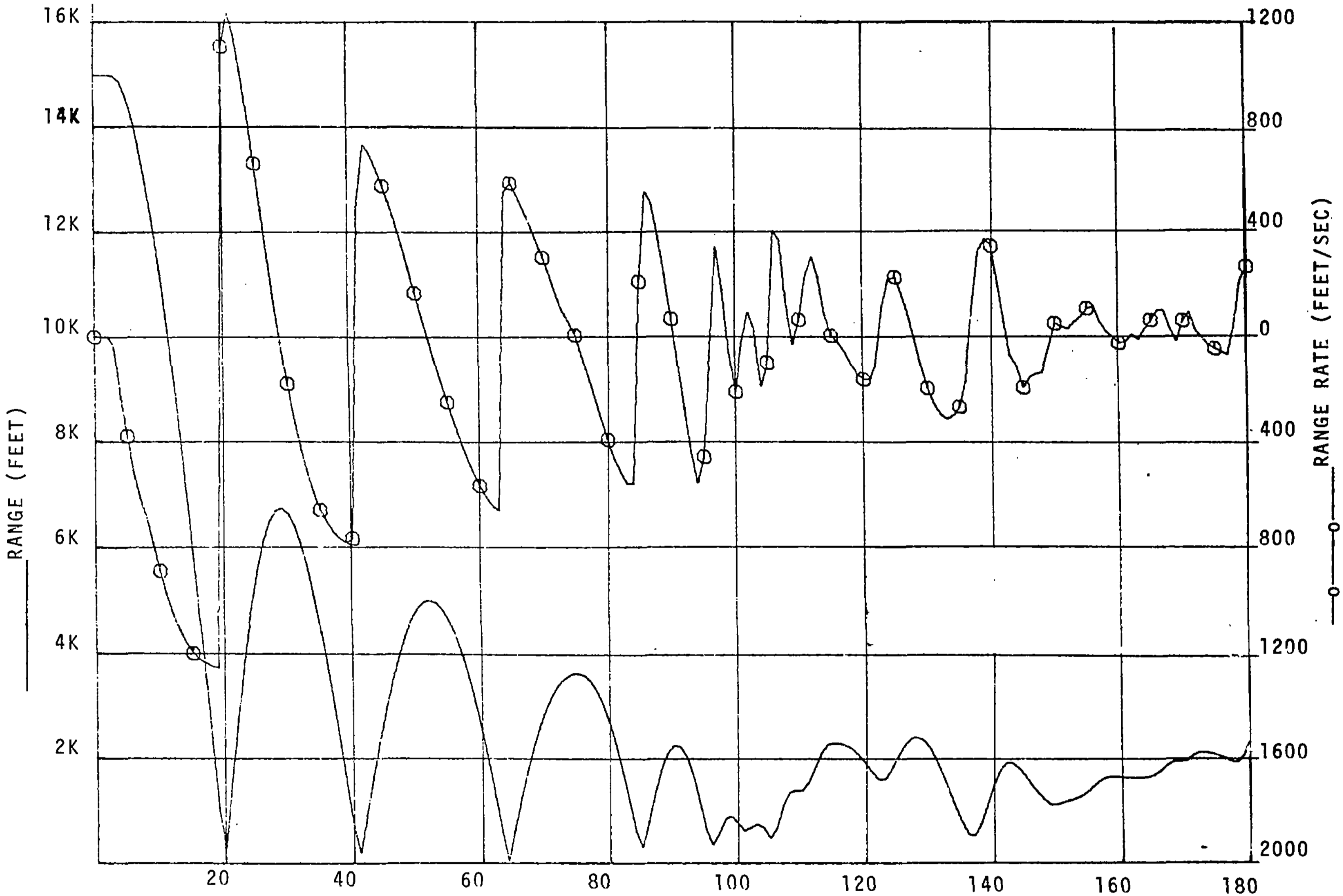


Figure 8.- Time histories of range and range rate.

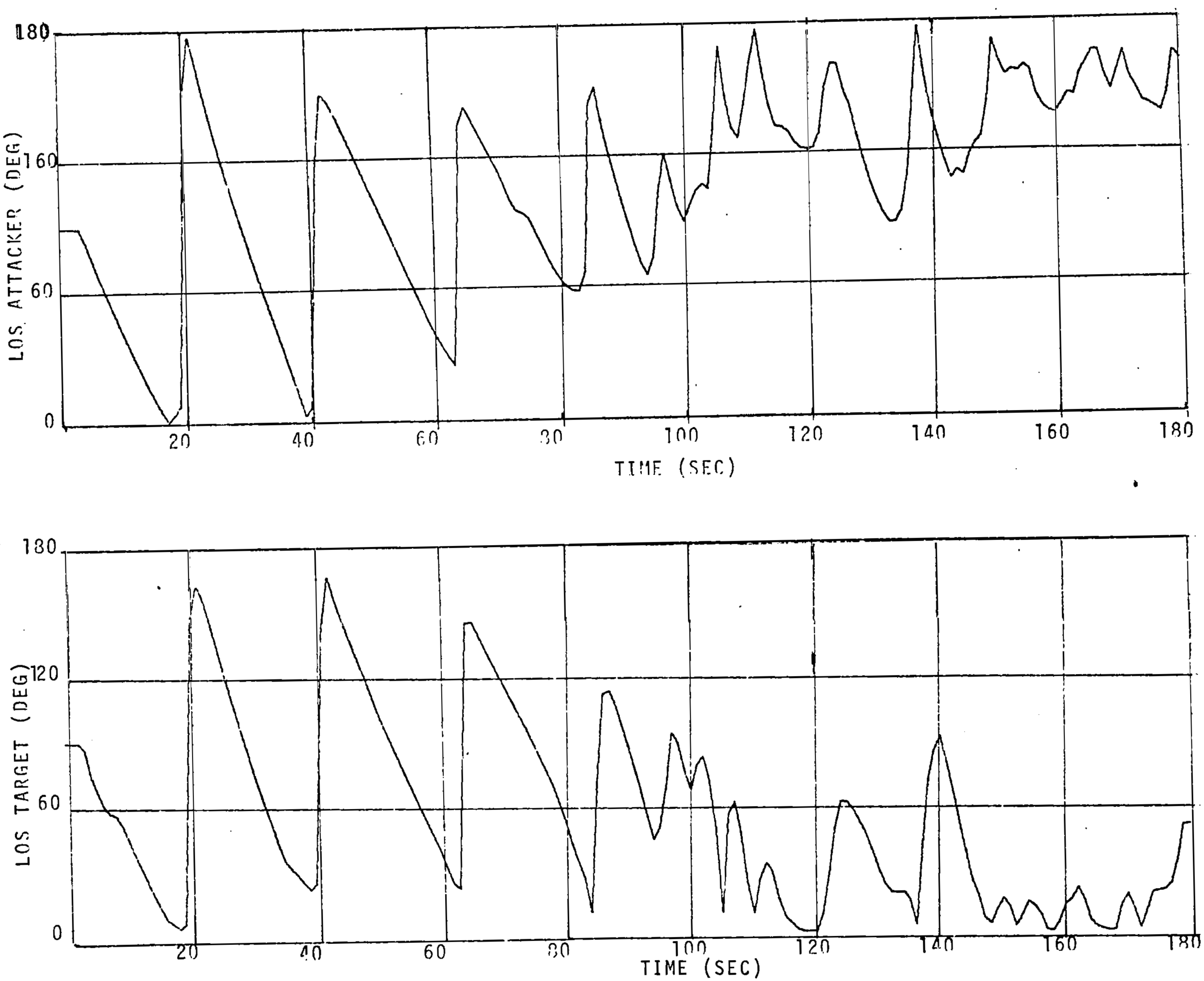


Figure 9.- Line-of-sight angles for off-line sample engagements.

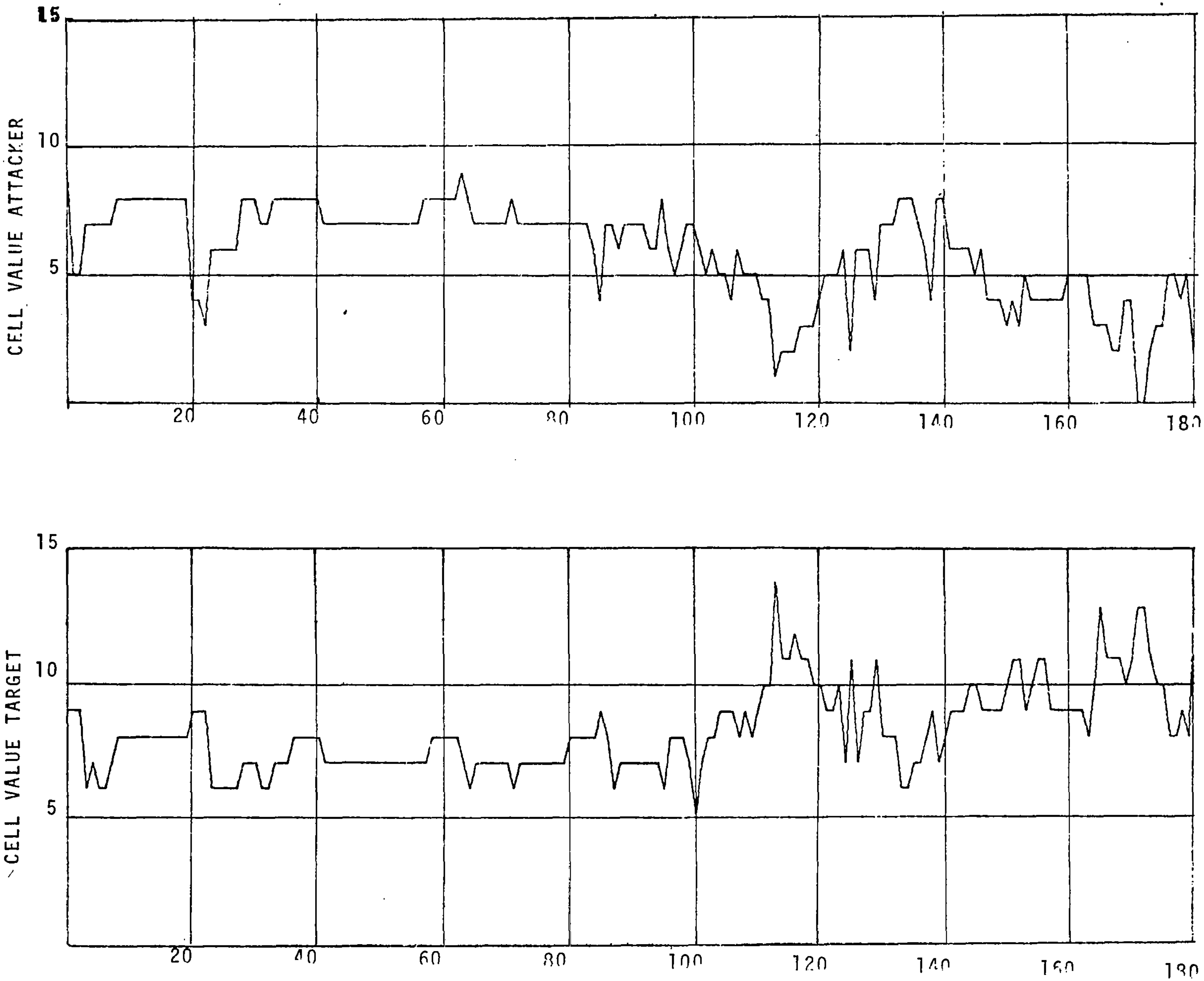


Figure 10.- Cell values for off-line sample engagement.

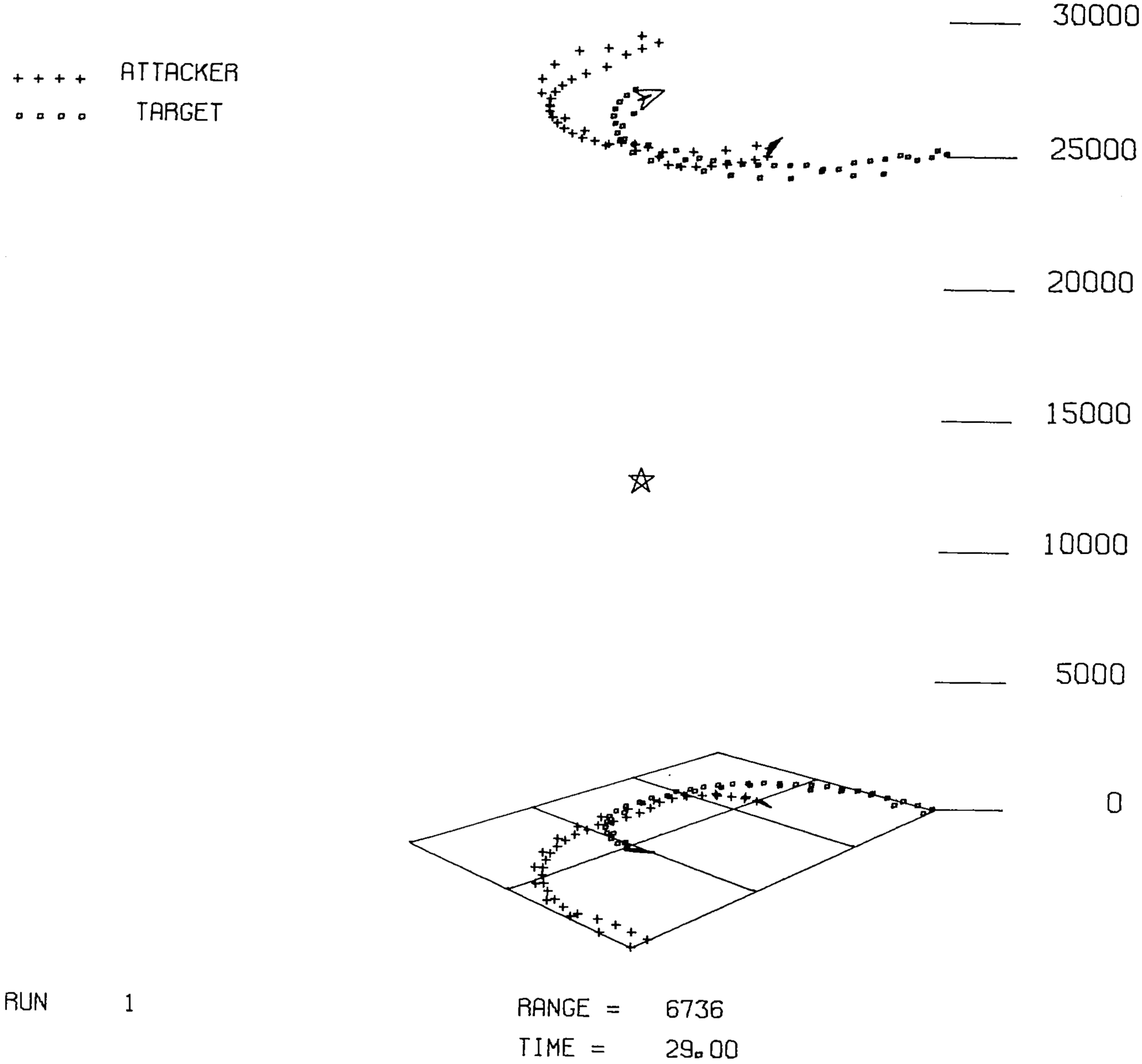


Figure 11.- Perspective view of sample off-line engagement.

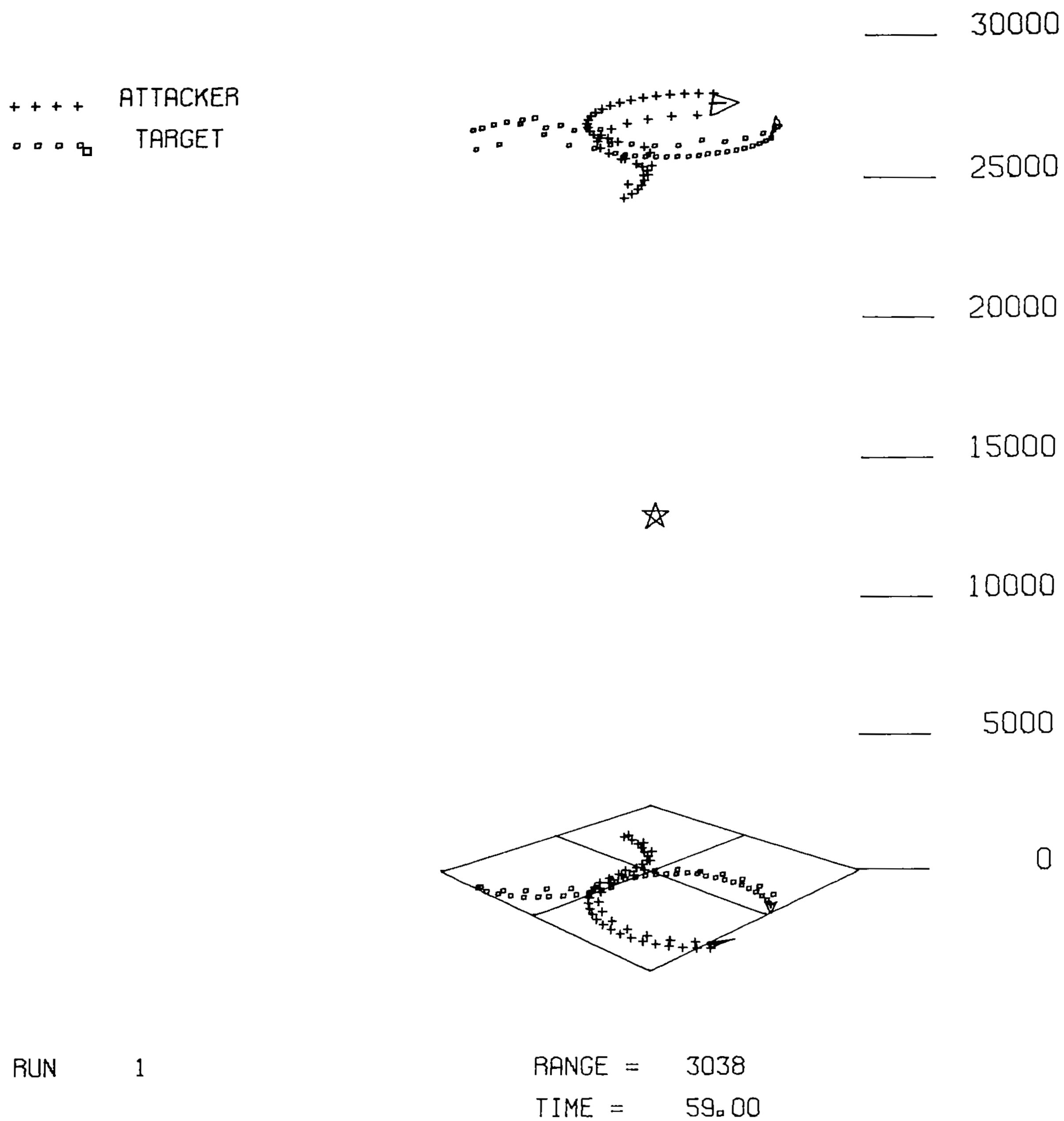


Figure 11.- Continued

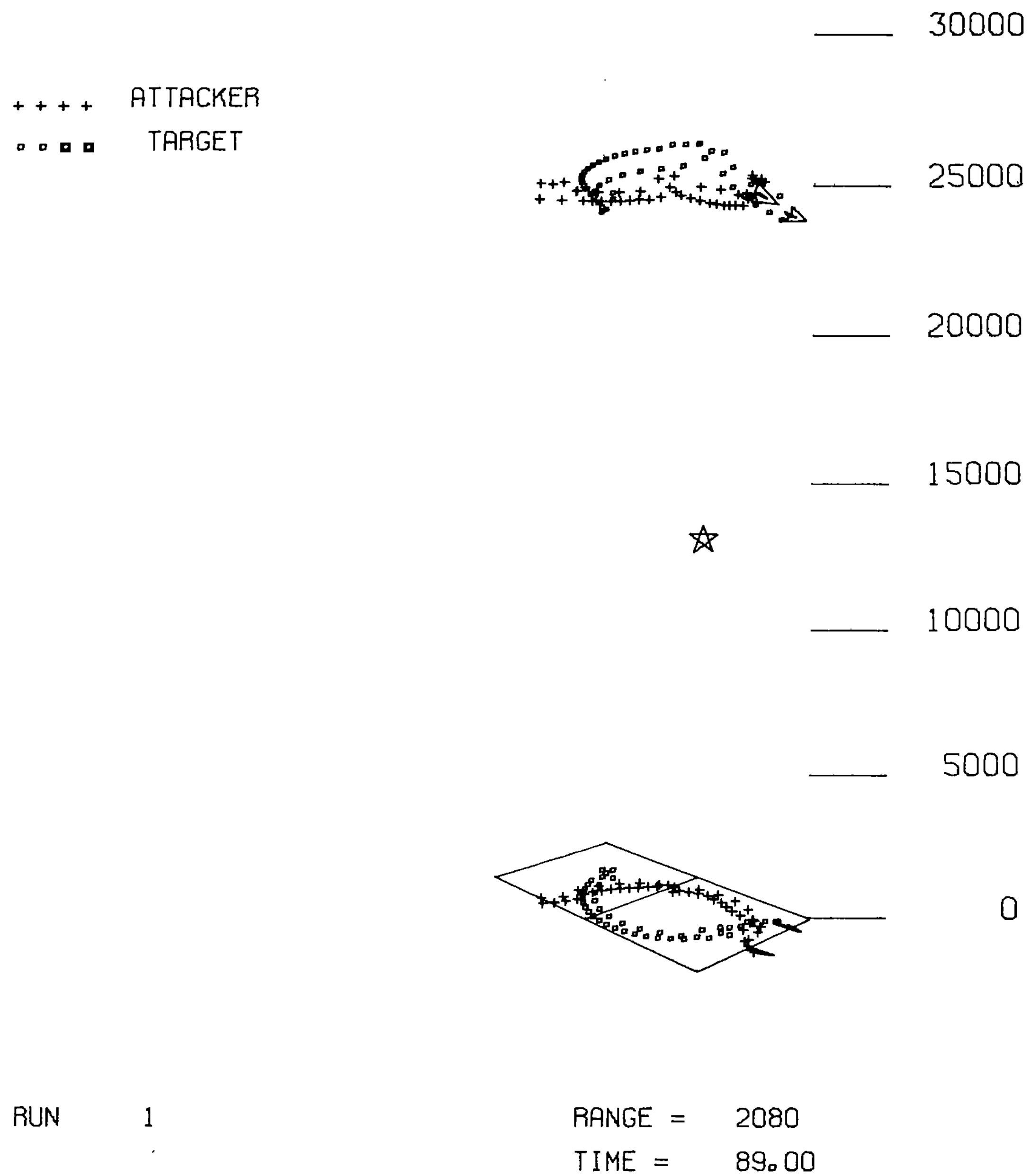


Figure 11.- Continued

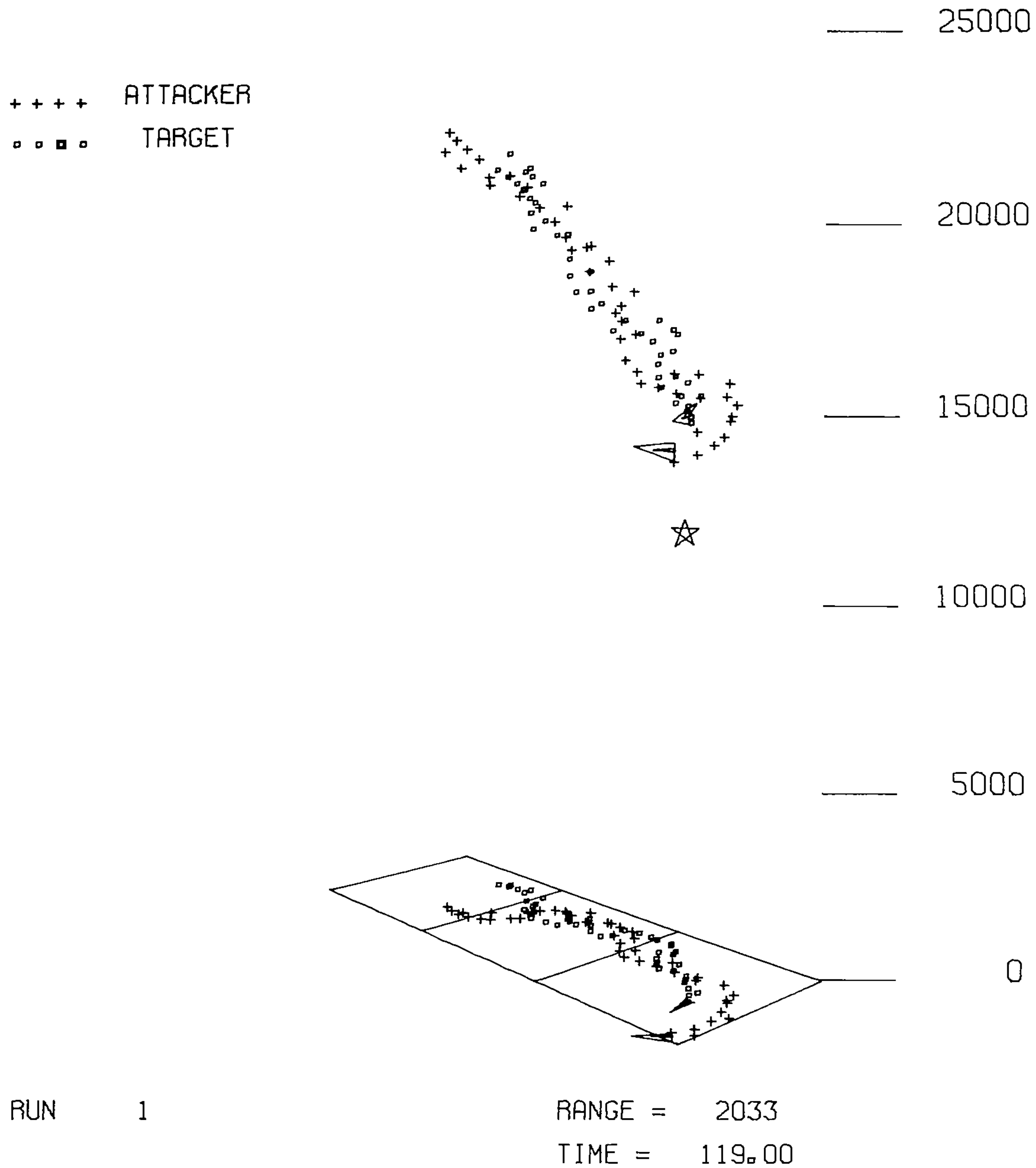


Figure 11.- Continued

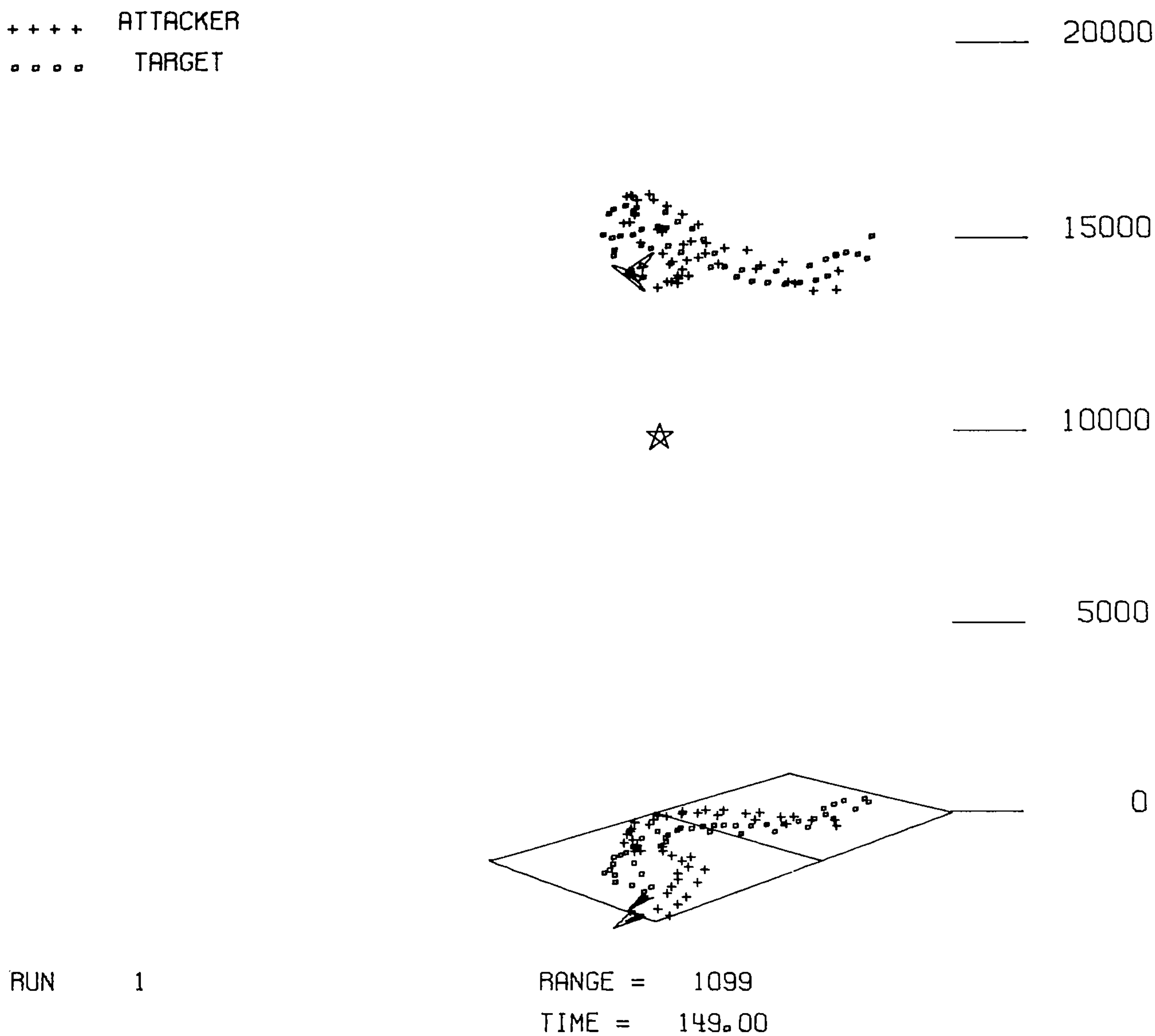


Figure 11.- Continued

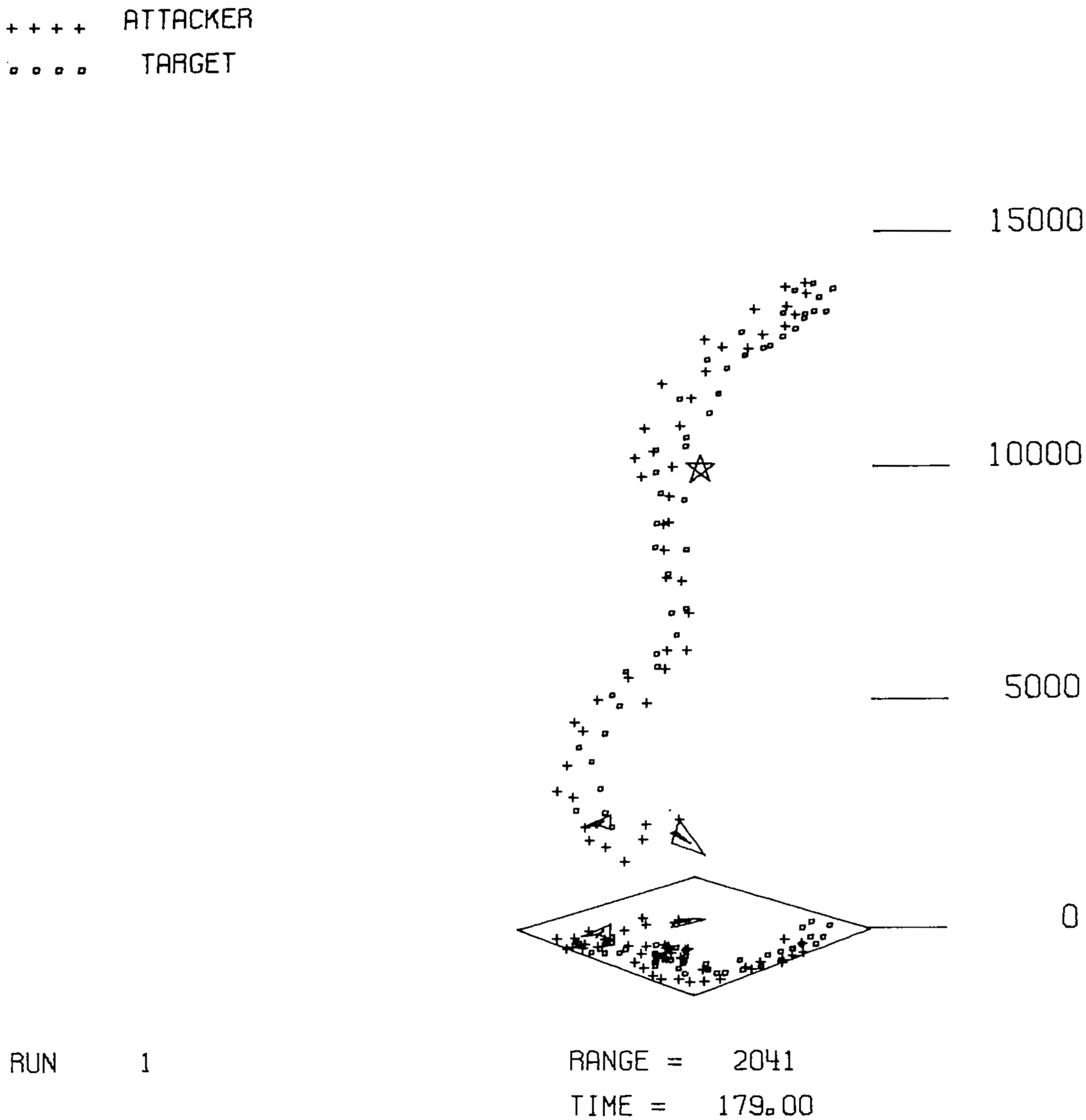


Figure 11.- Concluded

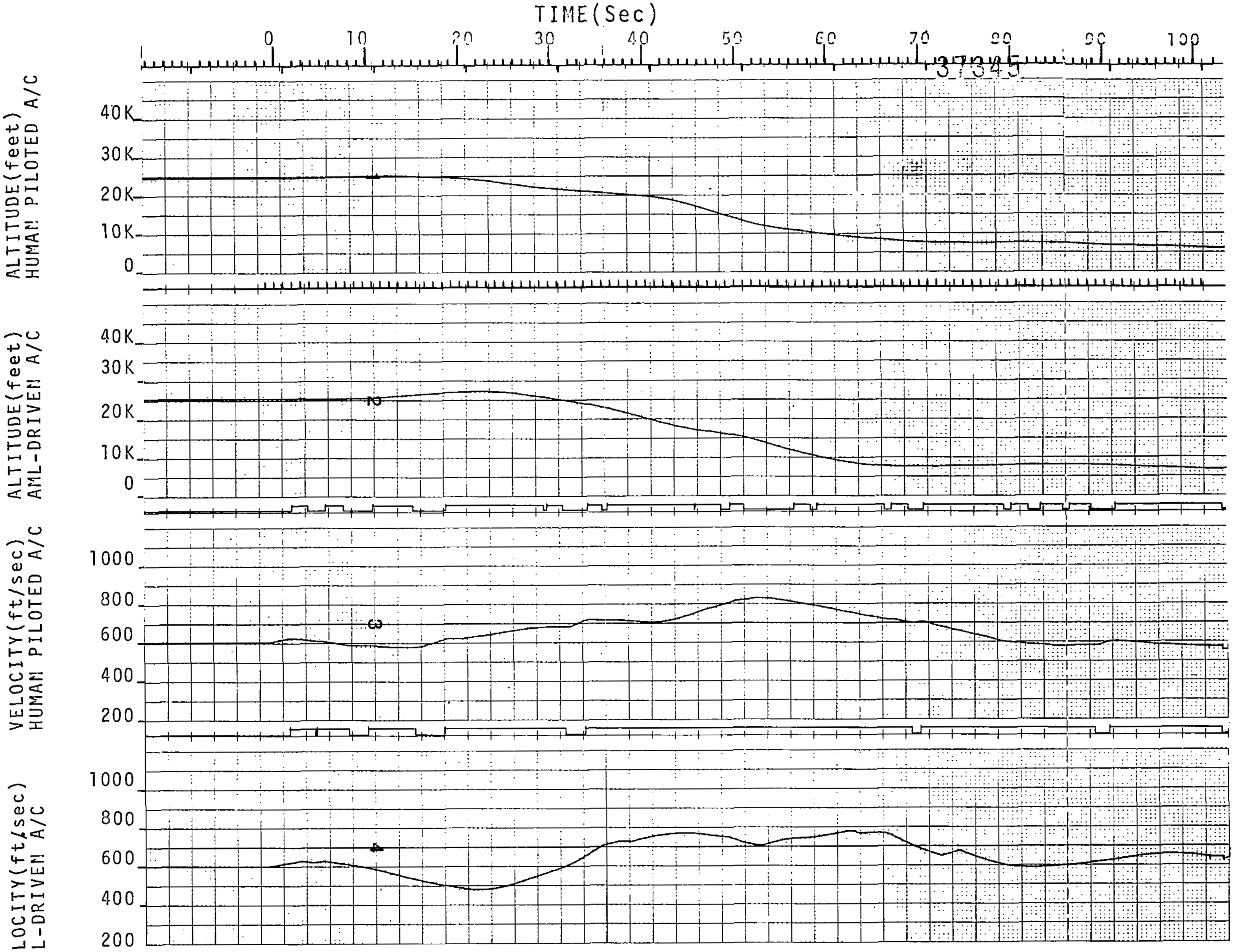


Figure 12 - Altitude and velocity for DMS engagement.

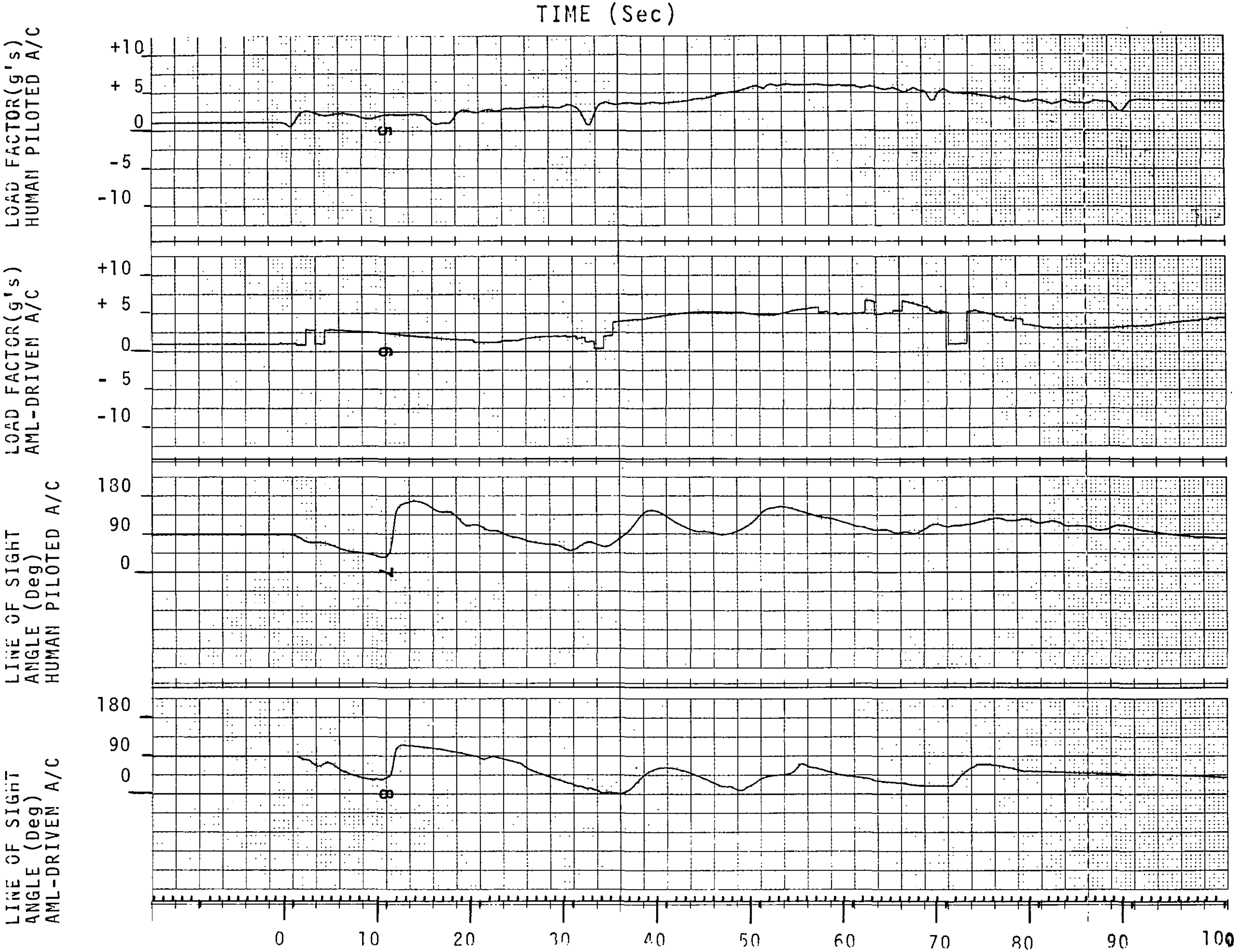


Figure 13-Load factor and line-of-sight angle for DMS Engagement.

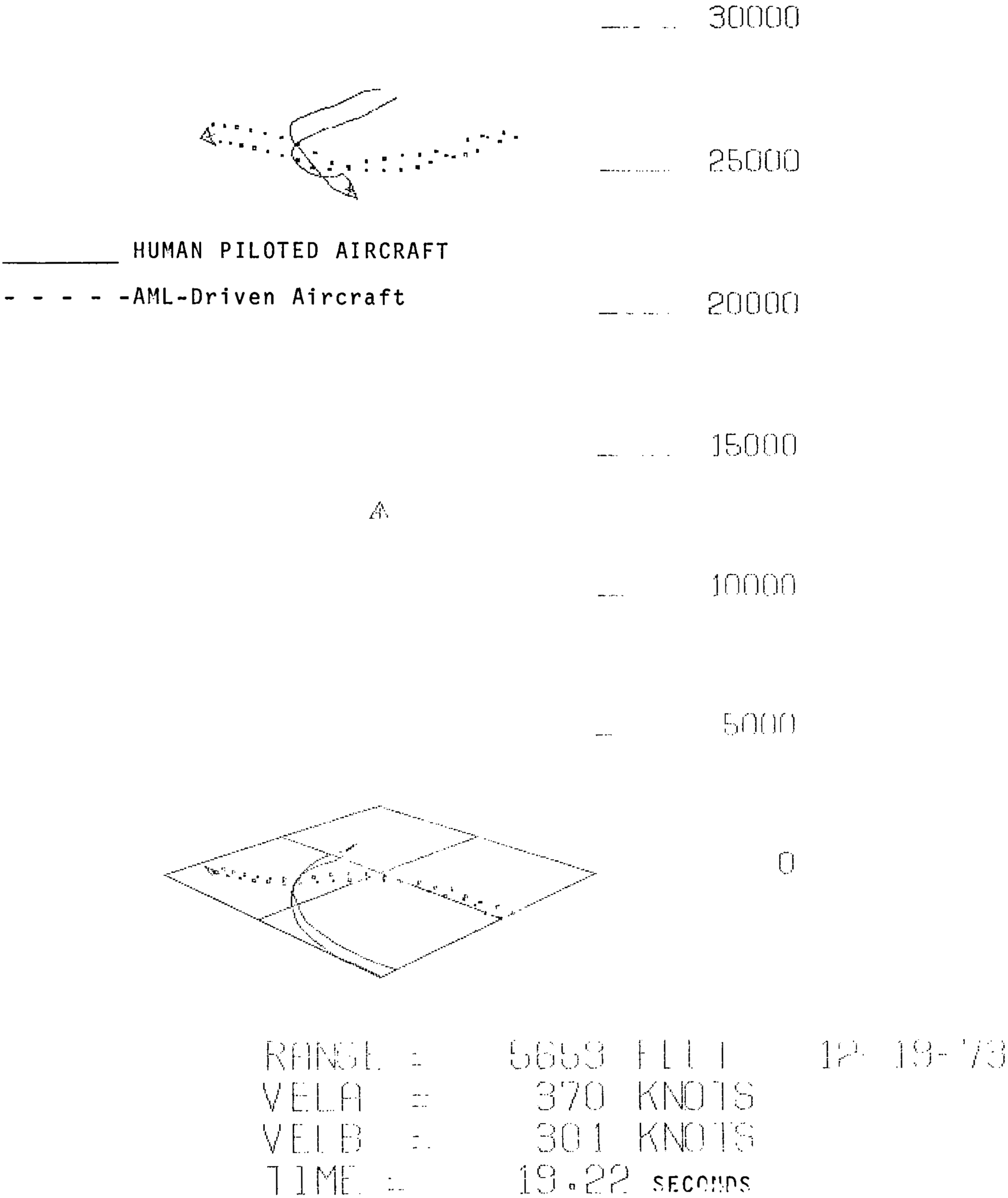


Figure 14.- Run 12 of the DMS engagement.

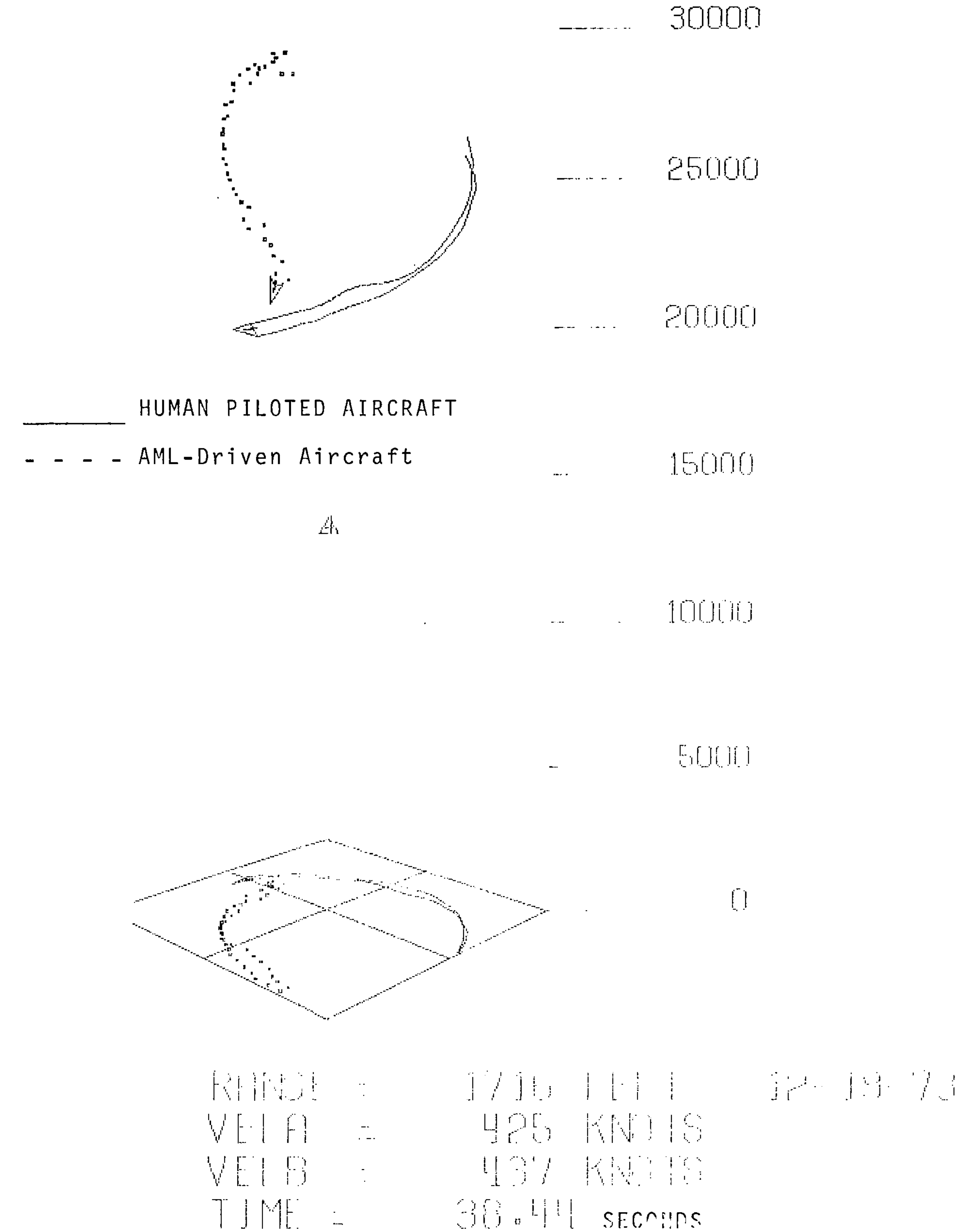
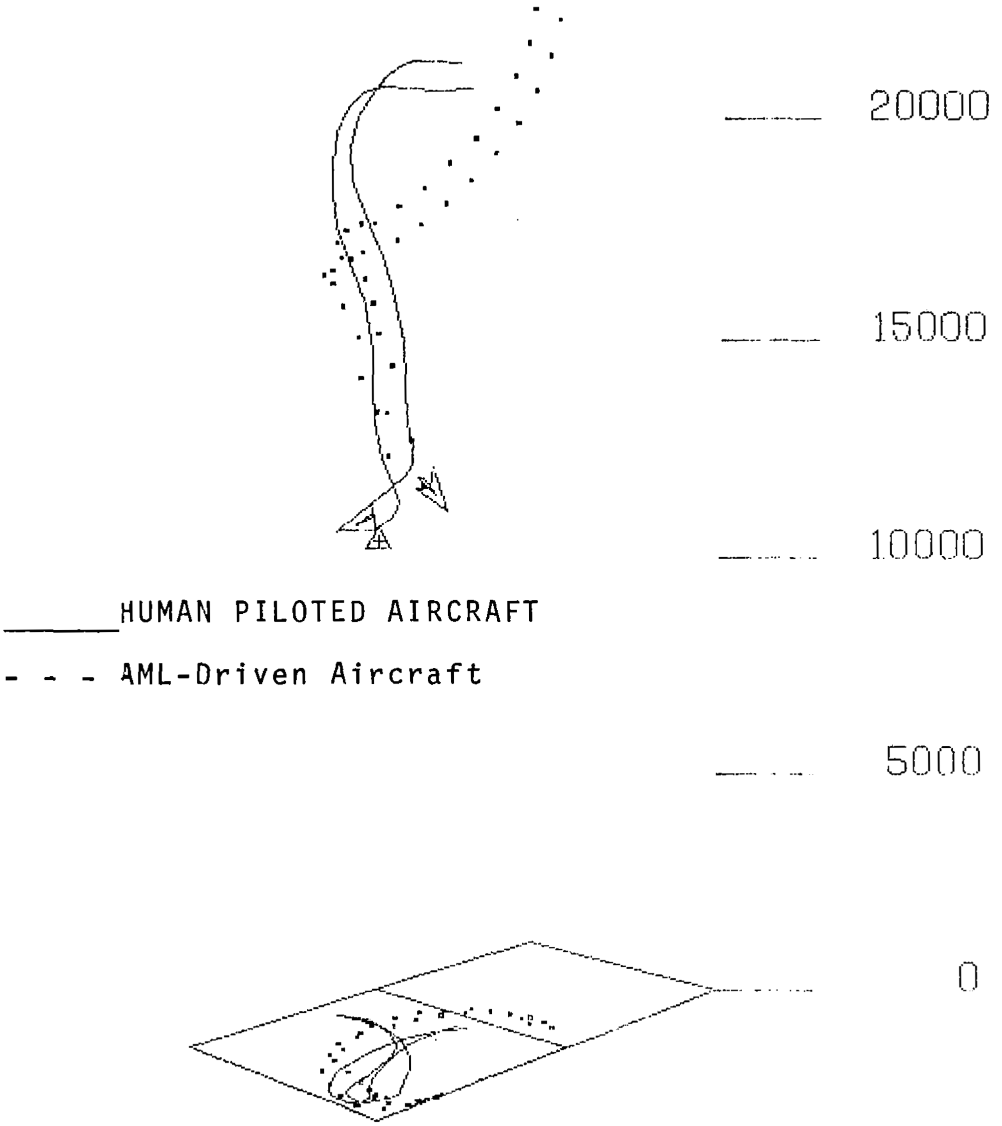


Figure 14. Continued



RANGE = 4781 FEET 12-19-73
VELA = 478 KNOTS
VELB = 445 KNOTS
TIME = 57.66 SECONDS

Figure 14. Continued.

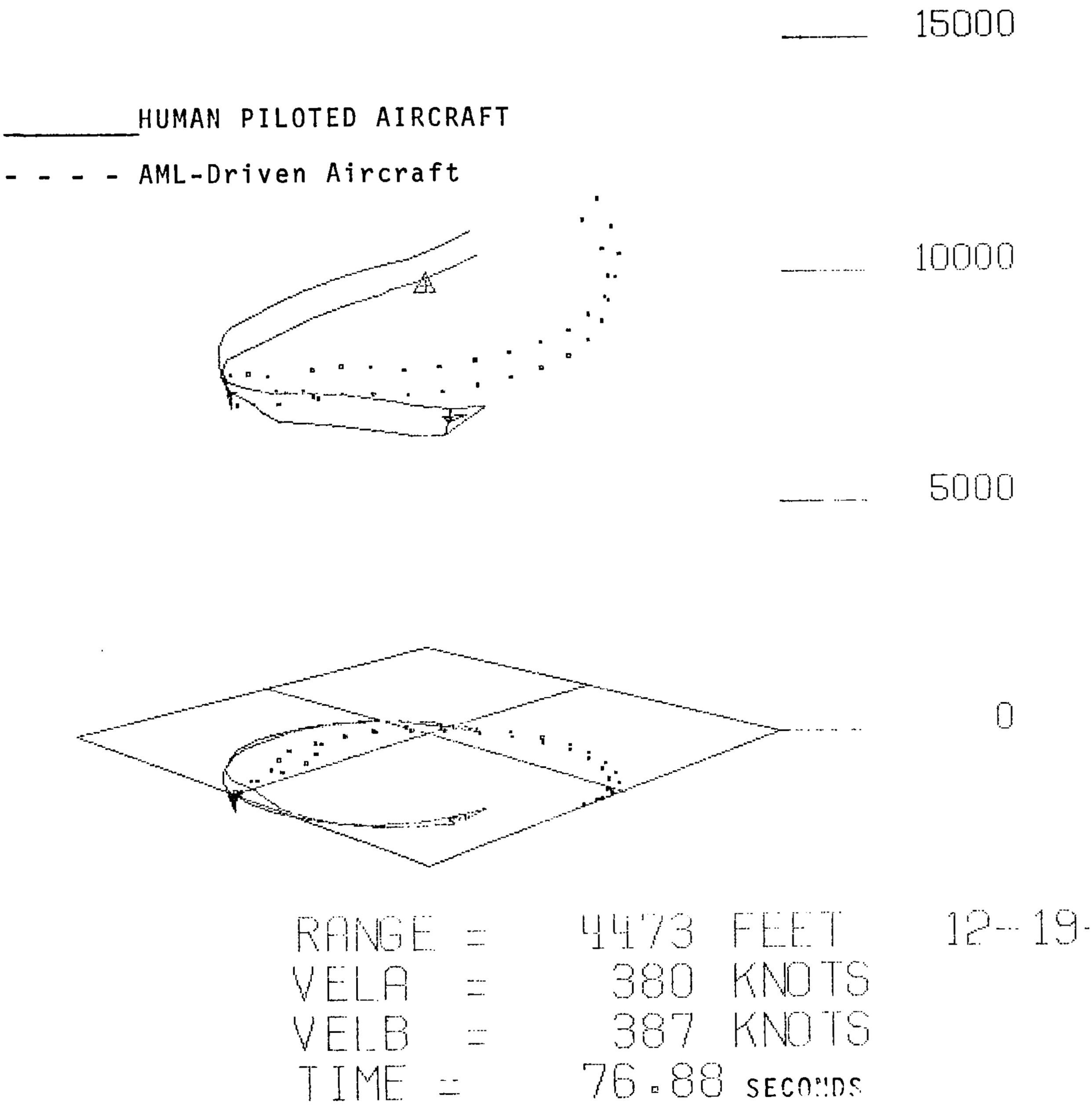


Figure 14. Continued.

________ HUMAN PILOTED AIRCRAFT

- - - - AML-Driven Aircraft

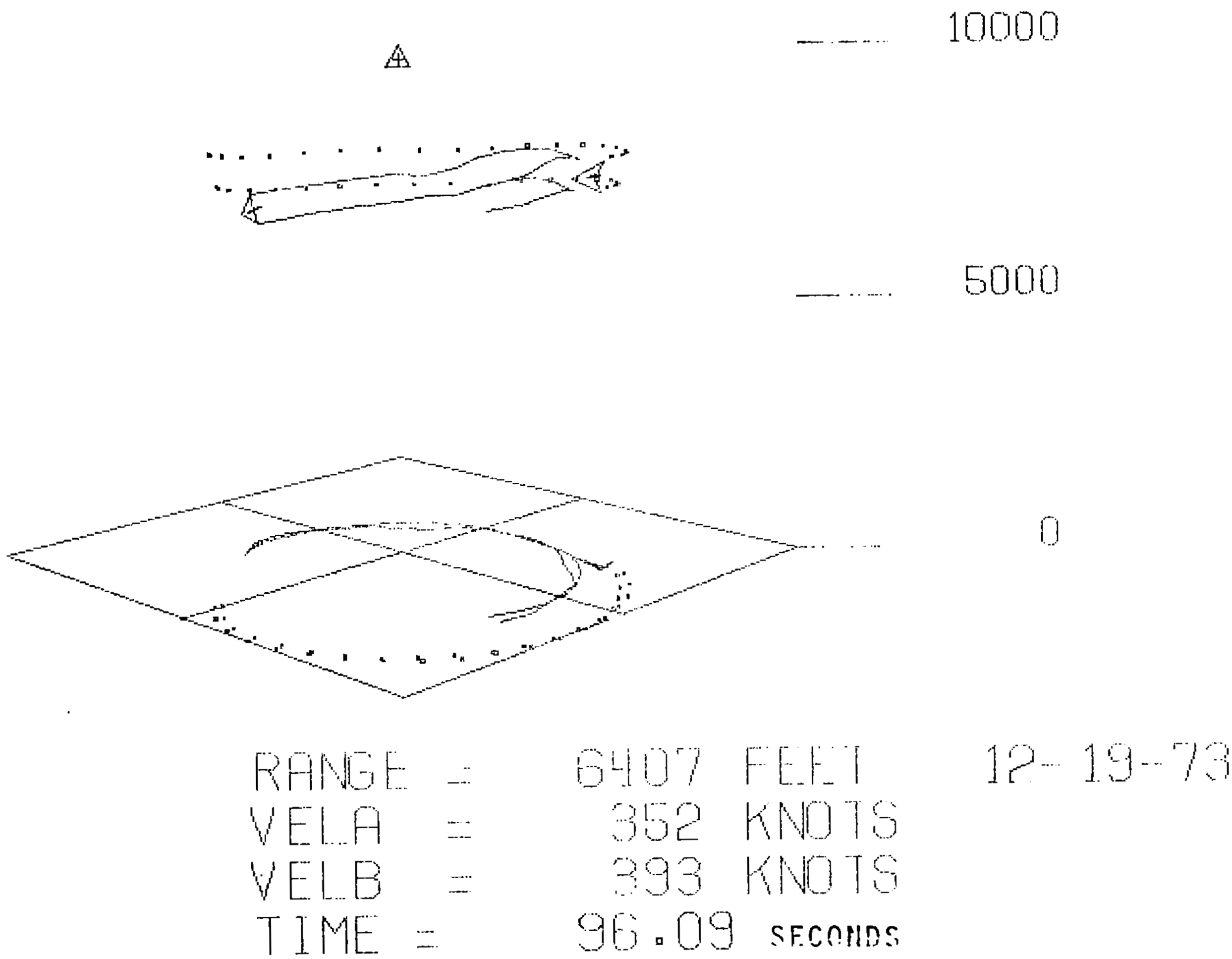


Figure 14. Continued.

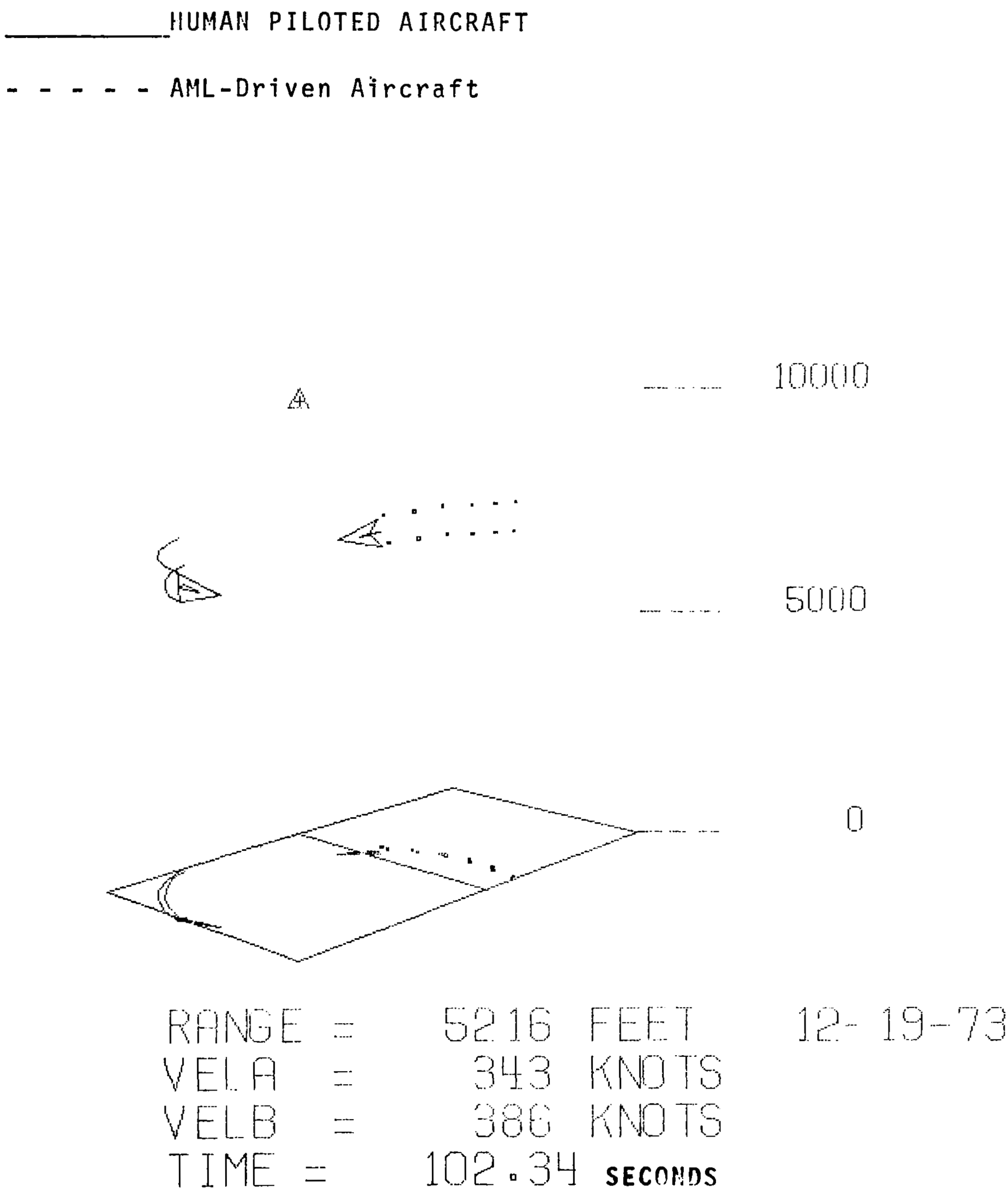


Figure 14. Concluded.

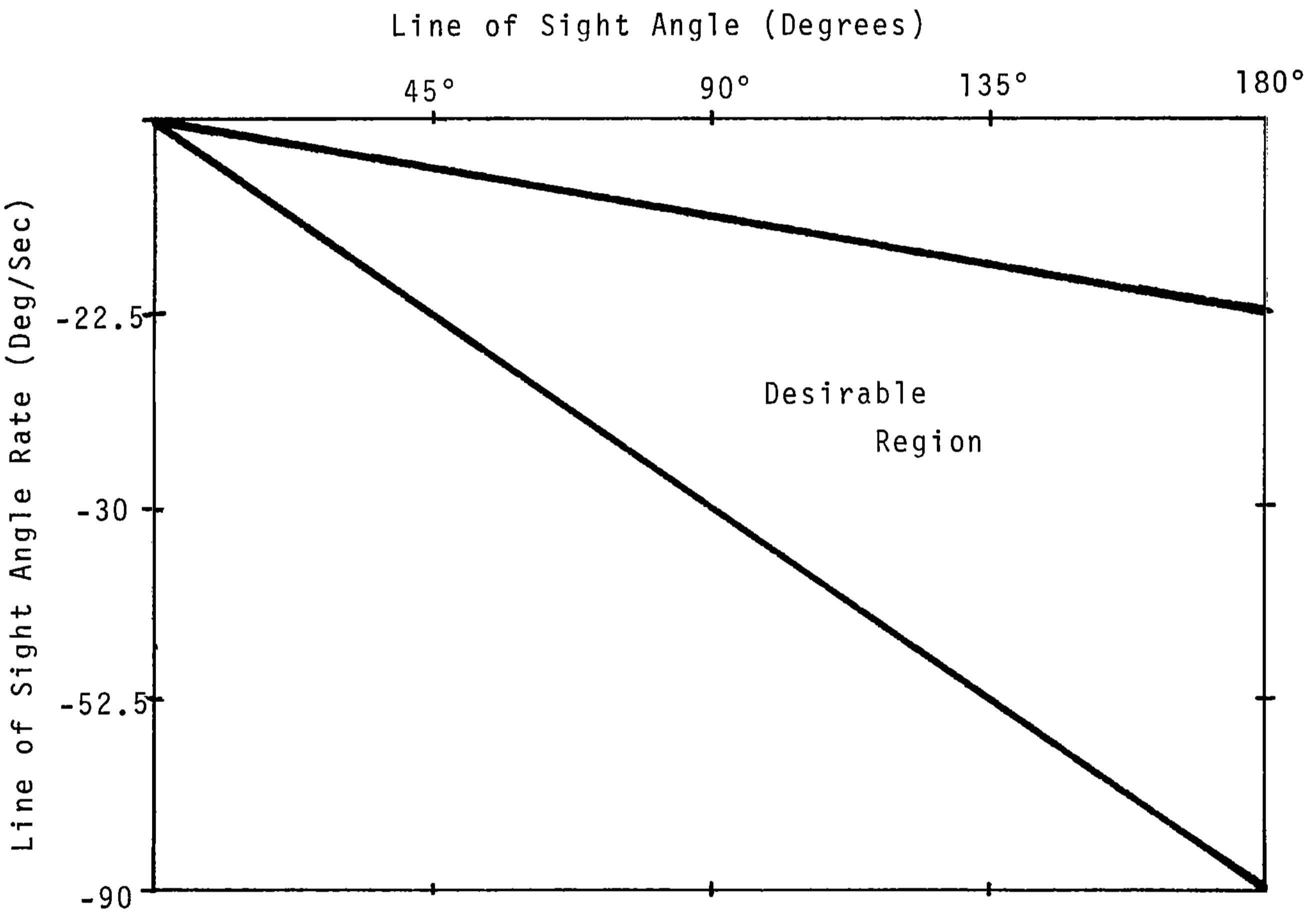


Figure 15.

Desirable line of sight angle rate
as function of line of sight angle.