KAMAN AVIDYNE TR-57

PHASE 1 REPORT COMPUTER SIMULATION MODEL OF TERMINAL AIR TRAFFIC AND PWI SYSTEMS

by

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FOREWORD

This research was carried out by Kaman AviDyne, Burlington, Massachusetts for the National Aeronautics and Space Administration, Electronics Research Center, Cambridge, Massachusetts, under Contract Number NAS 12-698. Mr. Albert S. Richardson of the office of Aircraft Hazard Avoidance Programs served as the technical monitor.

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Kaman AviDyne TR-57
Errata

p. 57 In subtitle change "Tan" to "Tau"
p. 58 In subtitle change "Modified-Tan" to "Modified-Tau"
p. 61 In title change "Role" to "Rate"

ABSTRACT

This report describes the collision avoidance system technical evaluation (CASTE) computer program developed for the simulation of PWI systems operating in air terminal traffic. The traffic model is comprised of measured flight tracks from the FAA Atlanta ARTS facility and intruder tracks generated by program instructions. The program is designed to provide an evaluation of PWI system performance in the air traffic model by comparing the alarms produced to the collision hazards that exist.

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SECTION 1

INTRODUCTION

This report covers Phase 1 of a study to evaluate the performance of candidate configurations of the NASA/ERC proximity warning indicator (PWI) for aircraft flying in terminal air traffic. The objective of Phase 1 is to develop the computer program that will be used in the study. Hereafter it will be called the COLLISION AVOIDANCE SYSTEM TECHNICAL EVALUATION (CASTE) program.

The ERC PWI, as now envisioned, is an optical infrared system employing the xenon flash from the standard beacon on an aircraft. The flash is to be sensed by an optical detector carried by the "protected" aircraft.* The PWI system is currently under development, so the final configuration of the system remains to be established.

The CASTE program, to be of the greatest value in the development phase of the PWI, has been designed to be as flexible as possible in order to serve in the evaluation of various configurations, operational parameters, and alarm logic. Therefore, the program was written as a group of readily modifiable or replaceable subroutines.

*Throughout this report the terminology "protected" aircraft designates the aircraft the collision avoidance system (CAS) is charged to protect, and is the aircraft that carries the CAS; all other aircraft are designated "threat" aircraft with respect to the protected aircraft.

The data input to the CASTE program describing the flight tracks are the FAA Atlanta Airport Radar Terminal System (ARTS) magnetic tapes and/or selectable tracks of up to 25 "intruder" aircraft.* The CASTE output identifies the hazard situations and alarm events, and these data are stored on tape for evaluation using statistical methods.

Twelve one-hour runs of flight data were obtained by the FAA Atlanta personnel consisting of digitized raw radar data, smoothed radar data, controller-pilot voice records, and controller log sheets. The data were obtained during peak travel periods in the morning, afternoon and evening at Atlanta, Georgia.

At the FAA National Avaiation Facility Experimental Center (NAFEC), Atlantic City, N.J., the Atlanta ARTS data were edited, the altitude data were digitized onto the magnetic records, and the resulting data were numerically smoothed. The FAA obtained these data for use in air traffic simulation studies at NAFEC, and they were made available to NASA for use in the present research program.

The CASTE program calculates the relative locations and velocities of aircraft at each time from the FAA data and/or the intruder aircraft input data. From these computed data the flight hazards are then determined, based on any of four

*The term "intruder" designates an aircraft introduced into the terminal area on a flight track prescribed by equations.

criteria. Simultaneously the calculations to simulate the operation of the PWI system are performed.

In the CASTE output the hazard and alarm situations are identified by aircraft pair, and the pertinent aircraft locations and flight data are given. The PWI alarms are compared against the hazards to obtain the statistics of the valid alarms, false alarms, and missed alarms.

The performance of a PWI would be rated by determining its capability and reliability for detecting hazards. The satisfactory determination of when a collision hazard exists then becomes the performance index for the PWI evaluation. In many cases, the selection of competing systems, and the gross selection of system configuration and parameters can be accomplished without a precise collision-hazard index. However, when the system performance reaches the level where differences become relatively sophisticated to evaluate, then the selection of the hazard criterion is subject to discussion and assessment. Not to commit the present program to a particular selection of the hazard criterion, four hazard criteria have been incorporated into the CASTE program. Each criterion has been programmed with parameters, such as escape time, that are selectable inputs to the CASTE program.

The CASTE program has been developed and tested in all three operational forms: ARTS data input, intruder data input, and combined ARTS data and intruder data input. Results have been obtained for one hour of the ARTS data, Hour 10.

SECTION 2

TERMINAL AREA DATA

2.1 CAS Coordinate System

The coordinate system used in this report for aircraft position and velocity in the terminal area is shown in Fig. 1.

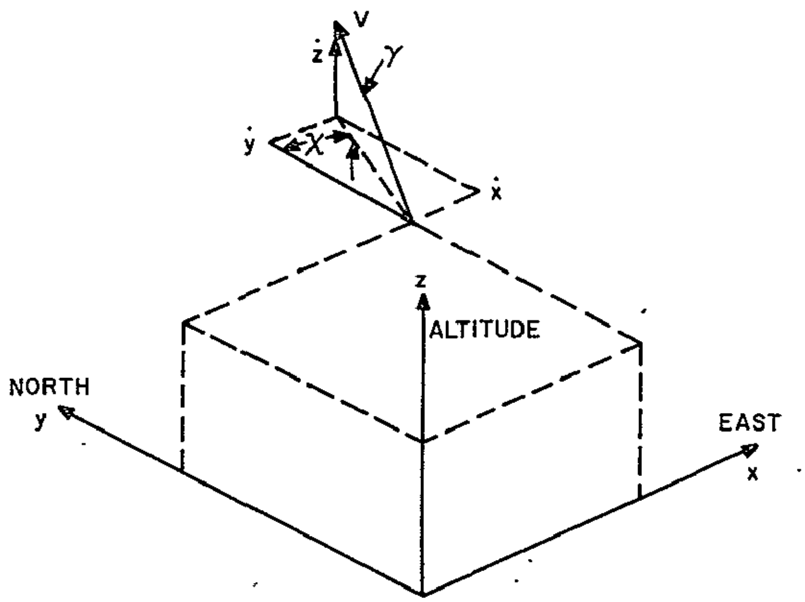


Figure 1. COORDINATE SYSTEM FOR AIRCRAFT FLIGHT PATH IN TERMINAL AREA

The x coordinate is directed East, the y coordinate North, and the z coordinate is the altitude. The flight path heading from North is χ, and the flight path elevation angle is γ. The aircraft velocity along the flight path is V, and the component x, y, z velocities are $\dot{x}$, $\dot{y}$, and $\dot{z}$, respectively.

The orientation of the coordinates of the collision avoidance system (CAS) sensors relative to the flight path is shown in Fig. 2. Here the aircraft is in a climbing turn. The

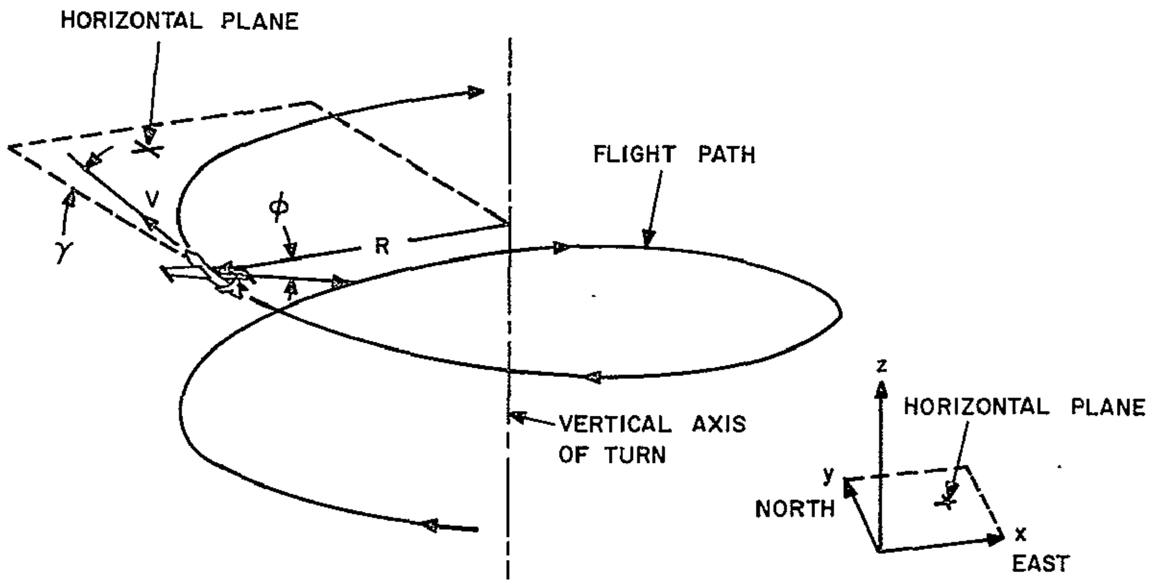


Figure 2. COORDINATE SYSTEM OF CAS IN AN AIRCRAFT

longitudinal axis of the CAS coordinates is assumed to be tangent to the flight path. The roll angle of the CAS coordinates is assumed to be equal to the bank angle of the aircraft, Φ. The bank angle is taken positive for right wing down.

The orientation of the threat aircraft (j) to the projected aircraft (i) is shown in Fig. 3. Here the polar coordinates for aircraft j are oriented with respect to the CAS

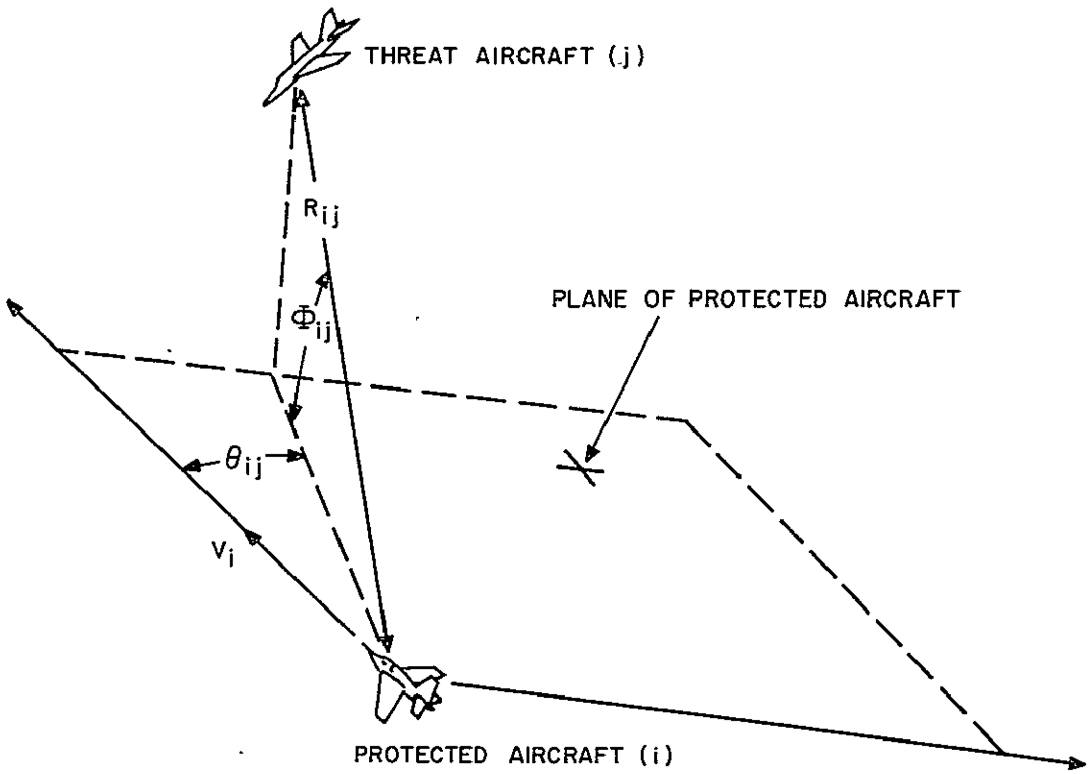


Figure 3. RELATIVE POSITION OF THREAT AIRCRAFT (j) IN POLAR COORDINATE SYSTEM FIXED ON PROTECTED AIRCRAFT (i)

coordinates in aircraft i. The azimuth angle, Θ_{ij}, is in the plane of the CAS and the elevation angle, Φ_{ij}, is referred to this plane.

2.2 FAA ARTS Data

The FAA has collected data for twelve one-hour periods of aircraft operations in the terminal area of the Atlanta airport. These data were taken during morning, afternoon, and evening peak traffic hours within a five-day period. Data sources include the Atlanta ARTS raw radar data, smoothed radar data, controller-pilot voice communication tapes, and controller log sheets. These data were edited and combined at NAFEC to obtain time histories of the position coordinates and velocity components of each aircraft in the terminal area. These data are available on magnetic tapes in several forms that will be described.

The ARTS system has a "track while scan" (TWS) computer which predicts the location of each aircraft under radar surveillance in terms of radar range and azimuth. The terminal area controller initiates TWS computer tracking of an airplane appearing on his PPI display by entering a track instruction, along with aircraft identification, into the computer. So long as the radar position of the given aircraft corresponds within a prescribed tolerance of the predicted position, the tracking of that aircraft is automatically continued until either the controller terminates the track or the aircraft passes beyond the cutoff range for the radar.

On each scan of the radar the TWS computer determines whether the radar position of each aircraft target falls within its predicted imaginary "bin." If it does, a correction procedure adjusts the target position and velocity, based on the reported position of the target. Then, using a weighting function based on the target position history, a new predicted position is calculated for the expected location of the target at the time of the next radar scan. A predicted velocity is calculated similarly. Data for all tracked aircraft on each scan are put on a data tape referred to as the ARTS SNAP Tape.

In the event the radar scan shows an aircraft target to be outside its predicted bin, the bin size is increased and the process continued, with a notation on the SNAP tape, called the "firmness number," indicating that the data quality has degraded. Good data quality is indicated by a high firmness number. When the data quality degrades below a preassigned firmness number, the TWS computer projects a permanent coast mode. In the permanent coast mode the aircraft position is extrapolated each scan based on the last available velocity. Velocity remains constant in this mode. A keyboard entry by the controller is required to remove the track from this dormant state and to start reacquisition procedures. Sometimes, on the other hand, data quality does not degrade to the preassigned firmness number for permanent coast, but improves after intermittent degradation. In this situation, firmness number increases (up to the maximum of 31). Further details of the tracking procedure are described in reference 1.

The SNAP tape data were combined at NAFEC with the aircraft altitude information obtained from the controller-pilot voice communications tapes by using the Data Synthesizer Program (DSP) described in Reference 2. The DSP produces two kinds of output tapes, a binary tape and a binary coded decimal (BCD) tape. A binary tape, designated as type A8 Tape, contains the information shown in Table 1, for each of the twelve hours of Atlanta terminal area data. A BCD tape, designated as type A7 tape, contains only a portion of the information shown in Table 1.

The first set of DSP tapes of the Atlanta ARTS data provided NASA/ERC by FAA/NAFEC were the binary A8 tapes. These DSP tapes contained the "unsmoothed data," so-called for reasons described later.

Hand plots of the unsmoothed data were made on x, y coordinates and z, t coordinates for a number of tracks for Hours 5, 10, and 11. Inspection of the tracks revealed serious anomalies in the data, particularly during turns. A method for handling the anomalies could not be reached from an examination of the limited number of hand plots. Therefore, machine plots of a large number of tracks were made.

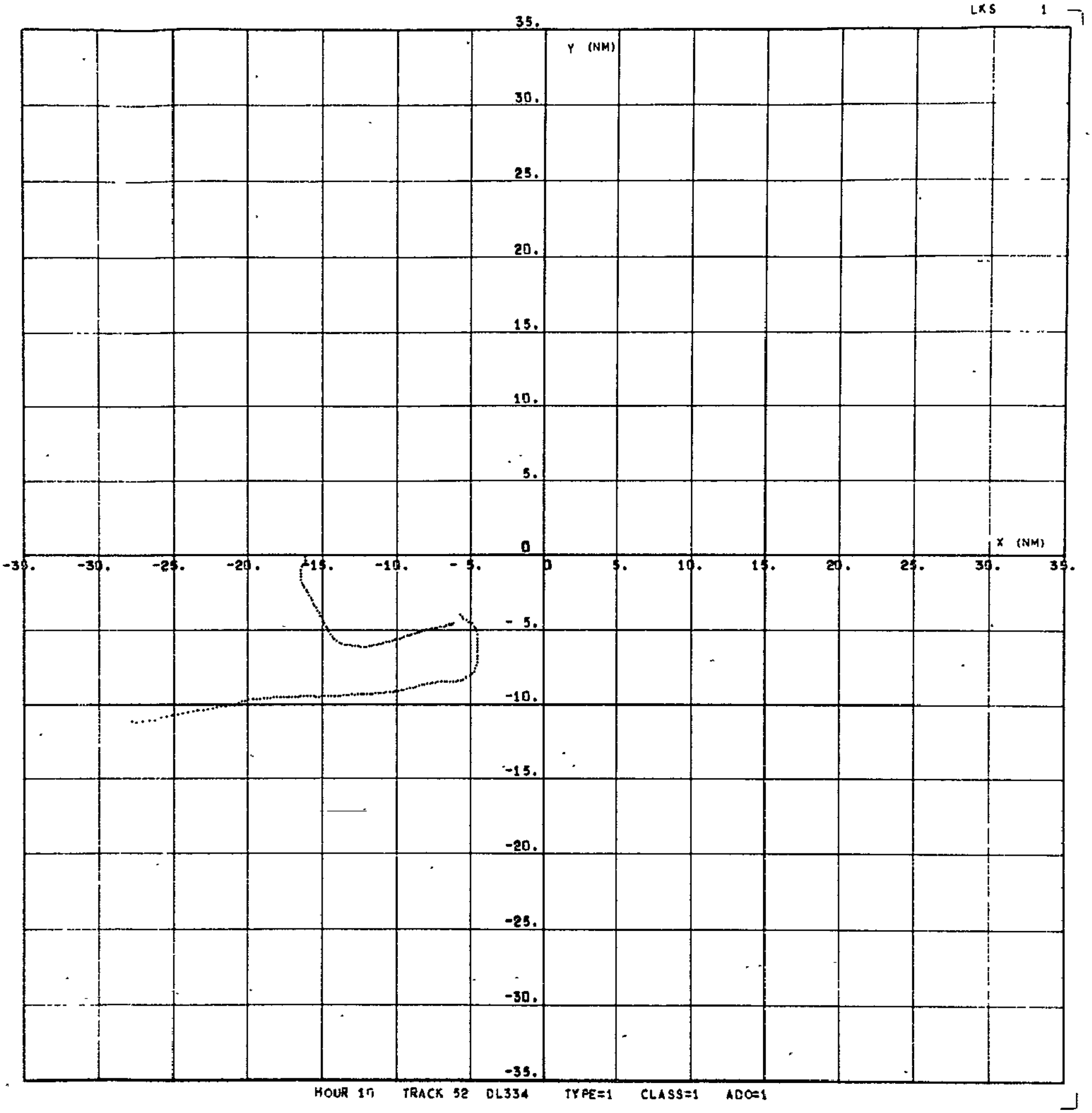
A computer program was written for making machine plots of the unsmoothed data using the Stromberg Carlson 4020 machine plotter. All of the tracks were plotted for Hour-10 data. Selected plots are shown in Figure 4.

Inspection of the Hour-10 plots, such as Figure 4a, showed that the x, y tracks from the A8 data were frequently discontinuous during turns, as can be seen by the "dog leg" in the turn which occurs in Figure 4a near point (-6, -4). It was

TABLE 1

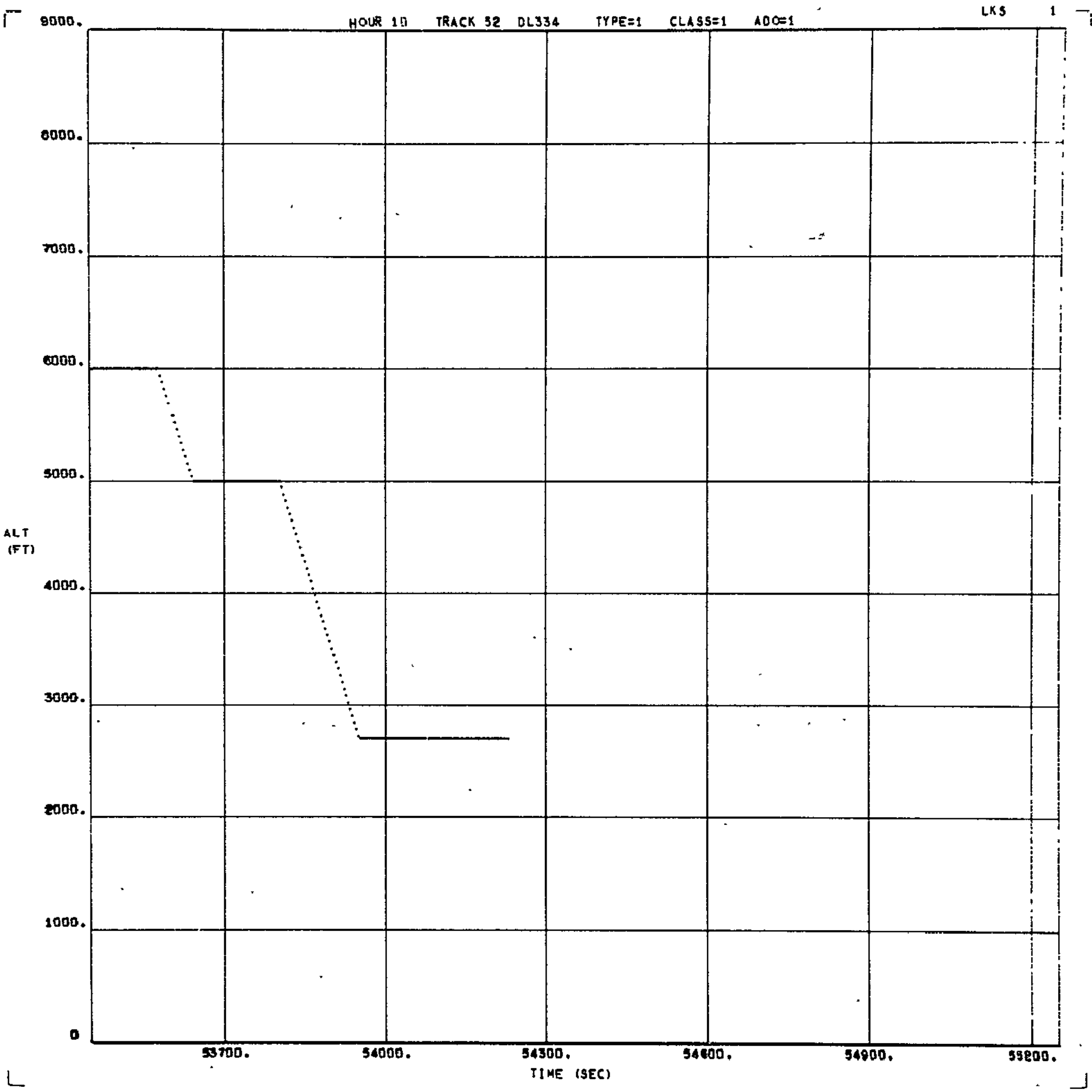
FORMAT OF BINARY OUTPUT, A8

Word	Type of Word	Description	Units
1		FORTRAN control word	
2	I	Number of targets	One scan of radar
3	I	Track number	
4	F	Time	Seconds
5	F	x position	Nautical miles
6	F	y position	Nautical miles
7	F	Altitude z	Feet
8	I	Firmness number	1 to 31
9	A	Aircraft identification	Alphanumeric
10	I	Aircarrier, military, general aviation	1, 2, 3
11	I	Type or class of aircraft	1, 2, 3, 4
12	I	Arrival, departure, overflight	1, 2, 3
13	F	$\dot{x}$ velocity	Knots
14	F	$\dot{y}$ velocity	Knots
15	F	Radar range	Nautical miles
16	F	Radar azimuth angle	From 0.0 to 0.9999
17	F	Test	



a. Ground track

Figure 4. TRACK OF TYPICAL AIRCRAFT IN TERMINAL AREA. UNSMOOTHED DATA



b. Elevation history

Figure 4. (CONCLUDED)

reasoned that the data discontinuities, presumably caused by radar moving target indicator (MTI) and TWS logic, would cause unrealistic velocity and heading histories. These irratic values of velocity and heading could cause false alarms if these unsmoothed data were used in CASTE simulation. Therefore it was decided to obtain smoothed data for use in program CASTE.

The FAA/NAFEC had further processed the DSP tapes by smoothing the x, y, z time histories using nine point-least square fits of second-degree polynomials in time. Velocities and headings were obtained by the FAA using first differences on the smoothed data. The resulting data were placed on tapes, herein called the "smoothed" tapes.

The FAA, through NASA/ERC, furnished Kaman AviDyne with a smoothed tape of the Hour-10 data, as a representative tape of the smoothed Atlanta ARTS data tapes. (It should be noted that the format of the smoothed tapes differs from the format of the unsmoothed tapes.) The information contained on a smoothed FAA tape is listed in Table A.1 of Appendix A. For each time, each aircraft identification number is given, together with the aircraft x, y, and z position and the corresponding ground track velocity and heading. The intervals between the times on the tape are usually three seconds.

Inspection of the plots of the smoothed Hour-10 data showed that the "dog leg" anomalies in turns were removed by the smoothing process, as shown in Figure 5. However, inspection of the velocity and heading data revealed unexplainably large variations in these variables for some aircraft. For example, during one period of 27 seconds, the data indicated that the aircraft velocity ranged from 159 knots to 250 knots and back to 129 knots. The heading oscillated over a range of $\pm$ 24 deg. It was concluded, however, that the data generally fulfilled the needs of a CAS study. Therefore, the decision was made to proceed with the development of program CASTE using the data on the smoothed tapes, despite these variations. Nevertheless, some future effort might be usefully devoted to applying additional smoothing techniques to the data.

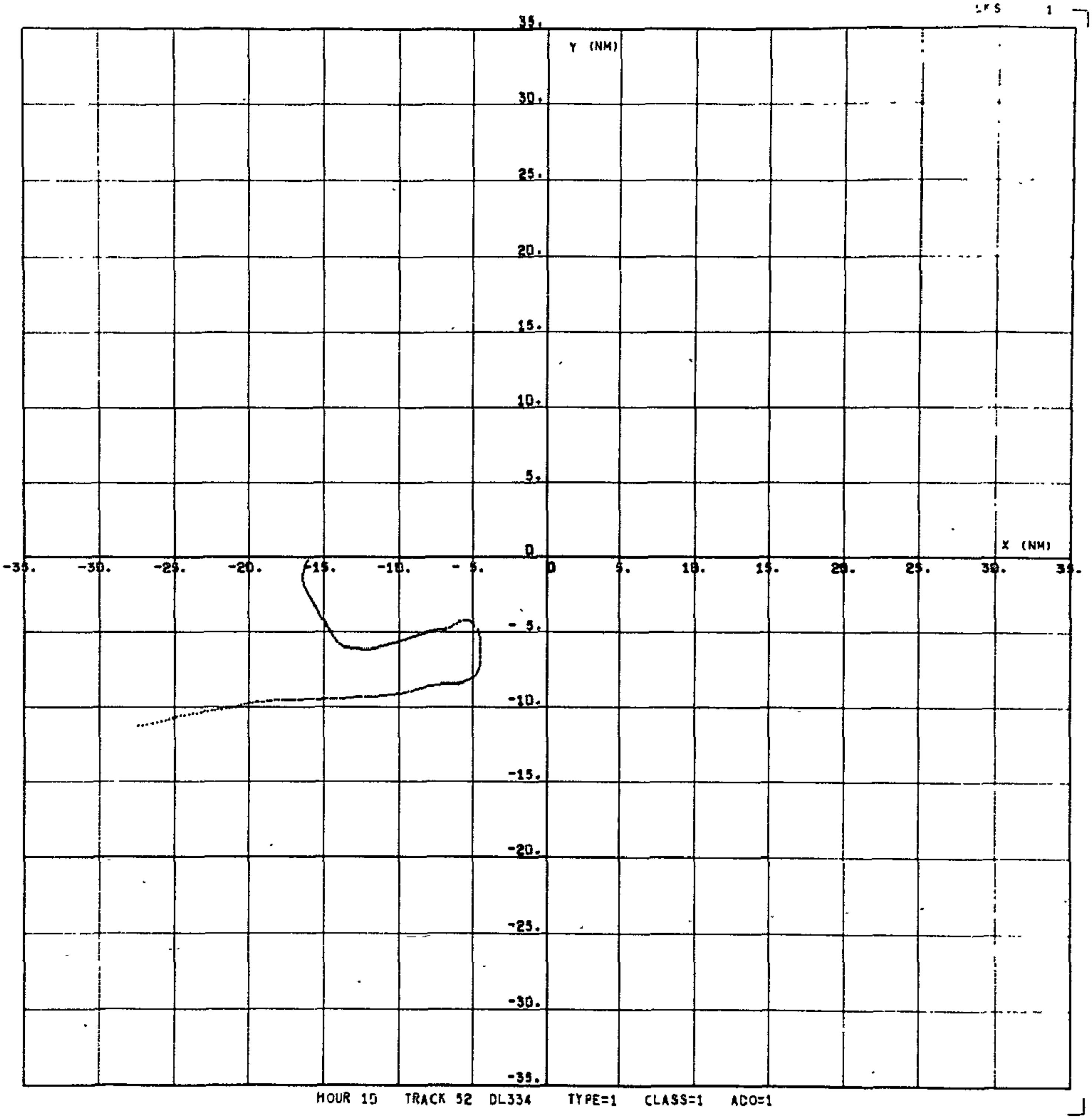


Figure 5. GROUND TRACK OF TYPICAL AIRCRAFT IN TERMINAL AREA. SMOOTHED DATA

SECTION 3

CASTE PROGRAMS

3.1 General Discussion

The general layout of the CASTE program is shown in the flow diagram of Figure 6. The CASTE program consists of five separate computer programs. The overall flow of the calculations in the CASTE program will be discussed here, and the details of the five programs will be presented in the following subsections.

The data inputs to the CASTE program are the FAA/NAFEC ARTS smoothed data (magnetic tape) and/or the intruder instructions (IBM cards). The FAA data are processed by the DATA PREPROCESSOR PROGRAM (PREPR2) giving: aircraft position and velocity components in the x, y, z coordinates, and roll angle, ϕ, at each time instant. The intruder instructions are inputted to the INTRUDER AIRCRAFT MANEUVER PROGRAM (INTRDR) where similar data are computed for each time instant. A magnetic tape output is obtained from each of the PREPR2 and INTRDR programs.

The PREPR2 and INTRDR output tape data enter the CASTE MAIN PROGRAM (CASTEM) through the TERMINAL AIR TRAFFIC SIMULATION subroutine. Either or both the PREPR2 output tape and the INTRDR output tape can be inputted into CASTEM. In the TERMINAL AIR TRAFFIC SIMULATION subroutine, the relative orientation and relative velocity of all aircraft to all other aircraft are computed.

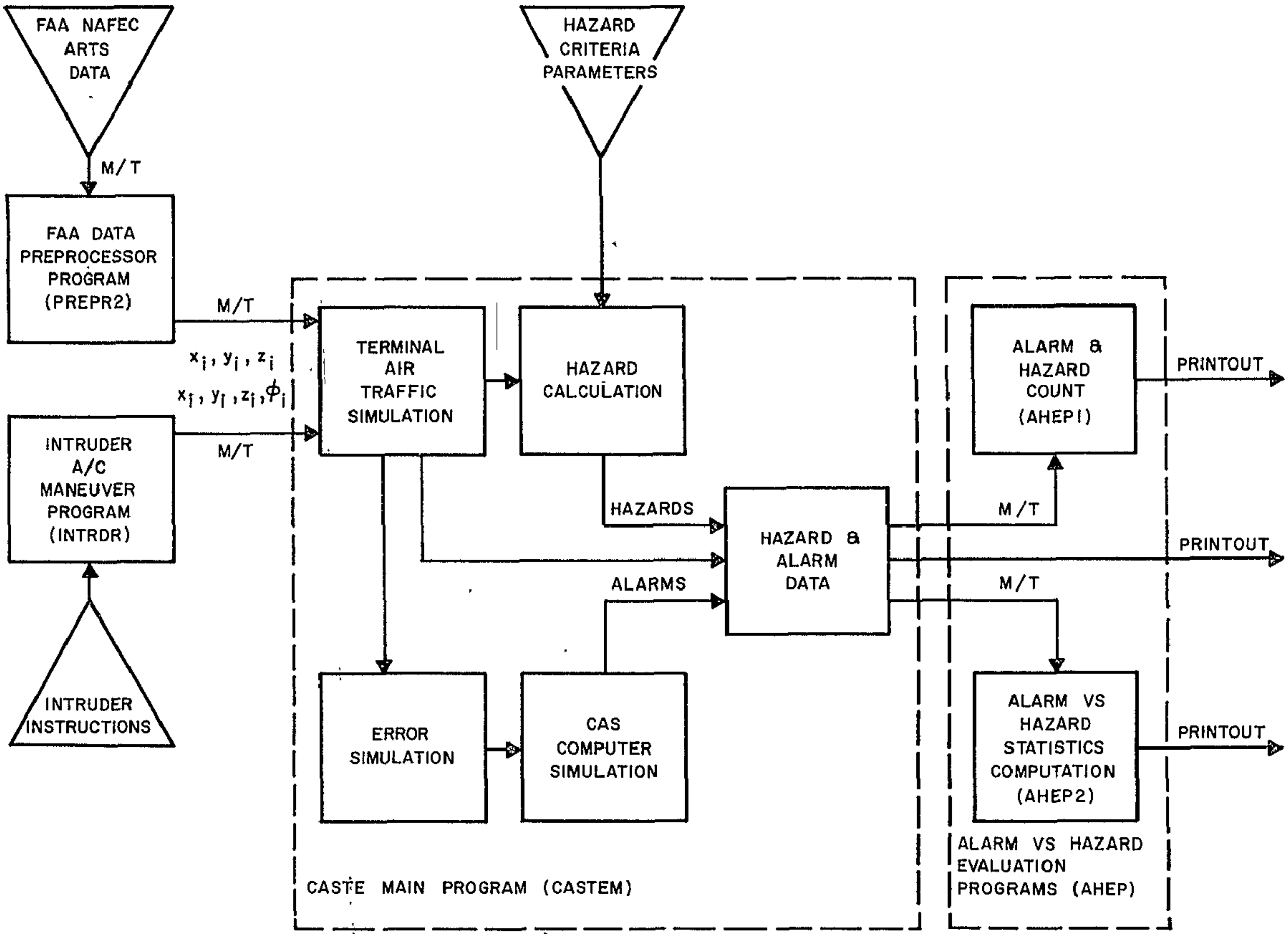


Figure 6. NASA/ERC CASTE COMPUTER PROGRAMS FOR EVALUATION OF CAS IN TERMINAL AIR TRAFFIC

Using the data in the TERMINAL AIR TRAFFIC SIMULATION, the relative collision hazard between each aircraft pair is computed in the HAZARD CALCULATION subroutine. Four collision hazard criteria are programmed in CASTEM. If these calculations indicate a collision hazard exists, the relevant data are stored in the HAZARD AND ALARM DATA.

The internal alarm analysis performed by a collision avoidance system is simulated in the CAS COMPUTER SIMULATION subroutine. If these calculations indicate the CAS would alarm for an aircraft, the relevant data are also stored in the HAZARD AND ALARM DATA.

These hazard and alarm calculations are made for each aircraft as a protected aircraft, treating every other aircraft as a threat aircraft. If it has been determined that either a hazard or an alarm exists for any protected aircraft/threat aircraft combination, the pertinent data are collected in the HAZARD AND ALARM DATA and are outputted on magnetic tape, for subsequent analysis.

The calculations in program CASTEM are repeated for all aircraft at each successive instant of time. The time interval for each calculation is selectable, but generally it would be taken equal to the time interval of the FAA or intruder input data.

The analysis of the alarms is performed using the ALARM VERSUS HAZARD EVALUATION PROGRAMS (AHEP). Statistical data are computed on the number of "valid" alarms (alarm when a hazard exists), "false" alarms (alarm when no hazard exists), and "missed" alarms (no alarm when a hazard exists).

Program AHEP1 tabulates the number of valid alarms, false alarms, and missed alarms. Program AHEP2 computes the statistical data on the distribution of valid alarms, false alarms, and missed alarms as a function the duration of the respective alarm type.

3.2 FAA DATA PREPROCESSOR PROGRAM (PREPR2)

To prepare the FAA data for use in program CASTEM, a simple preprocessor program was written. A smoothed FAA ARTS track history data tape is the input. The output data are put on a magnetic tape to be inputted to program CASTEM. The function of PREPR2 is to determine the number of aircraft in the terminal area at each time point, to calculate $\dot{x}$, $\dot{y}$, $\dot{z}$ velocities from the information on the FAA tape, and to transfer this information, along with position and ID data to program CASTEM. Provision has been made in the output tape format to include an equilibrium roll angle for each aircraft. (The roll angle calculation was not performed in the present PREPR2 runs because of the irregularities in velocity and heading data on the smoothed data tapes. All output tapes generated with the present PREPR2 program have had the roll angle set to zero.) The input and output listings for PREPR2 are given in Appendix A.

3.3 INTRUDER PREPROCESSOR PROGRAM (INTRDR)

The desireability of being able to introduce an intruder aircraft into the terminal air traffic for purposes of CAS evaluation has lead to the development of a method of prescribing the tracks for such aircraft.

The track of an intruder aircraft is generated by specifying a series of flight segments consisting of simple maneuvers. Three general types of flight segments have been chosen as being representative elements of actual flight tracks: (1) rectilinear flight, (2) constant turn radius, and (3) constant turn rate (deg/sec). The equations for the position and velocity of an aircraft following these three types of segments are programmed in INTRDR. For purposes of determining the orientation of the CAS sensor system, the bank angle ϕ of the aircraft can be computed. All three types of flight segments require specification of initial position x_o, y_o, z_o, velocity V_o, and heading χ_o at an initial time t_o.

The first type of flight segment, rectilinear flight, Table 2, is characterized as involving constant heading, constant climb rate, and constant longitudinal acceleration. The heading χ, flight path elevation angle γ, and longitudinal acceleration $\dot{V}$, are specified for the leg. The position, velocity, and roll-angle equations for this flight mode are given in Table 2.

The second type of flight segment, a constant radius turn, Table 3, also includes a constant climb rate and constant longitudinal acceleration. The turn radius, flight path elevation angle and longitudinal acceleration are specified. Equations for this flight mode are given in Table 3. One should note that the turn radius convention used considers a clockwise turn to have a positive radius.

The third type of flight segment, a constant turn rate, Table 4, allows a constant climb rate and constant longitudinal acceleration. Turn rate $\dot{\chi}$, flight path elevation angle, and longitudinal acceleration, are specified. Equations for this flight mode are given in Table 4. The sign convention for turn rate is a positive turn rate for a clockwise turn.

When maneuver specifications for intruder aircraft are to be used in program CASTEM, the number of such aircraft are specified, together with an ID and initial conditions for the first leg for each aircraft. The different maneuver legs for each aircraft are specified by giving the equation to be used for each leg (together with all parameters for that equation on that leg) and the terminal condition for each leg. The initial conditions for each leg after the first are computed internally

TABLE 2

EQUATIONS FOR RECTILINEAR FLIGHT

Initial Conditions: $t_o, x_o, y_o, z_o, V_o, \chi_o$

Maneuver Specifications: $\dot{V}, \gamma, \chi$

Maneuver Equations:

$$\chi = \chi_o$$

$$V = V_o + \dot{V}\,(t - t_o)$$

$$\dot{x} = V \cos\gamma \sin\chi$$

$$\dot{y} = V \cos\gamma \cos\chi$$

$$\dot{z} = V \sin\gamma$$

$$x = x_o + \left(V_o + \frac{\dot{V}\,(t - t_o)}{2}\right)(t - t_o) \cos\gamma \sin\chi$$

$$y = y_o + \left(V_o + \frac{\dot{V}\,(t - t_o)}{2}\right)(t - t_o) \cos\gamma \cos\chi$$

$$z = z_o + \left(V_o + \frac{\dot{V}_o\,(t - t_o)}{2}\right)(t - t_o) \sin\gamma$$

$$\phi = 0$$

TABLE 3

EQUATIONS FOR CONSTANT RADIUS TURN

Initial Conditions: t_o, x_o, y_o, z_o, V_o, χ_o

Maneuver Specifications: R, $\dot{V}$, γ

Maneuver Equations:

$$\chi = \chi_o + \frac{(t - t_o)}{R} \left(V_o + \frac{\dot{V}(t - t_o)}{2} \right) \cos \gamma$$

$$V = V_o + \dot{V} \; (t - t_o)$$

$$\dot{x} = V \cos \gamma \sin \chi$$

$$\dot{y} = V \cos \gamma \cos \chi$$

$$\dot{z} = V \sin \gamma$$

$$x = x_o - R \; (\cos \chi - \cos \chi_o)$$

$$y = y_o + R \; (\sin \chi - \sin \chi_o)$$

$$z = z_o + \left(V_o + \frac{\dot{V} \, (t - t_o)}{2} \right) (t - t_o) \sin \gamma$$

$$\phi = \tan^{-1} \left(\frac{V^2 \cdot \cos^3 \gamma}{g \; R} \right)$$

TABLE 4

EQUATIONS FOR CONSTANT RATE TURN

Initial Conditions: t_o, x_o, y_o, z_o, V_o, χ_o

Maneuver Specifications: $\dot{\chi}$, $\dot{V}$, γ

Maneuver Equations:

$$V = V_o + \dot{V}\,(t - t_o)$$

$$\chi = \chi_o + \dot{\chi}\,(t - t_o)$$

$$\dot{x} = V \cos\gamma \sin\chi$$

$$\dot{y} = V \cos\gamma \cos\chi$$

$$\dot{z} = V \sin\gamma$$

$$x = x_o + \left\{\frac{V_o}{\dot{\chi}}(\cos\chi_o - \cos\chi) + \frac{\dot{V}}{\dot{\chi}^2}(\sin\chi - \sin\chi_o - \dot{\chi}\,(t - t_o)\cos\chi)\right\}\cos\gamma$$

$$y = y_o - \left\{\frac{V_o}{\dot{\chi}}(\sin\chi_o - \sin\chi) - \frac{\dot{V}}{\dot{\chi}^2}(\cos\chi - \cos\chi_o + \dot{\chi}\,(t - t_o)\sin\chi)\right\}\cos\gamma$$

$$z = z_o + \left(V_o + \frac{\dot{V}\,(t - t_o)}{2}\right)(t - t_o)\sin\gamma$$

$$\phi = \tan^{-1}\left(\frac{\dot{\chi}V}{g}\cos^2\gamma\right)$$

in the INTRDR program. The input and output listings for INTRDR are given in Appendix B.

3.4 CASTE MAIN PROGRAM (CASTEM)

3.4.1 Terminal Area Model

At each time instant, program CASTEM obtains the following information for each aircraft from the PREPR2 output tape and/or the INTRDR output tape: ID, x, y, z, $\dot{x}$, $\dot{y}$, $\dot{z}$, ϕ. The ID is the aircraft track number assigned by the ARTS system. χ (nmi), y (nmi), and z (ft) give aircraft position while $\dot{x}$, $\dot{y}$, $\dot{z}$ give aircraft velocity components in knots. The bank angle ϕ is given in radians. This information is stored in subscripted arrays. For purposes of identification, aircraft data, such as x, are referred to by the subscript denoting the order that the aircraft it represents appears on the tape at the time instant being considered. Thus ID_i, x_i, y_i, z_i, etc. represent data for the ith aircraft on the tape at that time; the ID number and the subscript i are not identical.

The primary function of the terminal area model is to calculate the relative positions, velocities and orientations of each aircraft pair. For each protected aircraft i the program calculates for any other threat aircraft j such quantities as relative range R_{ij}, relative velocity V_{ij}, relative closing velocity $V_{c_{ij}}$, relative azimuth Θ_{ij}, and relative elevation

Φ_{ij}. The result of this calculation is a set of matrices $[R_{ij}]$, $[V_{ij}]$, $[V_{c_{ij}}]$, $[\Theta_{ij}]$, $[\Phi_{ij}]$. The first three of these matrices are symmetric; the last two are not. All diagonal elements of the matrices are not used in any subsequent calculation and are set equal to zero.

Definitions of R_{ij}, V_{ij} and V_{c_j} are as follows:

$$R_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}$$

$$V_{ij} = \sqrt{(\dot{x}_j - \dot{x}_i)^2 + (\dot{y}_j - \dot{y}_i)^2 + (\dot{z}_j - \dot{z}_i)^2}$$

$$V_{c_{ij}} = - \dot{R}_{ij}$$

The angles Θ_{ij} and Φ_{ij} are defined in Section 2.1

3.4.2 Hazard Criteria

A criterion is sought that expresses quantitatively the collision hazard of a threat aircraft to a protected aircraft. Once this criterion is available, then the collision hazard can be computed for each aircraft. This hazard criterion then serves as a standard against which the performance of the CAS for detecting collision hazards is evaluated. In the event a collision hazard exists for an aircraft, then the CAS should indicate an appropriate alarm. Conversely, an ideal CAS would not alarm if there is no hazard. Because an ideal CAS would always alarm, and only alarm, when a hazard exists, the selection of the hazard criterion is critical to the design of a CAS.

The most elemental hazard criterion is a "go/no-go" criterion that indicates only whether a hazard does or does not exist - a one-step criterion. In reality, it seems more correct to say that the collision hazard of one aircraft to another increases or diminishes on a continuous scale, so that a continuous scale of the degree of collision hazard might be considered. However, instrument flight rules (IFR) do not enable one to vary the flight to a continuous scale of hazard criteria, so attention has been directed to multiple degrees of collision hazard. At present, in order to not become drawn into a detailed study on collision hazards, a single degree of hazard has been programmed: a hazard is said to exist or to not exist. Multi-degree criteria could be programmed readily at a later time. All of the criteria have been programmed with variable parameters so that any number of degrees of collision hazard could be examined by making successive runs.

The following four hazard criterion have been programmed into the HAZARD CALCULATION subroutine.

1. Range-Altitude Guard Criterion. The range-altitude guard, Figure 7, tests whether a threat aircraft at the range R_{ij} is within a hazard range, R_{haz}, and simultaneously

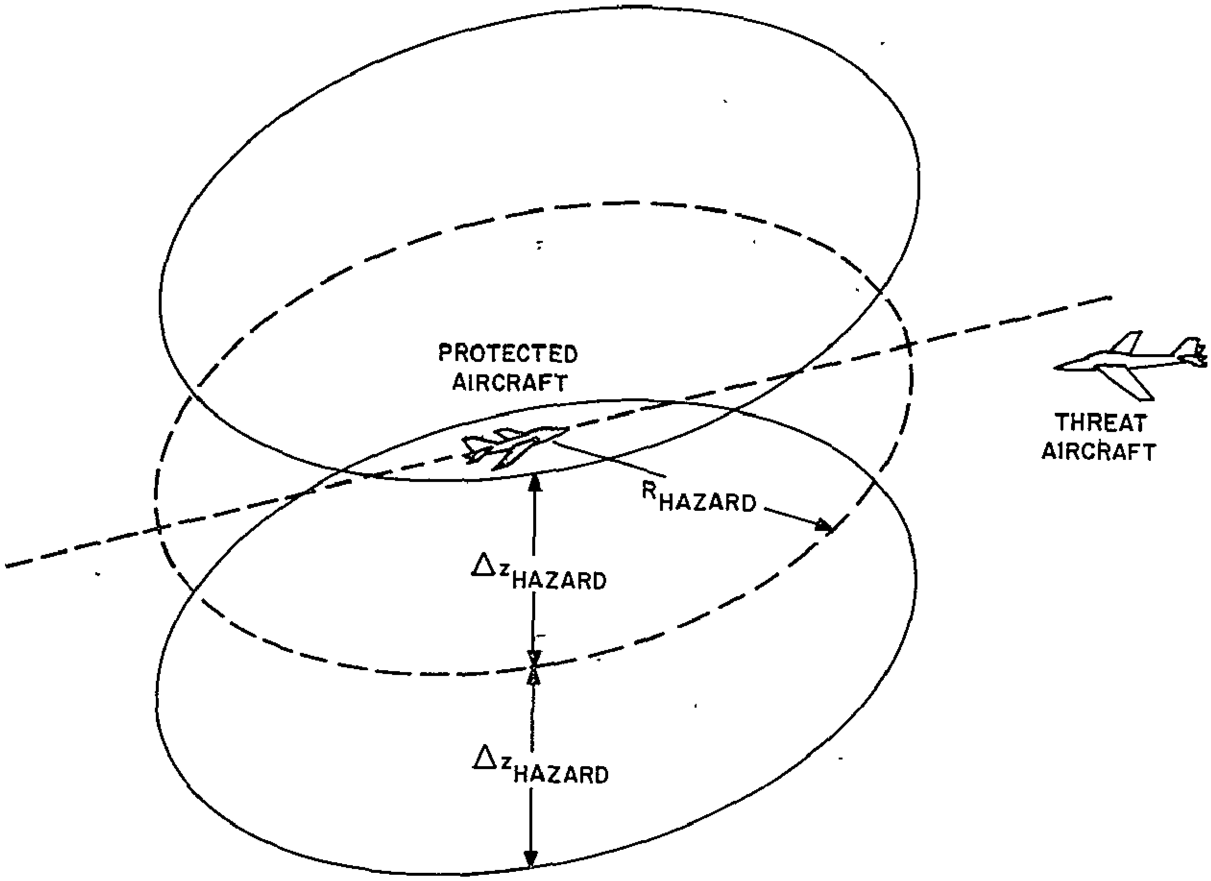


Figure 7. SKETCH OF RANGE-ALTITUDE GUARD CRITERION. GUARD BOUNDARY FIXED IN SPACE

within a hazard altitude separation, z_{haz}.

Hazard Criterion:

$$R_{ij} \leq R_{haz}, \quad \text{and}$$

$$|z_j - z_i| \leq \Delta z_{haz}$$

The values of R_{haz} and Δz_{haz} are inputs to the program.

In the program this criterion is identified as the "FAA criterion," following regulations that aircraft in a terminal area under IFR fly the 1000-ft flight levels and, at one flight level, be separated by 3 nmi. A tolerance must be allowed for the deviations from flight level due to flight technical error, so, in the calculations that have been made, Δz_{haz} has been taken to be 500 ft. However, R_{haz} and Δz_{haz} are selectable inputs to the program.

A simple range-altitude criterion has some definite limitations for defining collision hazards. One of the principal problems is that aircraft operating under visual flight rules are not restricted to the 3-nmi separation or to the 1000-ft flight levels.

2. Acceleration Criterion. With the acceleration criterion, the envelope of points that every aircraft could reach pulling a constant acceleration a, during an escape time t_e is computed. A collision hazard is defined to exist for the aircraft if the envelopes for the two aircraft intersect.

This criterion can also be expressed in terms of the relative position, velocity, and acceleration to the protected aircraft, Figure 8. The vector $\vec{R}_{ij}$ is the relative position of the threat aircraft to the protected aircraft

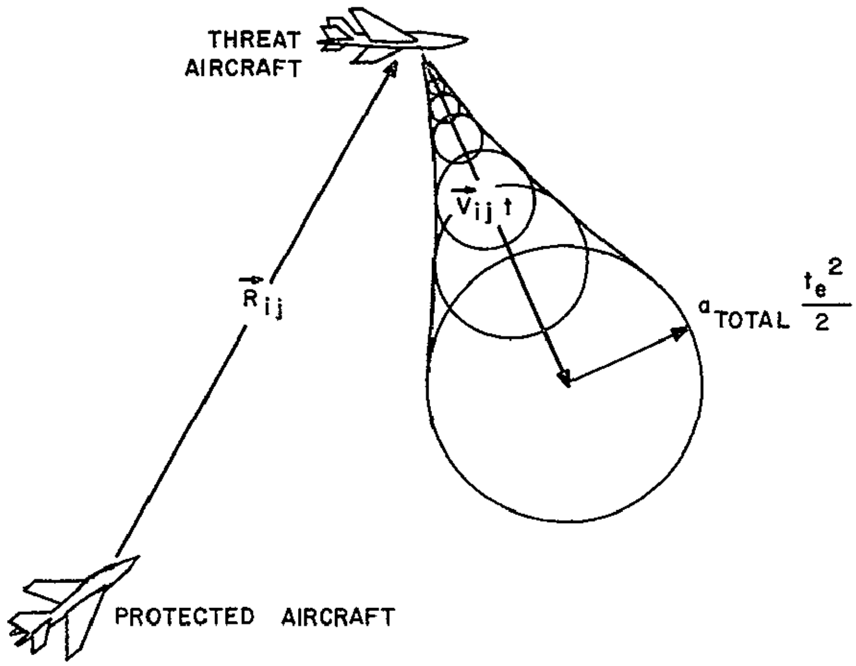


Figure 8. SKETCH TO ILLUSTRATE ACCELERATION CRITERION. CO-ORDINATES FIXED ON PROTECTED AIRCRAFT

and the vector $\vec{V}_{ij}$ is the relative velocity. The envelope of the maximum relative distances that the threat aircraft could reach in time t from the relative position $\vec{V}_{ij}\, t$ is represented by the sphere with radius $a_{tot}\, t^2/2$, where $a_{tot} = a_i + a_j$. If the protected aircraft falls inside the sphere, then a hazard would exist, according to this criterion.

Hazard criteria:

$$|\vec{R}_{ij} + \vec{V}_{ij}\, t| - a_{tot} \frac{t^2}{2} < 0 \qquad (2)$$

for

$$0 < t < t_e$$

where

$$\vec{R}_{ij} = (x_j - x_i)\,\vec{i} + (y_j - y_i)\,\vec{j} + (z_j - z_i)\,\vec{k}$$

$$\vec{V}_{ij} = (\dot{x}_j - \dot{x}_i)\,\vec{i} + (\dot{y}_j - \dot{y}_i)\,\vec{j} + (\dot{z}_j - \dot{z}_i)\,\vec{k}$$

The values of a_{tot} and t_e are parameters in this criterion.

The merit of the acceleration criterion is that it reflects a physical limitation of the flight path of a threat aircraft—the acceleration that the aircraft might undergo. In addition it makes allowance for the acceleration the protected aircraft could make in a turn. But, again, the problem is to assign numbers to the parameters involved—specifically, a_i, a_j, and t_e. For example, an acceleration limit for a normal turn might be 1/2 g. However, in an escape maneuver, the acceleration could easily reach several g's. So, if one desires to protect against a threat aircraft that is escaping from a possible collision, one might select an acceleration limit a_{tot} of 2 g's. Similarly, a number of values have been used in various studies for the escape time, ranging from about 10 to 60 seconds.

The program is written so that both a_{tot} and t_e are selectable inputs to the program. In the calculations that have been made, the values of a_{tot} of 1 g and t_e of 20 seconds have been used.

3. Tau Criterion. Aircraft on a collision course for linear flight have a collision time given by τ, where $\tau = R_{ij}/V_{c_{ij}}$. If a warning time, τ_{crit}, is allowed for the pilot to avoid the collision hazard, then τ_{crit} might be considered a hazard criterion.

Hazard criteria:

$$\frac{R_{ij}}{V_{c_{ij}}} \leq \tau_{crit} \tag{3}$$

Tau has been extensively explored in CAS studies as a collision criterion, so it has been programmed in the HAZARD CALCULATION subroutine. However, the tau criterion does not account for the component of the relative velocity of the threat aircraft that is normal to the closing velocity, V_θ. It only accounts for the closing velocity V_c. If the normal component V_θ is large enough, the collision hazard would not exist. Therefore, tau may be considered in this sense to be a conservative criterion, in that the worst case is used, i.e., $V_\theta = 0$. In other words, because tau neglects V_θ, it indicates more hazards than otherwise would be considered to exist.

4. Modified-Tau Criterion. Another problem with the tau criterion has been pointed out by Holt, et al.[3] Two aircraft might be flying parallel courses at very close range, yet

tau would be infinite. The problem is illustrated in Figure 9. The two aircraft are first flying parallel, and tau would be infinite. Each could suddenly turn toward the other aircraft, and tau could suddenly be so small that the aircraft do not have sufficient time to avoid collision.

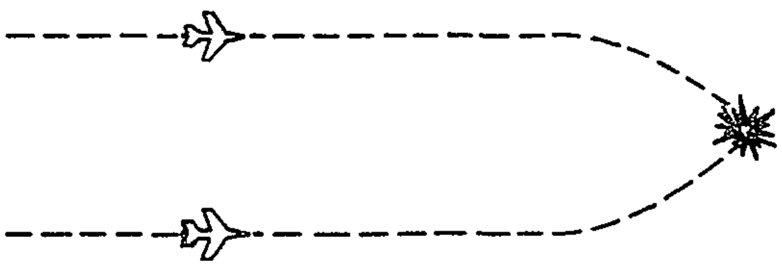


Figure 9. PARALLEL FLIGHT TRACKS

In the modified-tau criterion, a distance d is added to allow for possible acceleration of the two aircraft. If a warning time $\tau_{mod_{crit}}$ is allowed to avoid the collision hazard, then $\tau_{mod_{crit}}$ could be considered the hazard criterion.

Hazard criteria:

$$R_{ij} - V_{c_{ij}} \tau_{mod_{crit}} < d \tag{4}$$

where $\tau_{mod_{crit}}$ and d are parameters to be selected.

For aircraft in rectilinear flight and on a collision course, the modified-tau criterion protects against accelerations from the rectilinear path. This protection applies not only to aircraft on parallel courses, as in Figure 9, but also, of course, on non-parallel courses. This protection against possible accelerations makes the modified-tau criterion similar to the acceleration criterion. The difference is that the tangential velocity V_θ is neglected in the modified-tau criterion, so that it indicates more hazards than the acceleration criterion.

Holt, et al.[3] present arguments for handling separately the analysis of altitude separation and horizontal separation during aircraft encounters. The two arguments of Reference 3 that are applicable to the determination of collision hazards are: (1) the aircraft separations in the altitude dimension are much smaller than in the horizontal direction, and (2) the most precise measurements are taken in altitude.

The altitude dimension is handled separately in the range-altitude guard criterion, reflecting the differences in the FAR vertical-separation and horizontal-separation standards. Regarding the acceleration criterion, the maximum horizontal acceleration usually encountered in a turn would be about the same as the maximum vertical acceleration in a climb or dive, about 1/2 g. Therefore, the acceleration criterion is applied in the altitude coordinate in the same way that it is applied in the horizontal plane. However, it should be pointed out that the duration of the acceleration in the altitude direction generally would be less than the duration of acceleration in the horizontal plane. But this subject needs more study before the hazards can be differentiated to this detail. However, it would not be unreasonable at a later date to incorporate different durations of the vertical and horizontal accelerations.

Regarding the tau criterion, the time to intercept on a collision course, tau, is independent of the direction, so the altitude is not treated separately. Finally, the modified-tau criterion incorporates both tau and a protection against acceleration, so altitude is not treated separately.

A final comment on separating the altitude coordinate from the horizontal coordinate. Examination of data from the 12 hours of FAA Atlanta ARTS data indicates that the aircraft in the terminal area generally encounter other aircraft nearly at co-altitude. The explanation, apparently, is that most of the aircraft in the terminal area are in the process of descent and climb from the airport, so the tracks generally lie along rather flat cones, centered at the airport. The principal situations where altitude separation might be involved appears to be either where departing aircraft have turned and overfly arriving aircraft headed toward final approach or where aircraft under Atlanta airport control pass near aircraft from satellite airports. The ARTS data appear to indicate that these two types of encounters are relatively few. This is not a closed question, however, because altitude data were not available for about 15 percent of the aircraft, which may be aircraft operating from satellite airports.

Therefore, for the present, the collision hazard in the altitude dimension is treated the same as in the horizontal dimension, with the exception of the range-altitude guard criterion. This approach is believed to be conservative, that is, the number of hazards tends to be overestimated, and it is subject to a more thorough analysis of collision hazard criteria.

All four hazard criterion are tested for each pair of flight tracks at each time instant. If any one of the hazard criteria indicates that a hazard exists between a pair of aircraft, the hazard data, aircraft trajectory data, and alarm data are stored in the HAZARD AND ALARM DATA.

3.4.3 CAS Model

The CAS model programmed into the CAS COMPUTER SIMULATION is intended to simulate the class of PWI that is based on the detection of an optical or electromagnetic signal radiated from a beacon.

The NASA/ERC Optical/IR PWI concept falls within this class. It employs a xenon light source that radiates spherically, except for blanking in certain sectors due to blockage by the aircraft.

The general equation for the strength of the receiver signal P_{ij} on aircraft (i) due to the radiated signal from the beacon on aircraft (j) is

$$P_{ij} = \frac{e^{-\frac{R_{ij}}{R_o}}}{R_{ij}^2} [A_1 \cos(B_1 \Psi_{1_{ij}}) + A_2 \cos(B_2 \Psi_{2_{ij}}) + A_3 \cos(B_3 \Psi_{3_{ij}})] \quad (5)$$

with $\cos \beta_n \Psi_{n_{ij}} = 0$ for $\beta_n \Psi_{n_{ij}} > \frac{\pi}{2}$ or $< -\frac{\pi}{2}$

Here R_o is the characteristic distance representing the one-dimensional attenuation of the beacon signal in a uniform atmosphere. The distance-squared law of the radial decay of the signal is represented by the denominator. The three terms in the bracket represent three sensors on the aircraft. The constants A_1, A_2, and A_3 give the signal for a beacon in a vacuum detected by sensors directed at the beacon from unit range. Each sensor is assumed to obey a cosine detection law with the coefficients B_1, B_2 and B_3 indicating the off-axis angular decrement. The off-axis angles of the beacon to the axis of sensors 1, 2, and 3 are $\Psi_{1_{ij}}$, $\Psi_{2_{ij}}$, and $\Psi_{3_{ij}}$, respectively, as shown in Figure 10. The angles $\Psi_{1_{ij}}$, $\Psi_{2_{ij}}$, etc. in Equation (5) are computed in the program using the azimuth Θ_{ij} and elevation Φ_{ij} angles and the direction angles of the optical axes to CAS coordinates. The convention for defining the direction angles of the optical axes of a PWI is illustrated in Figure 11. These direction angles are defined with respect to the CAS coordinate system fixed to the aircraft, where x' is out the nose, along the flight path, y' is out the left wing, and z' is up. The angles between the x', y', z' axes and the sensor optical axis are respectively a_1, b_1, c_1 for sensor 1, etc.

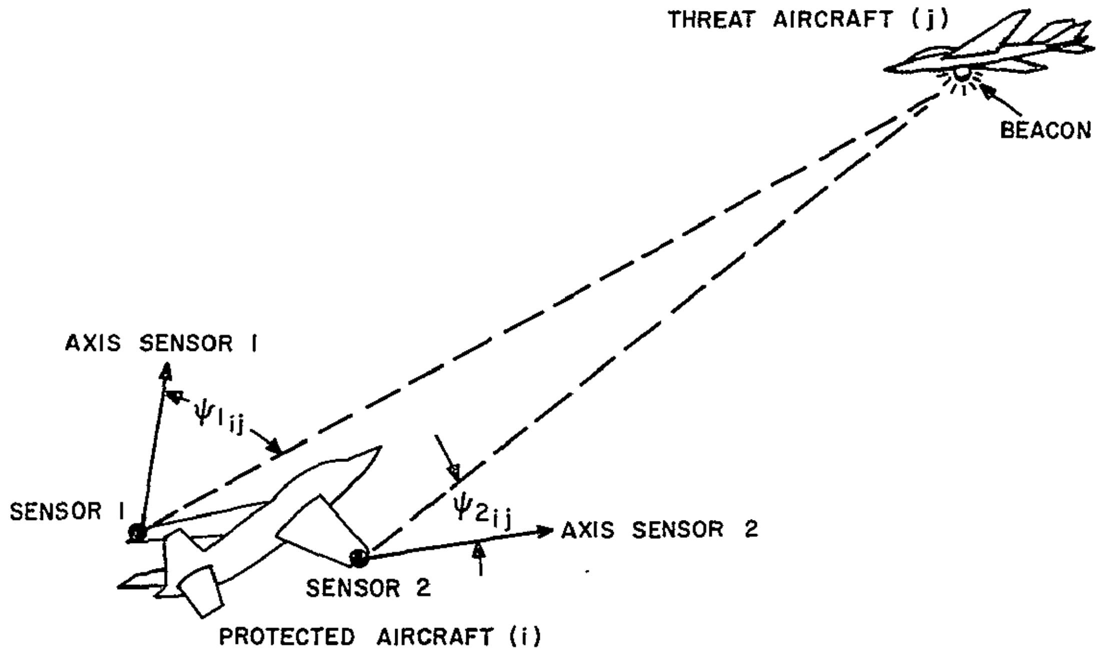


Figure 10. ORIENTATION OF SENSORS ON PROTECTED AIRCRAFT RELATIVE TO THREAT AIRCRAFT

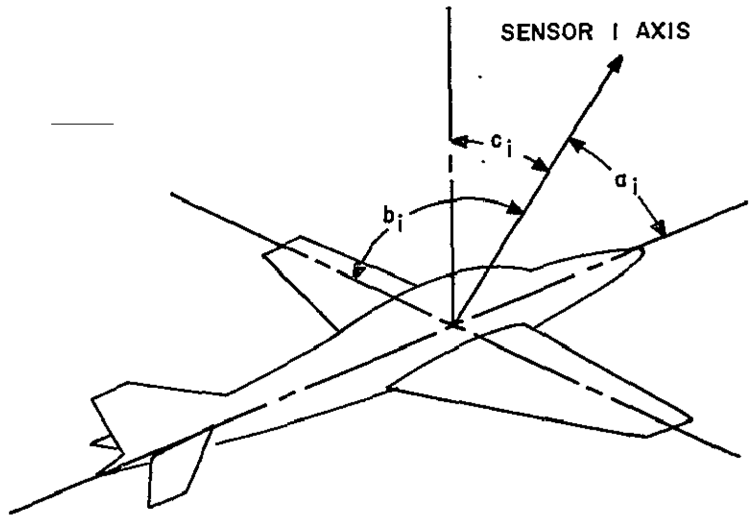


Figure 11. DIRECTION ANGLE CONVENTION FOR OPTICAL SENSOR ORIENTATION

When the receiver signal P_{ij} in Equation (5) exceeds a threshold for an alarm, P_{alarm}, the alarm of the CAS is simulated. The values of the times when the alarms occur, along with other pertinent data, are then stored in the HAZARD AND ALARM DATA, along with the other alarm data, hazard data, and airplane trajectory information.

The above describes the CAS COMPUTER SIMULATION as it now is programmed. From time to time it will be desirable to alter the subroutine to study candidate changes in the CAS. For example, it may be desirable to evaluate a system with multiple alarm levels - perhaps, a "warning" alarm when an aircraft is 5 nmi ahead, and successively more "intense" alarms at 3 nmi, 2 nmi, etc.

Other CAS can be modeled using replaceable subroutines in the CAS COMPUTER SIMULATION, provided the system employs only measurement data on aircraft position, velocity, and orientation. For a system that might employ measured data on acceleration or higher derivatives, the CASTEM program would have to be modified to store data at several time instants.

3.5 ALARM VERSUS HAZARD EVALUATION PROGRAMS (AHEP)

Two computer programs have been written for analyzing the alarm and hazard data from program CASTEM. To discuss these evaluations, several terms must be defined. The definitions will be discussed with reference to Figure 12.

Figure 12 represents a time sequence of hazard and alarm events. Time progresses to the right. The existence of a hazard or an alarm for protected aircraft (i) due to the intruder aircraft (j) is indicated, respectively, by a cross and an x. At the first two times there is neither a hazard nor an alarm. At the next 5 times the alarm is on, but there is no hazard; in the terminology employed here, this is called a "false alarm." At the succeeding 4 times, there is a hazard and the alarm is on, called a "valid" alarm. At the following 3 times there is a hazard but there is no alarm, so this is called a "missed" alarm. The objective, of course, is to design a system yielding a small number of missed alarms while maintaining a tolerable number of false alarms.

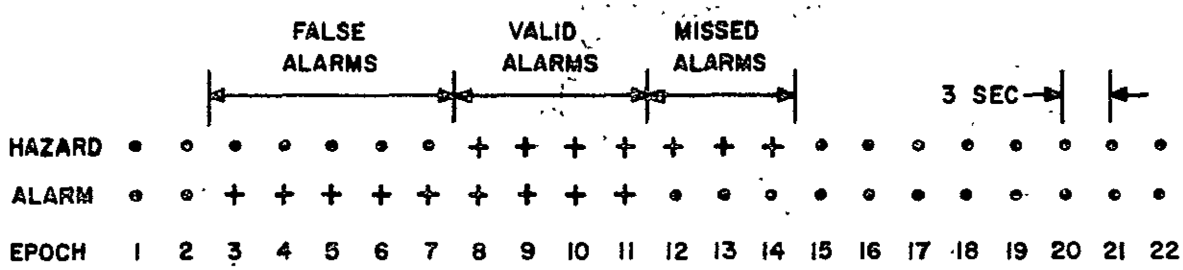


Figure 12. EXAMPLE OF DIFFERENT ALARM TYPES COMPARED TO A PARTICULAR HAZARD CRITERION

All of the alarm types must be considered together. For example, a system could be designed that has no missed alarms, by simply alarming all the time. In this event the false alarm rate would be unacceptable.

3.5.1 AHEP1 Program

This program counts the number of times when there is an alarm, hazard, valid alarm, false alarm, or missed alarm. Therefore there are 5 numbers representing these totals. The symbols Q, R, S represent

$$Q = \text{total number of valid alarms}$$

$$R = \text{total number of false alarms}$$

$$S = \text{total number of missed alarms}$$

AHEP1 computes these quantities from the tape output of the CASTEM program.

The total number of hazard times are equal to Q + S. The ratios listed below are also computed

$$q = \frac{Q}{Q + S}$$

$$r = \frac{R}{Q + S}$$

$$s = \frac{S}{Q + S}$$

The valid-alarm ratio q and missed-alarm ratio s would always fall between zero and one. The false alarm ratio r has no limit.

It is expected that program AHEP1 would be employed in studies directed at determining how various configurations of the PWI sensors, settings of the alarm threshold, etc., affect the quantities q, r, and s.

This method of evaluation treats each time equally, without consideration for how continuous the alarms or hazards may be.

3.5.2 AHEP2 Program

Program AHEP2 analyses the durations of the hazards, alarms, valid alarms, false alarms, and missed alarms. The symbol K represents the duration of a hazard or alarm type; specifically, it is the number of consecutive times of a hazard or an alarm type. For example, referring to Fig. 12, the alarm duration is K = 9, the hazard duration is K = 7, the false-alarm duration is K = 5, the valid-alarm duration is K = 4, and the missed-alarm duration is K = 3. Program AHEP2 reads the CASTEM output tape and tabulates the frequency distribution of the hazard duration, alarm duration, etc., for K = 1, 2, 3, etc. The frequency distributions are tabulated values of the following variables.

Symbol	Meaning
$N_H(K)$	Number of hazard periods of duration K
$N_A(K)$	Number of alarm periods of duration K
$N_{VA}(K)$	Number of valid alarm periods of duration K

Symbol	Meaning
$N_{FA}(K)$	Number of false alarm periods of duration K
$N_{MA}(K)$	Number of missed alarm periods of duration K

After the frequency distributions are computed, AHEP2 calculates the (cumulative) distribution functions and the complementary distribution functions for the periods of the alarms, hazards, valid alarms, false alarms, and missed alarms.

SECTION 4

ERROR SIMULATION

The operation of a collision avoidance system is affected by errors in the measurements and errors in the alarm calculation.

In most CAS systems measurement errors include altimeter errors and range measurement errors. In an optical PWI system, range, azimuth angle and elevation angle are measured. The range measurement is the most critical measurement, and it is affected by signal variation, scintillation of the recieved light due to refraction in the atmosphere, atmospheric attenuation due to haze, etc., and characteristics of the receiver lens, sensors, and electronics. The azimuth and elevation angles, on the other hand, are only measured for aid in locating the threat aircraft, so accuracy here is not so important.

Alarm calculation errors reflect the quality of the electronic components and the circuit design. With reasonable care in design and fabrication, these errors should be negligible.

The terminal air data employed in the simulation study reflect errors in the radar measurements and altimetry. The Atlanta ARTS radar data are quantized in bins (increments) of 0.0625 nm for range and 1/4096 revolution (0.038 nm at a range of 25 nm) for azimuth. These data are smoothed on-line at the Atlanta facility, so the resultant data would be expected to contain errors less than the bin size. The data were smoothed further at NAFEC. On this basis, an accuracy estimate of ±0.05 nm would seem reasonably conservative (high).

Data errors were introduced evidently by the radar MTI suppression system that screens out raw radar data where the range rate is zero. In a number of cases the tracks in the Atlanta ARTS data had gaps of 1/2 to 3/4 nm, where the TWS computer temporarily went into a coast mode and later recaptured the target. The data smoothing performed at NAFEC reduced the magnitude of these discontinuities, but, unfortunately, at the expense of introducing large variations in the velocity - as much as 120 knots in 12 sec.

The altimetry error is a problem common to both the CAS measurements and the simulation data. Because of this, a separate study was made of altimetry errors for commercial transports and general aviation aircraft. The results of this study are presented in Section 4.1.

The various errors described above can be introduced into the computer program by employing an error generation calculation using the Monte Carlo technique. In this method the "error-free" value of the quantity, such as altitude, range, etc., is fed into the subroutine for generating errors, along with the standard deviation of the error. The subroutine randomly generates values of the quantity based on the Gaussian error distribution. At each epoch, a number of random values of each quantity would be used in successive calculations for each aircraft pair in order to reflect the entire error distribution of each quantity.

4.1. Altimetry Error

The altimetry error is subdivided into instrument error, static pressure error, and flight technical error. The definition of these terms is taken from Gracey[4].

Instrument error — statistical sum of the errors due to the mechanical imperfection of the altimeter (i.e., scale or diaphragm, hysteresis, drift, friction, temperature, instability and backlash) and the errors due to readability (altitude and barometric-setting scales).

Static-pressure error — the difference between free-stream pressure and the pressure registered by the aircraft static-pressure source (static-pressure tube or fuselage vent); for a given airplane, the statistical sum of the fixed error (the error applicable to the aircraft type) and the variable error (the probable departure of the actual error from the fixed error).

Flight technical error — random deviations of an airplane from its cruise flight level.

System error — statistical sum of the instrument error and the static-pressure error.

Altimetry error — statistical sum of the system error and the flight technical error.

Data have been assembled on altimetry errors for three classes of aircraft: general aviation, transport, and military. These data are presented in Table 5. Either the 3σ value or the 99.7 percent probability value is tabulated.

The instrument error for general aviation aircraft was measured in a survey made by Wright[5]. The error of 365 ft represents the 99.7 percent value from the reported data. The instrument error for the aircraft surveyed is probably even larger than indicated by this value, because the instrument error was not reported by Wright if the altimeter had an excessive leak rate. Of the general aviation aircraft, 70 percent had excessive leaks in the static pressure system. In addition, a few percent had barometric scale setting mechanisms that were inoperable or malfunctioning. These were excluded in the sample, so the error of 365 ft does not reflect these potentially greater error sources.

There were no data on the static pressure error for general aviation aircraft. If the static pressure error were also 365-ft the error would correspond to 0.13 q, where q is the dynamic pressure. Presumably the static-pressure error would not be this large, although it cannot be ruled out in view of the surprisingly large instrument error found in general aviation aircraft. In the absence of further data, the static-pressure error is assumed to be negligible.

TABLE 5. ALTIMETRY ERRORS (3σ, 99.7%)
BEST ESTIMATE, FEET
6000 FEET, 250 KNOTS

	General Aviation	Transport	Mil.
Instrument Error	<u>365</u> (1)	40 (2)	*
Static pressure			
Fixed	*	15	*
Variable	*	110	110
Combined	*	110 (3)	110
System error	*	132 (4)	*
Flight technical error	600 (5)	120 (6)	*
Altimetry error	700 (7)	178 (8)	*

* No data

(_) Highly uncertain data

(1) Exclusive of (70%) data from altimeter systems with leaks.

(2) Approximate ICAO (1961) value for precision altimeters.

(3) From square-root of sum-of-squares.

(4) Probably somewhat large. Obtained from 35,000 ft data, scaled by $\frac{dp}{dh}$.

(5) Negative exponential distribution.

(6) Large non-Gaussian deviations at tails. Measured for propellor transports. Assumed to be same for jet transports.

(7) Computed from instrument error and flight technical error assuming Gaussian distributions. Six times as large as approach-landing error measured by Gracey (1960).

(8) Computed from system error and flight tech. error, assuming Gaussian distributions. 55% greater than Gracey (1960) measured for approach and landing. Main factor is 110 ft variable static pressure error.

The data on the flight technical error for general aviation aircraft were taken from a survey of six types of aircraft reported by Clay[6], et al. The 99.7-percent error is 650 ft. However, here it should be noted that the error distribution approximates better a negative exponential than a Gaussian. This means that the instances of large flight technical errors is greater than for a Gaussian distribution. In fact there were a significant number of excursions near 1000 ft. The significance of the negative exponential distribution to the collision hazard will be discussed later.

Combining these values of the instrument error and the flight technical error by the root-of-the-summed-squares, which assumes Gaussian distributions, gives an altimetry error of 700 ft for general aviation aircraft. This is about 6 times larger than the 115-ft* altimetry error measured during landing approaches by Gracey[7]. However, it is difficult to justify a smaller altimetry error in view of the large instrument error and flight technical error that have been measured.

The flight technical error of 700 ft for general aviation aircraft is very large for the 1000-ft separations that are allowed in the terminal area. Gracey[4] shows for aircraft

*All error data are corrected for 250 knots at 6000-ft altitude.

separated along a vertical line that the collision probability is near zero for altimetry errors up to 400 ft, increases to 10^{-5} for an altimetry error of 500 ft, and increases thereafter at a very rapid rate for altimetry errors greater than 500 ft. That analysis is based on a Gaussian distribution of the altimetry error. Trewek[8] shows that the collision probability for the negative-exponential distribution is even greater (in fact, the probability of collision is shown to be uniform between the assigned altitudes, due to the large distribution at the tails, whereas for the Gaussian distribution the largest probability of collision occurs midway between assigned altitudes). The upshot of the discussion is that the flight technical errors for general aviation aircraft are, evidently, large for a 1000-ft separation standard.

For transports the instrument error was given by ICAO[9] as 40 ft for precision altimeters. The fixed static pressure error would be 15 ft at jet cruise altitudes if the ICAO and IATA corrections are applied, and it should be less at 250 knots at 6000 ft, but the larger value is taken here. The variable static pressure error for current aircraft was estimated by IACO to be 110 ft at 5000 ft.[(4)] This was confirmed in an earlier investigation by Fine[10]. The combined static pressure error, assuming normal distributions, is 100 ft. Combining these errors statistically, assuming normal distributions, gives a system error of 132 ft for transports.

The flight technical error for 19 propellor transports was measured by Kolnick and Bentley[11]. It should be mentioned for transports, as remarked for general aviation aircraft, that a greater number of large deviations were measured compared to a Gaussian distribution. Consequently the estimated altimetry error of 178 ft for transports, which is the statistical sum of the system and flight technical errors, assuming normal distributions, does not adequately reflect the high number of large deviations. Gracey, et al.[7] reported measurements of the altimetry error for approach landing aircraft, and the (scaled) errors were 115 ft. This is about 35 percent less than the 178-ft altimetry error estimated above. In view of the lower speeds during landing approach and other factors such as reduced pilot attention, winds, etc. at altitude, it is assumed that the data of Gracey[7] essentially confirm the 178-ft altimetry error assigned to transports.

Regarding the altimetry error for military airplanes, insufficient data were found in the available literature on the various constituent errors to make an estimate.

2

SECTION 5

HOUR-10 EXAMPLE RESULTS

The CASTE program has been applied to the FAA Atlanta ARTS Hour-10 data. A few of the results are presented here to whet the readers interest in uses of the CASTE program. A more extensive analysis, using the Atlanta ARTS data, will be the subject of the subsequent research phase.

One approach to studying the performance of a PWI system operating in terminal air traffic is to examine each aircraft-aircraft encounter where a hazard or alarm occurs. Figure 13 shows the track of an inbound airplane arriving from the north, and Figure 14 shows the track of an outbound airplane simultaneously departing northward. The area where the two airplanes experience the closest approach is shown in Figure 15. Arriving track 22 is at flight level 60 (FL60), which is at 6000 ft, and departing track 25 is at FL40.

At the 647-sec epoch, the PWI alarm would go on for the aircraft, for the particular sensor configuration and sensitivity selected. The alarm would remain on for 18 epochs (3-sec separation) until the 698-sec epoch. The duration of the acceleration hazard for a 20-sec escape time and 1-g total relative acceleration is identified in Figure 15a. The acceleration hazard here begins at the 650-sec epoch and continues for

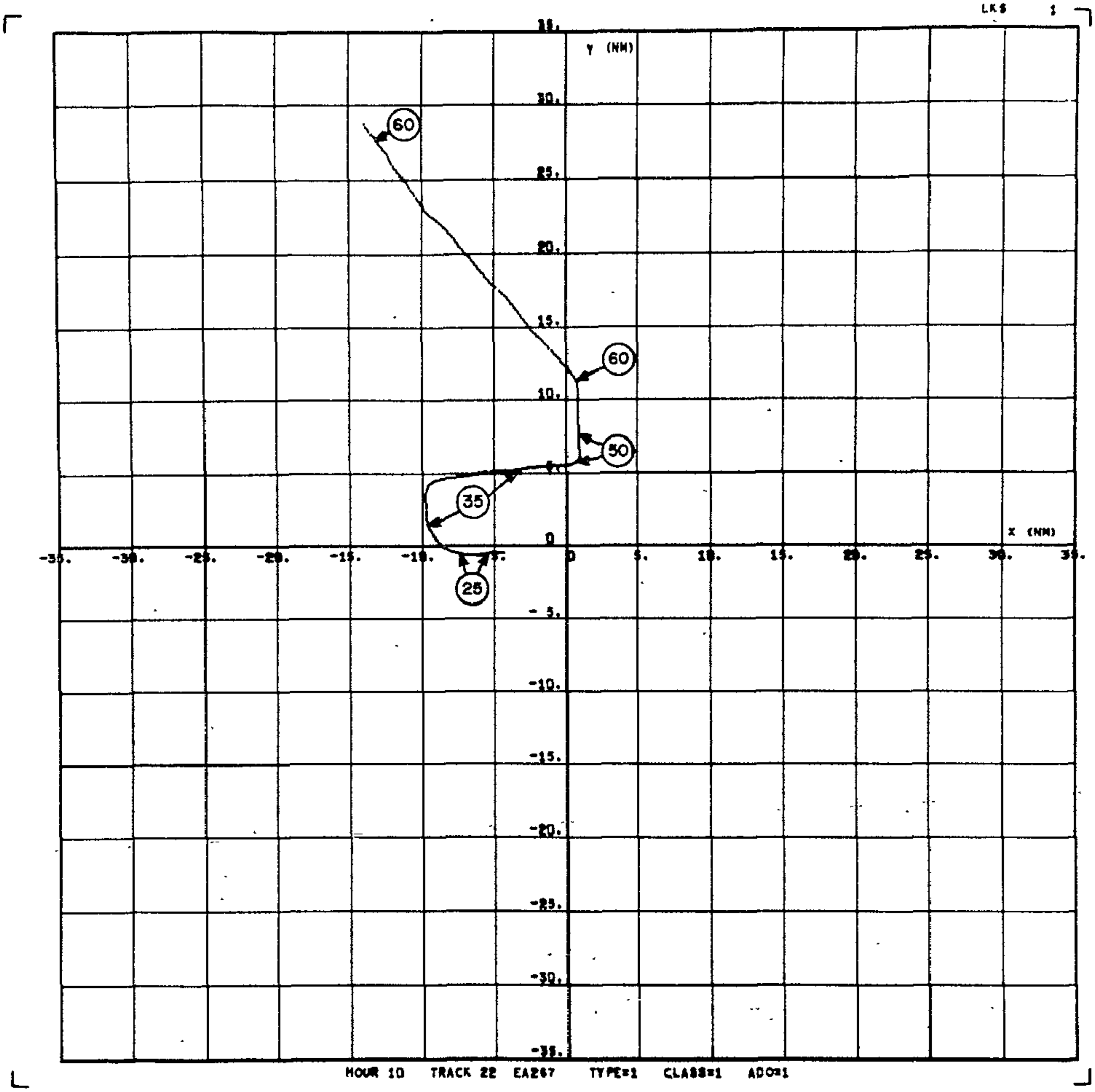


Figure 13. TRACK 22 OF HOUR-10 DATA. ALTITUDE INDICATED IN HUNDREDS OF FEET

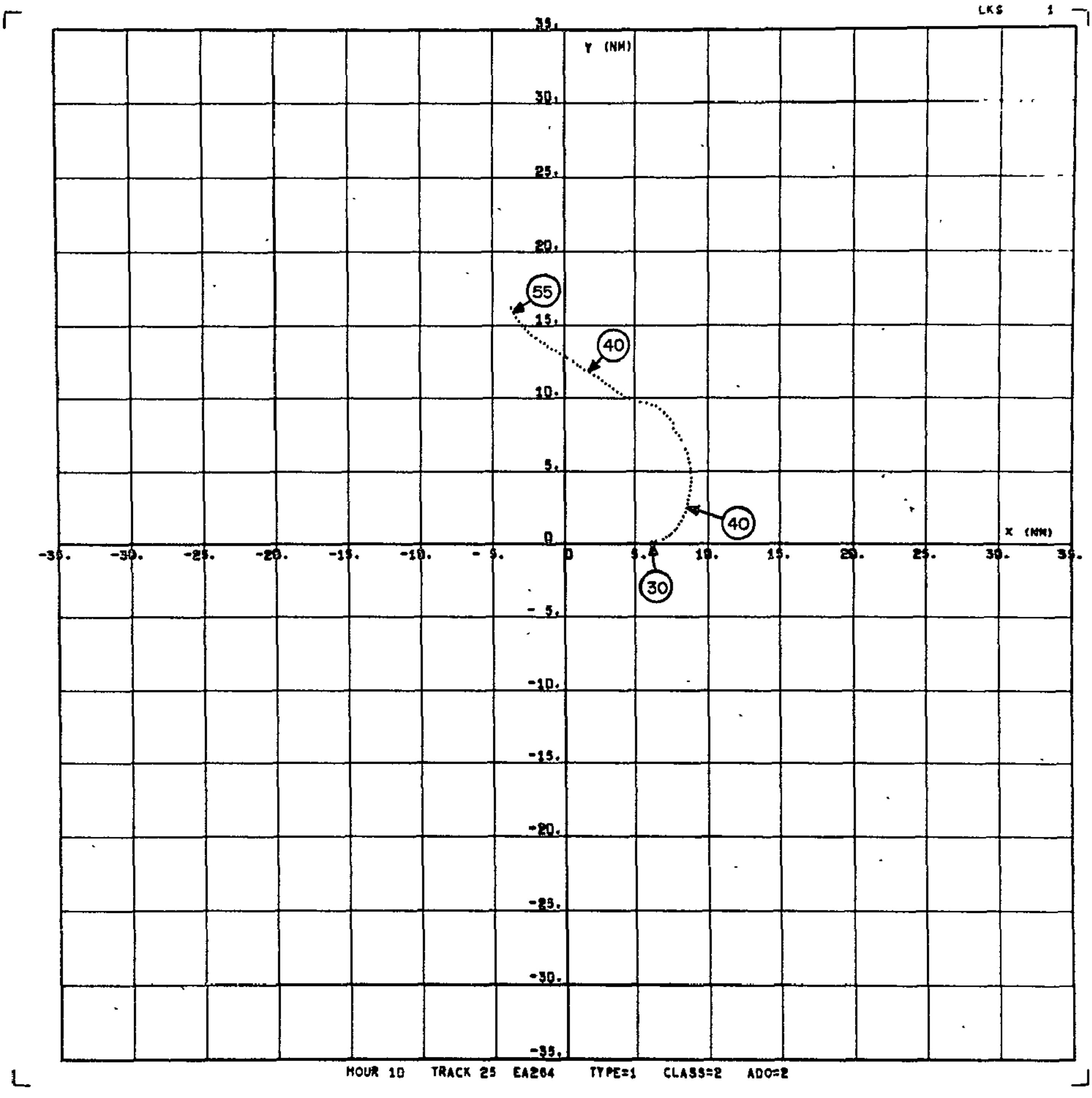
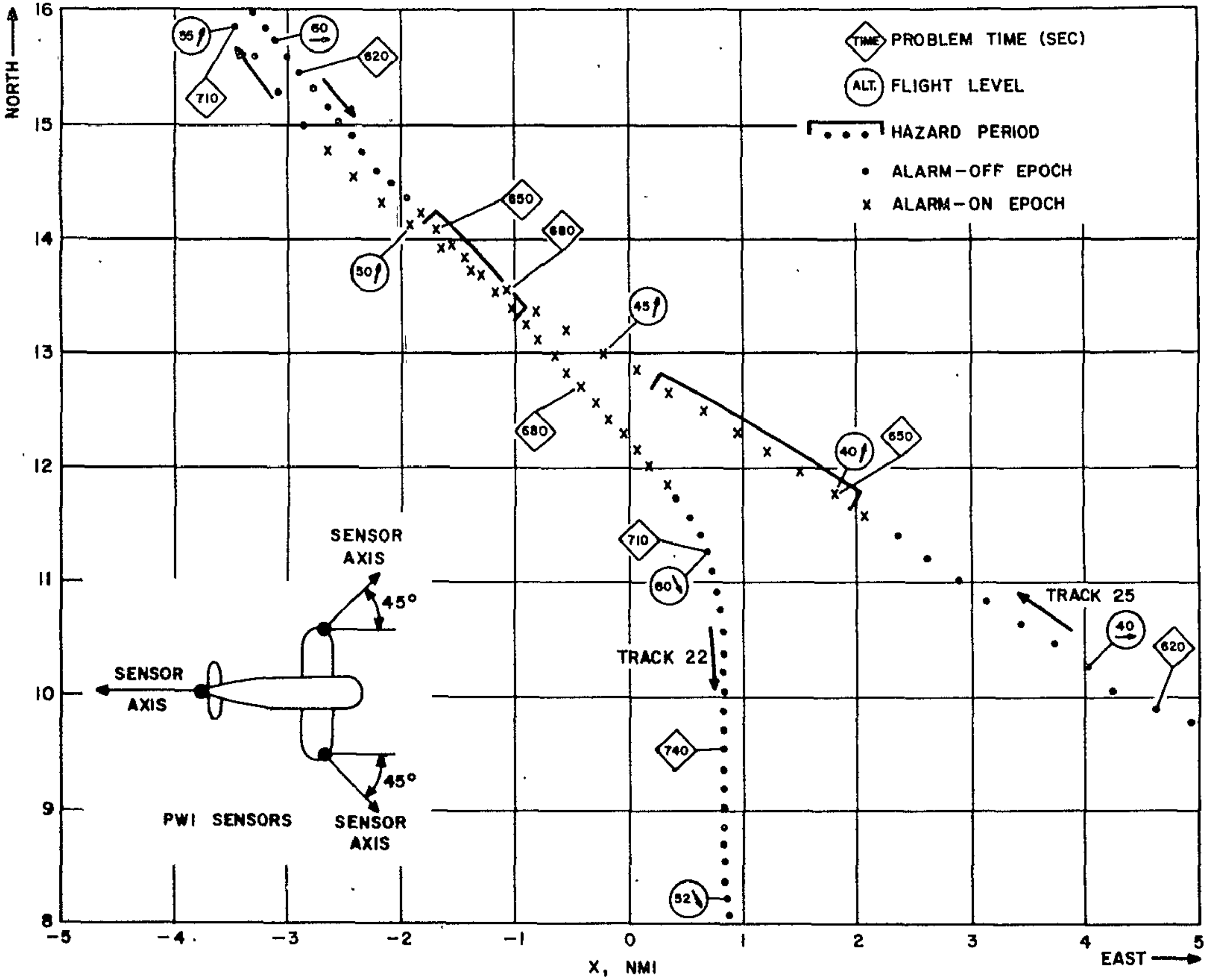
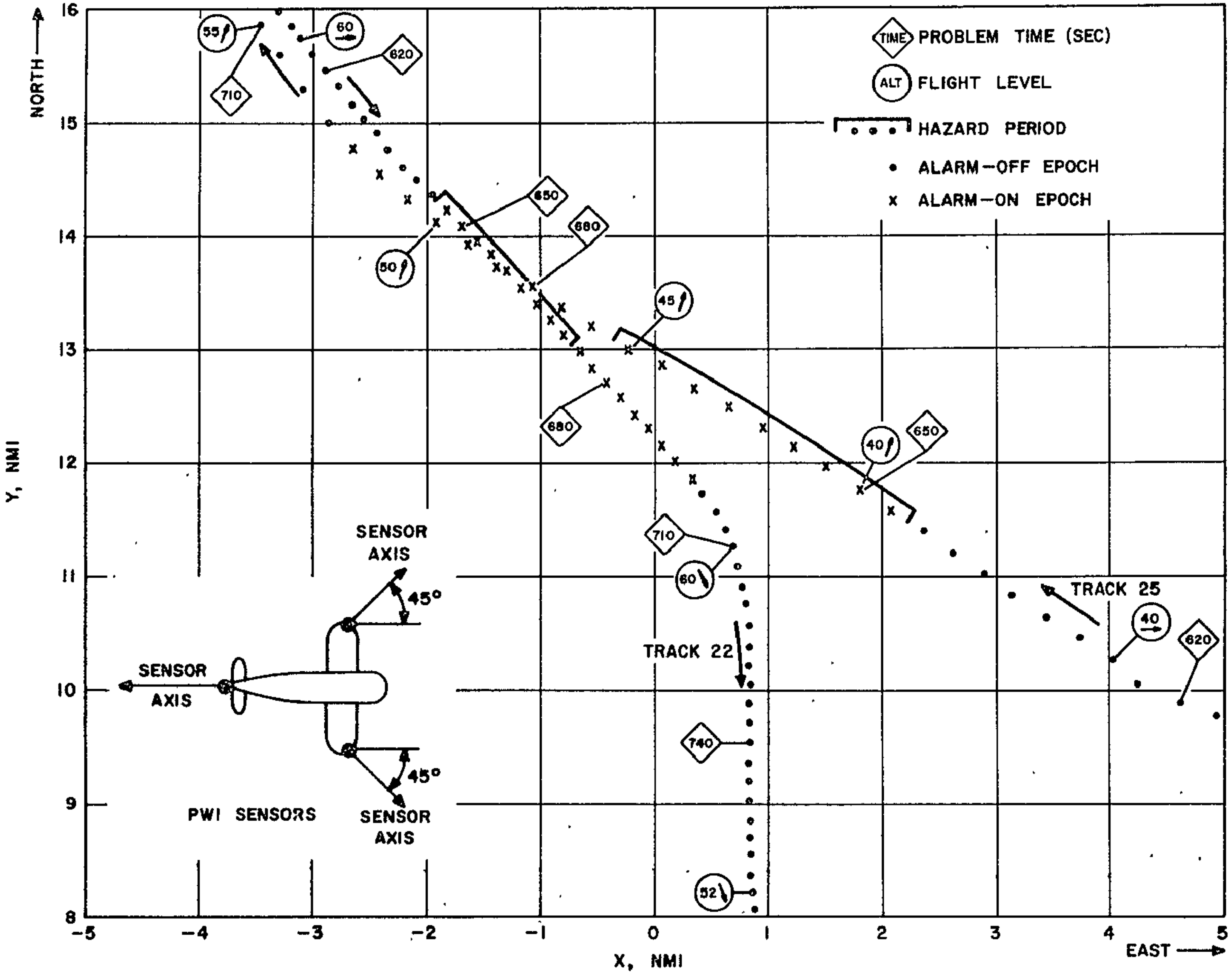


Figure 14. TRACK 25 OF HOUR-10 DATA. ALTITUDE INDICATED IN HUNDREDS OF FEET



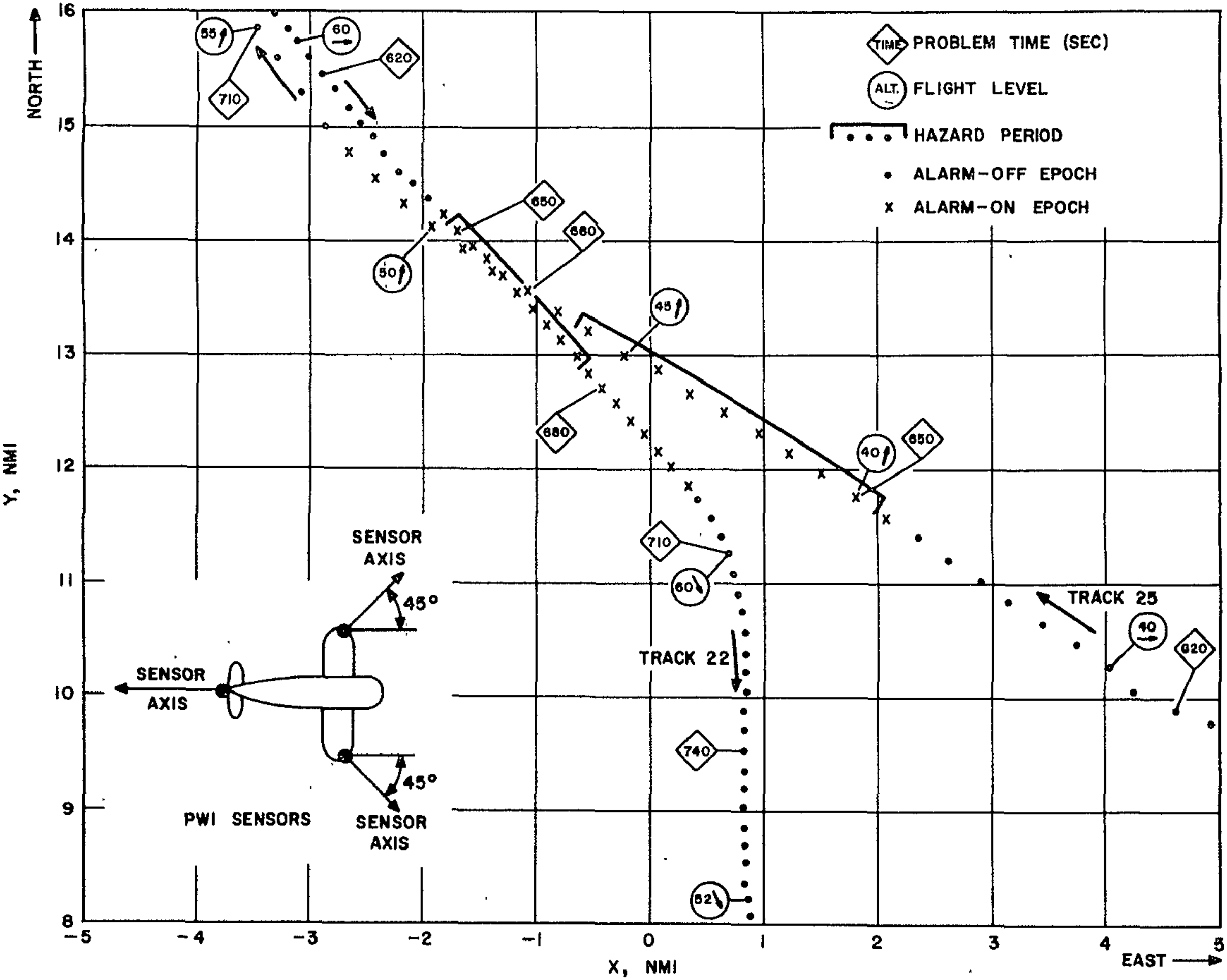
a. Acceleration hazard criterion; 20 sec, 1g total

Figure 15. CONFLICT HISTORY BETWEEN AIRCRAFT 22 AND 25.
ALARM RANGE STRAIGHT AHEAD 5 NMI



b. Tan hazard criterion; 30 sec.

Figure 15. (CONTINUED)



c. Modified-tan hazard criterion; 20 sec, 1.06 nmi

Figure 15. (CONCLUDED)

6 epochs through the 665-sec epoch. Only one alarm epoch precedes the onset of the acceleration hazard. (This is very good; but it would be premature to conclude from this one encounter that the sensor configuration and sensitivity are acceptable.) The alarm remains on for both aircraft for 11 epochs after the acceleration hazard ends. This would tend to indicate that the rearward-looking sensors have too great a range (although, again, this conclusion is premature until more hazard situations are examined).

The hazard period defined by the tau criterion with a 30-sec warning time is indicated in Figure 15b. Based on this hazard criterion, the duration of the hazard is 9 epochs, or 50 percent longer than the duration of the acceleration hazard. The alarm goes on at the first hazard epoch. After the hazard period has ended, the alarm remains on for 9 epochs.

The hazard period as defined by the modified-tau criterion with a 20-sec warning time and a distance d of 1.06 nmi is indicated in Figure 15c. The duration of the hazard period is the same as for the tau criterion, 9 epochs, but it is delayed in time by one epoch. The alarm goes on one epoch before the onset of the modified-tau hazard and remains on for 8 epochs after this hazard terminates.

Based on these three hazard criteria, the PWI system alarms quite well for this particular situation. The alarm lingers on too long, but this would be readily corrected by reducing the sensitivity of the rearward sensor.

A few remarks are appropriate on the various hazard criteria used in these comparisons. The range-altitude criterion, the tau criterion, and the modified-tau criterion are compared in the range-range rate graph of Figure 16 with the parameters used. For the particular encounter shown in Figure 15, the closing velocity initially is about 620 knots. At this high a closing velocity, the tau criterion indicates a hazard first, followed by the modified-tau criterion. If the closing velocity is under 382 knots, the modified-tau criterion would indicate a hazard before the tau criterion. The range-altitude criterion does not indicate a hazard for the example of Figure 15 because the aircraft are separated vertically by more than 500 ft. The acceleration criterion is not shown in Figure 16 because it does not have a unique curve in these coordinates. The outer boundary of the FAA/ATA zone 2 criterion is also shown in Figure 16 for comparison.

This is only one conflict situation. Many more conflict situations should be examined to arrive at a satisfactory evaluation of the PWI system. All of the conflicts occurring during the 12-hour data period could be examined individually. This procedure probably would be reasonable if only a few conflicts were encountered. However, for a large number of conflicts, a

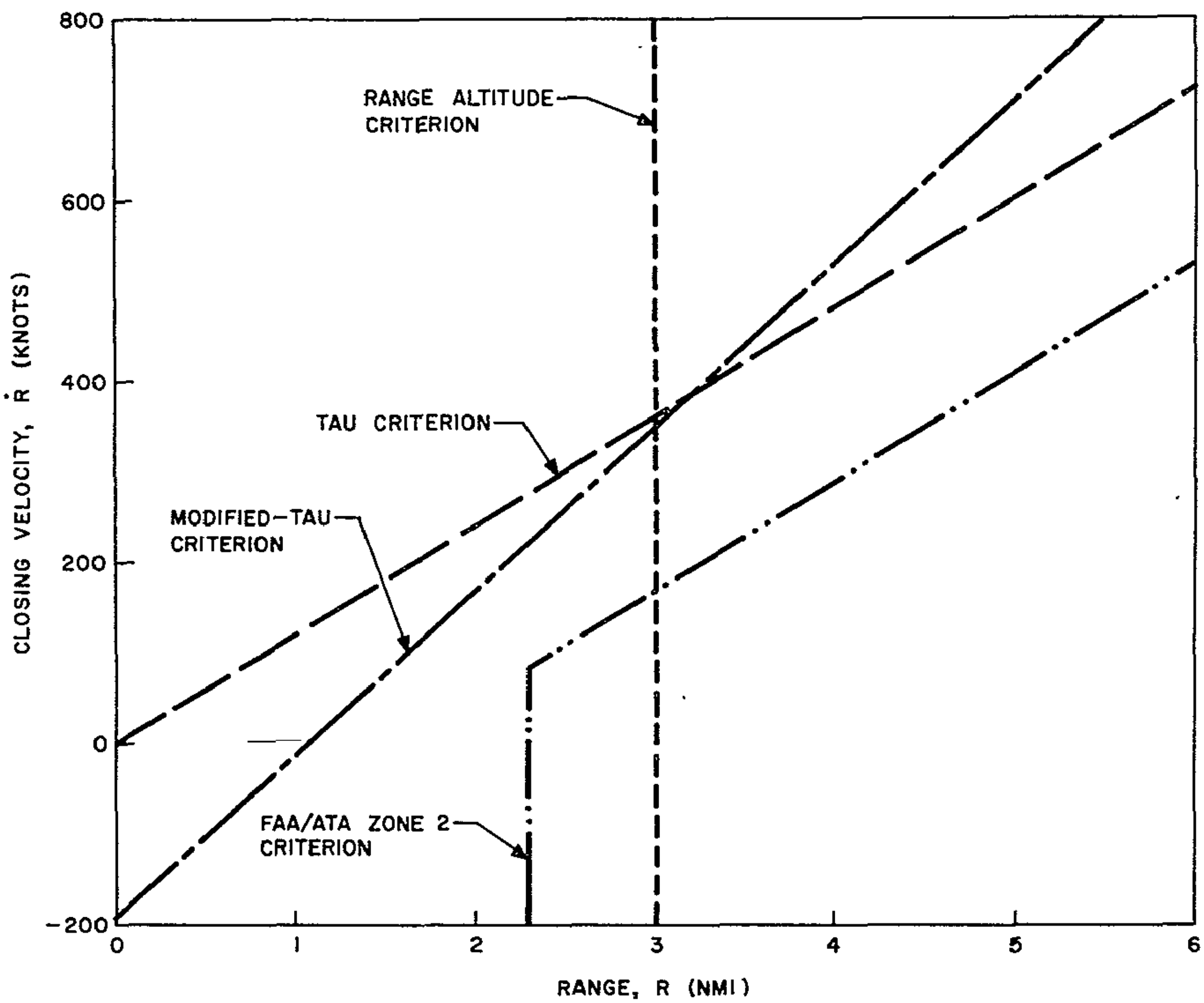


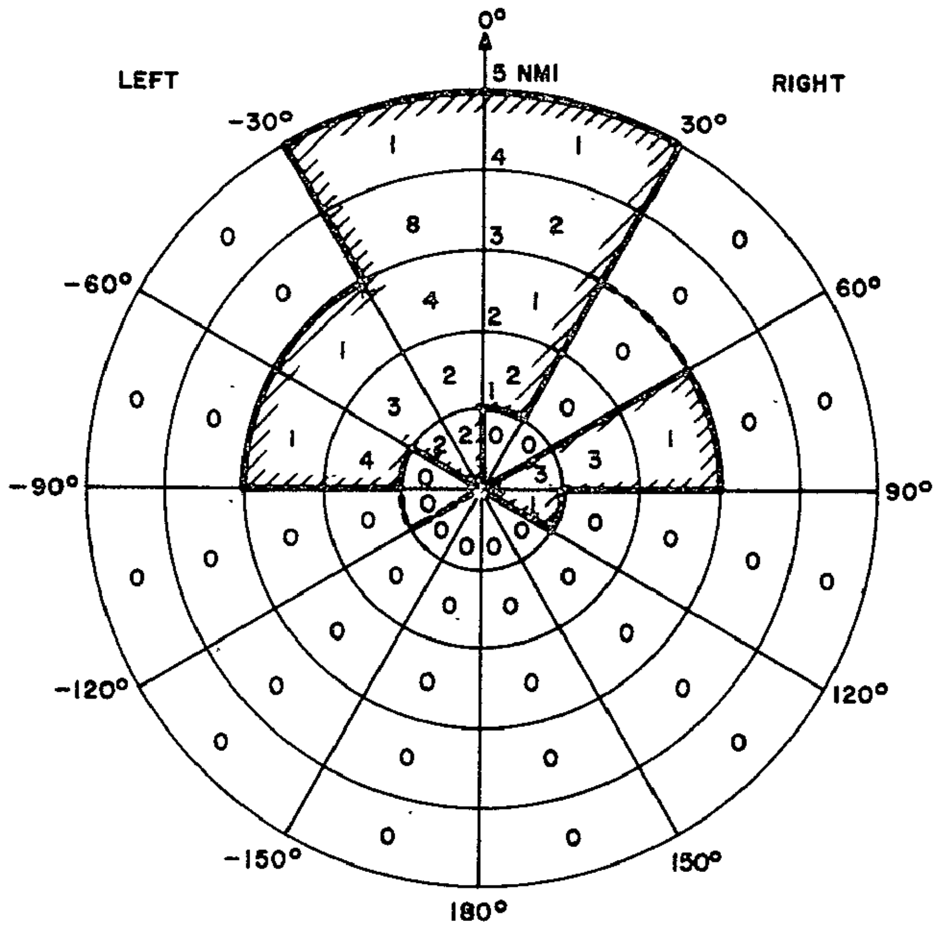
Figure 16. RANGE-RANGE ROLE COMPARISON OF HAZARD CRITERIA

statistical compilation of the conflict data would appear to be advantageous.

AHEP1, wherein the number of valid alarms, false alarms, and missed alarms are counted, is useful for this purpose. This program furnishes an overall tally of the various type alarms and hazards. However, AHEP1 data are not sufficient in themselves for evaluation of PWI parameters because they do not indicate enough about the individual encounters. For example, one long period of false alarms in a single encounter could unduly bias the total number of false alarms. Therefore, along with the statistical data of AHEP1, it would be desirable to tabulate the encounters according to durations of valid alarms, false alarms, etc., which is the function of AHEP2.

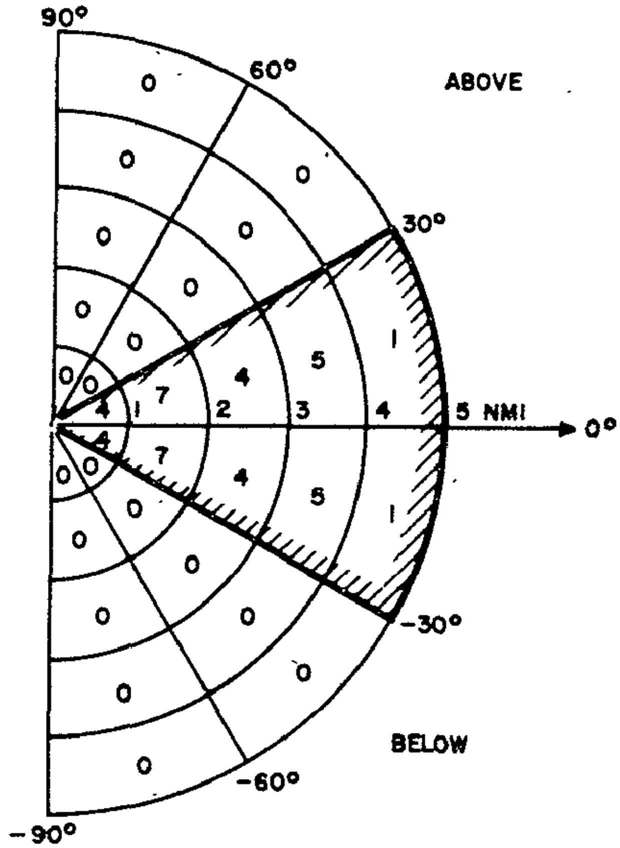
The work described above concerns the evaluation of a particular PWI system in the terminal air traffic. But for the selection of a PWI system it would be helpful, as a design tool, to provide data on the relative positions of threat aircraft which are a collision hazard. This means to collect data on the relative range, azimuth and elevation of aircraft that are identified as collision hazards.

To indicate one way this objective might be met, the Hour-10 output data of the CASTEM program are plotted in the polar coordinates shown in Figure 17. Here the polar coordinates are centered on the protected aircraft and are oriented in the flight



a. Range - azimuth diagram

Figure 17. LOCATION OF COLLISION HAZARDS FOR HOUR-10 TRACKS BASED ON ACCELERATION CRITERION WITH 1g TOTAL RELATIVE ACCELERATION AND 20 SEC. ESCAPE TIME



b. Range - elevation diagram

Figure 17. (CONCLUDED)

direction. In each cell is indicated the number of collision hazard occurrences falling within the particular solid sector element. Each occurrence is defined as one time when a hazard exists. The data in Figure 17 are based on the acceleration hazard criterion for a 1-g total relative acceleration and an escape time of 20 seconds. There is a total of 42 occurrences in the Hour-10 data.

Figure 17a is an azimuthal plot of the hazard occurrences for the elevation angle sector of -30^o to $+30^o$. All of the hazard occurrences fall inside of this elevation sector and within a 5 nmi range. The greatest range for hazard occurrences lies within the azimuthal sector of -30^o to $+30^o$. Laterally, the maximum range of the occurrences decreases. From 30^o to 90^o, the maximum hazard range is only 3 nmi. Only one hazard occurrence falls beyond $\pm 90^o$, and this is within a 1 nmi range.

Figure 17b is an elevation plot of the hazard occurrences for all azimuthal angles. As mentioned, all of the hazard occurrences fall within the elevation sector of -30^o to $+30^o$.

From this examination of various presentations using the Atlanta ARTS Hour-10 data, it is concluded that the CASTE program is a useful tool for (1) the evaluation of a particular configuration of a PWI system and (2) the selection of a PWI to meet the collision threat situation existing in realistic terminal air traffic. The employment of the CASTE program to fulfill these two objectives will be the subject of the succeeding study.

APPENDIX A

FAA DATA PREPROCESSOR PROGRAM (PREPR2)

This program reads an FAA Atlanta ARTS BCD smoothed-data tape and produces a data tape in the format required for the CASTEM program input.

The FAA tapes list smoothed data at 3-second time intervals for all radar-identified aircraft. Each input record contains the track data in the format indicated in Table A1. Each record contains the data for one aircraft at one time. The records are grouped in sequence of track number at one time, and the record groups are in time sequence.

Several comments are in order concerning the values of the variables in Table A1. The FAA fitted the radar data using a smoothing technique, providing fitted data at one-second intervals. Data points are provided on the tape for all active tracks at 3-second intervals except when data points from the smoothing process are missing, say at time n. When this occurs, data are entered on the tape at the n + 1 second time. The tape data then return to the regular 3-second time at n + 3 after this one irregular jump. When data points are found to be missing at time n, and when the n + 1 list is incomplete, and the data points which are missing are found in the n + 1 list appear in the n + 3 list, the values in the heading column H(I) are zero. Irregularities in the velocity are also found on the tape. A minus sign preceding the velocity indicates that the value is different from the preceding value by more than 10%. Also, the first time a track appears, the velocity value is indicated as zero; the next velocity listed for that track is flagged with a minus sign.

TABLE A1

FAA ATLANTA ARTS SMOOTHED-DATA TAPE RECORD

PREPR2 FORTRAN Symbol	BCD Format	Description
Blank	IX	Spacing on tape
T	F11.1	Time t, initialized at beginning of hour (sec)
Blanks	2X	Spacing on tape
NT	I6	Track number
Blanks	4X	Spacing on tape
X	E20.8	x position (nmi)
Y	E20.8	y position (nmi)
Z	E20.8	Altitude z (ft)
V	F20.2	Velocity V (kts)
H	F20.2	Heading χ (deg)

There are no special start or stop indications on the FAA tape. The PREPR2 program tests each record to see if the final track, final time condition exists to determine the end of the tape.

The beginning of the PREPR2 output tape is indicated by a (-10, -10) record. Where there are no tracks or only one track at a given time, this is designated by a (-10, -10) record. Where there are more than one aircraft at a given time, a record is put on the PREPR2 output tape which designates time in seconds and number of tracks (LT(NUP), NUP). Following this header record, there is a record for the data on each track at that time. These data are listed in Table A2. (At the present time the roll angle is set to zero in PREPR2, because the FAA smoothed data is not sufficiently smooth to give reasonable roll angle histories using second differences.) The end of the PREPR2 output tape is indicated by a header record containing (-25, -25). This is followed by two END OF FILE statements.

For the convenience of the person running the PREPR2 program, printed output is provided to allow inspection of the results. These printed data are the same as in Table A2.

Operation of program PREPR2 using IBM 7094 systems and an FAA ARTS smoothed-data tape can be done using FORTRAN logical units as described in Table A3. Use of PREPR2 with FAA Atlanta ARTS Hour-10 data required 16 minutes of machine time.

TABLE A2

PREPR2 BINARY OUTPUT TAPE DATA

FORTRAN Symbol	Description
Time and Number of Tracks	
LT	Time (sec)
NUP	Number of tracks at time LT
Track Data	
NTSAVE	Track number
XSAVE	x position (nmi)
YSAVE	y position (nmi)
ZSAVE	Altitude z (ft)
VX	$\dot{x}$ velocity (kts)
VY	$\dot{y}$ velocity (kts)
VZ	$\dot{z}$ velocity (kts)
ROLL	Bank angle ϕ (rad)

TABLE A3

PREPR2 TAPES

Description	FORTRAN Logical Unit No.
FAA ARTS smoothed-data tape, BCD	11
PREPR2 output tape, binary	9
System output	6

APPENDIX B

INTRUDER PREPROCESSOR PROGRAM (INTRDR)

Program INTRDR generates tracks of intruder aircraft using punch card sequences of maneuver instructions specified by the engineer. The output of the program is a binary tape with the same types of information and format as the output tape generated by the PREPR2 program, Table A2.

Three basic kinds of maneuvers can be specified, referred to as maneuver types one, two, or three. These represent, respectively, rectilinear flight, constant radius turns, and constant heading rate turns. An intruder aircraft track consists of a sequence of legs, each leg having one maneuver.

For each leg, constant acceleration is specified in the forward direction of the flight path. The flight path elevation-angle is also specified for each leg.

The initial location, velocity, heading, and flight path elevation angle are specified for the first leg. A stop condition is specified for each leg so that the INTRDR program can calculate the initial values for the next leg of the intruder track.

Instructions for preparing the punch card input to the INTRDR program are described below with reference to the card layouts shown in Table B1.

TABLE B1

INTRDR INPUT CARD DATA

Card Type	FORTRAN Symbol	Card Format	Description and Controls
1	IT	I12	Output list start time (sec)
2	NT INCT	2I12	Number of intruders Time increment Δt (sec)
3	ID NML	2I12	Intruder track number Number of legs
4	TTI XI YI ZI VI HI	6F12.1	Track start time (sec) Initial x position (nmi) Initial y position (nmi) Initial z altitude (ft) Initial velocity V (kts) Initial heading χ (deg)
5	NEQ	I10	Maneuver type for leg 1 = rectilinear flight 2 = constant radius turn 3 = constant rate turn
	ITYP	I10	Stop type for leg 1 = time interval (sec) 2 = x position (nmi) 3 = y position (nmi) 4 = z altitude (ft) 5 = heading χ (deg) 6 = velocity V (kts)
	STOP	F10.1	Numerical value for stop parameter in appropriate units
	VDOT	F10.1	Acceleration $\dot{V}$ along flight path (g's)
	GAMMA	F10.1	Flight path elevation angle γ (deg)
	HDOT	F10.1	Heading rate $\dot{\chi}$ (deg/sec)
	R	F10.1	Radius of curvature R (nmi)

There are five types of intruder track input cards. Type 1 card specifies IT, the time when the output tape is to start listing. The start time IT must be equal to the start time of the first intruder, whichever intruder starts first. Type 2 card lists NT, the total number of intruder tracks and INCT, the time increment (sec) for the output tape data.

Type 3 card specifies the particular intruder track number ID and the number of legs for that track NML. Type 4 card specifies the initial conditions for a particular track including TTI, track start time (sec); XI (nmi), YI (nmi), ZI (ft) position; VI, the velocity (kts); and HI, the heading clockwise from North (deg).

Type 5 card specifies NEQ, the type of maneuver for a given leg; ITYP, the type of stop parameter for that leg; STOP, the numerical value of the stop parameter, in appropriate units; VDOT, the acceleration along the flight path (g's); GAMMA, flight path elevation angle (deg); HDOT, heading rate (deg/sec) with clockwise turns positive; and R, the radius of curvature (nmi) in the horizontal plane, positive for clockwise turns. The maneuver type NEQ and the stop type are each designated by a single number. The value of the heading rate HDOT is only specified with maneuver type 3, and the value of the radius of curvature R is only specified with maneuver type 2.

The correct sequence of input data cards must be observed. In each run, one Type 1 card and one Type 2 card are placed first, in that order. These cards are followed by a group of Type 3, 4 and 5 cards for each intruder, one group per intruder. Within each group there is one Type 3 card, one Type 4 card, followed by as many Type 5 cards as there are maneuver legs for the intruder. The card group for one intruder is followed by the card group for the another intruder, etc.

A sample set of input cards is shown in Table B2. This set demonstrates card sequencing for three intruders which have 2, 4, and 1 legs, respectively.

The (binary) output tape produced by INTRDR has exactly the same format as the (binary) output tape produced by PREPR2. (See Appendix A for details). It is possible, however, to prepare an INTRDR output tape for a single intruder aircraft at one time, whereas the PREPR2 output tape only gives aircraft data if there are two or more aircraft present. The reason for the latter is that these are the data provided on the FAA/NAFEC ARTS tapes. It is possible however, to prepare an INTRDR output tape for a single intruder. This capability allows program CASTEM to be run with an intruder tape for a single intruder at the same time as the PREPR2 output tape is being run, to test the effect of an intruder on the terminal area alarms and hazards.

TABLE B2

SAMPLE INTRDR INPUT CARD LAYOUT

Card Sequence	Card Type		Variables, Parameters, Controls
1	Control Cards	1	IT
2		2	NT , INCT
3	First Intruder	3	ID_1 , NML_1
4		4	TTI_1, XI_1, YI_1, ZI_1, VI_1, HI_1
5		5 (leg 1)	NEQ_{11}, $ITYP_{11}$, $STOP_{11}$, $VDOT_{11}$, $GAMMA_{11}$, $HDOT_{11}$, R_{11}
6		5 (leg 2)	NEQ_{12}, $ITYP_{12}$, $STOP_{12}$, $VDOT_{12}$, $GAMMA_{12}$, $HDOT_{12}$, R_{12}
7	Second Intruder	3	ID_2, NML_2
8		4	TTI_2, XI_2, YI_2, ZI_2, VI_2, HI_2
9		5 (leg 1)	NEQ_{21}, $ITYP_{21}$, $STOP_{21}$, $VDOT_{21}$, $GAMMA_{21}$, $HDOT_{21}$, R_{21}
10		5 (leg 2)	NEQ_{22}, $ITYP_{22}$, $STOP_{22}$, $VDOT_{22}$, $GAMMA_{22}$, $HDOT_{22}$, R_{22}
11		5 (leg 3)	NEQ_{23}, $ITYP_{23}$, $STOP_{23}$, $VDOT_{23}$, $GAMMA_{23}$, $HDOT_{23}$, R_{23}
12		5 (leg 4)	NEQ_{24}, $ITYP_{24}$, $STOP_{24}$, $VDOT_{24}$, $GAMMA_{24}$, $HDOT_{24}$, R_{24}
13	Third Intruder	3	ID_3, NML_3
14		4	TTI_3, XI_3, YI_3, ZI_3, VI_3, HI_3
15		5 (leg 1)	NEQ_{31}, $ITYP_{31}$, $STOP_{31}$, $VDOT_{31}$, $GAMMA_{31}$, $HDOT_{31}$, R_{31}

For the convenience of the user of the INTRDR program, printed output is prepared by the program to allow inspection of the results, Table B3. These data consist of initial conditions (Type 4 input card information) and leg specifications (Type 5 input card information) for all legs of each intruder. Following these data are a listing for each intruder of the computed initial conditions for each leg and a listing of the computed terminal conditions for the last leg. These data start with time (sec) followed by track number, x (nmi), y (nmi), z (nmi) positions; $\dot{x}$ (kts), $\dot{y}$ (kts), $\dot{z}$ (kts) velocities; and ϕ roll angle (rad). These data are followed by a listing for each time interval of the data for each intruder. The time appears first, followed by the data for each intruder: track number, x, y, z, $\dot{x}$, $\dot{y}$, $\dot{z}$, and ϕ.

Operation of INTRDR using IBM 7094 systems is accomplished using FORTRAN logical units as described in Table B4. Use of INTRDR and a fairly complex set of maneuvers for three intruders required 2 minutes of machine time.

TABLE B3

INTRDR PRINTED OUTPUT DATA

FORTRAN Symbol	Description
a. Initial Conditions and Maneuver Specifications	
	Type 4 Input card information
TTI	Track start time (sec)
XI	Initial x position (nmi)
YI	Initial y position (nmi)
ZI	Initial z altitude (ft)
VI	Initial velocity V (kts)
HI	Initial heading χ (deg)
	Type 5 Input card information
NEQ	Maneuver type for leg
ITYP	Stop type for leg
STOP	Numerical value for stop parameter
VD	Acceleration $\dot{V}$ (g's)
GR	Flight path elevation angle γ (deg)
HD	Heading rate χ (deg/sec)
R	Radius of curvature R (nmi)
	Terminal conditions for each leg
TSTO	Time (sec)
IDSTO	Track identification number
XX	x position (nmi)
YY	y position (nmi)
ZZ	z altitude (nmi)
VX	$\dot{x}$ velocity (kts)
VY	$\dot{y}$ velocity (kts)
VZ	$\dot{z}$ velocity (kts)
ROLL	Bank angle ϕ (rad)
b. Data for each time	
	Time and number of tracks
ITS	Time (sec)
INDEX	Number of track at time ITS

TABLE B3 (Cont'd)

FORTRAN Symbol	Description
	Track data
IDS	Track identification number
XS	x position (nmi)
YS	y position (nmi)
ZS	z altitude (ft)
VXS	$\dot{x}$ velocity (kts)
VYS	$\dot{y}$ velocity (kts)
VZS	$\dot{z}$ velocity (kts)
ROLLS	Bank angle ϕ (rad)

TABLE B4

INTRDR CARDS AND TAPES

Description	FORTRAN Logical Unit No.
Input cards	5
INTRDR output tape, binary	9
System output	6

APPENDIX C

CASTE MAIN PROGRAM (CASTEM)

The CASTE main program (CASTEM) uses as input either the PREPR2 output tape, INTRDR output tape, or both tapes. Program CASTEM determines times when alarms are generated by the CAS being simulated or times when hazard conditions exist, as defined by the hazard criteria. The hazard conditions are determined in the HAZARD CALCULATION subroutine, and the CAS simulation is performed in the CAS COMPUTER SIMULATION subroutine. All input-output functions and most geometrical calculations are performed in TERMINAL AIR TRAFFIC SIMULATION.

Four hazard criteria, defined in Section 3.4.2, have been programmed: the range-altitude guard criterion, the acceleration criterion, the tau criterion, and the modified-tau criterion.

Currently, program CASTEM simulates operation of the NASA/ERC optical/IR PWI.

The format of the input tapes has been described in Appendices A and B. The input parameters and program controls are read into the program in three namelists. The first namelist is called NAMM, the second NAMH, and third NAME. These are associated with the CASTEM executive routine, the hazard subroutine, and the NASA/ERC PWI subroutine, respectively. A summary of the data in these three namelists is given in Table C1.

TABLE C1

CASTEM NAMELIST CARD DESCRIPTION

FORTRAN Symbol	Description
a. Namelist NAMM - main program	
NRUN	Run number (negative NRUN stops automatic continuation of runs)
INCT	Input tape time interval (sec), 3 sec for most runs
NSYS	Program control 0 denotes CAS simulation only 1 denotes CAS simulation and hazard calculation 2 denotes hazard calculation only
ISTART	Time CASTEM program is to start reading PREPR2* output tape (sec)
ISTOP	Time CASTEM is to stop reading PREPR2* output tape (sec)
IS	Time CASTEM is to start reading INTRDR output tape (sec); set negative if only PREPR2 output tape is to be used
NSUB	CAS subroutine control 1 reserved for other CAS 2 NASA/ERC PWI subroutine
PAA	Sensor alarm threshold
ITAPE	Output control 0 denotes no binary tape output 1 denotes binary tape output
INTS	Time CASTEM is to stop reading INTRDR output tape (sec); set negative if only PREPR2 or INTRDR output tape is to be used

*INTRDR output tape if PREPR2 output tape is not used.

TABLE C1 (Cont'd)

FORTRAN Symbol	Description
b. Namelist NAMH - hazard subroutine	
D3	d in the modified-tau criterion (nmi)
TE2	τ_{crit} in the tau criterion (sec)
TE3	$(\tau_{mod})_{crit}$ in the modified-tau criterion (sec)
TE4	t_e in the acceleration criterion (sec)
ATOT	a_{tot} in the acceleration criterion (g's)
FAAH	Δz_{haz} in the range-altitude guard criterion (ft)
FAAR	R_{haz} in the range-altitude guard criterion (nmi)
c. Namelist NAME - NASA/ERC PWI subroutine	
RO	Characteristic length R_o of atmospheric attenuation of beacon signal in Eq.(5) (nmi)
A1,B1,C1	Direction angles for sensor no. 1, Fig. 11 , (deg)
A2,B2,C2	Direction angles for sensor no. 2
A3,B3,C3	Direction angles for sensor no. 3
CA1,CA2,CA3	Gain parameters A_1, A_2, A_3 in Eq. (5)
CB1,CB2,CB3	Optical parameters B_1, B_2, B_3 in Eq. (5)

The sequencing of the namelist cards is important, and it depends on the values of NSYS and NSUB. Table C2 has been prepared to list the sequences of namelists that may be required with the current form of program CASTEM.

It is important to note that the program starts a new run automatically if the namelist cards for the new run are stacked in their correct sequence behind the namelist cards of the preceding run. To stop this automatic feature, a namelist NAMM card with a negative run number must be placed after the namelists of the last desired run.

Program CASTEM produces several kinds of output: a binary output tape, for evaluation by the ALARM AND HAZARD EVALUATION programs, and several forms of printed output.

The binary tape is prepared for statistical analysis of the alarm and hazard data. To obtain the binary tape set NSYS = 1, NSUB = 2, and ITAPE = 1. The contents of a line of the binary tape are described in Table C3.

The printed output that appears for NSYS = 1, NSUB = 2 and either ITAPE = 0 or 1 is referred to as normal printed output; it is much more detailed in scope than the binary output. It includes lists of the values of the controls and parameters in namelists NAMM, NAME, and NAMH. Following these lists is a line-by-line printout of the binary tape output data, but with

TABLE C2

NAMELIST SEQUENCES

NSYS	NSUB	Namelist Sequence	Comments
0	1		(reserved for alternate CAS)
0	2	NAMM,** NAME	NASA/ERC PWI simulation only
1	1		(reserved for alternate CAS)
1	2	NAMM,** NAME, NAMH	NASA/ERC PWI simulation and hazard calculation
2	*	NAMM,** NAMH	Hazard calculation only

*No number needed

**NAMM is followed by a title card

TABLE C3

CASTEM TAPE OUTPUT DATA

FORTRAN Symbol	Description
ISTOP	Initialization record
IT	Time
NT(I)	Track number of protected aircraft i
NT(J)	Track number of threat aircraft j
ALARM(I,J)	Sensor signal P_{ij} received by i from j
LFAA(I,J)	Range-altitude guard criterion indicator for aircraft pair i, j 0 = no hazard 1 = hazard
LTAU(I,J)	Value of tau for aircraft pair i,j (sec)
LTM(I,J)	Tau-mod. criterion indicator for aircraft pair i,j 0 = no hazard 1 = hazard
LACC(I,J)	Acceleration criterion indicator for aircraft pair i,j 0 = no hazard 1 = hazard

additional geometric data about the aircraft pair under consideration. These data are described in Table C4.

Two other kinds of printed output can be obtained. By specifying NSYS = 0 and NSUB = 2, the printed output described in Table A10 is obtained, except that LFAA(I,J), TAU (I,J), LTM(I,J), and LACC(I,J) are deleted. The corresponding output for hazard evaluation only is obtained by specifying NSYS = 2. The printed output for this case contains only IT, NT(I), NT(J), LFAA(I,J), LTAU(I,J), LTM(I,J) and LACC(I,J).

Operation of program CASTEM using IBM 7094 systems can be done using FORTRAN logical units as described in Table C5. Computation of program CASTEM using a PREPR2 output tape prepared from Hour-10 data required 20 minutes of machine time.

TABLE C4

CASTEM PRINTED OUTPUT DATA

FORTRAN Symbol	Description
IT	Time (sec)
NT(I)	Track number of protected aircraft i
NT(J)	Track number of threat aircraft j
R(I,J)	Range R_{ij} from i to j (nmi)
IVC	Closing velocity $V_{c_{ij}}$ between i and j (kts)
AZOUT	Azimuth angle Θ_{ij} of j relative to i (deg)
ELOUT	Elevation angle Φ_{ij} of j relative to i (deg)
X(I)	x_i position of protected aircraft (nmi)
Y(I)	y_i position of protected aircraft (nmi)
IZ	Altitude z_i of protected aircraft (ft)
X(J)	x_j position of threat aircraft (nmi)
Y(J)	y_j position of threat aircraft (nmi)
JZ	Altitude z_j of threat aircraft (ft)
IV	Velocity V_i of protected aircraft (kts)
JV	Velocity V_j of threat aircraft (kts)
ITI	Heading χ_i of protected aircraft (deg)
ITJ	Heading χ_j of threat aircraft (deg)
ICP1	Angle ψ_1 for aircraft j relative to aircraft i (deg)
ICP2	Angle ψ_2 for aircraft j relative to aircraft i (deg)
ICP3	Angle ψ_3 for aircraft j relative to aircraft i (deg)
ALARM(I,J)	Sensor power P_{ij} received by aircraft i from aircraft j

TABLE C4 (Cont'd)

FORTRAN Symbol	Description
LFAA(I,J)	Range-altitude guard criterion indicator for aircraft pair i,j 0 = no hazard 1 = hazard
LTAU(I,J)	Value of tau for aircraft pair i,j (sec)
LTM(I,J)	Tau-mod criterion indicator for aircraft pair i,j 0 = no hazard 1 = hazard
LACC(I,J)	Acceleration criterion indicator for aircraft pair i,j 0 = no hazard 1 = hazard

TABLE C5

CASTEM CARDS AND TAPES

Description	FORTRAN Logical Unit No.
Case 1 - Input: PREPR2 output tape only	
Namelists	5
Normal printed output, CAS simulation only, or hazard calculation only	6
PREPR2 output tape, binary	9
CASTEM output tape, binary	10
Case 2 - Input: PREPR2 output tape and INTRDR output tape	
Namelists	5
Normal printed output, CAS simulation only, or hazard calculation only	6
PREPR2 output tape, binary	9
INTRDR output tape, binary	8
CASTEM output tape, binary	10
Case 3 - Input: INTRDR output tape only	
Namelists	5
Normal printed output, CAS simulation only, or hazard calculation only	6
INTRDR output tape, binary	9
CASTEM output tape, binary	10

APPENDIX D

ALARM AND HAZARD EVALUATION PROGRAMS (AHEP1, AHEP2)

Two programs have been written to evaluate the binary output tape data from CASTEM. The first program, AHEP1, counts the number of times on the CASTEM tape that there are alarms, hazards, valid alarms, false alarms and missed alarms. The ratios of the number of valid alarm times, false alarm times, and missed alarm times to the number of hazard times is computed; these ratios are Q, R, and S, respectively.

There are four inputs to the AHEP1 program. These are placed on one card as listed in Table D1.

Operation of the AHEP1 program using IBM 7094 systems can be done using FORTRAN logical units as described in Table D2. Use of AHEP1 for evaluating the CASTEM tape for the FAA Atlanta ARTS Hour-10 data required less than 7 minutes of machine time.

The second program, AHEP2, computes statistical quantities from the CASTEM output data. First, the program computes the frequency distributions of the durations of uninterrupted alarms, hazards, valid alarms, missed alarms, and false alarms. From the frequency distributions of these durations, the distribution functions and the complementary distribution functions, as defined in Section 3.6, are calculated.

There are three types of input information cards to the AHEP2 program. The input information cards are described in Table D3. The Type 1 card gives the number of track numbers listed on the Type 2 cards. The Type 2 cards list the track numbers of all aircraft involved in alarms or hazards during the time evaluated by the CASTEM program. Note that the list size must be at most 63 due to storage limitations of the 7094 computer. As many Type 2 cards as are necessary to list the aircraft must be used. The Type 3 card indicates the hazard criterion to be employed in the evaluation. If the evaluation is to be made for several hazard criteria, then Type 3 cards with appropriate controls and parameters are stacked. The final Type 3 card has the value zero, which serves as a stop command.

The output of the various distribution functions calculated by AHEP2 is tabular in form. An index K going from 1 to 50 (0 to 49 for the complementary distribution function) represents the number of successive times of alarms, hazards, etc. The time durations are obtained by multiplying K by the time interval of the CASTEM evaluation. In the case of the frequency distribution functions, the number of aircraft having, for example, hazard durations of length K is tabulated as NTH(K). Note that all durations of greater than 50 are put in the 50 slot. For the distribution function of hazard durations, NDTH(K) is the number of hazard durations less than or equal to K. NDTH(K) is

TABLE D1

AHEP1 INPUT CARD DATA*

FORTRAN Symbol	Format	Description
N	I12	Hazard criterion control 1 = Range-altitude guard criterion 2 = Tau criterion 3 = Modified-tau criterion 4 = Acceleration criterion
IT2	I12	Critical value of tau for tau criterion (sec)
P	F12.1	Value of alarm threshold (should be same as PAA in CASTEM)
IS	I12	Stop time of CASTEM tape. To evaluate, entire tape should be set to -100

*One card

TABLE D2

AHEP1 AND AHEP2 CARDS AND TAPES

Description	FORTRAN Logical Unit No.
Input card	5
CASTEM output tape, binary	10
System output	6

TABLE D3

AHEP2 INPUT CARD DATA

Card Type	FORTRAN Symbols	Card Format	Description
1	NAC	I12	Number of track numbers in list (NAC must be no greater than 63)
2	ID(1) ID(2) ID(3) ID(4) ID(5) ID(6) ⋮ ID(NAC)	6I12	Track numbers of aircraft giving rise to alarms or hazards on the CASTEM tape. As many type-2 cards as are necessary to list NAC aircraft must be used
3	NTYPE	I12	Hazard criterion control 0 = program stop command 1 = range-altitude guard criterion 2 = tau criterion 3 = modified-tau criterion 4 = acceleration criterion
	PA	F12.1	Value of alarm threshold (should be same as PAA used in CASTEM)
	TAUC	F12.1	Value of tau critical for tau criterion (sec)

therefore the summation from 1 to K of NTH(K). Similarly, the complementary distribution function of hazard durations, written as NCTH(K), is the number of hazard durations greater than K, or NDTH(50) - NDTH(K). Table D4 has been prepared to summarize the nomenclature for the various distribution functions.

Operation of AHEP2 using IBM 7094 systems can be done using FORTRAN logical units as described in Table D3. Use of AHEP2 for evaluating the CASTEM tape for the FAA Atlanta ARTS Hour-10 data required 75 minutes of machine time.

TABLE D4

SYMBOLS USED FOR DISTRIBUTION FUNCTIONS

Description	Frequency Distribution Function	Distribution Function	Complementary Distribution Function
Alarms	NTA(K)	NDTA(K)	NCTA(K)
Hazards	NTH(K)	NDTH(K)	NCTH(K)
Valid Alarms	NTHA(K)	NDTHA(K)	NCTHA(K)
Missed Alarms	NTHNA(K)	NDTHNA(K)	NCTHNA(K)
False Alarms	NTNHA(K)	NDTNHA(K)	NCTNHA(K)

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